RESEARCH & DEVELOPMENT

# Cost Analysis on the Reuse of Concrete Residuals

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# FINAL REPORT

**North Carolina Department of Transportation**
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**Cost Analysis on the Reuse of Concrete Residuals**


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16. Abstract

Concrete hydrodemolition and diamond grinding/grooving operations performed for the North Carolina Department of Transportation (NCDOT) generate large amounts of concrete residuals. Currently these residuals can be classified by the North Carolina Department of Environmental Quality (NCDEQ) as Class A Residuals and are treated as "inert debris" thus allowing them to be reused instead of being disposed at Publicly Owned Treatment Works (POTW) and Municipal Solid Waste (MSW) sites. The NCDOT needs to develop a method to compare the potential savings from possible alternatives of disposal such as the use of the concrete residual material as liming amendments on NCDOT right of way highways, Class B residual sites and agricultural applications. Contractors bidding on NCDOT projects need guidance to assist them in identifying available options for concrete residuals based on project locations. As part of this work, best practices for the disposal/reuse of the concrete residual material both from North Carolina and other states were identified. By surveying DOT personnel and contractors, the attributes contributing to the costs of the various alternatives were identified. A benefit-cost analysis (BCA) was performed to investigate potential savings from other alternative options to disposal such as the use of the material as liming amendments on NCDOT right of way highways, Class B residual sites and agricultural applications. Using these attributes, a Benefit-Cost Model (BCM) using Multi-Criteria Analysis was developed that enables the estimation of the costs of disposing and/or reusing concrete residual material that is produced by the hydrodemolition and diamond grinding/grooving processes. In addition to the BCM, a tool was developed that can be used by contractors undertaking such projects to better estimate their costs and to allow them to compare alternatives for the disposal/reuse of the concrete residual material. This model incorporates a risk analysis for the comparison of several feasible alternatives to disposal of concrete residuals, a tool for contractors to use to estimate their anticipated costs for disposal or reuse of concrete particulars, and recommendations on acceptable methods for handling concrete residuals after monetary, environmental factors and risk have been considered. For model simulations performed using project constraints and assumptions typical to NC projects generating residuals, key findings included: use of decanting ponds were determined to be the most cost effective means of handling residuals, disposal options for solids vary across the state and are highly dependent on the tipping fees waste disposal facilities charge, and solid disposal options using beneficial fill were determined to be the least expensive.

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# EXECUTIVE SUMMARY

Construction operations in North Carolina that require hydrodemolition, diamond grinding and diamond grooving generate large amounts of concrete residuals. According to the North Carolina Department of Water Resources (NCDWR), these materials are classified as Class A residuals and re treated as “inert debris,” allowing them to be reused instead of disposing them as publicly owned treatment works (POTW) and municipal solid waste (MSW) sites. The North Carolina Department of Transportation (NCDOT) is currently writing a special provision that will address reuse of concrete residuals on NCDOT projects in accordance to federal guidelines. The NCDOT needs to develop a method to compare the potential savings from possible alternatives of disposal such as the use of the concrete residual material as liming amendments on NCDOT right of way highways, Class B residual sites and agricultural applications. Contractors bidding on NCDOT projects that require hydrodemolition and diamond grinding/grooving need guidance to assist them in identifying available options for concrete residual recycling.

The research team identified best practices for the disposal/reuse of the concrete residual material currently utilized in North Carolina and other nearby states. In addition, by surveying DOT personnel, consultants, and contractors, the attributes contributing to the costs of the various alternatives were identified. This information allowed the creation of model for a benefit-cost analysis (BCA) to investigate potential savings from other alternative options to disposal such as the use of the material as liming amendments on NCDOT right of way highways, Class B residual sites and agricultural applications. Using these attributes, a Benefit-Cost Model (BCM) using Multi-Criteria Analysis was developed that enables the estimation of the costs of disposing and/or reusing concrete residual material that is produced by the hydrodemolition and diamond grinding/grooving processes. Inputs to this model include project characteristics, such as the type of work performed, the surface area of work, as well as choices for collection of residuals, and the handling of the solid and liquid waste products. The researchers also contacted industry professionals, such as contractors, consultants, and DOT personnel, in order to gather information on the variability of parameters that affect the cost of the disposal options. This model incorporates a risk analysis for the comparison of several feasible alternatives to disposal of concrete residuals, a tool for contractors to use to estimate their anticipated costs for disposal or reuse of concrete residuals, and recommendations on acceptable methods for handling concrete residuals after monetary, environmental factors and risk have been considered.

In addition to the BCM, a tool was developed that can be used by contractors undertaking such projects to better estimate their costs and to allow them to compare alternatives for the disposal/reuse of the concrete residual material. A Map Tool was also produced that allows contractors to estimate hauling distances between their projects and the nearest disposal or recycling facilities.

Based on model simulations utilizing project characteristics typical of hydrodemolition, grinding, and grooving projects in North Carolina, some of the key findings were observed including the following:

- Disposal options involving decanting ponds were seen to be less expensive in comparison to the options that involve frac tanks. This finding comes with several caveats (discussed subsequently) that include the variability of labor costs for the construction and management of the decanting ponds.

- The tipping fees for the disposal of solid residuals affect the overall cost of projects, and these tipping fees vary by the type of disposal facility and its location in the state. Even though these tipping fees are not the biggest driver for costs, it might make a difference in deciding to dispose the solid residuals at an MSW facility over a LCID facility.
- Land application options for liquid disposal were observed to be more expensive than the alternative options involving liquid disposal at WWTP/POTW facilities. This might have been due to the small sample of price quotes the research team received from facilities currently permitted and accepting residuals for land application. The research team conjectures that with an increase of such facilities in the state, the land application costs for liquid residuals might decrease, making this option (seen as the most environmentally-friendly by many stakeholders) more attractive to contractors.

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# LIST OF ABBREVIATIONS

AHP – Analytical Hierarchy Process

BCM – Benefit Cost Model

C&D – Construction & Demolition

HOS – Hydrodemolition Operation Slurry

Gal/sy – Gallons per square yard

ICRI – International Concrete Repair Institute

LCID – Land Clearing and Inert Debris

MCDM – Multi-Criteria Decision Making

MSW – Municipal Solid Waste

NCDOT – North Carolina Department of Transportation

NCDEQ – North Carolina Department of Environmental Quality

PDF – Probability Definition Function

POTW – Publicly Owned Treatment Works

RAHP – Revised Analytical Hierarchy Process

TCLP – Toxicity Characteristics Leaching Procedure

WSM – Weighted Sum Method

WPM – Weighted Product Method

# 1.0 INTRODUCTION

Infrastructure projects on North Carolina Department of Transportation (NCDOT) roadways and bridges often require concrete removal via diamond grinding, diamond grooving, and hydrodemolition methods.

Hydrodemolition involves the removal of unsound concrete material from concrete structures through the use of high-pressure water jets. These jets are mounted on a mechanical hydrodemolition robots, or via worker spraying specific areas with a handheld lance. The process of diamond grinding is used to improve smoothness and skid resistance to in-situ concrete roadway structures, and can be used to improve surface characteristics of new roadways. The process involves using a large diamond studded circular saw blade, in conjunction with continuous water flow to grind the surface of a roadway, in a parallel direction, to improve ride-ability characteristics. Diamond grooving is used as a treatment technique on portland cement concrete paved roadways, using a diamond studded saw blade, to cut parallel or perpendicular grooves into a pavement surface to improve drainage characteristics. The cuts in the grooved section can be up to six times the size of the grinded section, and the cuts are spaced much further apart. According to a 2014 report by the International Concrete Repair Institute (ICRI 2014) the four waste products associated with these processes are waste water, wet sand, chips/chunks of concrete, and concrete slurry water. The residuals for hydrodemolition, diamond grinding, and grooving have many similar properties; however the chips/chunks of concrete resulting from hydrodemolition activities are larger in size as compared to the chips/chunks resulting from grinding/grooving activities.

These concrete removal operations produce large amounts of residual slurry, liquid, and solids, which require time and resources to adequately manage. Recently, change orders and other delays associated with handling and disposal of these residuals are causing confusion to contractors and NCDOT personnel regarding the actual costs of the disposal or reuse of these residuals. Often, changes in handling and/or disposal methods (and associated delays) are caused by contractor's lack of knowledge of how to manage these residual materials in a way that is not detrimental to the environment or financially risky. Providing guidance regarding allowable methods for handling and disposal of concrete residuals is increasingly becoming a priority for the NCDOT and associated organizations including the North Carolina Department of Environmental Quality (NCDEQ). Ultimately, a goal of NCDOT is a clear path for contractors to identify and propose means of handling and disposal of the concrete residuals in a manner acceptable to the state and comfortable for the contractor in terms of risk. To this end, contractors bidding on NCDOT projects need guidance to assist them in identifying available options for concrete residuals based on project locations.

There are numerous methods of disposal/reuse of these materials. These methods have varying degrees of risk and environmental impact. The NCDOT's intent is to present the methods to contractors within the state, and provide them with a tool for estimating their costs for disposal/reuse of these residual materials, as well as realizing the risks and environmental benefits available with each option of disposal/reuse. At the time of this report publication, the permitted methods in North Carolina by the NCDOT and available to contractors for the disposal of liquid (water) waste are: disposal at wastewater treatment plants (WWTP), disposal at publicly owned treatment works (POTW), or reuse of the water via land application. The permitted methods by the NCDOT and available to contactors for solid disposal are: disposal at municipal solid waste (MSW) landfills, disposal at construction & demolition (C&D) landfills, and disposal at land clearing and inert debris (LCID) landfill. The permitted methods for solid waste reuse are beneficial fill onsite and beneficial fill offsite

The objective of the project is to provide the NCDOT with a Benefit-Cost Model (BCM) using Multi-Criteria Analysis to estimate the true costs of disposal/reuse of the residuals. This model will allow contractors in the future to provide more accurate bid estimates, which will ultimately lead to better utilization of funds and a more efficient bidding process. Another goal of the project is to conduct a risk analysis that can be used to compare several feasible alternative methods of disposal/reuse of the residuals. The risk analysis will account for the true costs of disposal/reuse, provide acceptable methods for disposing of residuals, and assess the monetary and environmental risks associated with the residual disposal options.

In addition, an online tool using Google Maps was created that allows contractors to estimate distances between their projects and the closest disposal facilities that would take concrete residuals. These facilities as mentioned above are MSW facilities, C&D facilities, LCID facilities, as well as WWTP and POTW locations.

With increasing and more stringent environmental restrictions, NCDOT reports that the costs of disposing and/or reuse of concrete residual material from hydrodemolition and diamond grooving/grinding operations are on the rise. The products of this research will allow NCDOT and NCDOT contractors to better estimate the costs of such operations up-front, possibly providing cost savings to NCDOT. The online tool will allow contractors to choose cost effective and/or environmentally-friendly alternatives for the disposal/reuse of concrete residuals while being aware of the risks associated with each possible solution.

# 2.0 LITERATURE REVIEW

## 2.1 SOURCES OF CONCRETE RESIDUAL MATERIAL

Residual concrete materials are generated in several construction processes utilized in construction of new concrete infrastructure, as well as processes used in rehabilitation and repair of existing concrete infrastructure. However, the construction processes that are of interest to this investigation are hydrodemolition, diamond grinding, and diamond grooving. As these processes are performed, concrete residual materials include solids, liquids, and slurries.

### 2.1.1 Hydrodemolition

Since its development in Europe in the 1970’s hydrodemolition has become one of the go-to methods for concrete bridge deck removal (Nittinger 2001). The emergence of hydrodemolition as a favorable technology can be attributed to the following (ICRI 2004):

- Consistent results on a project-to-project basis,
- Guaranteed total removal of degraded material,
- No damage to existing reinforcing steel or adjacent concrete,
- Creation of a rough surface for easy bonding to new concrete,
- No impacts, vibrations, dust, or fumes, and
- A rapid rate of work.

**Figure 1: Hydrodemolition Equipment (left) and Post Hydrodemolition Surface (right)**

Hydrodemolition equipment typically utilized for bridge deck removal consists of a motorized vehicle that slowly drives on a concrete surface, spraying a constant stream of water at very high pressures. The pressures, flow, and motion of the water jets are controlled to ensure a continuous demolition process of the concrete it is driving over. This method is shown in Figure 1 (left). Upon completion of the process, the contractor is responsible for cleaning up the area and removal of the water. The residual material, which is a combination of wastewater, wet sand, chips/chunks of concrete, and concrete slurry (ICRI 2004), is collected and treated until the criteria for disposal set by the state are met. Hydrodemolition is unique because it will only demolish sound and unsound concrete while also creating an appropriately roughened bonding surface for new concrete (Nasvik, 2001), this can be seen in Figure 1 (right).

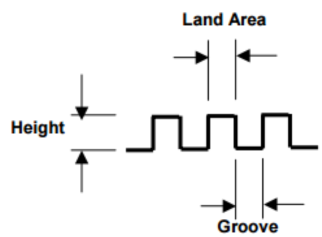
### 2.1.1 Diamond Grinding

The process of diamond grinding concrete roadway surfaces is used to rehabilitate a pavement surface texture to a condition that is often as smooth as a new pavement. The process is also used to reduce road noise while increasing surface macro texture and skid-resistance. The process uses closely spaced diamond equipped saw blades that are attached to a truck bottom and run longitudinally across a pavement surface. The saw requires a constant stream of water, which is provided to the machine by a separate truck run in conjunction with the diamond grinding equipment. A vacuum is attached around the saw blade in a fashion that picks up the water, concrete residuals, and slurry and sends them to a separate holding tank within the water holding truck (Caltrans 2008).The grinding equipment and water truck used can be seen in Figure 2. A picture of the saw blade can be seen in Figure 3 (left) and a typical grinded section can be seen in Figure 3 (right).

**Figure 2: Diamond Grinding Machine (left) and Water Supply Tank (right)**

The residual materials created from the diamond grinding process consist of waste water, hardened concrete fines, and concrete slurry, and are referred to as Concrete Grinding Residue (CGR). The CGR is collected by the vacuuming process, to be held, treated, and disposed of at a later time. The International Grooving & Grinding Association (IGGA) states that grinding slurry is an inert, nonhazardous byproduct of diamond grinding portland cement concrete pavement. Many tests have been done to ensure that the residual material is nonhazardous. The geometry of a typical grinded section as described by FHWA (2001), can be seen in Figure 4.

**Figure 3: Diamond Grinding Saw (left) and Typical Grinded Section (right)**




| | Range of Values mm (in) | Hard Aggregate mm (in) | Soft Aggregate mm (in) |
|---|---|---|---|
| Grooves | 2.0 – 4.0 (0.08-0.16) | 2.5 – 4.0 (0.1-0.16) | 2.5 – 4.0 (0.1-0.16) |
| Land Area | 1.5 – 3.5 (0.06-0.14) | 2.0 (0.08) | 2.5 (0.1) |
| Height | 1.5 (0.06) | 1.5 (0.06) | 1.5 (0.06) |
| No. Grooves per meter | 164 – 194 (50-60) | 174 – 194 (53-60) | 164 – 177 (50-54) |

**Figure 4: Typical grinding texture (FHWA, 2001)**

The CGR is a highly alkaline material (pH of 11-12.5+) containing many suspended solids, which may cause problems for existing roadside vegetation and nearby waters. Some slurries may contain sulfates, chlorides, hydrocarbons, or other materials derived from concrete admixtures. Concrete that has contains fly ash was initially thought to be of concern due to possibility of elevated levels of the heavy metals; mercury, cadmium, and arsenic. However according to a characterization of the CGR done at North Dakota State University (NDSU) (DeSutter et al. 2011), it was found that:

- Slurry samples displayed non-hazardous characteristics according to EPA hazardous waste standards.
- Slurry samples passed the 96-Hour Acute Toxicity testing, showing no toxic characteristics.

### 2.1.2 Diamond Grooving

Diamond grooving of portland cement concrete pavement is a treatment for increasing tire traction and decreasing the possibility of vehicular accidents caused by inclement weather. A study by IGGA showed that after grooving operations have been completed declines in wet pavement vehicular accidents of up to 70% have been reported (IGGA 2013c). Grooving of pavement can be either parallel or perpendicular to the lane, and is used to create paths to remove water from the surface of roadways to improve drainage characteristics. The grooving process is similar to that of grinding; however, grooving uses a vehicle with a mounted saw that uses cooling water while grooving, a source water tank, and a vacuum to pick up grooving residue. A picture of a grooving machine and its water tank truck can be seen in Figure 5. Grooving produces larger and deeper cuts that are spaced further apart than with grinding. Typically, grooved section cuts are up to six times larger than grinded sections, and are spaced much further apart. Engineers typically specify grooves to be 1/8- 3/16 inches deep, 1/8 inch wide, and spaced ¾ inch center-to-center (IGGA 2013b). At typical grooved section can be seen in Figure 6.

**Figure 5: Grooving Machine (left) and Grooving Machine Water Storage Tank (right)**

**Figure 6: Typical Grooved Pavement Section**

## 2.2 RESIDUAL PRODUCTS AND METHODS OF DISPOSAL

The aforementioned construction operations create large quantities of residual materials that have multiple disposal and/or reuse options. Current best management practices for the handling and disposal of the slurry material have been developed by IGGA. The IGGA suggests that in rural areas with vegetated slopes adjacent to the roadway, the slurry can be spread on these side-slopes as the grinding operation moves along the road. This is not the case when the work is conducted adjacent to wetlands or other sensitive or protected areas. When near these protected areas or in urban designated areas, IGGA suggests that the slurry be vacuumed, picked up, and disposed (IGGA 2013a). According to the Environmental Protection Agency (EPA), the wastewater from the process should be filtered to remove both coarse and fine solids and treated to lower the pH to acceptable levels and hauled to a publicly owned treatment works (POTW) or waste water treatment plant (WWTP). The POTW/WWTP should be contacted prior to delivery ensure that the residuals meet the facility's specific standards for dischargers. Another method for disposal is containing the slurry to allow for the water to evaporate away, leaving only the solids behind for disposal (EPA 2012).

According to IGGA (2013a), the disposal of the slurry is dependent upon the characteristics of the area in which the work is being conducted, such as rural or urban. In rural sites, as depicted by Figure 7, the slurry is allowed to be spread onto vegetated slopes as the equipment progresses along the road by means of a flexible hose, but not within one foot of the road shoulder. Any areas that have been deemed "protected" by the engineer must be kept clear from the slurry. The engineer should identify protected areas, clearly indicate/flag them, and describe the preventative action(s) that must be taken. Slurry is not to be disposed of within 100 feet of natural streams and lakes. It is also noted that the slurry is not permitted to flow into adjacent lanes, especially when there is traffic in that lane. Lastly, the slurry is not allowed to enter  closed drainage systems (IGGA 2013a).

**Figure 7: Side Slope Slurry Spreading (Penhall 2014)**

In urban areas IGGA (2013a) provides different guidance. The slurry is to be collected in water-tight hauling units as operations progress. The slurry is then to be deposited in a lined settlement pond that has been constructed by the contractor and designed by the engineer. These settlement ponds are permitted to be within the right of way, or outside of the right of way as long as the engineer's directives are upheld. The solids will settle to the bottom of the settlement pond, and the water is to be collected and reused for further grooving/grinding operations. After grinding/grooving has been completed, the water in the settlement pond can be left to evaporate or decanted and disposed of. The solids may be reused as a fill material or reused as a recycled aggregate. Upon completion, the pond area is generally required to be returned to its original condition.

Depending on the operation chosen, the size of the solid residuals will vary. Hydrodemolition has larger residual solids and a larger quantity of liquid than the residuals produced from grinding or grooving. The residual slurry contains suspended and dissolved concrete solids. Some state highway agencies allow for the residuals to be distributed on side slopes, while others mandate that all work be maintained as a non-discharge system. Land application has been another popular method of beneficial use, where the residual material is applied to open land at predetermined rates and has no detrimental effect on vegetation or groundwater (IGGA 2011).

The wastewater from these construction operations contains suspended solids, and is highly alkaline (pH of 11 – 12.5+) (ICRI 2014). The wastewater is commonly collected in a settling tank/pond to remove solids by addition of flocculants or simply by gravity settlement. The pH in these tanks/ponds will also need to be lowered for disposal by either introduction of acid, $CO_2$, or other compounds. ICRI (2014) suggests placing the remaining solids in a holding container for disposal by recycling/landfill placement with the cooperation of the controlling authority. The ICRI guidance, however, does not mention any possible methods for the reuse of the material.

The American Concrete Institute (ACI) has set limitations on the disposal of the waste water associated with hydrodemolition. ACI suggests following the state/local regulatory guidelines which may include acquiring permits to discharge into local sanitary systems. However in many cases the waste must be treated before discharge. In some cases, the waste may be discharged onto the ground where it will subsequently be allowed to evaporate or be absorbed. The waste should never be discharged into lakes, streams, or wetlands (ACI 2010).

Based on a review of the literature as well as interviews with regional and national personnel involved in these construction activities, the most commonly utilized options for managing grinding, grooving, and hydrodemolition slurry are:

- Disposing in vegetated slopes,
- Dumping on roadway shoulders where applicable,
- Placing into frac tank units to separate liquids and solids to process liquids, and
- Placing in a settlement pond to allow for separation of solids and liquids, and evaporation/decanting of liquids.

The options for liquid disposal/reuse are listed below and are discussed in detail in the following sections:

- Disposal via
    - waste water treatment plant (WWTP) and
    - publically owned treatment works (POTW)
- Reuse via land application

The options available for solid disposal or reuse are listed below and are discussed in detail in the subsequent sections:

- Disposal via
    - municipal solid waste (MSW) landfill,
    - construction & demolition (C&D) landfill, and
    - land clearing and inert debris (LCID) landfill.

- Reuse via
    - beneficial fill onsite and
    - beneficial fill offsite

## 2.3 CURRENT NORTH CAROLINA REGULATIONS

### 2.3.1 Wastewater Regulation

The residual materials generated from diamond grinding, diamond grooving, and hydrodemolition of Concrete Pavement are very similar. The EPA published Guidelines for Water Reuse (EPA 2012) which provides suggestions for states to follow to ensure proper cleanup of these activities. This is particularly important for sites located in sensitive areas, near natural water bodies, wetlands, or in urban areas. The EPA has set standards for which water must attain before being reused. The EPA (2012) requires for reuse of water in urban spaces:

- Adjustment of pH to a range of 6-9,
- Biochemical Oxygen Demand (BOD) less than 10mg/l,
- Nephelometic Turbidity Unit (NTU) less than 2,
- No Fecal Coliform per 100 mL, and
- No more than 1 mg/$Cl_2$

The recommendations that are provided by the EPA are meant to provide guidelines for states to develop their own regulations based on state specific characteristics. Specifically, in the state of North Carolina, the regulations that govern water reuse fall under "15a North Carolina Administrative Code Chapter 02 – Environmental Management." More specifically in subchapter 02-U "Reclaimed Water." The state standards for "reclaimed water effluent standards" (NCAC 2011) are as follows:

- Monthly BOD average of less than 10 mg/L,
- Daily BOD maximum of less than 15 mg/L,
- Monthly average of total suspended solids (TSS) of less than or equal to 5 mg/L, and a daily maximum TSS of less than or equal to 15 mg/L,
- Monthly limit on ammonia of less than or equal to 4 mg/L,
- Daily limit of less than or equal to 6 mg/L,
- Monthly geometric E. coli/fecal coliform level less than or equal to 25/100 mL, and
- Maximum turbidity level of 10 NTU's or less.

This however changes when considering water reuse for irrigation of food chain crops, which require much more stringent environmental standards. The criteria is as follows (NCAC 2011):

- Monthly BOD less than or equal to 5 mg/L,
- Daily maximum BOD of less than or equal to 10 mg/L,
- Monthly TSS average of less than or equal to 5mg/L and a daily maximum TSS of less than or equal to 10 mg/L.
- Monthly ammonia limit of less than or equal to 1 mg/L with a daily maximum ammonia limit of less than or equal to 2mg/L,
- Geometric average E. coli/fecal coliform level less than or equal to 10/100mL, and
- Maximum turbidity of 10 NTU's.

A flow chart was created to help visualize the NCDOT approved options available for reuse and disposal of the residual materials (both liquids and solids) from grinding, grooving, and hydrodemolition operations. The options for disposal and reuse of the various associated residual products within the North Carolina can be seen in Figure 8.

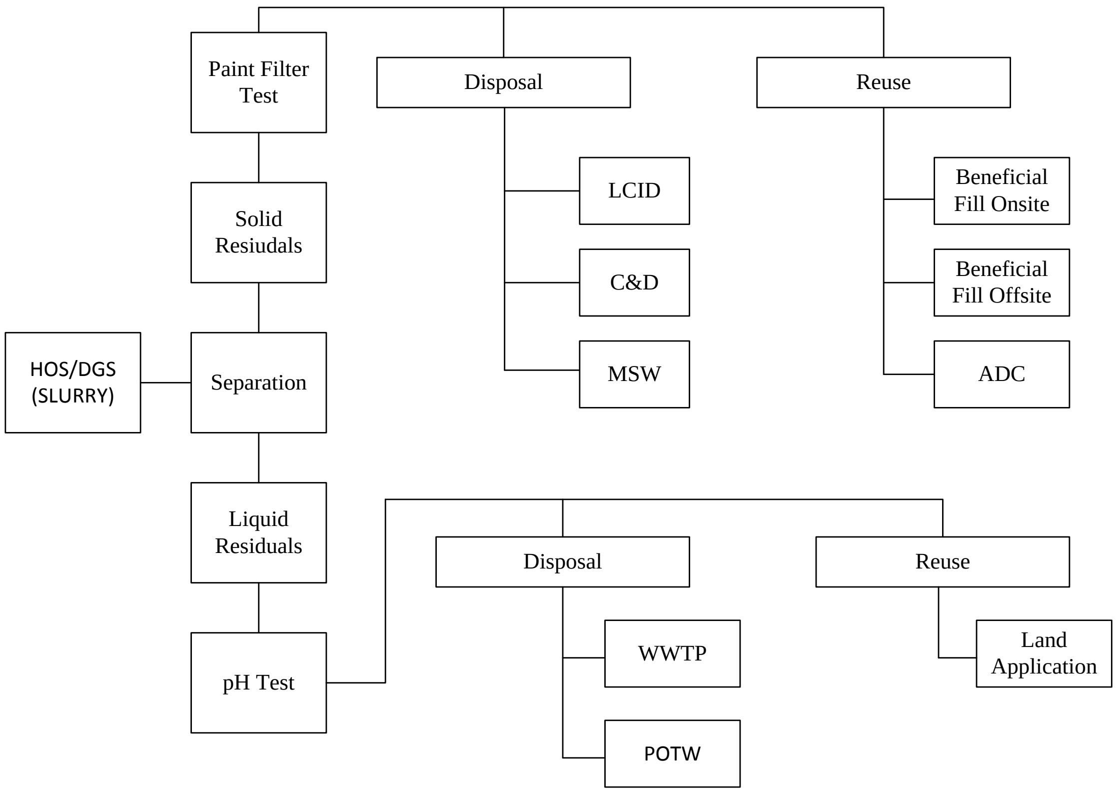



**Figure 8: Flow Chart of approved concrete residual disposal/reuse options**

### 2.3.2 Solid Waste Regulations

Identification, treatment, storage and disposal of the solid waste materials associated with hydrodemolition, diamond grinding, and diamond grooving of concrete is governed by the hazardous and solid waste amendment of the Resource Conservation and Recovery Act (RCRA). A cradle-to-grave approach is suggested by the RCRA when managing these waste products, and treatment of the waste prior to its disposal. The NCDOT's Roadside Environmental Unit works closely with the Division of Waste Management and North Carolina Department of Environmental Quality (NCDEQ) to develop the Residual Management Program (RMP) so that waste is disposed of in accordance with state and federal regulations (NCGA 2007).

The Environmental Protection Agency (EPA) specifies that the generators of waste materials are responsible for testing and identifying their waste as hazardous. Waste generators are required to perform an analysis of corrosivity, ignitability, and toxicity, as well as an analysis of the Toxicity Characteristics Leaching Procedure (TCLP) (EPA 2012). The goal for North Carolina's Residual Management Program is to work in conjunction with waste generators, land owners, and other stakeholders to identify, regulate, and manage land application and disposal of residual solids. According to NCDEQ, in their 2010 Residual Management Program Summary, under North Carolina General Statute (NCGS), "residuals are defined as waste, and any system designated to collect, treat, or dispose of waste cannot be constructed or operated without a permit" This statute grants power to the state's Environmental Management Commission (EMC) to work with NCDEQ to develop regulations and issue permits to the generators of residuals. These functions are to be carried out by NCDEQ's Division of Water Quality (DWQ). The DWQ has stated that for the Residuals Management Program (RMP), residuals are not to be discharged to surface waters. These rules have defined residuals as solid, semi-solid, or liquid waste, that are considered to be a non-effluent/residue from agricultural products and processes, generated from wastewater treatment facility, water supply treatment facility, or air pollution control facility permitted under the authority of the EMC (NCAC 2011).

#### *2.3.2.1 Land Clearing and Inert Debris (LCID)*

Inert debris, as defined in the North Carolina General Statutes, "is solid waste which consists solely of material that is virtually inert and that is likely to retain its physical and chemical structure under expected conditions of disposal" (NCGA 1983). While this definition is very broad, several counties specify exactly what LCID landfills accept. One example from Mecklenburg County states that LCID landfills accept the following materials: untreated wood (natural wood, no paint), brick, concrete, concrete block, asphalt, uncontaminated soil, rock and gravel, and stumps, brush, limbs (Mecklenburg County 2016). To dispose of inert materials, the contractor is generally instructed to transport all solid residual materials LCID landfill locations. Concrete is only accepted as an inert debris if it is considered "clean" by the accepting facility. "Clean" was described as free of rebar by employees of the various LCID landfills within North Carolina contacted as part of this research effort.

#### *2.3.2.2 Municipal Solid Waste (MSW)*

Municipal Solid Waste (MSW), as defined by North Carolina General Statute, is any solid residual waste from residential, commercial, industrial, governmental, or institutional operation that would have been collected, processed, and disposed of via a public or private waste management service. This does not include hazardous waste, sludge, or solid waste from mining or agricultural operations. MSW also does not include industrial waste that is managed in a solid waste facility owned and operated by the generator of that waste (NCGA 1983) . The solid concrete residual material could be disposed of at a MSW landfill according to the state statute.

#### *2.3.2.3 Construction and Demolition (C&D) Waste*

Construction & Demolition (C&D) waste, as defined by North Carolina General Statute, is the residual material from construction, remodeling, repair, or demolition operations on pavements or structures. C&D waste does not include inert debris, or debris that has been cleared from land or yard waste (NCGA 1983). The solid concrete residuals resulting from the demolition/remediation techniques studied in this project could also be considered C&D waste, allowing it to be disposed of in C&D landfills.

#### *2.3.2.4 Beneficial Fill*

NCDOT mandates that residual solids can be used beneficially inside ROW fill sections. North Carolina Administrative Code (NCGA 1993) states that beneficial fill must consist of only inert debris, which concrete is considered. In order for the fill to be considered beneficial, no excavation is to be done, and the purpose must be to improve land use potential or other beneficial purposes. The fill activity must comply with all applicable zoning, flood plain, wetland, and sedimentation and erosion control restrictions and regulations. Perhaps most importantly, the beneficial fill should not result in violation of any groundwater protective requirements.

In an effort to reduce the amount of solid waste that is getting distributed to landfills, local governments have implemented various waste reduction programs. North Carolina promotes methods of solid waste reduction as management policy. According to this policy (NCGA 1996), disposal of solid waste in a landfill is the least preferred method of disposal.

A memo from the North Carolina Department of Environment and Natural Resources (NCDENR) (currently named North Carolina Department of Environmental Quality (NCDEQ)), Solid Waste Division goes further to state "dewatered CGR's may be beneficially reused within the DOT project boundary or areas under DOT control at agronomic rates suitable for the establishment of vegetation (Scott 2013). Dewatered CGR's may also be used within the roadbed at rates approved by DOT staff for soil modification purposes" (Scott 2013). If the residual solids are to be reused as beneficial fill, NCDOT states that there is to be only one representative TCLP sample from the project taken to ensure that no RCRA 8 metals in the sample (Scott 2013).

#### *2.3.2.5 Land Application*

In the state of North Carolina, residuals may be applied to agricultural lands as long as EPA and NCDEQ regulations are adhered to and the regulations as outlined in the previous sections are met. In North Carolina, concrete residuals have been classified as Class A (treated, exceptional quality), and are suitable for land application or burial. Federal rules on residuals also contain provisions for limiting metal content, as well as pathogens and use requirements that are similar to the disposal of organic waste solids (municipal sewage sludge). The EPA has designated regulations for land application of "sludge", which includes an analysis of composition of the waste material, toxicity, and liquid/solids content (EPA 2012). The EPA also calls for an evaluation of the disposal sites including topography, soil profiles, and provisions for monitoring the site (NCGA 2006).

The state of North Carolina requires the issuance of a permit for land application of residuals (NCDOT 2015). A Land Owner's Agreement form must be completed, which provides the application parameters, describes the land use, and outlines the responsibilities for the generator of the residuals, the landowner, and other parties that are involved in each situation. Permits are specific to the site, and may need to be modified to allow for changes related to residual source, type, application parameters or other variables. The Department of Water Quality is responsible for reviewing the permits, communicating with local agencies, and delegating responsibilities. Responsibilities for the permit holders include the submittal of an annual report, which will highlight information on application activities, tests on water quality, and nutrient management. Permit holders are also responsible for self-reporting of any violations of the permit. Although the permit requirements address limitations on components of residuals, operations, monitoring, and reporting, the permit does little to address the final disposal of the residuals after the completion of the construction operations (NCDEQ 2013).

## 2.4 CURRENT REGULATIONS IN OTHER STATES

An investigation was conducted to examine the current regulations that exist for the diamond grinding, diamond grooving, and hydrodemolition operations around the United States. A large amount of disparity on a state-to-state basis was found to exist in this scan of the current state-of-practice. Some states specify thorough regulations in regards to cleanup and disposal of the residual materials, while others make no mention of the processes whatsoever. The data obtained during this state-to-state examination of state highway agency policies regarding diamond grinding, diamond grooving, and hydrodemolition survey is presented in Appendix A, along with supporting details. However, a summary of this findings of this effort is presented below.

### 2.4.1 Grinding & Grooving

Currently there are 35 states that reference the processes of diamond grinding and grooving in standard specifications, and provide guidance or regulation on processing, storing and/or disposing of the residual materials. Figure 9 displays the 28 of the 35 states, highlighted in blue, that mention minimum requirements for grinding and grooving. These 28 states require, at a minimum, the following:

- Continuous removal of CGR,
- Collection via vacuum pumping or equivalent, and
- No CGR to enter:
    - Adjacent lanes,
    - Drainage structure/gutters, or
    - Natural bodies of water (lake, river, etc.)

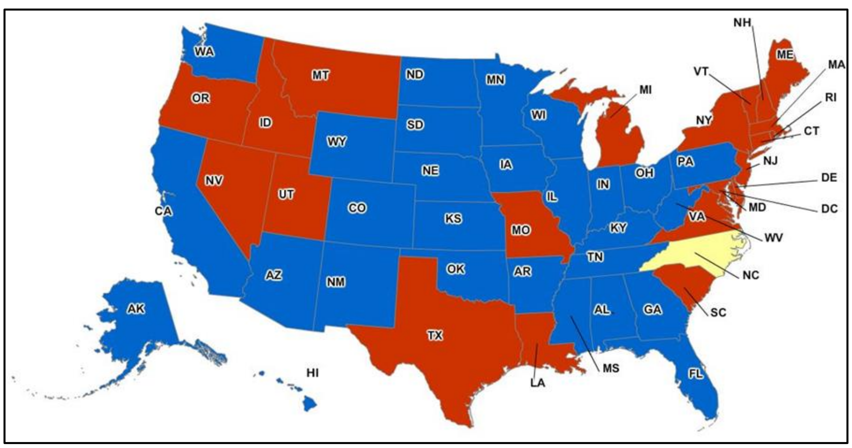



**Figure 9: States meeting minimum CGR requirements**

Of the 35 states that mention residual materials from the grinding/grooving process, there are 13 that make mention of the residual materials being contained, treated, or filtered. Specifications state that this can be done by requiring the contractor furnish wastewater treatment plans, residual management plans, or some other plan to minimize the residuals impact. Some specifications say the residuals are to be maintained onsite in temporary concrete washout facilities, and routed into a sedimentation basin or stored in tanks for holding.  Figure 10 displays these states, highlighted in blue.

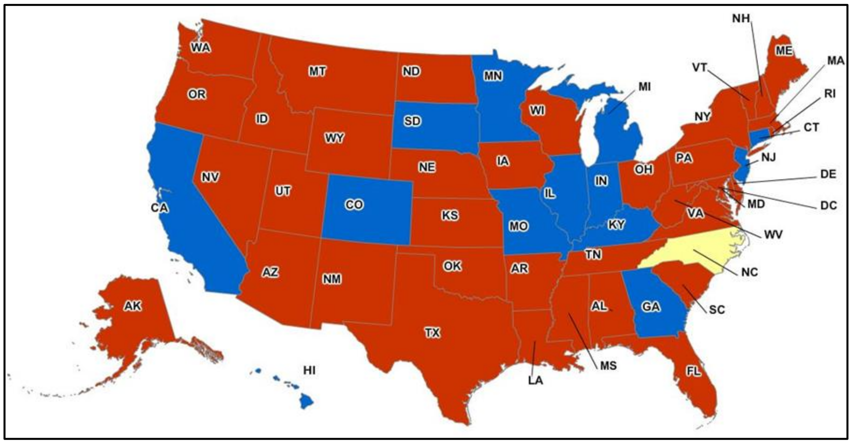



**Figure 10: States requiring containment/filtrations/treatment**

Finally, 19 of the 35 states make mention of some type of disposal, recycling, or reuse option that exists in regards to the residual materials. The environmental implications of these options, however, are not the same. Some states allow for the residuals to be disposed of in bulk directly onto the side slopes of the project ROW. Others indicate that solid residuals can be placed inside of embankments as a beneficial fill material, taken to MSW or C&D landfills, or disposed of at a permanent waste management facility. Some states allow for the liquid residuals to be decanted from the slurry and reused for other construction operations, while others recommend the liquid be diverted to a sanitary sewer or POTW. These states are shown highlighted in blue in Figure 11.

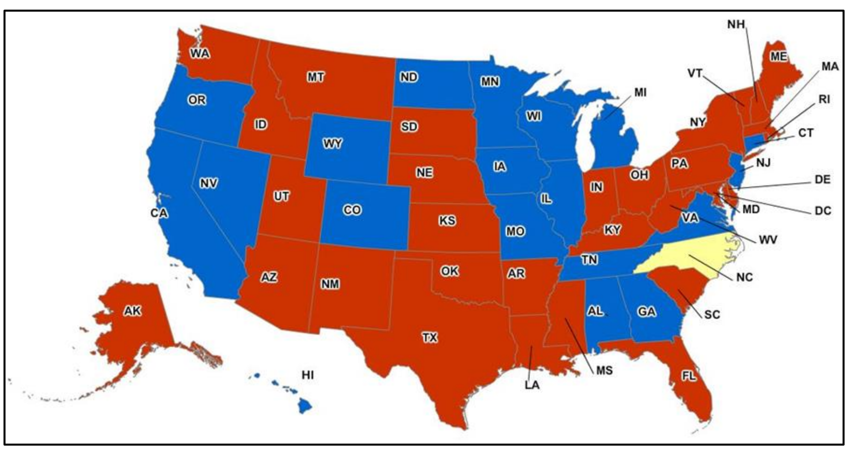



**Figure 11: States requiring residual disposal/reuse methods**

### 2.4.2 Hydrodemolition

Of the construction processes researched in this project, hydrodemolition is the least regulated construction process across the United States. Based on the results of this scan, there are only 15 state DOT's that mention the process within their standard specifications. Of those 15 states, only

10 (shown in blue in Figure 12) mention that hydrodemolition operation slurry (HOS) be removed from the surface, no residual materials are to flow across adjacent lanes, or to enter into drainage facilities or bodies of water within the state.

There are 15 state DOT's that require that there be a plan for collection, containment, or treatment of the residual material. These states are shown in blue in Figure 12. For these state DOT's, plans for collection, containment, or treatment included:

- Onsite wastewater treatment plant,
- Placing into concrete washout facilities,
- Submitting a plan for containing residuals and contaminants generated from the hydrodemolition process, and
- Chemical additions to reduce the pH of residuals.

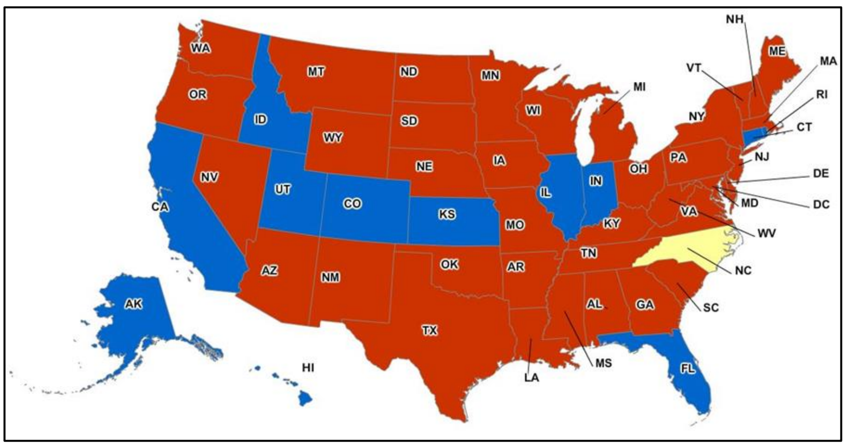



**Figure 12: States requiring HOS collection/containment/treatment**

Ten of the fifteen DOT's mention of the methods of disposal or reuse for the residual materials. These states can be seen in Figure 13 and Figure 14 highlighted in blue. For liquid residuals, some states recommend:

- Placement in a settlement pond where liquids can be decanted and disposed/reused or allowed to evaporate,
- Slurry placed in temporary onsite concrete washout facilities,
- Dispersed on the side of the road,
- Beneficially reused via land application, and
- Liquids recycled at appropriate treatment plant.

For solid residuals of hydrodemolition activities, some states recommend that these residuals be:

- Placed within embankments,
- Solid disposal at DEC approved landfill,
- Solids recycled at appropriate treatment plant, and
- Solids beneficially reused inside ROW as a fill material.

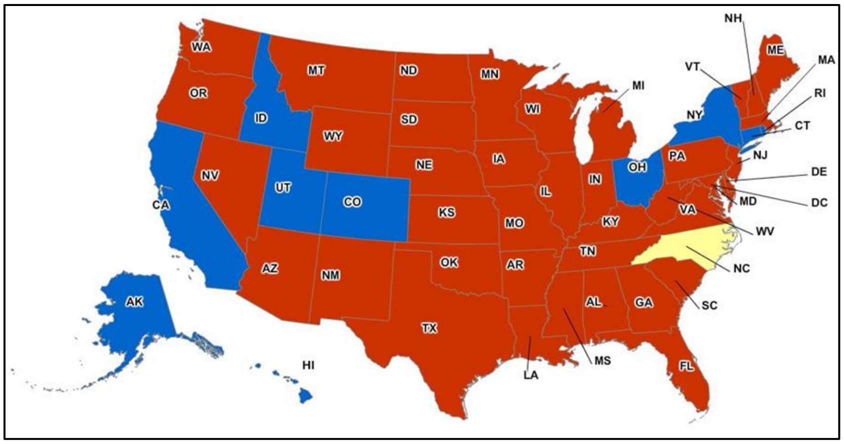



**Figure 13: States requiring disposal/reuse of hydrodemolition liquids**

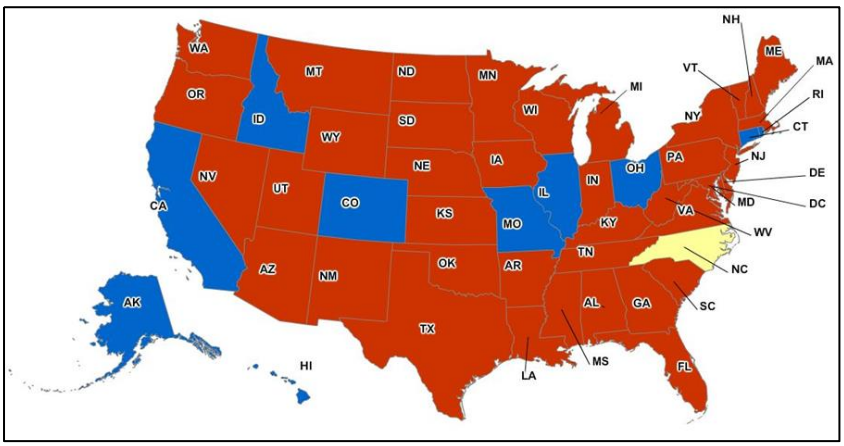



**Figure 14: States requiring disposal/reuse of hydrodemolition solids**

### 2.4.1 States Where Literature was not Identified

- Based on the findings of this survey, the states that did not mention the operation or cleanup of hydrodemolition, diamond grinding, or diamond grooving in their standard specification were as follows: Arkansas, Delaware, District of Columbia (DC), Louisiana, Maine, Maryland, Massachusetts, Montana, New Hampshire, South Carolina, Texas, and Vermont.

## 2.5 MULTI-CRITERIA DECISION MAKING

Multi-Criteria Decision Making (MCDM) tools provide the user with the ability objectively judge alternative decisions based on input criteria to evaluate and choose the best decision (Triantaphyllou 2000). MCDM tools can be particularly helpful for complex decisions that have multiple alternatives, with their own separate cost items. Examples of such studies include a study by Stansbury et al. (1992) who evaluated the disposal of dredged material alternatives, and a study by Shafike et al. (1992) who used MCDM to analyze a groundwater contamination management problem. MCDM allows the user to select which criteria are important to them, based on a relative score or weight, and come to the decision that is most optimal for the user. MCDM is based upon the notion of "alternatives" and "attributes." Alternatives are the different choices or options the decision maker has at their disposal, while attributes are various details and metrics about an alternative. Each alternative has many attributes that make it different from the other alternatives. Attributes may also be represented as a goal or decision criteria (Triantaphyllou 2000).

A MDCM model may be either "discrete" or "continuous." Discrete models have their decision alternative predetermined, while continuous models are far more complex and contain an infinite/very large number of alternatives and must contain mathematical programming with many objective functions. Discreet models are more practical and user friendly. MCDM is a blanket term for tools used to facilitate decision-making, and there are many different techniques that fall under the definition of MCDM. In order to choose the most appropriate technique to use, the following three steps are to be considered (Triantaphyllou 2000):

1. Determine the relevant criteria and alternatives,
2. Attach numerical measures to the relative importance of the criteria and to the impacts of the alternatives of these criteria, and
3. Process the numerical values to determine a ranking of each alternative. (Triantaphyllou 2000)

The most popular methods are represented in the form of decision matrix, which are shown seen in Figure 15. The "A" values represent the possible alternatives for the specified decision. The "C" values represent the decision criteria used in the evaluation of each alternative. Each "C" value is given a weight of importance to the overall decision, as specified by the decision maker. The coming subsections will discuss the most used methods of MCDM, which are the following:

- Weighted Sum Method (WSM)
- Weighted Product Method (WPM)
- Analytical Hierarchy Process (AHP)
- Revised Analytical Hierarchy Process (RAHP)

$$\begin{array}{ccccc} & C1 & C2 & \cdots & C_n \\ \text{Alt} & w_1 & w_2 & \cdots & w_n \\ A_1 & a_{11} & a_{12} & \cdots & a_{1n} \\ A_2 & a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & a_{m1} & a_{m2} & \cdots & a_{mn} \end{array}$$

**Figure 15: Typical MCDM decision matrix (Triantaphyllou 2000)**

## 2.5.1 Weighted Sum Method (WSM)

The weighted sum method is the most widely used MCDM method for conducting an analysis of alternatives. The WSM is particularly useful when measuring alternatives in a singular dimension. Since all criteria is measured in the same dimension, each alternative will have a relative score, and the alternative with the highest score is the one that should be chosen. An alternative's score is calculated using Equation 2.1. This is the simplest MCDM method when conducting an investigation in one dimension (Triantaphyllou 2000).

$$A_i = \sum_{k=1}^{n} a_{ij}\ w_j \qquad \text{(Eq. 2.1)}$$

### 2.5.2 Weighted Product Method (WPM)

The Weighted Product Method differs from the WSM in that instead of addition, multiplication is used to find the ranking score. This method can be done in terms of ratios, or as a standalone calculation; the former is used to compare two different alternatives directly to each other. Each ratio is then raised to the power equivalent of the relative weight of that criteria within the model as shown in in Equation 2.2.

$$R\left(\frac{A_K}{A_L}\right) = \prod_{j=1}^{n} \left(\frac{a_{Kj}}{a_{Lj}}\right)^{w_j} \qquad \text{(Eq. 2.2)}$$

If the term "R ($A_K/A_L$)" is greater than 1, then alternative $A_K$ is comparatively better than $A_L$. The most desirable alternative is the one that scores best relative to the other alternatives. The use of the ratio is particularly effective because it eliminates the need for a dimension, and alternatives with different units can be compared directly to each other. The WPM can also be used without ratios, as seen in Equation 2.3. This method is used to find the relative performance value of each alternative to be compared (Triantaphyllou 2000).

$$R(A_K) = \prod_{j=1}^{n} \left(a_{Kj}\right)^{w_j} \qquad \text{(Eq. 2.3)}$$

### 2.5.3 Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP), uses a system of hierarchies to compare alternatives (Saaty et al. 2012). The AHP is similar to the WSM, however each alternative criterion is normalized by dividing its score by the sum score for that criterion. As with the WSM, the best alternative is the one that receives the best score. The AHP is a popular method due to its application in single and multi-dimensional decision making, and it is easy to implement with readily available online software programs (Bhushan et al. 2007). The AHP is not without its limitations however. When identical alternatives are being compared in a model, the numbers are skewed since each criteria adds up to one; this can lead to false results to occur when the identical alternatives cancel each other out (Triantaphyllou 2000). The decision matrix for the AHP can be seen in Figure 16.

### 2.5.4 Revised Analytical Hierarchy Process (RAHP)

The Revised Analytical Hierarchy Process (RAHP) was developed to deal with the inconsistencies that existed in the AHP. Instead of each alternative criterion being divided by the sum total for that criterion, it is divided by the maximum value for that criteria, creating a method where two identical alternatives can be evaluated at the same time without skewing the results. As with the

WSM and AHP, the best alternative for the specified decision is the one with the highest score. RAHP is allowed to be used for single and multi-dimensional decision making (Triantaphyllou 2000). The decision matrix for the RAHP is shown in Figure 17.

$$
\begin{array}{ccccc}
 & C_1 & C_2 & \cdots & C_n \\
 & w_1 & w_2 & \cdots & w_n \\
\text{Alt.} & & & & \\
A_1 & a_{11}/\sum_1^m a_{i1} & a_{12}/\sum_1^m a_{i2} & \cdots & a_{1n}/\sum_1^m a_{in} \\
A_2 & a_{21}/\sum_1^m a_{i1} & a_{22}/\sum_1^m a_{i2} & \cdots & a_{2n}/\sum_1^m a_{in} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
A_m & a_{m1}/\sum_1^m a_{i1} & a_{m2}/\sum_1^m a_{i2} & \cdots & a_{mn}/\sum_1^m a_{in}
\end{array}
$$

**Figure 16: Decision matrix for AHP (Triantaphyllou 2000)**

$$
\begin{array}{ccccc}
 & C_1 & C_2 & \cdots & C_n \\
 & w_1 & w_2 & \cdots & w_n \\
\text{Alt.} & & & & \\
A_1 & a_{11}/\max(a_{i1}) & a_{12}/\max(a_{i2}) & \cdots & a_{1n}/\max(a_{in}) \\
A_2 & a_{21}/\max(a_{i1}) & a_{22}/\max(a_{i2}) & \cdots & a_{2n}/\max(a_{in}) \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
A_m & a_{m1}/\max(a_{i1}) & a_{m2}/\max(a_{i2}) & \cdots & a_{mn}/\max(a_{in})
\end{array}
$$

**Figure 17: Decision matric for RAHP (Triantaphyllou 2000)**

### 2.5.5 MCDM Method Used in this Project

The cost criteria were obtained from interviews/surveys with contractors of these operations. The MCDM method chosen was the Revised Analytical Hierarchy Process (RAHP) method since the alternative were compared with multiple dimensions. Applying RAHP to this study, attributes to be included in the evaluation can be categorized under cost, risk, and environmental benefit. RAHP will allow multiple alternatives to be evaluated based on their cost, risk, and environmental benefit attributes to be added together and compared to each other to identify the alternative with the most optimal benefit.

## 2.6 MONTE CARLO METHOD

The Monte Carlo Method is used to obtain numerical solutions in situations where solving analytically is too complicated. It was first used by scientists working on the atom bomb (Rubinstein et al. 2013; Palisade-Corporation 2016). The Monte Carlo Method uses computerized mathematical techniques to simulate an outcome through the use of information related to that outcome. The model used in the simulation takes into account the ranges of estimates for several variables, allowing the statistical simulation to consider a multitude of possibilities, identifying an outcome of the most likely situations (Rubinstein et al. 2013).

In practice, the Monte Carlo Method can be used to create a model to solve a given question that has many variables with differing probabilistic values. By running many hundreds, or even thousands, of iterations, a sample average may be considered acceptable, by the probabilistic theory the law of large numbers (Renze 2016). Factors that influence the outcome of the model have a range of values associated with them. The Monte Carlo Method requires that the user put the anticipated range of values into a probability distribution function. The model therefore utilizes many of these probability distribution functions, one for each factor that could reasonably be assumed to vary (and therefore influence the resulting outcome). The model is run many times, (often over a thousand), and the results are calculated over and over again, each time with a different set of values from each probability distribution function. The final values in a model created using the Monte Carlo Method will be a distribution of values from high to low, allowing the user to get a range that is most likely to occur for that outcome based on the input values (Takeshi 2013).

The Monte Carlo Method holds advantage over deterministic models because it shows not only what could happen, but how likely that result is to happen in a clear graphical manner. The Monte Carlo Method also allows for the user to easily determine what factors are likely to have the largest impact on the final outcome, identifying for the user what factors should be most closely monitored to decrease risk. By using data that has been gathered directly by means of survey or other direct data collection methods, the range of values for each factor can be reasonably assumed to represent likely values that may occur in practice. When these ranges and distributions are assumed to be correct, it can be assumed that the model, and the results from the simulation, are valid. Data gathering is therefore a very important part in creating a Monte Carlo Simulation (Rubinstein et al. 2013).

The EPA has used Monte Carlo Simulations as a supplementary data gathering tool for Risk Assessment when there is multiple descriptors of risk (Smith 1994). The Monte Carlo Simulation can repeatedly calculate randomly selected “what if scenarios” and report the likely outcomes in simple, user friendly graphs and tables. The EPA however notes that Monte Carlo Simulations have significant limitations associated with uncertainty. If values are unknown, it is impossible for the simulations to assign an accurate value to a given range. Similarly, if the ranges or distributions used for certain factors are unknown (or incorrectly assumed), and their data is estimated, the validity of the model as a whole is called into question (Smith 1994).

# 3.0 METHODOLOGY

The research team used several methods to gather the information to build the Cost Benefit Analysis Model. These methods include surveys and interviews for understanding and recording the methods for disposal/reuse of concrete residuals, and the identification of costs and production rates using valid cost estimation techniques. This section provides an outline on the methods used to gather all the pertinent information to identify sources of costs for the disposal/reuse of all the waste materials. The methods chosen by the researchers included surveys and interviews, as well as construction industry references such as R.S. Means (R.S. Means 2009), and the US Army Corps of Engineers Construction Equipment Handbook (USACE 2014).

## 3.1 SURVEYS AND INTERVIEWS

To gather information on the specifics involved in the disposal and reuse of the concrete residuals from hydrodemolition and grinding/grooving, a survey was developed to interview contractors about their chosen methods of disposal/reuse. A copy of this survey is provided in Appendix B. The cost variables of disposal/reuse must be identified to create a reasonably accurate cost model for the disposal/reuse of these residuals. The information provided by the contractors was used to highlight the factors that influence cost on a project. Based on the literature review and the goals of this project, the survey concentrated on the following areas:

- Types of materials generated,
- Testing methods used,
- Disposal/reuse options,
- Contractual obligations
- Quantities of residuals generated, and
- Unforeseen cost variables.

The contractors were asked a series of questions about the residual products and their recycling/disposal processes. These questions were developed to identify the cost factors that existed throughout these construction processes in regards to residual management, collection, storage, treatment, and ultimately reuse, recycling, or disposal of the residuals. Each method of residual management has its own set of regulations and testing procedures that would influence cost. Since the goal was to create a model that could be used to accurately estimate the cost of conducting these operations from residual generation to disposal/reuse, gathering information on the most up-to-date regulations and requirements was necessary.

Once sufficient variables were gathered, the BCM was created to reflect an accurate summation of costs associated with these construction activities. The RAHP method was used to compare the alternatives with each other to find the alternative with the highest score on a project specific basis for all options of disposal or reuse. The purpose of the interview/survey was to gather relevant information from industry professionals to create an accurate pricing model to be used by contractors in future bid estimations.

Additional questions in the above areas asked the survey participants to identify risks associated with the operations as well as perceived environmental benefits associated with disposing or reusing the waste material generated. The identified risks and perceived environmental benefits allow the comparison of alternatives for disposal or reuse in more subjective terms that are not quantifiable by a direct cost.

### 3.1.1 Types of Material

Questions in this section of the survey focused on determining the type of residual material that the contractor has experience in dealing with, and identifying the construction activities generating those residuals. The survey was also used to gather specifics about the equipment used in the process. Respondents were also asked to identify risks that exist within the processes, as well as the precautionary measures taken to mitigate those risks. Perceived environmental benefits, as defined by the interviewee, were also identified to determine the relative environmental friendliness of each method of disposal/reuse, although it is noted that quantification of the environmental benefits associated with each option was beyond the scope of this project. This section of the survey/interview was also used to identify which options for disposal/reuse were considered by the contractor before decisions were made.

### 3.1.2 Tests Performed

This part of the survey/interview focused on the disposal/reuse method chosen, and identification of tests that must be performed on the residuals in order to use that method. Depending on whether the residual is solid, slurry, or liquid, different testing methods exist for managing that residual. Typical testing methods included the Paint Filter Test, ASTM certified pH testing, and a TCLP if the solid residuals are to be buried. These questions sought to find out what tests were performed, who performed them, the testing frequency and procedure, and costs involved with these tests.

### 3.1.3 Disposal of Solids

The disposal methods available to contractors for residual solids and their alternatives were discussed in this subsection. Locations for disposal of solids were identified in this section of the survey. Transportation methods were also an item of interest, including who performed the hauling, additional cost factors, and additional materials needed to support hauling. Any unforeseen costs resulting in change orders to the NCDOT were also requested to be noted in the survey response.

### 3.1.4 Beneficial Use of Solids

This portion of the survey focused on the available options for reuse of solid residuals and the contractor rationale for deciding on the options used for beneficial use. Respondents were also requested to report transportation methods, as well as identify hidden costs, and/or risks or risk mitigation techniques that could impact costs.

### 3.1.5 Alternative Daily Cover (ADC)

This subsection of the survey was presented to facilitate exploration of whether the contractor took the residuals to a landfill facility for use as alternative daily cover (ADC). ADC refers to a material that is spread over the "active face" of a landfill at the end of each day to control the material within the landfill. Transportation methods were also identified, as well as the details on contractual agreements, and the acceptor(s) of the residual material. The possible costs/benefits of the acceptance of material were also identified.

### 3.1.6 Land Application

Lastly, in this subsection, respondents were requested to report details on land application of concrete residuals. Per NCDOT regulations, this method requires that specific tests be performed on the residuals. Questions in this section of the survey/interview focused on identifying costs incurred from activities related to land application, including tests, agreements, legal fees, hidden costs, risks associated with spill control prevention plan, reporting costs, and any other additional costs that may exist.

## 3.2 CONTACTING DISPOSAL FACILITIES WITHIN NORTH CAROLINA

To identify the costs associated with the disposal of materials, disposal facilities within the state of North Carolina were contacted to determine whether or not they would accept the residual material, and at what price. The list of these facilities were found on the NCDEQ website (NCDEQ 2016). These facilities were then grouped and organized based on region and type, then selected at random to be contacted. These facilities were contacted by telephone to find out the level of quality at which they would accept these materials, whether pre-treatment was necessary, and at what price the materials would be accepted. These cost points were then compiled based upon type of facility and location, and can be seen in Appendix C. The cost data was then utilized in the CBA to better estimate the price at which the residual materials would be disposed once generated. The costs varied based on location and type of facility. In certain cases, the residuals are placed in a pond for settlement to allow the solids to settle out over one or more days. The liquid residual, once separated, can be taken to a WWTP/POTW for disposal. The cost data collected for WWTP/POTW disposal can also be seen in Appendix C.

## 3.3 COST ESTIMATION TOOL

Once the information was collected, a cost estimating tool was created to better estimate the costs of various methods of disposal and reuse for the concrete residual materials from hydrodemolition, diamond grinding, and diamond grooving. The tool allows the user to provide inputs and selections for various options associated with handling, processing, reuse and/or disposal of the concrete residuals produced during these activities. The various inputs and selections allow for estimation of costs for all the possible disposal options. The details and sources of this information to support this tool, is discussed in the following sections of the report. Information was gathered from a number of sources and combined to create the cost estimation tool.

### 3.3.1 R.S. Means

The R.S. Means Manual (R.S. Means 2009) was used to identify various costs, inputs, and selections, particularly in regards to the types of equipment used on the project, and the capacities of those pieces of equipment. The R.S. Means Manual provides information on associated output and production rates based on the size and the type of earth that the equipment is handling. The typical crews for each piece of equipment were also noted from the R.S. Means Manual, however within the tool, user will be allowed to select crews used based on their own preference. Information presented in the R.S. Means Manual was also used to find the information associated with the activities involved in choosing the decanting pond option for slurry handling. The activities involved in the decanting pond method of slurry handling are: excavation, geosynthetic layering, backfilling, and compaction.

### 3.3.2 US Army Corps of Engineers

Hourly costs for equipment necessary to perform the necessary operations for the disposal or reuse of the concrete residuals, the Construction Equipment Ownership and Operating Expense Schedule for Region III (USACE 2014) was used. The USACE manual was used to estimate the costs of:

- Hydraulic excavators,
- Front-end loaders,
- Compaction equipment,
- Transportation trucks,
- Water tank attachments for transportation trucks, and
- Solid waste transportation vehicles.

### 3.3.3 Davis Bacon Act – Wage Determination

The Davis Bacon Wage Act website was used to determine the minimum hourly wages of workers on the jobsite for government projects (NTIS 2016). It is possible that labor costs associated with the activities for disposal and reuse of concrete residuals might be higher than the rates obtained from the Davis Bacon Act website. However, since that information is proprietary to the contractors and is generally not shared, The Davis Bacon Act values are a good approximation. The website was used to find the hourly costs of laborers and equipment operators. The wages were generated using Mecklenburg County as a baseline, and included the necessary fringes and benefits.

### 3.3.4 Grinding/Grooving/Hydrodemolition Contractors

Contractors with expertise in grinding, grooving, and hydrodemolition construction operations were contacted in regards to finding ranges for the slurry generation rates, production rates, and percent solids of operation slurry. The slurry generation rates of the machinery were provided in gallons per minute. The general size of the diamond grinding/grooving or hydrodemolition head was four feet in width. The contractors also provided a figure for the linear distance covered over a given period of time. These figures were combined to find a figure for slurry generated per designated area. The percent solids of the slurry generated was also provided by the contractors. This percentage was used to estimate the quantity of solids and liquids in the given quantity of slurry. These figures were used further in calculating disposal/beneficial reuse costs.

### 3.3.5 Grinding/Grooving/Hydrodemolition Contractors

The tank rental company most widely recommended by the local contractors was contacted to determine the costs of renting frac tanks, water holding tanks, and delivery costs of those tanks to the site. This company was used for the majority of grinding/grooving/hydrodemolition projects involving NCDOT that used frac tanks as their chosen method of slurry handling. This company also has many locations throughout North Carolina making its figures applicable in all regions of North Carolina. The cost for renting the tanks were given in terms of daily use and for a “cycle”. The term cycle was used to describe 28 consecutive days of onsite use. The delivery costs were given on a per mile basis for delivery from the company’s location to the location of the jobsite.

### 3.3.6 WWTP/POTW

Various WWTP’s and POTW’s were contacted throughout North Carolina. These facilities were identified based upon information found on the NCDEQ website. Operators at each site gave information in regards to the qualifications for which the material would be accepted. These qualifications were generally based on the quantity of suspended solids within the liquid and the pH. Each of these water quality parameters needed to be lowered for slurry disposal at these facilities. Reduction of suspended solids can be achieved by manual settlement or screening, similar to using the decanting pond or the frac tank respectively. The pH can be lowered by the addition of acid or $CO_2$ to achieve acceptable levels. The acceptable pH levels were generally provided by respondents as pH values below 9, however the chosen facility should be contacted beforehand to find their unique parameters.

### 3.3.7 Land Application

Various certified land application sites were contacted throughout North Carolina. These facilities were identified using the NCDOT website. Site operators were surveyed to find a range of costs at which they would accept the various liquid residual materials. The operators of these sites were also contacted to discuss the method of delivery to their site. The operators indicated that if the site was within reasonable distance from the project site, the operator would include delivery of the material in the cost of beneficial reuse.

### 3.3.8 Landfills

Various landfill sites were contacted throughout North Carolina. These facilities were also identified using the NCDEQ website. Operators at these landfill sites were surveyed to find a range of costs at which the residual material would be accepted at the facilities. To accurately identify the costs, the sites were split up based on regional location within the state and type of facility. The types of facilities that were sampled were LCID, C&D and MSW facilities.

### 3.3.9 North Carolina Office of State Human Resources

The State of North Carolina Salary Plan, which was developed by the North Carolina Office of State Human Resources, was used to determine the cost of hiring a Class III vehicle operator (NCOSHR 2014). This is most likely the operator that would be doing the hauling of the residual material from the jobsite to the disposal/reuse site, since driving a large vehicle requires special licensing and additional skills. The NCOSHR website provided the operators salary, which was divided by (2000 hours × 40 miles per hour) to determine a figure for dollars per mile. This operator cost was used for the delivery operator for the liquid and solid residuals.

### 3.3.10 Environmental Consultants

Selected North Carolina environmental consultants were contacted to discuss the methods and payment options for testing the residuals for pH, liquids in the solid residual material, and performing a TCLP. NCDOT states that if the residual solids are to be buried, a representative TCLP test must be performed. It was found that many of the contractors would hire outside environmental consultants to come to the job site to do the pH, Paint Filter tests, and a TCLP test if necessary to ensure permit compliance, as well as to reallocate the risk. The consultants provided an average cost for visiting the job site, performing the necessary tests, and recording the results of that test in a way that can be handed down the chain of custody to the final receiving location of the residuals.

## 3.4 RISK ASSESSMENT

For each method of handling slurry, liquids, and solids, there are specific risks involved. These risks have been defined by North Carolina General Statutes and EPA regulations, and were also specifically identified (or inferred) from conversations with experienced contractors. The contractors were asked to provide the method(s) of disposal/reuse they were familiar with, and to identify (and discuss) the risks associated with those methods. The risks were then summarized to provide a set of risks available for each unique option for disposal/reuse. This was used in conjunction with the RAHP to provide a score for including associated risks with each option, so that cost is not the only factor being evaluated in the model.

These risks were identified in hopes that their consideration in the model may help to mitigate risks in future work. The risks identified were concerns that were unforeseen to the contractors at the time of the bid, and could cost them more money than anticipated in the form of change orders or additional disposal costs. The set of risks were scored by the contractors for each choice. The score and the weight of importance will give the overall Risk Assessment for each unique method of disposal/reuse.

## 3.5 ENVIRONMENTAL BENEFITS

Each combination of reuse/disposal methods has its own associated environmental benefits and impacts. Potential environmental benefits were identified from conversations with contractors, state statutes/regulations, and various published research sources available on the subject. The benefits were then summarized to provide a set of potential benefits associated with each unique option for disposal/reuse. In the model, the set of benefits were scored by the contractors for each choice. The score and the weight of importance will assess the potential environmental benefits for each unique method of disposal/reuse. In the end, the environmental benefit score will be used in conjunction with costs and risks to find the contractor's most preferred method of disposal/reuse.

## 3.6 COST BENEFIT MODEL OPTIONS

The costs, risks, and potential environmental benefits were collected for each specific portion of residual management so that they could be directly compared to one another. The tool will allow the user to weight and rank cost, risk, and potential environmental benefit for the 20 total options of residual management available to the user (shown in Table 1). Based on the user's opinion of the importance of the three indicators, (cost, risk, and environmental benefit), the model will rank the 20 available options in a way that reflects the user's opinion. This allows the user to select the best option not only based on cost, but also allows the user to account for environmentally friendly and risk averse options as well, based on those factors that are most important to them.

**Table 1: Available Options of Disposal/Reuse combinations**

| Option # | Slurry Handling Method | Liquid Management Method | Solid Management Method |
|---|---|---|---|
| 1 | (A) Decanting Pond | (A) POTW/WWTP | (A) MSW |
| 2 | (A) Decanting Pond | (A) POTW/WWTP | (B) C&D |
| 3 | (A) Decanting Pond | (A) POTW/WWTP | (C) LCID |
| 4 | (A) Decanting Pond | (A) POTW/WWTP | (D) Beneficial Fill (onsite) |
| 5 | (A) Decanting Pond | (A) POTW/WWTP | (E) Beneficial Fill (offsite) |
| 6 | (A) Decanting Pond | (B) Land Application | (A) MSW |
| 7 | (A) Decanting Pond | (B) Land Application | (B) C&D |
| 8 | (A) Decanting Pond | (B) Land Application | (C) LCID |
| 9 | (A) Decanting Pond | (B) Land Application | (D) Beneficial Fill (onsite) |
| 10 | (A) Decanting Pond | (B) Land Application | (E) Beneficial Fill (offsite) |
| 11 | (B) Frac Tank | (A) POTW/WWTP | (A) MSW |
| 12 | (B) Frac Tank | (A) POTW/WWTP | (B) C&D |
| 13 | (B) Frac Tank | (A) POTW/WWTP | (C) LCID |
| 14 | (B) Frac Tank | (A) POTW/WWTP | (D) Beneficial Fill (onsite) |
| 15 | (B) Frac Tank | (A) POTW/WWTP | (E) Beneficial Fill (offsite) |
| 16 | (B) Frac Tank | (B) Land Application | (A) MSW |
| 17 | (B) Frac Tank | (B) Land Application | (B) C&D |
| 18 | (B) Frac Tank | (B) Land Application | (C) LCID |
| 19 | (B) Frac Tank | (B) Land Application | (D) Beneficial Fill (onsite) |
| 20 | (B) Frac Tank | (B) Land Application | (E) Beneficial Fill (offsite) |

# 4.0 COST BENEFIT ANALYSIS (CBA) MODEL

In this section, the methodology used to generate the cost benefit analysis model is explained. The information collected to support the generation of the probability distribution functions is shown in in Appendix C. The model that was produced using the data gathered from various sources is explained. In this chapter, the various parts of the model are described, and the methodology in which line items are calculated is explained.

## 4.1 RESIDUAL DISPOSAL AND REUSE OPTIONS

The scope of this project was framed to include operational considerations associated with the collection, containment, management, handling, transportation, and disposal/reuse options for the residual liquids and solids. This led to identifying the cost items associated with each activity, finding a range of costs for each cost item, and assembling them to create a model for estimating the costs associated with the management of those residuals.

A major part of the CBA model included creation of a tool to be used by contractors that could be used to better estimate costs. This portion of the tool is referred to as the Cost Estimator. To produce a cost analysis, the cost estimator utilizes input data associated with each of the previously stated methods of disposal and reuse: from the generation of the slurry, to the disposal/reuse of the liquid, to finally the disposal/reuse of the solids. The cost estimator uses a range of values for many different variables to create a simulation that can compare each method of disposal/reuse for the same activity. This allows the user to view and assess costs associated with each feasible option prior to selecting a method.

### 4.1.1 Probability Distribution Functions Affecting Cost Data

Costs for several factors can vary based upon project type, equipment used, and characteristics of the residuals. Specifically, these factors include:

- Slurry Generation Rates
- Solid Disposal Costs
- Percent Solids
- Liquid Disposal Costs

To account for the potential variation in these factors that could reasonably be assumed to occur in North Carolina, data to support the cost analysis was obtained from a wide spectrum of potential sources. For these factors, the data gathered was utilized to generate a probability distribution function (PDF) in order to produce a model that would vary based on realistic expectations of actually performing the work. The following sections include a brief description of the factors mentioned above.

### 4.1.2 Slurry Generation

Information on slurry generation rates was gathered from various IGGA members as well as contacts provided by NCDOT, based on a list of the contractors that had worked on slurry-producing operations in North Carolina. These contractors were contacted to identify the approximate rates of slurry generation, in gallons per minute, experienced in past work. This information was compiled in order to identify a distribution in gallons of slurry per square yardage from each of the contractors.

#### *4.1.2.1 Diamond Grinding Slurry Generation*

To support generation of a PDF for diamond grinding slurry generation, data was collected from eight grinding contractors active in North Carolina on the generation of slurry, in gallons per square yards grinded. Most contractors provided data was in the form of a range due to the many variables that can affect the actual slurry generation rate on a given project. The data ranged from a low of two gal/sy to a high of 7 gal/sy with an average value of 4.22 gal/sy. Since a small number of contractors perform this type of work and the response rate was relatively low, a triangular distribution was chosen for use in the model. The minimum value was set at 2, the maximum value was set at 7, and the average/mostly likely value was set at 4. The 4 gal/sy figure was chosen as opposed to the 4.22 gal/sy figure because the median of most ranges skewed toward the lower end of the distribution. The distribution can be seen in Figure 18.

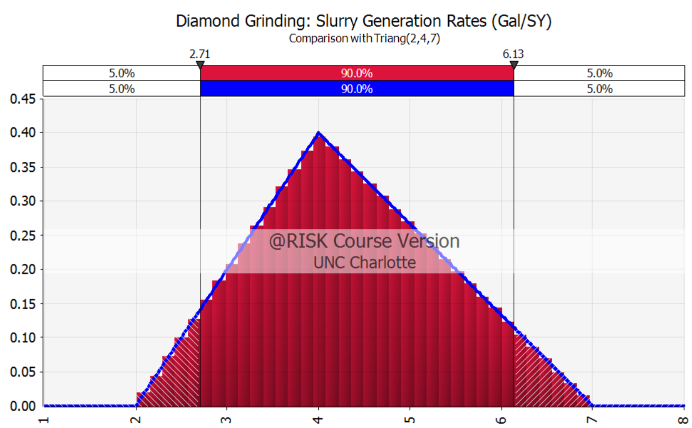



**Figure 18: Grinding Slurry Generation PDF**

#### *4.1.2.2 Diamond Grooving Slurry Generation*

Data on slurry generation rates was collected from four different grooving contractors, with information provided in units of in gallons per square yards grooved. The data ranged from a low of 0.47 gal/sy to a high of 1.8 gal/sy with an average value of 0.9 gal/sy. Since there were a small number of responses, a triangular distribution was selected for use in the model. The minimum value was set at 0.5 gal/sy, the maximum value was set at 1.8, and the most likely value was set at 0.7 gal/sy. The 0.7 gal/sy value was chosen over the mean value of 0.9 gal/sy because the data was more skewed to the lower end of the range. The PDF is provided in Figure 19.

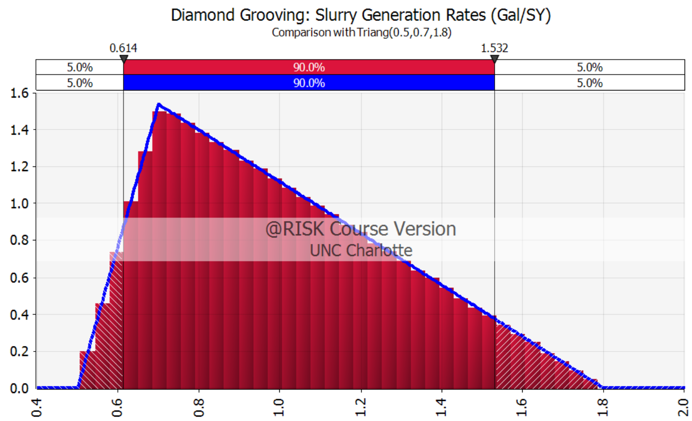



**Figure 19: Grooving Slurry Generation PDF**

#### *4.1.2.3 Hydrodemolition Slurry Generation*

Data was obtained from one hydrodemolition company that has performed most of the hydrodemolition work for NCDOT projects requiring hydrodemolition over the past four years. Although highly active in the North Carolina market, this company had also performed similar work in other states along the east coast of the United States. The company provided a range of slurry generation rates, as well as a most likely value for slurry generated during the hydrodemolition activities. The data ranged from a low of 10 gal/sy to a high of 18 gal/sy, with an average of 14 gal/sy. Because the limited amount of information available in this category, a triangular distribution was chosen for use in the model. The minimum value was set at 10, the maximum was set at 18, and the most likely value was set at 14. The distribution can be seen in Figure 20.

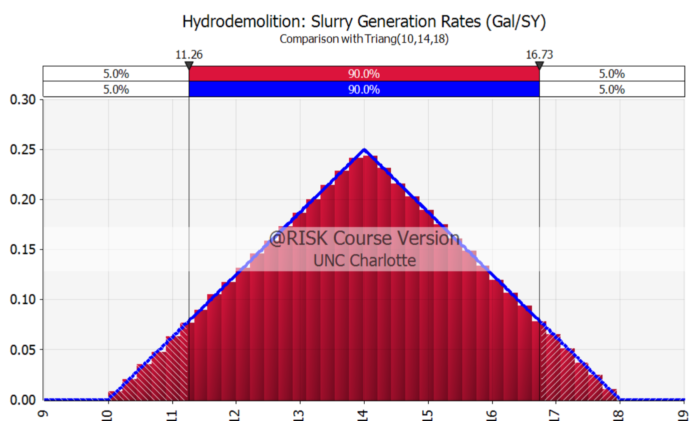



**Figure 20: Hydrodemolition Slurry Generation PDF**

### 4.1.3 Solid Disposal Costs

The NCDEQ website was utilized to identify the location, name, and function of various solid disposal facilities throughout North Carolina. These facilities were contacted to determine whether or not they would take the solid residual material, under what circumstances they would refuse to accept the material, the manner in which the solids were to be delivered, and finally the cost at which the facility would typically accept the material. Three PDF's were developed based on the regional location of the facility; Mountain, Piedmont, or Coastal, and the type of receiving landfill: LCID, MSW, or C&D.

#### *4.1.3.1 Piedmont Region Solid Disposal Facilities*

A total of 108 solid waste disposal facilities located throughout the Piedmont region of North Carolina were contacted. Of these, 65 (60.1%) responded with information that could be used to support the model. This information was used to establish price points for disposal of the solid residual material, in dollars per ton of material.

A total of 46 LCID landfill facilities throughout the Piedmont region were contacted, from which the research team obtained a total of 20 responses (a 43.5% response rate). The responses were normalized so that all prices for the solid material to be disposed was expressed in $/ton. The disposal costs provided ranged from a low of $0 per ton to a high of $46 per ton, with an average of $11.05 per ton. Since there was a large concentration of data towards the low end of the pricing, a triangular distribution was selected for use in the model. The minimum value was set at $0 per ton, the maximum value was set at $46 per ton, and the most likely value was set at $0 per ton since nine of the twenty total data points represented $0 per ton of material. Many of the facilities that were taking the material for free reported that they were utilizing the residual solids it in their road bases onsite or as an alternate daily cover material at their landfills. The distribution is shown in Figure 21.

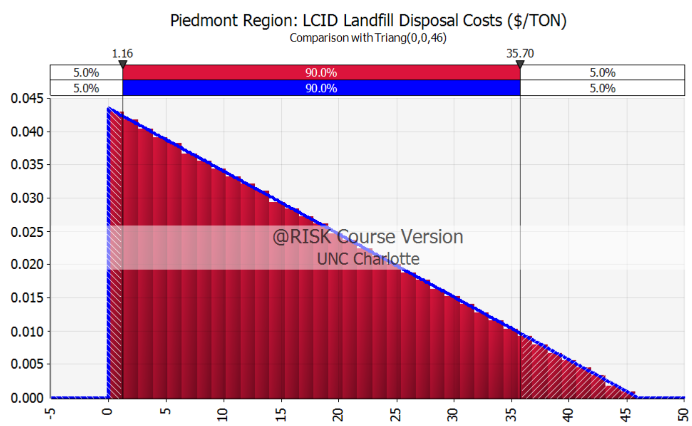



**Figure 21: Piedmont LCID landfill price for disposal PDF**

A total of 26 MSW landfill facilities located within the Piedmont region were contacted, with a total of 8 (30.7%) responses received. The disposal cost data ranged from a low of $22 per ton to a high of $41 per ton, with an average value of $32.05 per ton. Due to the limited amount of information available in this category, a triangular PDF distribution was selected for use in the model. The minimum value was set at $22 per ton, the maximum value was set at $41 per ton, and the most likely value was set at $34.08 per ton. This value was used instead of the average, since there was a large concentration of values in the middle of the range, and the best estimate of a most likely value was found by averaging the clustered values together, which was $34.08 per ton. The distribution can be seen in Figure 22.

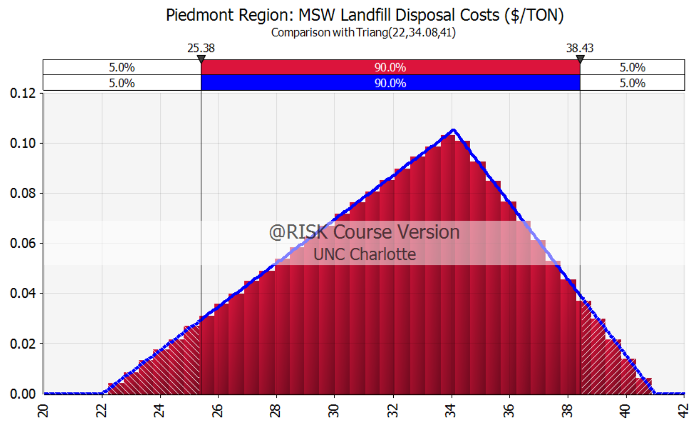



**Figure 22: Piedmont MSW landfill price for disposal PDF**

A total of 36 C&D landfill facilities from within the Piedmont region were contacted, with a total of 20 responses received (a 55.5% response rate). The disposal cost data provided ranged from a low of $5 per ton to a high of $46 per ton, with an average of $30.7 per ton. The cost data was evenly distributed, and there were enough data points to produce a normal distribution. The normal distribution was created using the average of $30.7 per ton, with a standard deviation of $9.51 per ton. The distribution is shown in Figure 23.

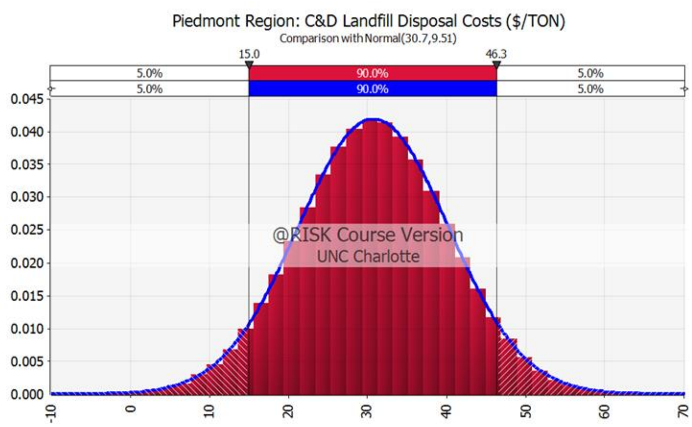



**Figure 23: Piedmont C&D landfill price for disposal PDF**

#### *4.1.3.2 Coastal Region Solid Disposal Facilities*

A total of 31 facilities located throughout the Coastal region of North Carolina were contacted. A total of 22 of these facilities responded back with information to support development of the model (a 70.9% response rate). This information was used to establish price points for disposal of the solid residual material, in dollars per ton.

A total of 16 LCID landfill facilities from within the Coastal Region were contacted, and 11 (68.7%) responses were received. The data ranged from a low of $0 per ton to a high of $65 per ton, with an average of $17.1 per ton. Due to the limited amount of information available in this category, a triangular distribution was chosen for use in the model. The minimum value was set at $0 per ton, the maximum value was set at $65 per ton, and the most likely value was set at $0 per ton, due to the majority (4), of facilities taking the solid residual material for free. The distribution is shown in Figure 24.

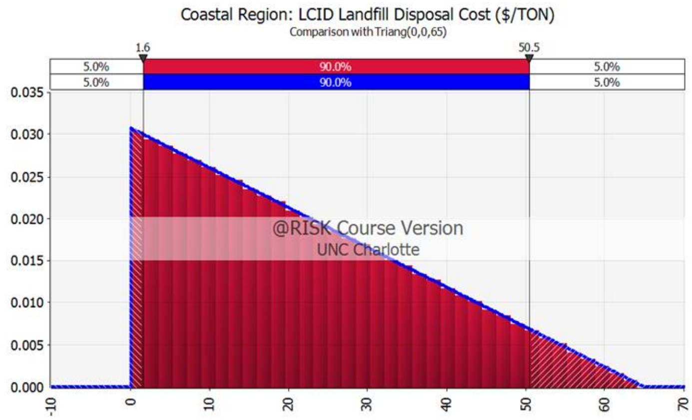



**Figure 24: Coastal LCID landfill price for disposal PDF**

A total of six MSW landfill facilities within the Coastal Region were contacted, with a total of three responses received (a 50% response rate). The data ranged from a low of $7 per ton to a high of $40 per ton, with an average of $28.7 per ton. Again, due to the limited amount of information available in this category, a triangular distribution was selected for use in the model. The minimum value was set at $7 per ton, the maximum was set at $40 per ton, and the most likely value was set at $28.7 per ton. The distribution is provided in Figure 25.

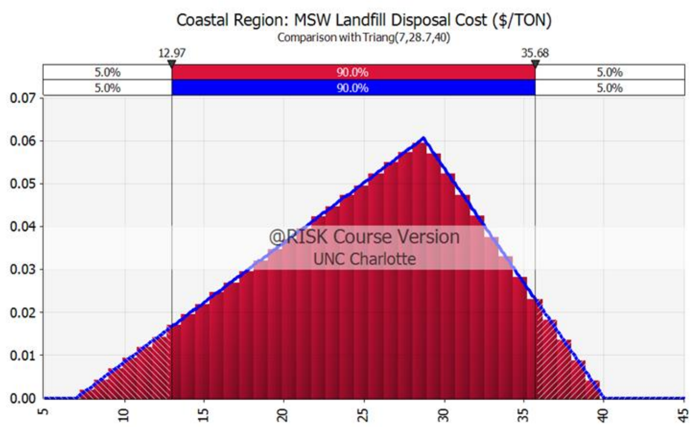



**Figure 25: Costal MSW landfill price for disposal PDF**

A total of 9 C&D landfill facilities within the Coastal Region were contacted, with a total of 8 responses received (an 88.8% response rate). The data provided by these facilities ranged from a low of $34 dollars per ton to a high of $68 dollars per ton, with an average of $49.1 dollars per ton. Again due to the limited amount of information available in this category, a triangular distribution was chosen for use in the model. The minimum value was set at $34 per ton, the maximum value was set at $68 per ton, and the most likely value was set at $48 per ton, which was the average of the middle cluster of values. The distribution is shown in Figure 26.

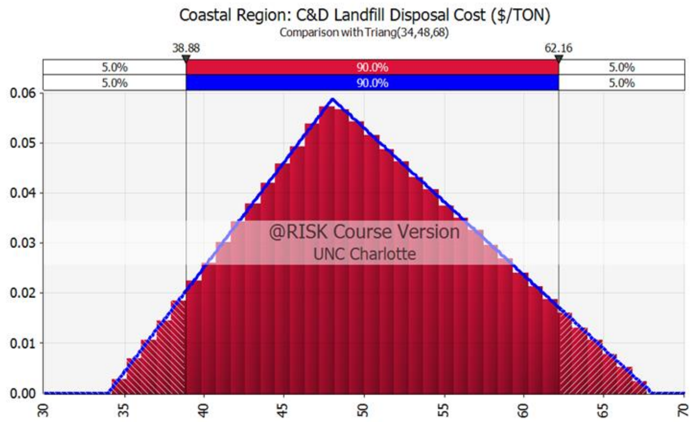



**Figure 26: Costal C&D landfill price for disposal PDF**

#### *4.1.3.3 Mountain Region Solid Disposal Facilities*

A total of 25 facilities throughout the Mountain Region of North Carolina were contacted. Of these facilities, 16 (64%) responded back with information. This information was used to establish price points for disposal of the solid residual material, in dollars per ton.

A total of 9 LCID landfill facilities were contacted within the Mountain Region, and a total of six responses were received (a 66.6% response rate). The disposal cost ranged from a low of $0 per ton to a high of $42 per ton with an average of $17 per ton. Due to the limited amount of information available in this category, a triangular distribution was chosen for use in the model. The minimum value was set at $0 per ton, the maximum value was set at $42 per ton, and the most likely value was the same as the average, $17 per ton. The distribution is shown in Figure 27.

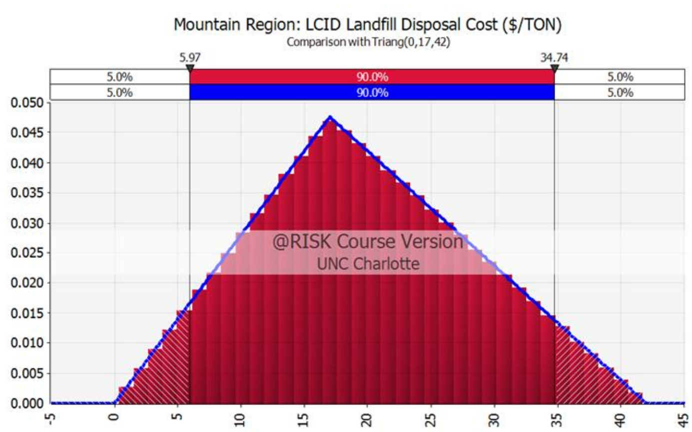



**Figure 27: Mountain LCID landfill price for disposal PDF**

A total 10 of MSW landfill facilities within the Mountain Region were contacted, and a total of six responses were received (a 60% response rate). The disposal cost ranged from a low of $43 per ton, to a high of $67 per ton, with an average of $54.7 per ton. Due to the limited amount of information available in this category, a triangular distribution was again chosen for use in the model. The minimum value was set at $43 per ton, the maximum value was set at $67, and the most likely value was set at $57 per ton. The most likely value of $57 per ton was selected because it was the average of the center clustered data, both of which happened to be $57 dollars per ton. The distribution can be seen in Figure 28.

Five C&D landfill facilities within the Mountain Region were contacted, and a total of three responses were received (a 60% response rate). The data ranged from a low of $31 per ton to a high of $57 per ton with an average of $46.70 per ton. Due to the limited amount of information available in this category, a triangular distribution was chosen. The minimum value for the distribution was set at $31 per ton, the maximum value was set at $57 per ton, and the most likely value was set at $46.70 per ton, the same value was the average. The distribution is shown in Figure 29.

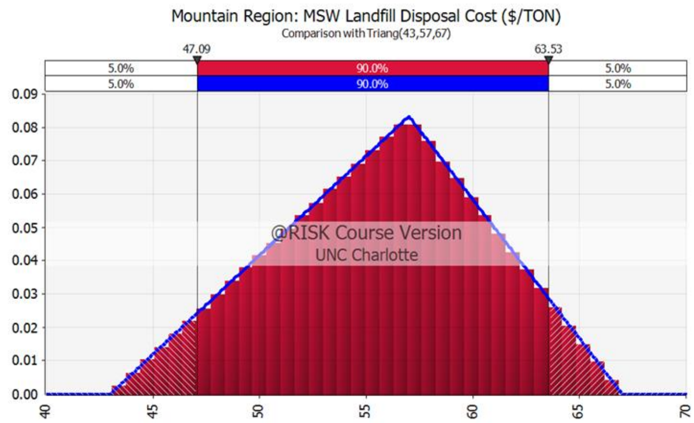



**Figure 28: Mountain MSW landfill price for disposal PDF**

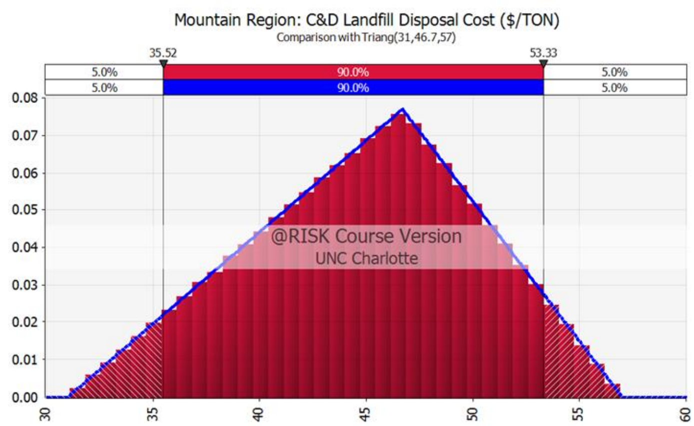



**Figure 29: Mountain C&D landfill price for disposal PDF**

### 4.1.4 Percent Solids

The quantity of solid material in a slurry can be computed using the percent solids comprising the residual slurry material. The percent solids varies depending on the construction operation producing the slurry, production rates, and potentially other influencing factors such as equipment type, blade wear, etc.

#### *4.1.4.1 Percent Solids Grinding*

Data to support identification of percent solids values to be utilized to support the model were provided by North Carolina-active grinding contractors identified based on IGGA membership. Based on the input received from these contractors, the low value to be utilized in the distribution was set at 20%, the high value was set at 33.3%, and the average value was 30%. A triangular distribution was chosen to depict this distribution. The minimum value was set at 20%, the maximum value was set at 33.3%, and the most likely value was set at 32.5%. This most likely value was chosen because the low value was thought to be a rarer event based on the collected data. The skew was more towards the higher end of the distribution. The distribution is shown in Figure 30.

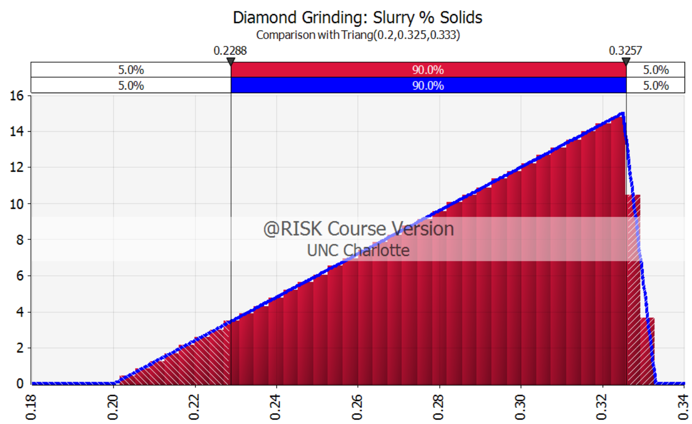



**Figure 30: Percent solids of grinding residual slurry**

#### *4.1.4.2 Percent Solids Grooving*

Grinding contractors active in the North Carolina market were contacted to provide the percent solids of typical slurry produced from grooving operations. These contractors were selected based on IGGA membership. Based on the responses received, the low value for percent solids was set at 30%, the high value was set at 50%, and the average value was 40%. A triangular distribution was chosen to depict this distribution. The minimum value was set at 30%, the maximum value was set at 50%, and the most likely value was set at 40%. This distribution can be seen in Figure 31.

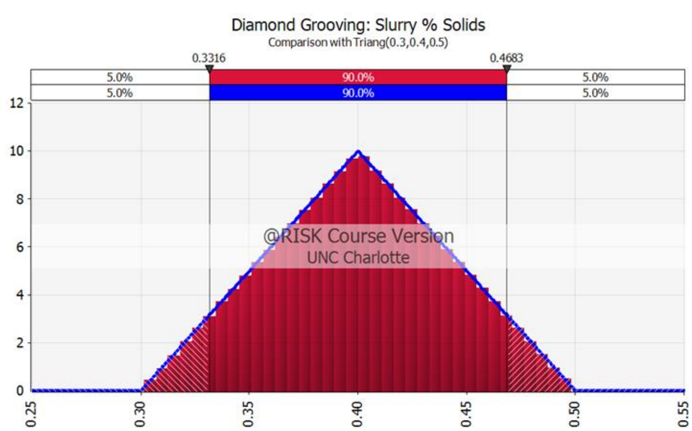



**Figure 31: Percent solids of grooving residual slurry**

#### *4.1.4.3 Percent Solids Hydrodemolition*

Information to support generation of a PDF for percent solids resulting from the hydrodemolition process was gathered from the hydrodemolition contractor that is most heavily active in the North Carolina (and east coast) market, as identified earlier. The hydrodemolition contractor was contacted and asked to provide a range for the percent of solids that make up the residual slurry material produced during typical hydrodemolition work. The low value was 5%, the high value was 15%, and the average was 10%. Therefore, for the PDF, a minimum value was set at 5%, the maximum value was set at 15%, and the most likely value was set at 10%. The distribution is shown in Figure 32.

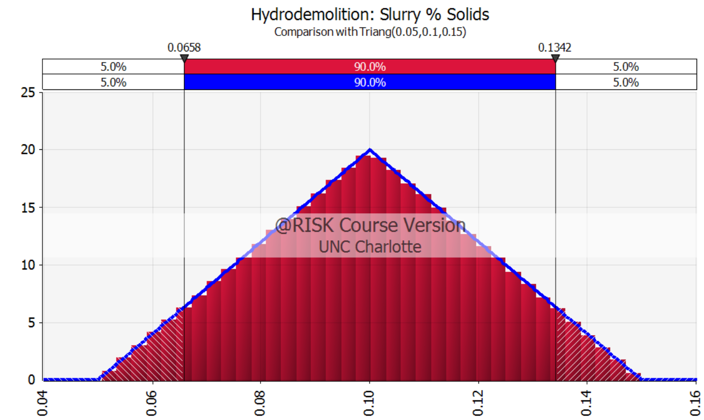



**Figure 32: Percent solids of hydrodemolition residual slurry**

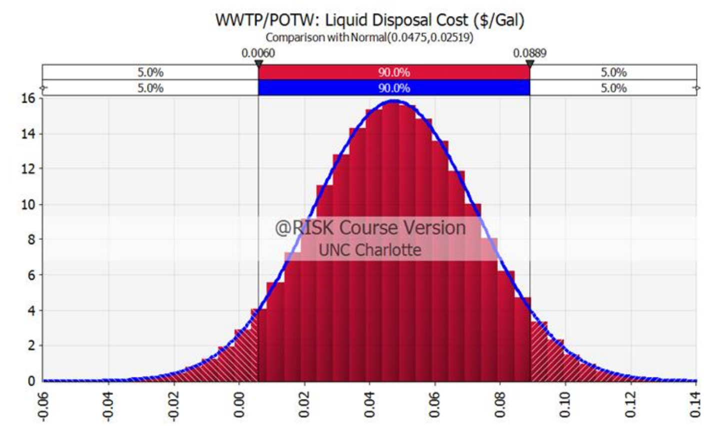



**Figure 33: Disposal costs at WWTP/POTW throughout North Carolina**

### 4.1.5 WWTP/POTW Liquid Disposal Costs

WWTP and POTW's that are currently willing to accept concrete residuals are not as prevalent throughout North Carolina as are landfills willing to accept concrete residuals. Additionally, it was determined that these WWTP and POTW facilities willing to accept concrete residuals are not well-distributed within each region. The data was gathered from WWTP and POTW facilities that accept materials from contractors. These facilities were identified from a list on the NCDEQ website. A total of 42 facilities located throughout the state were contacted, and a total of 12 responses were received (a 28.6% response rate). The data ranged from a low of $0.013 per gallon of liquid material received to a high of $0.10 per gallon received. Since there was a fairly even distribution throughout the range of gathered data, a normal distribution was utilized in the model. The average value for this PDF was $0.0475 per gallon of accepted material with a standard deviation of $0.02519 per gallon. The distribution is shown in Figure 33.

## 4.2 COST ESTIMATOR DESIGN

The information gathered from the interviews was entered into a spreadsheet, with supporting calculations and commands incorporated to create a model that could be used by a contractor to accurately predict costs based on industry standard wages, and user inputs based on past experience. To facilitate ease of use, the cost estimator tool was created using a Microsoft Excel spreadsheet platform. The probabilistic nature of the model required use of the the analytical capabilities provided by Palisade @Risk 6, an “Add-In” module to Excel.

### 4.2.1 Project Characteristics Utilized in Demonstration Simulation

To provide a demonstration of the model functionality in this report, characteristics of a typical project were utilized to facilitate a trial simulation and to provide sample analysis output. Assumptions supporting this typical project are outlined in the following list, and could be considered typical of projects recently occurring in North Carolina, based upon NCDOT and contractor inputs.

<u>General project considerations</u>

- The area to be grinded, grooved, or hydrodemolished was chosen to be 10,000 square yards. This area of operations was selected to provide a sample worksite area large enough to produce a significant amount of residuals.

<u>Decanting pond</u>

- The construction of the decanting pond, common earth was the selected earth type.
- The equipment used to excavate the decanting pond was assumed to be the wheel mounted hydraulic excavator with capacity of 0.75 cubic yards, and wheel mounted front-end loader with capacity of 0.75 cubic yards. It was assumed that the equipment would be used at the same time, and would require two operators and two laborers.
- For simplicity purposes and based on contractor recommendations, the height of the excavation was chosen to be three feet, or one yard.
- The equipment selected for backfilling the excavation was assumed to be the same wheel mounted front end loader with capacity of 0.75 cubic yards. This was assumed because it is the same piece of equipment used in the excavation and would therefore already (typically) be on site.
- Lastly the compaction equipment chosen for the comparison was a ride-on sheepsfoot roller, with compaction operations performed using 12 inch lifts, and making two passes.

<u>Frac tank</u>

- For the estimation of the frac tank, it was assumed that the distance from the supplier to the jobsite was 50 miles.

- The tanks were estimated to be rented for 28 days, or one cycle according to the supplier.

Liquid disposal considerations

- To estimate the liquid disposal, a 4,000 gallon truck attachment was chosen. It was assumed that the pH would only need to be tested by an environmental consultant once during the project.
- The distance traveled from the jobsite to the liquid disposal site was assumed to be 50 miles.

Solid disposal considerations

- For disposal of solids, it was assumed that there would only be one truck making multiple trips with the solid residuals from the jobsite to the disposal facility.
- The truck making those trips was assumed to have a capacity of 10 cubic yards.
- The distance from the jobsite to the disposal facility/reuse location was assumed to be 50 miles.

Testing

- It was assumed that during the project, an environmental consultant would only be required to run the paint filter test one time, and only one TCLP test would be performed.

### 4.2.2 Model Flowchart

The logic built into the model follows the flowchart shown in Figure 34. Calculations incorporated into the model supporting the analysis described in this section are presented in detail in Appendix D. In order to produce a range of possible costs, multiple simulations of the model are performed, calculating numerous possible outcomes. For this demonstration case, 5000 simulations (or iterations) were performed. Every time the model is run, slightly different results are produced, but the magnitude of the results remains the same, providing a distribution of possible results. The steps taken by the model are the following:

- **Step 1** – The process starts with the identification of the construction operation that takes place: either hydrodemolition, concrete grinding, or concrete grooving.
- **Step 2** – Each of these operations produces waste products in the forms of slurry, liquids and solids. The quantities of the slurry, liquid, and solid waste products for the selected operation from Step 1 are determined by the PDFs that were generated from the contractor interviews. Sample calculations for this step are provided in Appendix D. When the simulation is performed using the @Risk add on, the PDFs incorporated into the model, along with the supporting calculations, multiple possible solutions from the variables discussed previously are generated. That information is utilized in the subsequent steps of the model computations.
- **Step 3** – After ranges for the quantities of the waste product are generated by the model, that information is directed to the "Initial Handling" calculations. The two possible options for initial handling include decanting pond and frac tank. The costs associated with the decanting pond option include equipment, personnel and materials associated with the following activities:
    - Excavation of the pond,

  - Placement of lining,
  - Backfill, and
  - Compaction.

  Costs associated with the frac tank option include rental and delivery of the tanks.
- **<u>Step 4</u>** – The model then calculates the cost of water disposal/reuse, where two different options are possible; POTW/WWTP and land application. Costs associated with the POTW/WWTP option, include labor, personnel and equipment associated with the following operations:
  - Tanker truck hauling
  - Disposal fees, and
  - Environmental tests

  Costs associated with the land application option include environmental tests and delivery of the waste water.
- **<u>Step 5</u>** – The model then proceeds to calculate the costs of solid disposal where, as stated previously, there are five possible options under consideration:
  - MSW disposal,
  - C&D disposal,
  - LCID disposal,
  - Beneficial fill offsite, and
  - Beneficial fill onsite.

  Disposal at MSW, C&D, and LCID facilities is treated similarly and the costs associated with this option include:
  - Environmental tests,
  - Collection of the material,
  - Hauling,
  - Disposal fees,
  - Personnel, and
  - Equipment

  The costs associated with beneficial fill offsite, include the required environmental tests, collection of material, hauling, personnel and equipment. For disposal onsite, only the environmental tests were considered.
- **<u>Step 6</u>** - Once each of the costs have been calculated by the model for the project characteristics, they are added together, and ranges for possible costs for multiple scenarios are generated. For the inputs for the example scenario described in Section 4.2.1, Project Characteristics Utilized in Demonstration Simulation, the results (model output) are provided in detail in the following chapter.

As mentioned previously, the model performs the same calculations many times (in this case, 5,000 times), and utilization of the PDFs supporting the Monte Carlo simulation results in a range of possible results generated each time the model simulation is performed. To provide an understanding of the functionality of the model as well as to show the typical output of the analysis, a sample run of the model is shown in the following chapter. Results from this demonstration simulation will provide a means of illustrating the trends that can be determined form the output, as well as demonstrate the impact of the various disposal and reuse options on the overall cost of disposing hydrodemolition, diamond grinding and diamond grooving residuals.

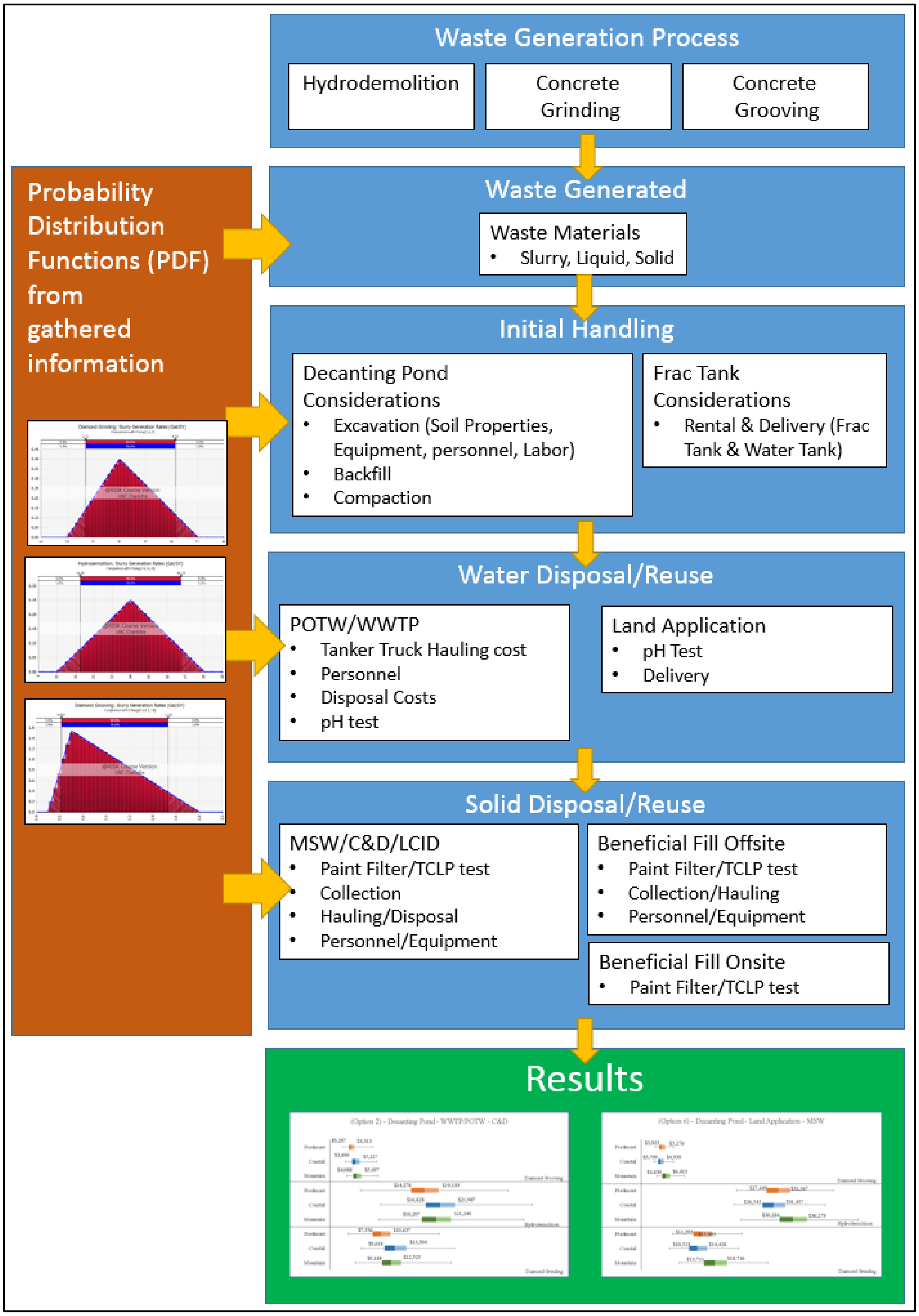



**Figure 34: Model Flow Chart**

# 5.0 RESULTS

The model produced as part of this work computes a cost analysis for multiple options for disposal and reuse of concrete residuals produced from hydrodemolition, grinding, and grooving operations. The summary results for the cost analysis provided by the model have been configured in a manner that should provide a contractor information on the likely costs associated with each of the possible project-specific options, insight into the potential ranges of costs given the variability associated with individual factors, and other data to support selection of options for disposal and/or beneficial reuse of concrete residuals.

To facilitate demonstration of the model in this report, as described in Chapter 4, a sample simulation was performed using characteristics of a theoretical project that had a diamond grinding, diamond grooving or hydrodemolition area of 10,000 square yards. To illustrate the model results and outputs, the outcomes for the sample simulation detailed in Chapter 4 are presented. The following sections of this report present the following model outcomes:

- the estimated cost generated with the help of the Monte Carlo simulation for the 20 potential combinations of disposal and reuse, and
- the results from contractor interviews that identify possible risks and environmental benefits associated with the processes involved with these operations.

## 5.1 RESULTS FROM THE MONTE CARLO SIMULATION

The Monte Carlo simulation method provides results based on the results compiled from specified number of simulations. The costs associated with the disposal or reuse of concrete residuals is displayed in a range of possible values that can exist with the given initial conditions. For the demonstration project, the Monte Carlo simulation was performed 5000 times for the input project characteristics. The results depicted in this section represent the outcome of the scenario and assumptions described in Section 4.2 of this report. Equations and calculations associated with these results are provided in Appendix D. As a reminder for the reader, the twenty possible disposal and reuse options associated with the results are numbered from 1-20, and are shown in Table 1 on page 27 of this report.

The model output provides ranges of costs displayed in a box plot format, where the box represents the range of cost values between the 25$^{th}$ and the 75$^{th}$ percentile. The mean (50% value) is in the middle of the plot, at the point where the color changes from darker to lighter. The "whiskers" of the box plots indicate the two extreme cost values of 0% and 100%. For comparison purposes box plots were generated for each of the 20 combinations for the three regions of North Carolina (Mountain, Piedmont, and Coastal). Additional box plots were generated showing all the 20 combinations together for each region. A sample of these box plots are shown in this chapter to help illustrate the cost trends associated with each disposal and reuse option. Box plots used to illustrate the results for all 20 combinations are shown in Appendix E.

It is important to remember that due to the probabilistic nature of the Monte Carlo analytical method supporting the model, the results of the simulation will be different each time it is run. Therefore, these plots can be used to compare the relative differences of the options when compared to each other. For the simulation displayed in this report, the numerical values of the estimates are displayed as well. For reference all plots with green color refer to the Mountain Region, all plots with orange color refer to the Piedmont Region, and all plots with blue color refer to the Coastal Region.

Specifically, the information presented in the following tables and figures is as follows:

- Table 2 and Figure 35 – Diamond grinding disposal/reuse options for the Mountain Region.
- Table 3 and Figure 36 – Hydrodemolition disposal/reuse options for the Mountain Region
- Table 4 and Figure 37 – Diamond grooving disposal/reuse option for the Mountain Region
- Table 5 and Figure 38 – Diamond grinding disposal/reuse options for the Piedmont Region.
- Table 6 and Figure 39 – Hydrodemolition disposal/reuse options for the Piedmont Region
- Table 7 and Figure 40 – Diamond grooving disposal/reuse options for the Piedmont Region
- Table 8 and Figure 41 – Diamond grinding disposal/reuse options for the Coastal Region.
- Table 9 and Figure 42 – Hydrodemolition disposal/reuse options for the Coastal Region
- Table 10 and Figure 43 – Diamond grooving disposal/reuse options for the Coastal Region

**Table 2: Diamond Grinding – Mountain Region**

| Option | Slurry Handling Method | Liquid Management | Solid Management | Min | 25th Percentile | 50th Percentile | 75th Percentile | Max |
|---|---|---|---|---|---|---|---|---|
| 1 | Dec. Pond | WWTP/POTW | MSW | $5,616 | $10,251 | $12,113 | $14,221 | $22,981 |
| 2 | Dec. Pond | WWTP/POTW | C&D | $4,938 | $9,159 | $10,780 | $12,642 | $19,716 |
| 3 | Dec. Pond | WWTP/POTW | LCID | $3,129 | $6,382 | $7,648 | $9,105 | $17,154 |
| 4 | Dec. Pond | WWTP/POTW | Ben. fill onsite | $2,075 | $4,094 | $4,774 | $5,600 | $9,334 |
| 5 | Dec. Pond | WWTP/POTW | Ben. fill offsite | $2,384 | $4,548 | $5,282 | $6,177 | $10,030 |
| 6 | Dec. Pond | Land App. | MSW | $8,300 | $13,711 | $16,078 | $18,800 | $27,411 |
| 7 | Dec. Pond | Land App. | C&D | $7,518 | $12,653 | $14,709 | $17,277 | $24,627 |
| 8 | Dec. Pond | Land App. | LCID | $5,871 | $9,930 | $11,656 | $13,597 | $21,513 |
| 9 | Dec. Pond | Land App. | Ben. fill onsite | $5,064 | $7,601 | $8,759 | $10,127 | $13,711 |
| 10 | Dec. Pond | Land App. | Ben. fill offsite | $5,372 | $8,024 | $9,260 | $10,707 | $14,329 |
| 11 | Frac Tank | WWTP/POTW | MSW | $8,605 | $12,940 | $14,636 | $16,574 | $24,922 |
| 12 | Frac Tank | WWTP/POTW | C&D | $7,905 | $11,822 | $13,323 | $15,005 | $21,661 |
| 13 | Frac Tank | WWTP/POTW | LCID | $6,123 | $9,027 | $10,178 | $11,513 | $19,111 |
| 14 | Frac Tank | WWTP/POTW | Ben. fill onsite | $4,643 | $6,752 | $7,315 | $8,015 | $11,444 |
| 15 | Frac Tank | WWTP/POTW | Ben. fill offsite | $5,145 | $7,197 | $7,812 | $8,561 | $12,140 |
| 16 | Frac Tank | Land App. | MSW | $11,300 | $16,413 | $18,622 | $21,141 | $29,352 |
| 17 | Frac Tank | Land App. | C&D | $10,516 | $15,352 | $17,268 | $19,629 | $26,572 |
| 18 | Frac Tank | Land App. | LCID | $8,863 | $12,626 | $14,202 | $15,951 | $23,461 |
| 19 | Frac Tank | Land App. | Ben. fill onsite | $8,068 | $10,305 | $11,326 | $12,475 | $15,651 |
| 20 | Frac Tank | Land App. | Ben. fill offsite | $8,377 | $10,743 | $11,832 | $13,050 | $16,269 |

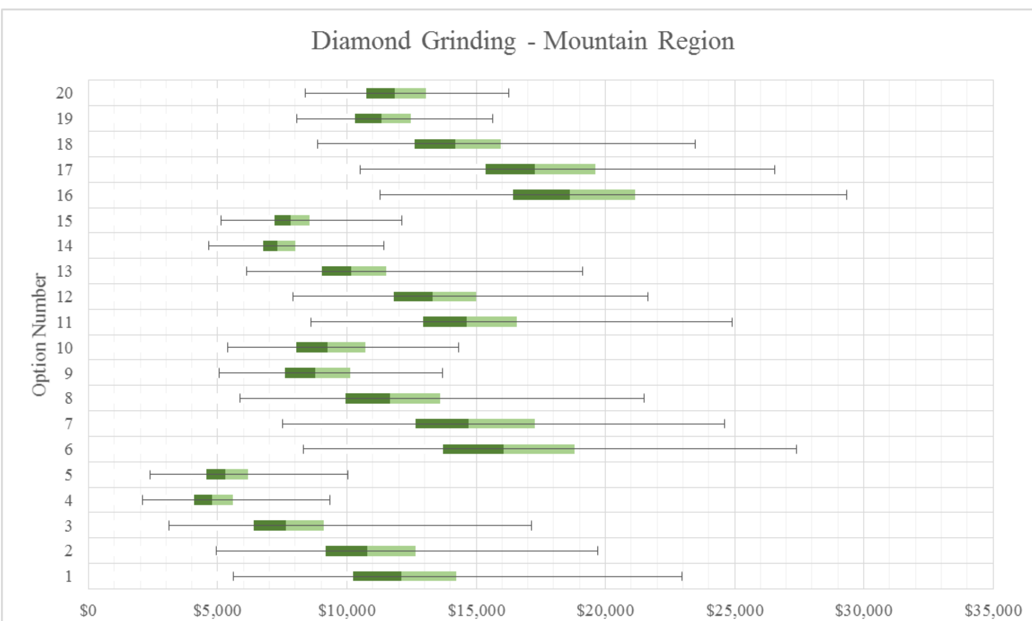



**Figure 35: Diamond Grinding – Mountain Region**

**Table 3: Hydrodemolition – Mountain Region**

| Option | Slurry Handling Method | Liquid Management | Solid Management | Min | 25th Percentile | 50th Percentile | 75th Percentile | Max |
|---|---|---|---|---|---|---|---|---|
| 1 | Dec. Pond | WWTP/POTW | MSW | $9,014 | $17,550 | $20,108 | $22,748 | $35,590 |
| 2 | Dec. Pond | WWTP/POTW | C&D | $7,945 | $16,221 | $18,632 | $21,136 | $34,502 |
| 3 | Dec. Pond | WWTP/POTW | LCID | $5,709 | $12,965 | $15,079 | $17,402 | $30,294 |
| 4 | Dec. Pond | WWTP/POTW | Ben. fill onsite | $3,051 | $9,976 | $11,757 | $13,738 | $24,624 |
| 5 | Dec. Pond | WWTP/POTW | Ben. fill offsite | $3,669 | $10,533 | $12,348 | $14,311 | $25,242 |
| 6 | Dec. Pond | Land App. | MSW | $22,300 | $30,372 | $33,201 | $36,175 | $48,014 |
| 7 | Dec. Pond | Land App. | C&D | $21,604 | $29,023 | $31,790 | $34,428 | $44,867 |
| 8 | Dec. Pond | Land App. | LCID | $18,851 | $25,819 | $28,146 | $30,611 | $40,773 |
| 9 | Dec. Pond | Land App. | Ben. fill onsite | $17,874 | $22,885 | $24,913 | $26,922 | $33,644 |
| 10 | Dec. Pond | Land App. | Ben. fill offsite | $18,341 | $23,416 | $25,496 | $27,521 | $34,382 |
| 11 | Frac Tank | WWTP/POTW | MSW | $9,878 | $18,019 | $20,404 | $22,936 | $35,196 |
| 12 | Frac Tank | WWTP/POTW | C&D | $8,809 | $16,658 | $18,886 | $21,309 | $34,118 |
| 13 | Frac Tank | WWTP/POTW | LCID | $6,381 | $13,369 | $15,364 | $17,559 | $29,900 |
| 14 | Frac Tank | WWTP/POTW | Ben. fill onsite | $3,097 | $10,388 | $12,081 | $13,936 | $24,269 |
| 15 | Frac Tank | WWTP/POTW | Ben. fill offsite | $3,715 | $10,933 | $12,645 | $14,534 | $24,887 |
| 16 | Frac Tank | Land App. | MSW | $23,401 | $30,864 | $33,478 | $36,228 | $47,625 |
| 17 | Frac Tank | Land App. | C&D | $22,706 | $29,543 | $32,048 | $34,468 | $44,483 |
| 18 | Frac Tank | Land App. | LCID | $19,966 | $26,334 | $28,406 | $30,634 | $40,511 |
| 19 | Frac Tank | Land App. | Ben. fill onsite | $18,978 | $23,429 | $25,191 | $26,920 | $33,054 |
| 20 | Frac Tank | Land App. | Ben. fill offsite | $19,443 | $23,943 | $25,758 | $27,541 | $33,815 |

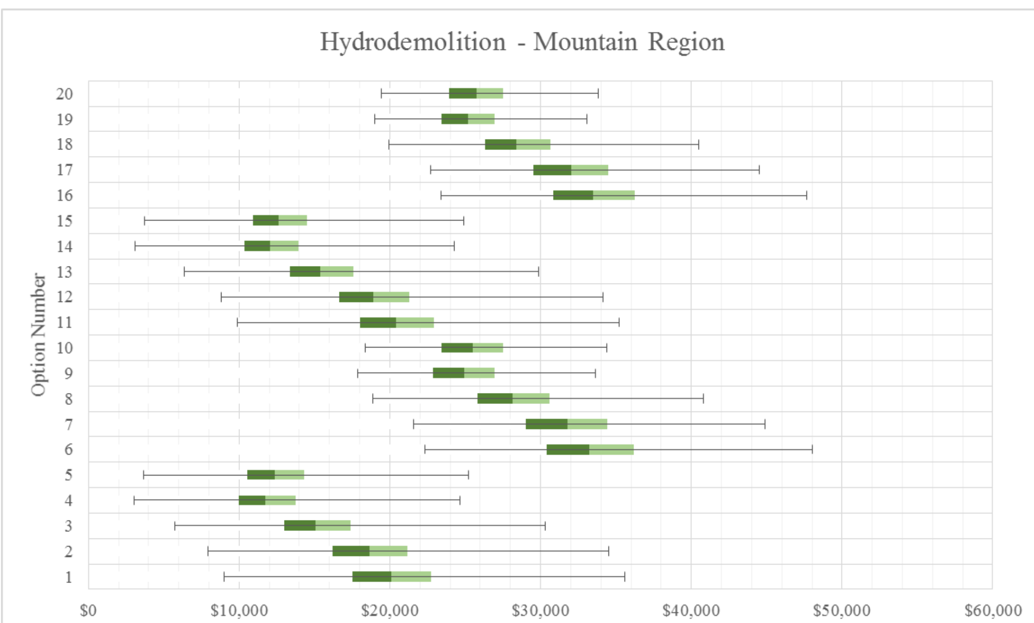



**Figure 36: Hydrodemolition – Mountain Region**

**Table 4: Diamond Grooving – Mountain Region**

| Option | Slurry Handling Method | Liquid Management | Solid Management | Min | 25th Percentile | 50th Percentile | 75th Percentile | Max |
|---|---|---|---|---|---|---|---|---|
| 1 | Dec. Pond | WWTP/POTW | MSW | $2,989 | $4,096 | $4,699 | $5,497 | $8,407 |
| 2 | Dec. Pond | WWTP/POTW | C&D | $2,817 | $3,766 | $4,297 | $4,976 | $7,642 |
| 3 | Dec. Pond | WWTP/POTW | LCID | $2,187 | $2,948 | $3,298 | $3,766 | $6,511 |
| 4 | Dec. Pond | WWTP/POTW | Ben. fill onsite | $1,824 | $2,231 | $2,396 | $2,595 | $3,976 |
| 5 | Dec. Pond | WWTP/POTW | Ben. fill offsite | $1,979 | $2,390 | $2,583 | $2,815 | $4,285 |
| 6 | Dec. Pond | Land App. | MSW | $3,508 | $4,638 | $5,435 | $6,380 | $9,218 |
| 7 | Dec. Pond | Land App. | C&D | $3,270 | $4,316 | $5,026 | $5,867 | $8,507 |
| 8 | Dec. Pond | Land App. | LCID | $2,638 | $3,528 | $4,014 | $4,654 | $7,639 |
| 9 | Dec. Pond | Land App. | Ben. fill onsite | $2,404 | $2,776 | $3,153 | $3,489 | $4,485 |
| 10 | Dec. Pond | Land App. | Ben. fill offsite | $2,544 | $2,932 | $3,340 | $3,713 | $4,717 |
| 11 | Frac Tank | WWTP/POTW | MSW | $6,376 | $7,452 | $7,966 | $8,684 | $11,548 |
| 12 | Frac Tank | WWTP/POTW | C&D | $6,205 | $7,115 | $7,553 | $8,165 | $10,783 |
| 13 | Frac Tank | WWTP/POTW | LCID | $5,555 | $6,272 | $6,573 | $6,983 | $9,648 |
| 14 | Frac Tank | WWTP/POTW | Ben. fill onsite | $5,084 | $5,557 | $5,667 | $5,801 | $7,110 |
| 15 | Frac Tank | WWTP/POTW | Ben. fill offsite | $5,316 | $5,724 | $5,851 | $6,011 | $7,419 |
| 16 | Frac Tank | Land App. | MSW | $6,894 | $8,003 | $8,667 | $9,566 | $12,355 |
| 17 | Frac Tank | Land App. | C&D | $6,658 | $7,679 | $8,262 | $9,048 | $11,638 |
| 18 | Frac Tank | Land App. | LCID | $6,024 | $6,868 | $7,272 | $7,838 | $10,777 |
| 19 | Frac Tank | Land App. | Ben. fill onsite | $5,791 | $6,140 | $6,375 | $6,674 | $7,618 |
| 20 | Frac Tank | Land App. | Ben. fill offsite | $5,932 | $6,295 | $6,556 | $6,899 | $7,849 |

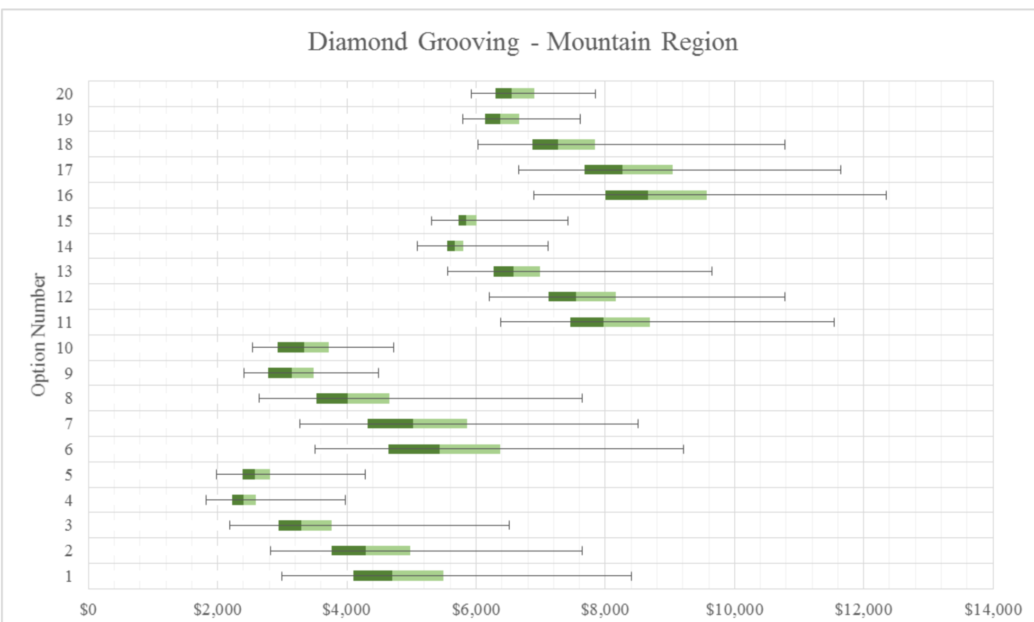



**Figure 37: Diamond Grooving – Mountain Region**

**Table 5: Diamond Grinding – Piedmont Region**

| Option | Slurry Handling Method | Liquid Management | Solid Management | Min | 25th Percentile | 50th Percentile | 75th Percentile | Max |
|---|---|---|---|---|---|---|---|---|
| 1 | Dec. Pond | WWTP/POTW | MSW | $4,401 | $7,880 | $9,275 | $10,808 | $17,707 |
| 2 | Dec. Pond | WWTP/POTW | C&D | $3,240 | $7,562 | $9,004 | $10,705 | $18,979 |
| 3 | Dec. Pond | WWTP/POTW | LCID | $2,589 | $5,819 | $7,028 | $8,480 | $17,924 |
| 4 | Dec. Pond | WWTP/POTW | Ben. fill onsite | $2,075 | $4,094 | $4,774 | $5,600 | $9,334 |
| 5 | Dec. Pond | WWTP/POTW | Ben. fill offsite | $2,384 | $4,548 | $5,282 | $6,177 | $10,030 |
| 6 | Dec. Pond | Land App. | MSW | $6,917 | $11,361 | $13,202 | $15,426 | $21,902 |
| 7 | Dec. Pond | Land App. | C&D | $6,169 | $11,006 | $12,990 | $15,225 | $25,329 |
| 8 | Dec. Pond | Land App. | LCID | $5,510 | $9,389 | $11,065 | $12,966 | $22,398 |
| 9 | Dec. Pond | Land App. | Ben. fill onsite | $5,064 | $7,601 | $8,759 | $10,127 | $13,711 |
| 10 | Dec. Pond | Land App. | Ben. fill offsite | $5,372 | $8,024 | $9,260 | $10,707 | $14,329 |
| 11 | Frac Tank | WWTP/POTW | MSW | $7,398 | $10,557 | $11,799 | $13,176 | $19,648 |
| 12 | Frac Tank | WWTP/POTW | C&D | $6,228 | $10,201 | $11,543 | $13,108 | $20,935 |
| 13 | Frac Tank | WWTP/POTW | LCID | $5,189 | $8,437 | $9,549 | $10,917 | $19,874 |
| 14 | Frac Tank | WWTP/POTW | Ben. fill onsite | $4,643 | $6,752 | $7,315 | $8,015 | $11,444 |
| 15 | Frac Tank | WWTP/POTW | Ben. fill offsite | $5,145 | $7,197 | $7,812 | $8,561 | $12,140 |
| 16 | Frac Tank | Land App. | MSW | $9,925 | $14,068 | $15,755 | $17,762 | $23,832 |
| 17 | Frac Tank | Land App. | C&D | $9,157 | $13,679 | $15,517 | $17,604 | $27,285 |
| 18 | Frac Tank | Land App. | LCID | $8,510 | $12,064 | $13,588 | $15,321 | $24,342 |
| 19 | Frac Tank | Land App. | Ben. fill onsite | $8,068 | $10,305 | $11,326 | $12,475 | $15,651 |
| 20 | Frac Tank | Land App. | Ben. fill offsite | $8,377 | $10,743 | $11,832 | $13,050 | $16,269 |

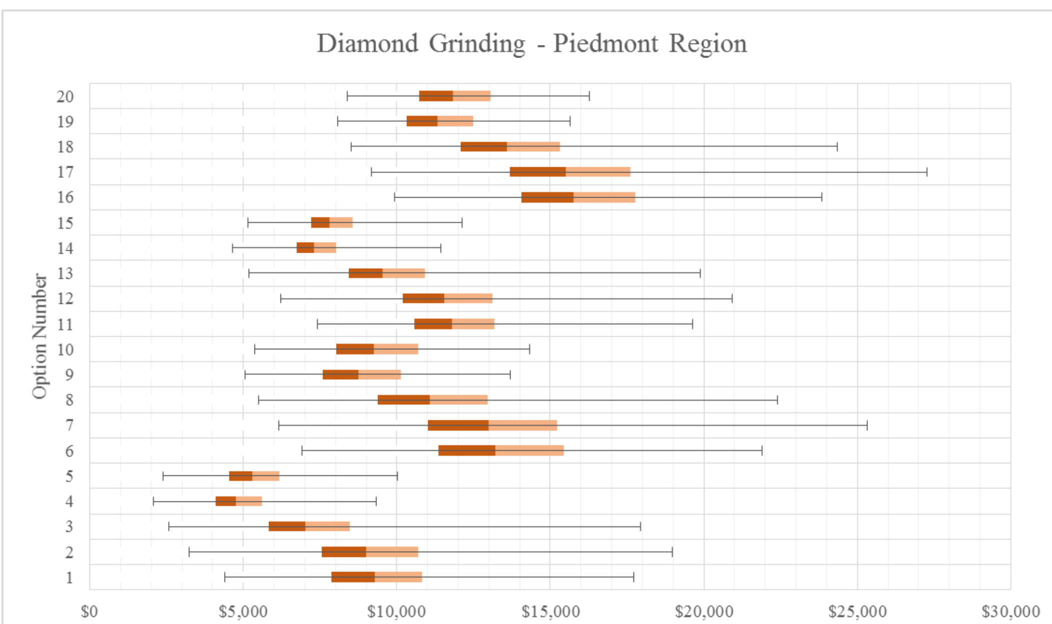



**Figure 38: Diamond Grinding – Piedmont Region**

**Table 6: Hydrodemolition – Piedmont Region**

| Option | Slurry Handling Method | Liquid Management | Solid Management | Min | 25th Percentile | 50th Percentile | 75th Percentile | Max |
|---|---|---|---|---|---|---|---|---|
| 1 | Dec. Pond | WWTP/POTW | MSW | $7,014 | $14,711 | $16,836 | $19,217 | $31,659 |
| 2 | Dec. Pond | WWTP/POTW | C&D | $6,636 | $14,350 | $16,613 | $19,044 | $30,141 |
| 3 | Dec. Pond | WWTP/POTW | LCID | $3,735 | $12,263 | $14,457 | $16,787 | $28,492 |
| 4 | Dec. Pond | WWTP/POTW | Ben. fill onsite | $3,051 | $9,976 | $11,757 | $13,738 | $24,624 |
| 5 | Dec. Pond | WWTP/POTW | Ben. fill offsite | $3,669 | $10,533 | $12,348 | $14,311 | $25,242 |
| 6 | Dec. Pond | Land App. | MSW | $20,240 | $27,470 | $30,033 | $32,439 | $42,109 |
| 7 | Dec. Pond | Land App. | C&D | $19,849 | $27,114 | $29,716 | $32,406 | $42,784 |
| 8 | Dec. Pond | Land App. | LCID | $18,459 | $25,128 | $27,557 | $29,984 | $41,966 |
| 9 | Dec. Pond | Land App. | Ben. fill onsite | $17,874 | $22,885 | $24,913 | $26,922 | $33,644 |
| 10 | Dec. Pond | Land App. | Ben. fill offsite | $18,341 | $23,416 | $25,496 | $27,521 | $34,382 |
| 11 | Frac Tank | WWTP/POTW | MSW | $7,878 | $15,160 | $17,121 | $19,379 | $31,264 |
| 12 | Frac Tank | WWTP/POTW | C&D | $6,655 | $14,772 | $16,940 | $19,171 | $29,731 |
| 13 | Frac Tank | WWTP/POTW | LCID | $3,781 | $12,653 | $14,767 | $16,982 | $28,224 |
| 14 | Frac Tank | WWTP/POTW | Ben. fill onsite | $3,097 | $10,388 | $12,081 | $13,936 | $24,269 |
| 15 | Frac Tank | WWTP/POTW | Ben. fill offsite | $3,715 | $10,933 | $12,645 | $14,534 | $24,887 |
| 16 | Frac Tank | Land App. | MSW | $20,240 | $27,470 | $30,033 | $32,439 | $42,109 |
| 17 | Frac Tank | Land App. | C&D | $19,849 | $27,114 | $29,716 | $32,406 | $42,784 |
| 18 | Frac Tank | Land App. | LCID | $18,459 | $25,128 | $27,557 | $29,984 | $41,966 |
| 19 | Frac Tank | Land App. | Ben. fill onsite | $17,874 | $22,885 | $24,913 | $26,922 | $33,644 |
| 20 | Frac Tank | Land App. | Ben. fill offsite | $18,341 | $23,416 | $25,496 | $27,521 | $34,382 |

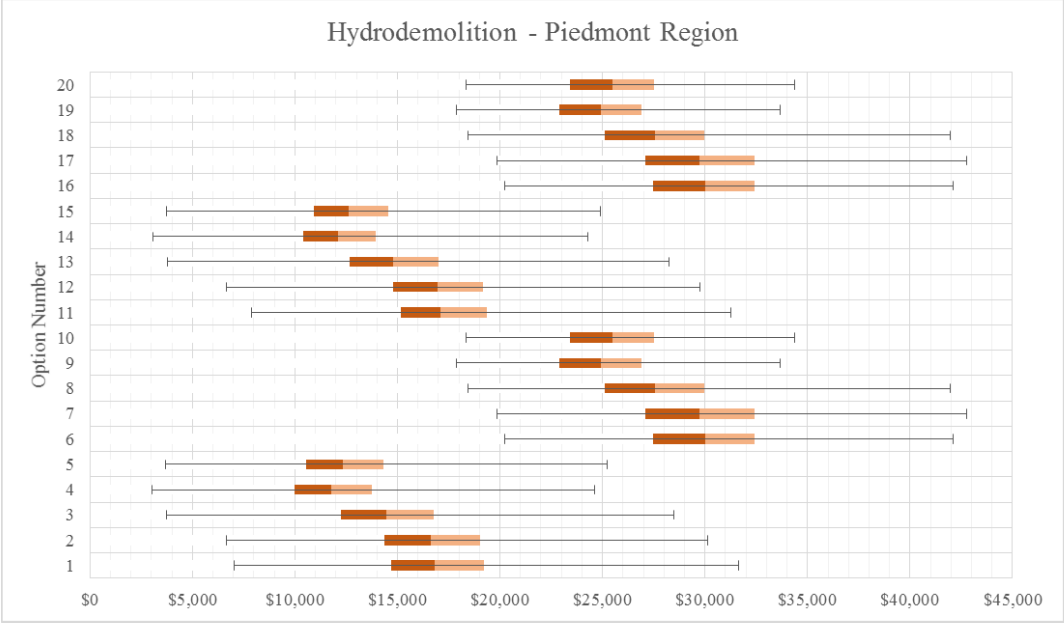



**Figure 39: Hydrodemolition – Piedmont Region**

**Table 7: Diamond Grooving – Piedmont Region**

| Option | Slurry Handling Method | Liquid Management | Solid Management | Min | 25th Percentile | 50th Percentile | 75th Percentile | Max |
|---|---|---|---|---|---|---|---|---|
| 1 | Dec. Pond | WWTP/POTW | MSW | $2,536 | $3,377 | $3,813 | $4,381 | $6,744 |
| 2 | Dec. Pond | WWTP/POTW | C&D | $2,281 | $3,286 | $3,721 | $4,312 | $7,142 |
| 3 | Dec. Pond | WWTP/POTW | LCID | $2,103 | $2,765 | $3,115 | $3,561 | $6,224 |
| 4 | Dec. Pond | WWTP/POTW | Ben. fill onsite | $1,824 | $2,231 | $2,396 | $2,595 | $3,976 |
| 5 | Dec. Pond | WWTP/POTW | Ben. fill offsite | $1,979 | $2,390 | $2,583 | $2,815 | $4,285 |
| 6 | Dec. Pond | Land App. | MSW | $3,051 | $3,923 | $4,552 | $5,290 | $7,363 |
| 7 | Dec. Pond | Land App. | C&D | $2,821 | $3,852 | $4,455 | $5,207 | $8,348 |
| 8 | Dec. Pond | Land App. | LCID | $2,574 | $3,368 | $3,855 | $4,415 | $7,276 |
| 9 | Dec. Pond | Land App. | Ben. fill onsite | $2,404 | $2,776 | $3,153 | $3,489 | $4,485 |
| 10 | Dec. Pond | Land App. | Ben. fill offsite | $2,544 | $2,932 | $3,340 | $3,713 | $4,717 |
| 11 | Frac Tank | WWTP/POTW | MSW | $5,924 | $6,726 | $7,072 | $7,569 | $9,885 |
| 12 | Frac Tank | WWTP/POTW | C&D | $5,585 | $6,620 | $6,996 | $7,511 | $10,279 |
| 13 | Frac Tank | WWTP/POTW | LCID | $5,338 | $6,061 | $6,384 | $6,793 | $9,362 |
| 14 | Frac Tank | WWTP/POTW | Ben. fill onsite | $5,084 | $5,557 | $5,667 | $5,801 | $7,110 |
| 15 | Frac Tank | WWTP/POTW | Ben. fill offsite | $5,316 | $5,724 | $5,851 | $6,011 | $7,419 |
| 16 | Frac Tank | Land App. | MSW | $6,438 | $7,287 | $7,782 | $8,475 | $10,505 |
| 17 | Frac Tank | Land App. | C&D | $6,209 | $7,199 | $7,696 | $8,397 | $11,484 |
| 18 | Frac Tank | Land App. | LCID | $5,962 | $6,695 | $7,107 | $7,616 | $10,416 |
| 19 | Frac Tank | Land App. | Ben. fill onsite | $5,791 | $6,140 | $6,375 | $6,674 | $7,618 |
| 20 | Frac Tank | Land App. | Ben. fill offsite | $5,932 | $6,295 | $6,556 | $6,899 | $7,849 |

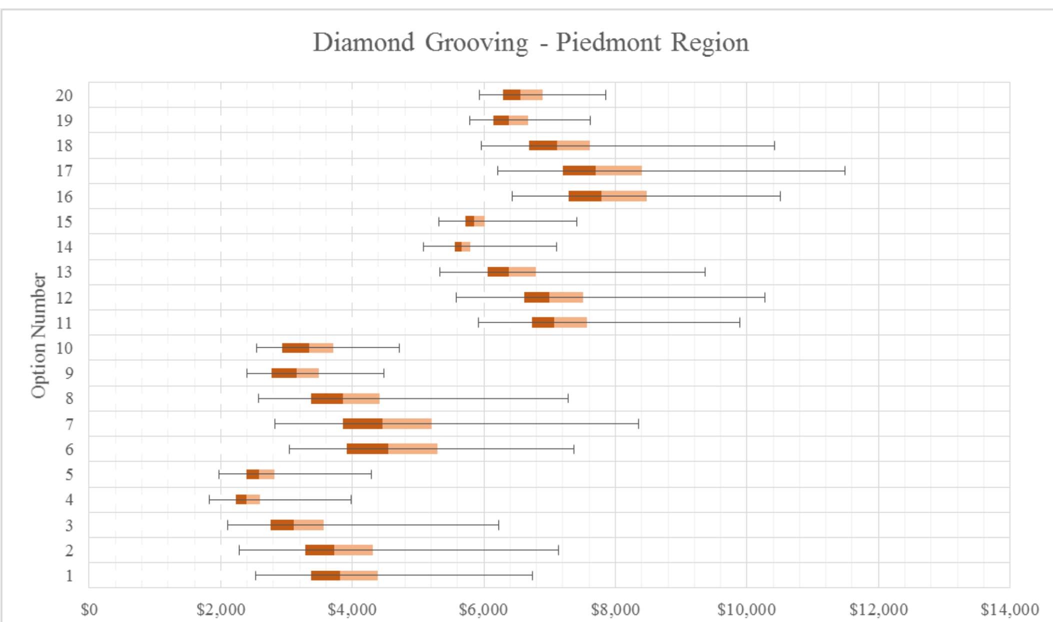



**Figure 40: Diamond Grooving – Piedmont Region**

**Table 8: Diamond Grinding – Coastal Region**

| Option | Slurry Handling Method | Liquid Management | Solid Management | Min | 25th Percentile | 50th Percentile | 75th Percentile | Max |
|---|---|---|---|---|---|---|---|---|
| 1 | Dec. Pond | WWTP/POTW | MSW | $3,750 | $7,081 | $8,371 | $9,849 | $16,375 |
| 2 | Dec. Pond | WWTP/POTW | C&D | $5,125 | $9,598 | $11,358 | $13,416 | $21,451 |
| 3 | Dec. Pond | WWTP/POTW | LCID | $2,834 | $6,111 | $7,721 | $9,680 | $19,363 |
| 4 | Dec. Pond | WWTP/POTW | Ben. fill onsite | $2,075 | $4,094 | $4,774 | $5,600 | $9,334 |
| 5 | Dec. Pond | WWTP/POTW | Ben. fill offsite | $2,384 | $4,548 | $5,282 | $6,177 | $10,030 |
| 6 | Dec. Pond | Land App. | MSW | $6,288 | $10,527 | $12,372 | $14,389 | $21,053 |
| 7 | Dec. Pond | Land App. | C&D | $7,844 | $13,078 | $15,305 | $18,007 | $27,682 |
| 8 | Dec. Pond | Land App. | LCID | $5,900 | $9,777 | $11,757 | $14,050 | $25,244 |
| 9 | Dec. Pond | Land App. | Ben. fill onsite | $5,064 | $7,601 | $8,759 | $10,127 | $13,711 |
| 10 | Dec. Pond | Land App. | Ben. fill offsite | $5,372 | $8,024 | $9,260 | $10,707 | $14,329 |
| 11 | Frac Tank | WWTP/POTW | MSW | $6,751 | $9,732 | $10,897 | $12,245 | $18,316 |
| 12 | Frac Tank | WWTP/POTW | C&D | $8,107 | $12,285 | $13,908 | $15,786 | $23,420 |
| 13 | Frac Tank | WWTP/POTW | LCID | $5,796 | $8,710 | $10,239 | $12,115 | $21,310 |
| 14 | Frac Tank | WWTP/POTW | Ben. fill onsite | $4,643 | $6,752 | $7,315 | $8,015 | $11,444 |
| 15 | Frac Tank | WWTP/POTW | Ben. fill offsite | $5,145 | $7,197 | $7,812 | $8,561 | $12,140 |
| 16 | Frac Tank | Land App. | MSW | $9,290 | $13,223 | $14,913 | $16,731 | $23,009 |
| 17 | Frac Tank | Land App. | C&D | $10,845 | $15,758 | $17,861 | $20,355 | $29,615 |
| 18 | Frac Tank | Land App. | LCID | $8,887 | $12,439 | $14,257 | $16,434 | $27,209 |
| 19 | Frac Tank | Land App. | Ben. fill onsite | $8,068 | $10,305 | $11,326 | $12,475 | $15,651 |
| 20 | Frac Tank | Land App. | Ben. fill offsite | $8,377 | $10,743 | $11,832 | $13,050 | $16,269 |

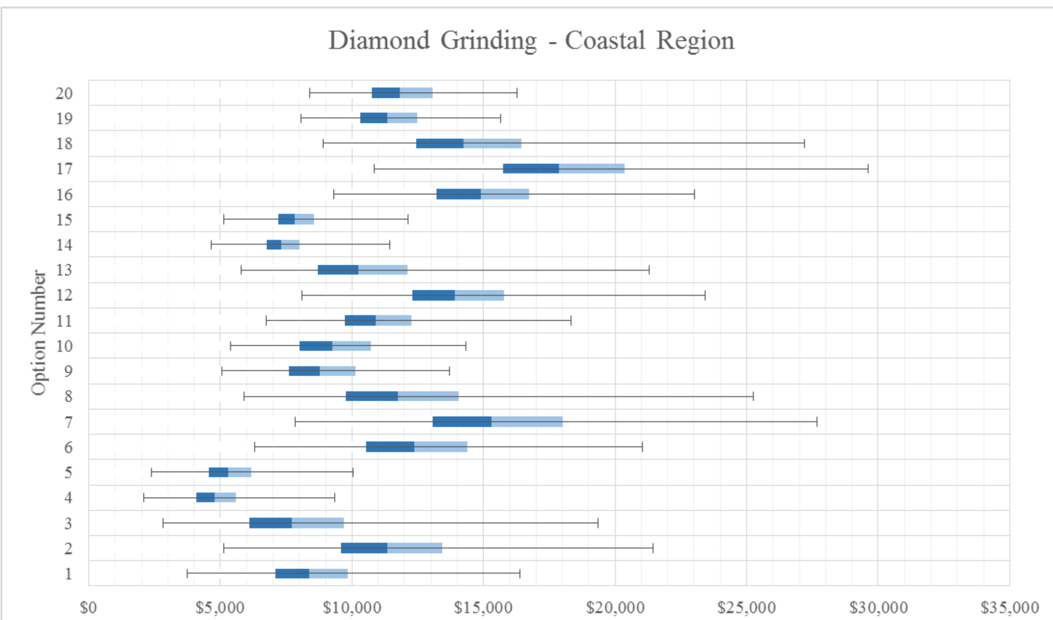



**Figure 41: Diamond Grinding – Coastal Region**

**Table 9: Hydrodemolition – Coastal Region**

| Option | Slurry Handling Method | Liquid Management | Solid Management | Min | 25th Percentile | 50th Percentile | 75th Percentile | Max |
|---|---|---|---|---|---|---|---|---|
| 1 | Dec. Pond | WWTP/POTW | MSW | $6,347 | $13,714 | $15,835 | $18,189 | $29,013 |
| 2 | Dec. Pond | WWTP/POTW | C&D | $8,214 | $16,833 | $19,284 | $21,885 | $34,613 |
| 3 | Dec. Pond | WWTP/POTW | LCID | $4,680 | $12,791 | $15,260 | $17,973 | $31,256 |
| 4 | Dec. Pond | WWTP/POTW | Ben. fill onsite | $3,051 | $9,976 | $11,757 | $13,738 | $24,624 |
| 5 | Dec. Pond | WWTP/POTW | Ben. fill offsite | $3,669 | $10,533 | $12,348 | $14,311 | $25,242 |
| 6 | Dec. Pond | Land App. | MSW | $19,329 | $26,618 | $28,993 | $31,398 | $40,355 |
| 7 | Dec. Pond | Land App. | C&D | $21,537 | $29,459 | $32,448 | $35,260 | $46,028 |
| 8 | Dec. Pond | Land App. | LCID | $18,450 | $25,691 | $28,306 | $31,136 | $42,569 |
| 9 | Dec. Pond | Land App. | Ben. fill onsite | $17,874 | $22,885 | $24,913 | $26,922 | $33,644 |
| 10 | Dec. Pond | Land App. | Ben. fill offsite | $18,341 | $23,416 | $25,496 | $27,521 | $34,382 |
| 11 | Frac Tank | WWTP/POTW | MSW | $7,019 | $14,143 | $16,111 | $18,346 | $28,633 |
| 12 | Frac Tank | WWTP/POTW | C&D | $9,077 | $17,272 | $19,592 | $22,080 | $34,229 |
| 13 | Frac Tank | WWTP/POTW | LCID | $4,726 | $13,193 | $15,554 | $18,165 | $30,900 |
| 14 | Frac Tank | WWTP/POTW | Ben. fill onsite | $3,097 | $10,388 | $12,081 | $13,936 | $24,269 |
| 15 | Frac Tank | WWTP/POTW | Ben. fill offsite | $3,715 | $10,933 | $12,645 | $14,534 | $24,887 |
| 16 | Frac Tank | Land App. | MSW | $20,429 | $27,107 | $29,275 | $31,436 | $39,775 |
| 17 | Frac Tank | Land App. | C&D | $22,638 | $29,995 | $32,724 | $35,301 | $45,639 |
| 18 | Frac Tank | Land App. | LCID | $19,554 | $26,187 | $28,595 | $31,188 | $42,196 |
| 19 | Frac Tank | Land App. | Ben. fill onsite | $18,978 | $23,429 | $25,191 | $26,920 | $33,054 |
| 20 | Frac Tank | Land App. | Ben. fill offsite | $19,443 | $23,943 | $25,758 | $27,541 | $33,815 |

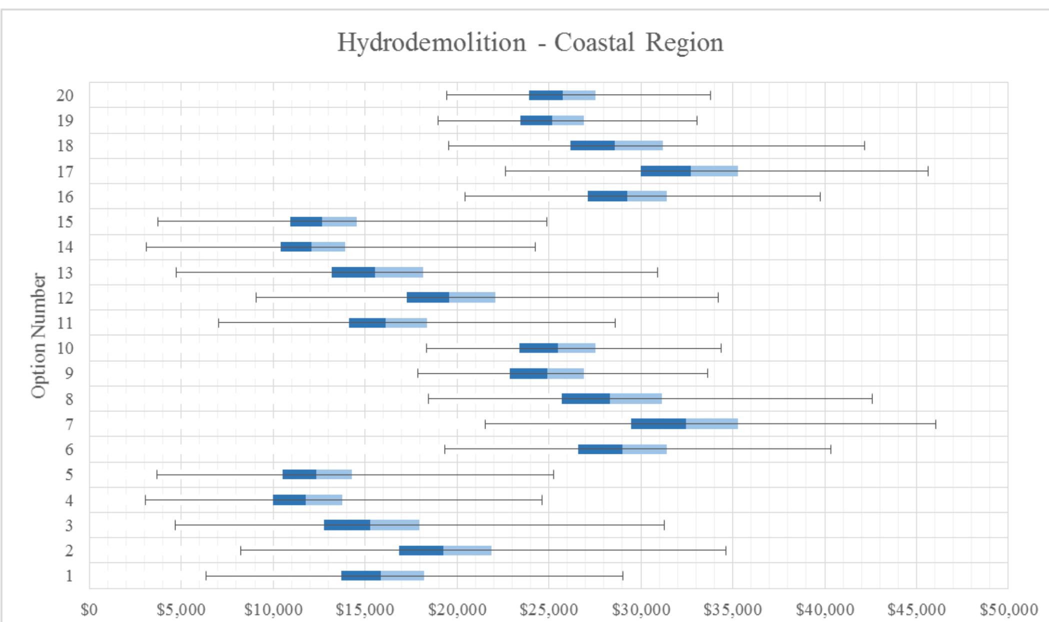



**Figure 42: Hydrodemolition – Coastal Region**

**Table 10: Diamond Grooving – Coastal Region**

| Option | Slurry Handling Method | Liquid Management | Solid Management | Min | 25th Percentile | 50th Percentile | 75th Percentile | Max |
|---|---|---|---|---|---|---|---|---|
| 1 | Dec. Pond | WWTP/POTW | MSW | $2,331 | $3,136 | $3,528 | $4,045 | $5,971 |
| 2 | Dec. Pond | WWTP/POTW | C&D | $2,745 | $3,907 | $4,484 | $5,214 | $7,884 |
| 3 | Dec. Pond | WWTP/POTW | LCID | $2,117 | $2,855 | $3,331 | $3,931 | $7,521 |
| 4 | Dec. Pond | WWTP/POTW | Ben. fill onsite | $1,824 | $2,231 | $2,396 | $2,595 | $3,976 |
| 5 | Dec. Pond | WWTP/POTW | Ben. fill offsite | $1,979 | $2,390 | $2,583 | $2,815 | $4,285 |
| 6 | Dec. Pond | Land App. | MSW | $2,891 | $3,690 | $4,258 | $4,939 | $7,269 |
| 7 | Dec. Pond | Land App. | C&D | $3,260 | $4,452 | $5,207 | $6,121 | $9,192 |
| 8 | Dec. Pond | Land App. | LCID | $2,622 | $3,488 | $4,051 | $4,775 | $8,957 |
| 9 | Dec. Pond | Land App. | Ben. fill onsite | $2,404 | $2,776 | $3,153 | $3,489 | $4,485 |
| 10 | Dec. Pond | Land App. | Ben. fill offsite | $2,544 | $2,932 | $3,340 | $3,713 | $4,717 |
| 11 | Frac Tank | WWTP/POTW | MSW | $5,703 | $6,476 | $6,794 | $7,240 | $9,113 |
| 12 | Frac Tank | WWTP/POTW | C&D | $6,133 | $7,257 | $7,742 | $8,403 | $11,018 |
| 13 | Frac Tank | WWTP/POTW | LCID | $5,487 | $6,152 | $6,595 | $7,173 | $10,656 |
| 14 | Frac Tank | WWTP/POTW | Ben. fill onsite | $5,084 | $5,557 | $5,667 | $5,801 | $7,110 |
| 15 | Frac Tank | WWTP/POTW | Ben. fill offsite | $5,316 | $5,724 | $5,851 | $6,011 | $7,419 |
| 16 | Frac Tank | Land App. | MSW | $6,276 | $7,045 | $7,511 | $8,120 | $10,408 |
| 17 | Frac Tank | Land App. | C&D | $6,646 | $7,817 | $8,450 | $9,307 | $12,325 |
| 18 | Frac Tank | Land App. | LCID | $6,008 | $6,801 | $7,327 | $7,978 | $12,092 |
| 19 | Frac Tank | Land App. | Ben. fill onsite | $5,791 | $6,140 | $6,375 | $6,674 | $7,618 |
| 20 | Frac Tank | Land App. | Ben. fill offsite | $5,932 | $6,295 | $6,556 | $6,899 | $7,849 |

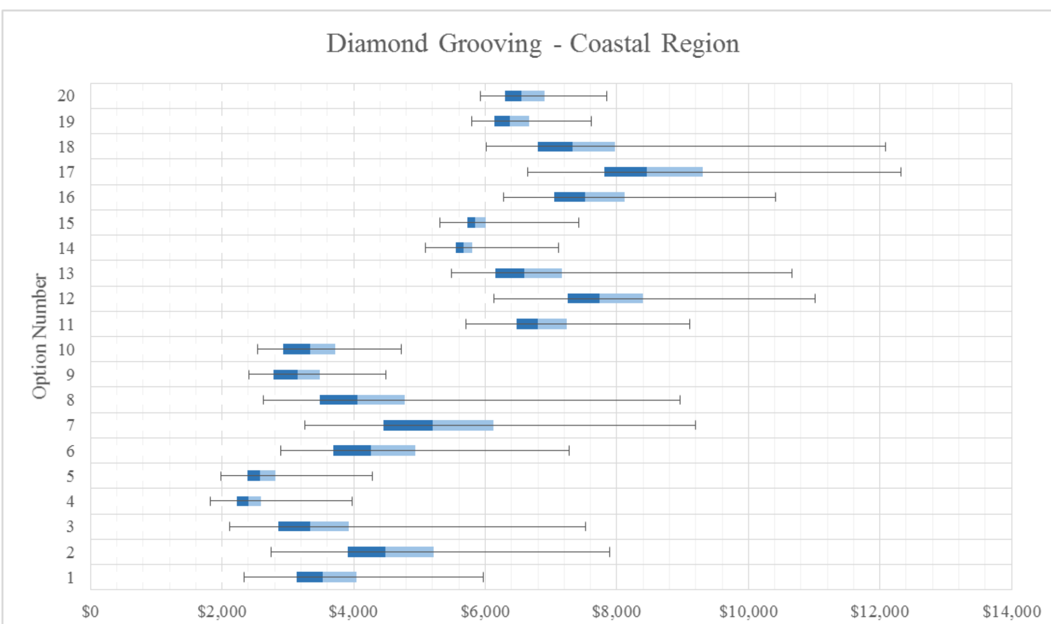



**Figure 43: Diamond Grooving – Coastal Region**

## 5.2 SUMMARY OF COST RESULTS

As observed in Table 2 through Table 10, and in Figure 35 through Figure 43 the ranges of costs associated with the different options follow some specific trends. A summary of the trends associated with the costs for disposal and reuse is provided in the subsequent paragraphs. Although these trends are specific only to the demonstration project (or projects with characteristics similar to the demonstration project), the trends provide insight into the costs associated with certain typical projects occurring in North Carolina that generate concrete residuals. If the model is utilized for other types of projects, a similar approach could be utilized to interpret the output.

For the characteristics assumed for the demonstration project, options involving the use of decanting pond (instead of a frac tank) tend to be less costly when all the other variables remain the same. This can be observed in the comparisons for all three regions of North Carolina, by observing the ranges of Option 1 through Option 10 (which include use of a decanting pond) when compared to options eleven through twenty (which include use of a frac tank). This is more evident when Option 1 is compared to Option 11, Option 2 is compared to Option 12, Option 3 is compared to Option 13, and so forth. This difference is less evident in cases where hydrodemolition is the operation to occur, and it is suspected that this difference can be attributed to the large amounts of slurry that are generated with the hydrodemolition process. The quantity of slurry is best handled using a larger decanting pond, which requires more effort in terms of labor and equipment to construct. An example of such comparison is shown in Figure 44, where Option 1 and Option 11 are compared. As can be observed, the ranges for hydrodemolition are similar in both cases, while for grinding and grooving, the range of costs is greater when the frac tank is selected for use. A similar outcome can be observed when options two and twelve are compared (Figure 45).


**Figure 44: Comparison of Option 1 (Left) and Option 11 (Right)**

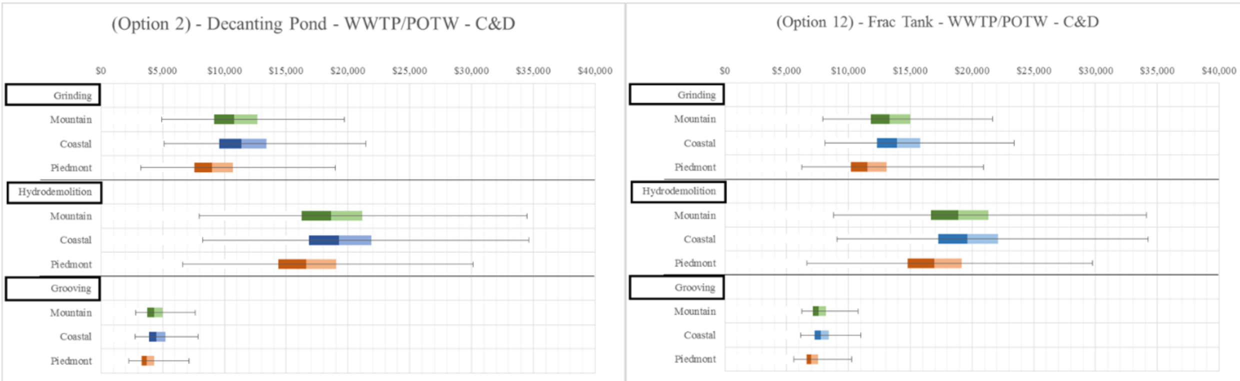



**Figure 45: Comparison of Option 2 (Left) and Option 12 (Right)**

Options involving the use of land application techniques over disposal of residuals at a WWTP/POTW tend to be more expensive. This can be observed by noting and comparing in Figure 35 through Figure 43 the differences between Option 1 through Option 5 (which include use of land application) to Option 6 through Option 10 (which include disposal at a WWTP/POTW facility), and by comparing Options 11 through 15 (which include use of land application) to Options 16 to 20 (which include disposal at a WWTP/POTW). The difference from operations involving hydrodemolition are more evident because of the large amount of slurry that are generated from this process. This is likely due to the high cost charged by land application facilities to accept waste water generated from these operations. An example of such a comparison is shown in Figure 46 where Options 3 and 8 can be compared. The effect of the cost of land application is more pronounced in hydrodemolition because of the large quantities of waste water generated.

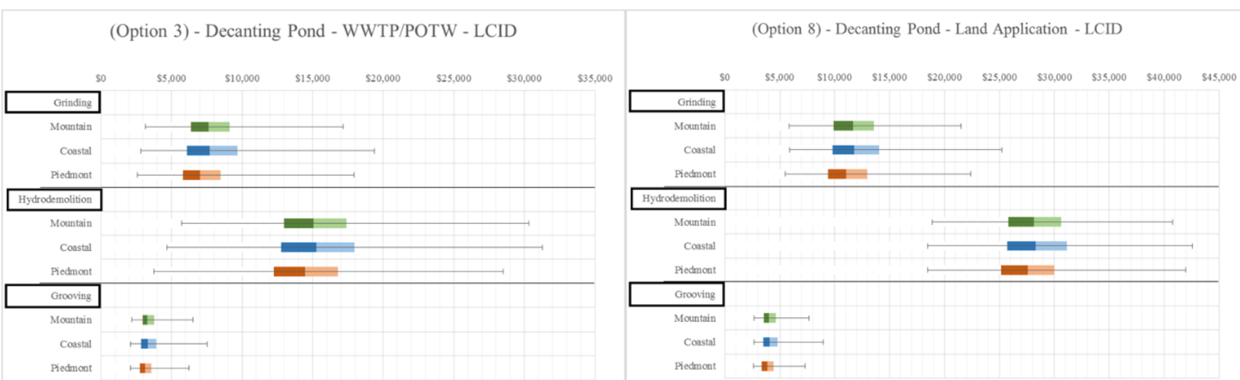



**Figure 46: Comparison of Option 3 (Left) and Option 8 (Right)**

A third observation involves the solid disposal options, where options involving beneficial fill on-site (Options 4, 9, 14, and 19) tend to be less expensive when compared to the other solid disposal options. This is likely due to the minimal handling of the material and the relatively short distance that in needs to be transported. The other options involve some form of hauling of the solid waste material. An example of such a comparison is shown in Figure 47 where Options 7 and 9 are shown. In option 7, disposal occurs at a C&D facility while in Option 9, residuals are utilized as beneficial fill on site.

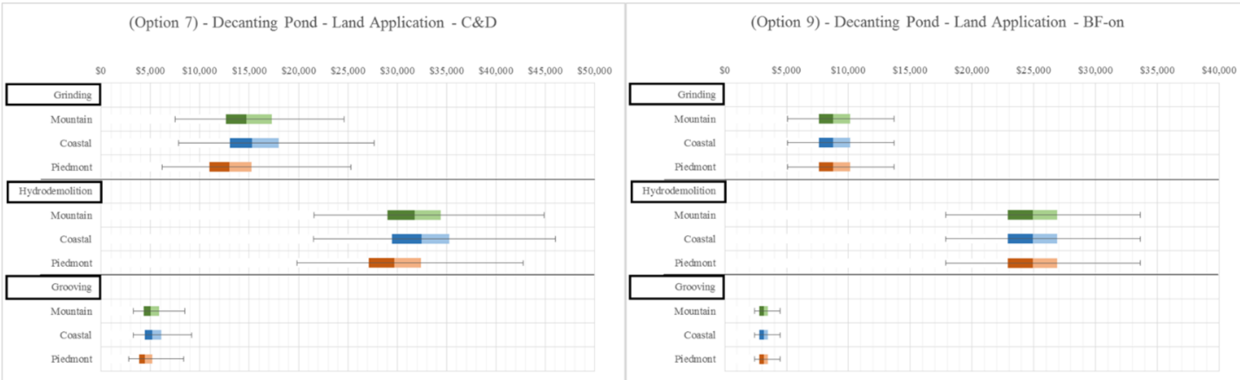



**Figure 47: Comparison of Option 7 (Left) and Option 9 (Right)**

Options involving the disposal of the solid material at MSW, LCID and C&D facilities tend to be more expensive than options in which the residuals are utilized as beneficial fill. This is primarily due to the cost of transportation of these types of disposal sites, as well as the fees charged by these facilities to accept the solid waste. In addition, when comparing between MSW, LCID, and C&D options, some slight differences exist between the costs that are dependent on the North Carolina region that the project might take place, as discussed in the following paragraphs.

Options involving C&D facilities in the Coastal Region (Options 2, 7, 12, and 17) tend to be more expensive when compared with the other solid disposal options when keeping selections for initial handling and liquid disposal the same. This can be observed in Figure 48, where Options 16 and 17 are shown, and for the coastal region (blue) the range of possible costs that involve C&D facilities is higher.

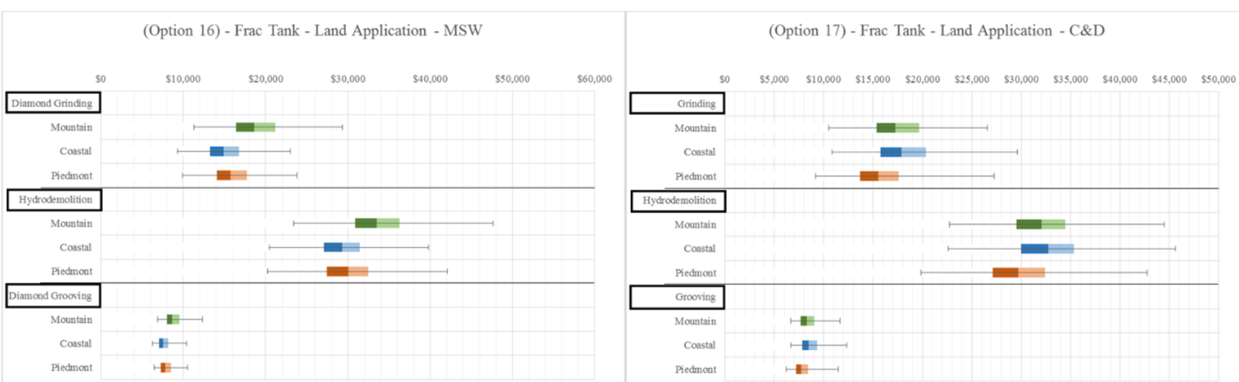



**Figure 48: Comparison of Option 16 (Left) and Option 17 (Right)**

Similarly, in the Mountain Region, options involving MSW facilities (Options 1, 6, 11, and 16) tend to be more expensive when compared to the other options. This can again be observed in Figure 48, where Options 16 and 17 are shown, and for the Mountain Region (green) the range of possible costs that include MSW facilities is higher.

In the Piedmont Region (by contrast), options involving LCID facilities (3, 8, 13, and 18) are less expensive when compared to the other options. The reasons for this variation between the regions can likely be linked to the tipping fees these facilities charge to accept this solid waste. This is again observed in Figure 49, where options sixteen and eighteen are shown, and for the piedmont (orange) the range of possible costs that include LCID facilities is higher.


**Figure 49: Comparison of Option 16 (Left) and Option 18 (Right)**

## 5.3 IDENTIFIED RISKS

Contractors that were interviewed during the data collection process also identified risks associated with the different options for material handling and disposal. Unlike the costs of these operations, the risks are not dependent on the region in which the project takes place, and could likely be applicable to the state of North Carolina as a whole. A summary of contractor responses regarding risks is outlined in this section, with the intent of providing NCDOT insight into the concerns of these stakeholders.

### 5.3.1 Risks Associated with Initial Material Handling

The risks associated with the initial material handling include the risks involving the creating, operation and deconditioning of the decanting pond as well as the process of resting and using the frac tanks. Specifically, the following risks were identified during the interview process:

<u>Decanting pond</u>

- *Additional construction work* – contractors expressed concern that with additional involvement of equipment and personnel there is a greater potential for errors and delays that might in turn create cost over runs. Some contractors expressed the concern that there is no single point of responsibility due to the need for multiple crews, personnel and equipment.
- *Possibility for precipitation entering the pond* – Since the decanting pond is exposed to the elements, it is possible due to precipitation for additional water to enter the pond, and increase the amount of wastewater that needs to be treated.
- *Possibility for a leak/tear in the lining* – A leak or tear in the geosynthetic lining can occur when the solid material is excavated from the pond to make room for more slurry. A leak or tear in the lining can cause the construction firm to fall out of compliance from the permit regulating the operation of the decanting pond.

Frac Tank

- *Delays in delivery* – Some contractors expressed that delays in the delivery of the tanks might cause a delay in the project.
- *Possibility of damage of rented equipment* – There is a possibility for damage to occur on the rented tanks, and that would be an additional cost for the contractors to repair and reimburse the tank rental company.
- *Possibility for spills* – There is a possibility of a spill of the liquid collected when it is transferred from the frac tank to the collection tank.

### 5.3.2 Risks Associated with Liquid Disposal/Reuse

The risks associated with liquid disposal/reuse include risks associated with the disposal of the water at WWTP/POTW facilities, and the risks associated with transporting the water to land application facilities. Specifically, the following risks were identified during the interview process:

WWTP/POTW

- *Possibility of non-acceptance* – A risk that was expressed by some contractors is that it might be difficult to identify a facility in close proximity to the area of a project that would accept the waste water generated. This would in turn increase transportation costs to another facility, or the need to dispose/treat the water using equipment or methods that are more expensive.
- *Transportation risks* – With transporting water, there is always the possibility of a spill.

Land Application

- *Possibility of non-acceptance* – Some contractors expressed the concern that the distance to an approved land application facility might be fairly large, thus increasing the cost of transportation to such a facility. Although the land application facilities that were interviewed suggested they collect the water from the construction sites, some contractors also expressed concern that there is possibility that the land application sites would not accept their generated water.

### 5.3.3 Risks Associated with Solid Disposal/Reuse

The risks associated with solid disposal/reuse include risks associated with the disposal of the solids at MSW, C&D, and LCID facilities, as well as the beneficial fill disposal onsite and offsite. Specifically, the following risks were identified during the interview process:

MSW

- *Transportation risks* – There is always the possibility of contamination when collecting waste material and transporting from the construction site to the disposal site.

C&D

- *Transportation risks* – This concern is similar to the MSW case.
- *Possibility for non-acceptance* – Contractors expressed the concern that there is a possibility for C&D facilities to choose to not accept their generated waste material. The possibility also exists that facilities close to the project location would not accept this

material, forcing the contractor to identify and utilize a facility more distant from the project.

<u>LCID</u>

- *Transportation risks* This concern is similar to the MSW case
- *Possibility of non-acceptance* – This concern is similar to the issues listed above for C&D disposal

<u>Beneficial Fill Onsite</u>

- No risks were identified during the interview process.

<u>Beneficial Fill Offsite</u>

- Transportation risks – This concern is similar to the issues identified as part of the MSW case, discussed above.

## 5.4 IDENTIFIED ENVIRONMENTAL BENEFITS

Contractors that were interviewed during the data collection process were also asked to identify perceived environmental benefits associated with the different options for material handling and disposal. Environmental consultants that were interviewed were also asked to contribute input as well. Once again, environmental benefits (as perceived by the stakeholders interviewed) were not dependent upon region, and are likely applicable to the state of North Carolina as a whole. A summary of responses is provided in the following sections.

### 5.4.1 Environmental Benefits Associated with Initial Material Handling

The environmental benefits associated with the initial material handling could include any benefits involving the creating, operation and deconditioning of the decanting pond as well as the process of resting and using the frac tanks. Specifically, the following environmental benefits were identified by personnel interviewed as part of this project:

<u>Decanting pond</u>

- No environmental benefits were identified during the interview process.

<u>Frac Tank</u>

- *Minimum disturbance to the job site* – When compared to the impacts associated with selection of decanting pond use, frac tanks impact the job site to a minimum degree, and there is minimal or no need for contactors to perform additional operations to return the site to its original condition.
- *Reduced mechanical work to be performed* – Frac tanks require less equipment and labor when compared with the construction of a decanting pond, and as a result, a reduced environmental impact.
- *Reduced potential for a leak/contamination* – Since water is contained in a metal enclosure, there is a reduced possibility of a leak (compared to use of a decanting pond with a geosynthetic liner).

### 5.4.2 Environmental Benefits Associated with Liquid Disposal/Reuse

Environmental benefits that could be realized with liquid disposal/reuse include benefits associated with the disposal of the water at WWTP/POTW facilities, and the benefits associated with transporting the water to land application facilities. Specifically, the following environmental benefits were identified during the interview process:

<u>WWTP/POTW</u>

- No environmental benefits were identified during the interview process.

<u>Land Application</u>

- *Beneficial reuse* – Since water from these operations (hydrodemolition, diamond grinding, and diamond grooving) is considered a liming agent for soils, it is beneficial to use it in an environmentally sound way instead of disposing of it.
- *No additional burden on Public Works* – Land application does not burden existing WWTP/POTW facilities with additional waste, conserving landfill space and reducing load placed on these facilities.

### 5.4.3 Environmental Benefits Associated with Solid Disposal/Reuse

Environmental benefits associated with solid disposal/reuse include identified benefits resulting from the disposal of solids at MSW, C&D, and LCID facilities, as well as the beneficial fill disposal onsite and offsite. Specifically, the following environmental benefits were identified during the interview process:

<u>MSW</u>

- No environmental benefits identified during the interview process.

<u>C&D</u>

- *Reduction of municipal waste stream* – The diversion of waste to C&D facilities minimizes the waste that would otherwise be interred at an MSW facility.

<u>LCID</u>

- *Reduction of municipal waste stream* – The diversion of waste to LCID facilities minimizes the waste that would otherwise end at an MSW facility.

<u>Beneficial Fill Onsite</u>

- *No transportation* – If waste is used onsite, then there is a reduced environmental impact from transporting that material at a different site.
- *Reduction of municipal waste stream* – The waste is diverted from the MSW waste stream.

<u>Beneficial Fill Offsite</u>

- *Reduction of municipal waste stream* – The waste is diverted from the MSW waste stream.

# 6.0 MODEL VALIDATION

In order to ensure that the assumptions used to generate the cost model are reasonable, it is necessary to validate these assumptions with field experts who agree that the results generated from the model are realistic and representative of actual experience. The CBA model was demonstrated to various members of the NCDOT (primarily members of the project Steering and Implementation Committee), as well as to industry professionals familiar with hydrodemolition, diamond grinding, and grooving in North Carolina and the southeast region.

Additionally, a meeting was held with an industry professional who had previously worked as a consultant performing work associated with management of the concrete residuals generated from diamond grinding, grooving, and hydrodemolition. This consultant assisted NCDOT personnel in development of the permit currently utilized for land application of the residuals as well as the proper methods for which the residuals liquid water could be reclaimed and reused. The industry professional was approved to perform this role by the technical project lead for NCDOT. Lastly, the model was presented to a representative sample of project managers and superintendents from a highway construction company undertaking projects requiring hydrodemolition and diamond grinding and grooving.

During these meetings, the CBA model was presented step-by-step, identifying the sources of the information used to develop the model. The 20 possible combinations for disposal and reuse were explained, along with the methodology for the information collection and sources of the cost data for all the processes were gathered. The industry professionals were then asked to review and validate the risks and perceived environmental benefits involved with each process.

The professionals' comments regarding the validity of the model are summarized below in the following sections:

- General CBA model setup and combinations considered
- Sources of costs associated with the disposal/reuse of residuals

## 6.1 MODEL SETUP AND COMBINATIONS CONSIDERED

The industry professionals thought that the number and variety of risks and benefits included in the model were well beyond what would typically be considered by personnel in the industry. This would indicate that the model could be viewed as fairly complex, and potentially difficult for the average contractor to use. Based on feedback from the NCDOT Steering and Implementation Committee, regarding this complexity, the following guidance and assessment was noted:

- NCDOT personnel agreed the model's framework is appropriate and agreed with the considerations that were taken for identifying the risks and environmental benefits for each option considered.
- The level of detail regarding the research for the cost information for all the items associated with the work performed was also deemed to be appropriate by NCDOT personnel.

- A simplified version of the model, using less variability in the prices and inputs, would need to be developed for contractor use.

## 6.2 SOURCES OF COSTS

Regarding the sources of the various cost items, the interviewed experts (consultants, contractors, and NCDOT personnel) made several comments. These are summarized here:

- The cost of land application on a per gallon basis seemed higher than expected, but within a realistic range for estimation. This price made the cost of options where land application is considered a more expensive option. The research team explained that many sites that accepted liquids for land application would not share their prices during the interviews, and the model only considered the data that was actually gathered. It is possible that a lower cost for land application on a per gallon basis can produce results where the land application options are more cost effective. With increasing use of land application in future projects, and as more cost data becomes available, it is recommended that a revision of the model be conducted to include this addition information.

- One contractor that was interviewed commented that the decanting pond constructed for different projects does not always share the same configuration and design characteristics. For that reason, the costs are not always calculated the same way. The decanting pond observed by the research team consisted of a single pond system, while one contractor commented that for one project they performed they constructed a three pond system. In this three pond system, residual material is collected in the first pond. In the second pond, the water is treated to lower the pH, while in the third pond, the treated water is held until it can be transported and disposed of. This variability in possible design methods cannot be accurately reflected in the model, since it is very dependent on the design decision in the field. It should be noted that Caltrans (2004) produced the only guidelines (identified in the literature review for this project) for the construction of a decanting pond, and it is very similar to the decanting ponds observed by the research team in the projects investigated.

- One contractor commented that the cost of labor seemed low. When the research team explained that the sources of labor were obtained from the Davis Bacon Act wage determination (NTIS 2016), the contractor expressed that they generally compensate their workers at a higher rate. The cost of labor is not standard across the construction industry, and it is an item that contractors, including the contractor interviewed during, are typically not willing to share. For this reason, labor intensive options can be costlier. Since labor information is difficult to collect, it was suggested that in the simplified version of the model, contractors can enter their own labor rates, and compare their costs internally.

- A risk item that was identified by contractors concerned the excavation of the solids from the decanting pond. It is possible for the geosynthetic layer to be damaged when equipment are picking the solids from the pond, and the contractors suggested that the excavators allow for a clearance of about a foot, when collecting the solids. Once the project is complete and no additional slurry is placed in the decanting pond, the excavators can pick the final layer of slurry as well, minimizing concern for damaging the geosynthetic layer.

- An additional comment regarding the decanting pond, is that when a pond is constructed close to residential areas, it might be necessary to construct a protective fence around it in order to limit access to pedestrians not involved with the project. The construction of the fence does increase the cost of the decanting pond, but it is not always necessary. In addition a fence was not observed in any of the projects investigated.

The model appeared to have been viewed relatively favorably by the parties that were requested to test its validity. The model was viewed as reasonably accurate in terms of costs, risks, and environmental benefit. The inclusion of future projects with more accurate land application costs would allow for improvement to the model's accuracy. However, unless that information is provided by the land application site managers, or the NCDOT, that information will remain as reported based on the information that was gathered as part of this research effort.

# 7.0 CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS

This section of the report will discuss the conclusions that were developed through the investigation of the costs associated with the disposal and reuse of concrete residuals generated from the hydrodemolition, diamond grinding, diamond grooving operations, as performed by contractors operating in North Carolina on NCDOT contracts. In addition the limitations that were discovered will be explained, as well as the recommendations that the research team has produced with the conclusion of this research.

## 7.1 CONCLUSIONS

Costs associated with handling, disposal, and reuse of concrete residuals can be reasonably predicted using the model developed as part of this work. This model will allow contractors in the future to provide more accurate bid estimates, which will ultimately lead to better utilization of funds and a more efficient bidding process. Risk analysis performed as part of this work incorporating costs of disposal/reuse, provide acceptable methods for disposing of residuals, and assessing the monetary and environmental risks associated with the residual disposal options provides additional insight and decision support to contractors.

As demonstrated in Chapters 4 and 5, the Excel model using @Risk can be used to estimate the variability of costs for the 20 different disposal/reuse combinations for hydrodemolition, diamond grinding, and diamond grooving debris as described in this report. Results of simulations using the model along with project constraints typical of North Carolina projects generating concrete residuals allowed the identification of the following trends:

- Options involving the use of decanting ponds (instead of a frac tank) were less costly, and this cost difference is more evident in operations that produced less amounts of liquid slurry, such as in diamond grinding/grooving. In hydrodemolition operations where the quantity of liquid slurry produced is high, the cost comparisons between options that utilize a frac tank and a decanting pond are less obvious.

- The use of frac tanks allows contractors to limit the amount of work and workers necessary to manage and operate the slurry handling, thus reducing the possibility of worker error and lowering risk.

- The model results showed that disposing of the liquid residuals at a POTW/WWTP facility is more cost effective than land application, unless diamond grooving performed. This is likely due to the cost of sending the water to the land application facility. The costs on a per gallon basis obtained during this investigation were reasonable according to experts who validated the model, but experts did comment that costs tended to be on the higher end of the range of expected values. It is possible that a lower price for the disposal at land application facilities might be lower, thus making land application options more cost effective. Based on feedback from NCDOT personnel and environmental consultants, land application is also perceived to be the less risky and more environmentally responsible option of liquid residual management.

- Regarding solid residual disposal, the simulation presented in this report showed that for all regions (Mountain, Piedmont and Coastal), beneficial fill onsite is the most cost effective, least risky, and likely the most environmentally responsible option available for solid residual management. Cost and risk benefits are due to the cost associated with transporting the material to a facility willing to accept the solid residual, and the tipping fees associated to that disposal. Similarly beneficial fill offsite was also seen as a favorable option as well for the same reasons, with the exception of transporting the residual material to a different site. When the other options are compared, some regional differences arise. C&D facilities in the Coastal Region have higher tipping fees, while that is also the case for MSW facilities in the Mountain Region. These higher costs make the use of options involving C&D facilities in the Coastal Region, and MSW facilities in the Mountain Region, more expensive. In the Piedmont Region, LCID facilities were seen to have lower tipping fees and as a result options involving LCID in that region are less expensive.

Through the interviews conducted with expert personnel, the research team was able to identify sources of risk and perceived environmental benefits for the various options studied. These can be summarized as follows:

- The creation of a decanting pond, requires contractor personnel to perform activities such as excavation, placing a liner, and removal of concrete sediment using excavation equipment, creating the potential for errors and the possibility of a tear in the decanting pond lining causing a spill. Contractors suggested that the use of a frac tank eliminates these concerns, and the ease of use allows for time savings as well.

- Regarding concerns for liquid and solid disposal and reuse, there were minor concerns from the contractors on the topics of non-acceptance of the material from the disposal facilities.

- Regarding environmental benefits, the major comment from contractors was that frac tanks allow for minimal disturbance to the work site, reduce mechanical work to be performed, and reduce the risk for contamination.

The distance required to transport residuals to the disposal facilities was not simulated in the model. This would have complicated the results, and as a result, distance of 50 miles was used for all transportation requirements. To assist contractors that might eventually use the model, an online tool was developed to calculate the distance from a project to a disposal facility such as MSW, LCID, C&D, and WWTP/POTW. This online tool uses Google Map tools, and it is described in detail in Appendix F. The map tool (shown in Figure 50) allows contractors to enter their project location, select a disposal facility and calculate the distance between these two locations.


**Figure 50: Map tool for estimating distances between jobsites and disposal facilities**

The model developed for the analysis of costs for concrete residuals appears to be robust and it can be used to provide contractors, and NCDOT personnel with insight on the various options for disposal or reuse. The use of the @Risk software for such a model, although powerful in determining ranges for costs by simulating a project numerous times, could potential makes the model complex for the average individual to access and use. For this reason, a simplified version of the model is necessary in a medium, such as a spreadsheet, that is easily accessible to contractors. This model is described in Appendix G.

## 7.2 LIMITATIONS

Several limitations to the research conducted have been identified, and are summarized below:

- The model is significantly influenced by the quality of the data collected during the interviews. One such example is that fact that many owners of land application sites were typically not comfortable sharing their cost data to support this research project. Also another key limitation to the model exists due to the fact that representatives of many POTW/WWTP's were unsure as to whether their facility would accept the liquid residual material. In fact, some operators contacted simply were not familiar with the material. Many stated that they would need a representative sample from the contractors before they could give a definitive answer as to whether or not they would accept the material. This approach, suggested by the POTW/WWTP representatives, is contrary to the typical work structure which states that the contractor should define where the residuals will be disposed/deposited before the start of work.

- Labor rates used for this investigation were estimated using the Davis Bacon Act website (NTIS 2016), and the contractors interviewed during the validation of the model considered such rates to be underestimating the actual labor costs. Actual labor costs are typically not shared by contractors, and were not made available to the researchers. Use of actual labor costs in the model may make the use of a decanting pond more expensive when compared to the use of a Frac Tank for the project.

- The decanting pond utilized in the model is a lined, single-pond system. A more complex decanting pond design, or a multi-pond design, would increase the cost. The need for additional safety measures around a decanting pond would also increase the cost of this option.

- A major limitation that the research team had run into was the fact that many wastewater facilities, especially within the Piedmont Region, would not provide a price for disposal at their facility unless they could first test the material.

- Evaporation from decanting ponds was not considered in the model, since that highly variable process would unnecessarily complicate the investigation.

- It should also be noted that this model is only applicable within the state of North Carolina. Other states may have different regulations that could alter costs, risks, and environmental benefit.

## 7.3 RECOMMENDATIONS

Based on the research performed, NCDOT should consider the following recommendations:

- Since land application was the most preferred method of residual management per NCDOT personnel, the agency should consider ways to increase the attractiveness of this disposal method as an option to private sector firms performing the majority of diamond grinding, diamond grooving, and hydrodemolition activities. This could be accomplished by creating more land application sites throughout the state, and especially distributing them more evenly throughout the regions. This would decrease the cost of land applying residuals.

- NCDOT should also look for possible ways to subsidize land application costs, since this is perceived as the agency's most environmentally friendly option, and does not add to the loading of current solid/liquid waste facilities. If private firms could see land application as a more economically viable option, this environmentally friendly option could also be the most favorable option. The agency should also try to encourage private firms to treat/handle residuals to help other companies streamline the process.

- The model should be periodically revisited and updated in order for it to remain useful and reliable. Costs supporting the model should be periodically updated to reflect current economic conditions. Additionally, the model framework should be revisited in several years to ensure it still includes the currently available methodologies and assumptions, and is consistent with ongoing practice.

- To facilitate implementation and use of the model, technology transfer documents or training webinar should be developed and disseminated to interested contractors or other stakeholders.

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# APPENDICES

**FOR**
**FINAL REPORT**

**North Carolina Department of Transportation**
**Research Project No. 2015-12**

**Cost Analysis on the**
**Reuse of Concrete Residuals**

# APPENDIX A – STATE REGULATIONS ON CONCRETE RESIDUAL DISPOSAL/REUSE

| State | Hydrodemolition | Grinding | Grooving |
|---|---|---|---|
| Alabama<br>(ALDOT 2012) | NA | 1-Lane, self-propelled equipment<br>Removed continuously; not to flow onto lanes or into drainage structures. | All residue, slurry, or other waste to be continuously removed.<br>Waste to be disposed in earthwork; if approved by an engineer.<br>If not approved by engineer; dispose according to applicable laws. |
| Alaska<br>(ADOT 2011) | Must submit WTP; Method of collection, filtration, storage, and disposal.<br>Debris disposed at DEC approved landfill. | Equipment must limit slurry generated, and maximize slurry captured. | NA |
| Arizona<br>(ADOT 2008) | NA | CGR to be removed by vacuum prior to re-opening lane.<br>Removed continuously; not to flow on lanes or into drainage structures.<br>Dry Residue to be picked up with "power broom." | Slurry/residue removed continuously<br>Not to flow across shoulder, into other lanes, or drainage facilities.<br>Dry residue to be picked up with "power broom." |
| Arkansas<br>(AHTD 2014) | NA | Self-propelled equipment<br>Contractor to remove grinding residue;<br>Solids removed immediately;<br>Slurries/liquids not to flow on lane or into drainage facilities. | Self-propelled equipment<br>Contractor to remove grinding residue;<br>Solids removed immediately;<br>Slurries/liquids not to flow on lane or into drainage facilities. |

| State | Hydrodemolition | Grinding | Grooving |
|---|---|---|---|
| California (Caltrans 2008; Caltrans 2010) | Remove HOS immediately by vacuum; not to flow onto lanes or into drainage facilities/gutters.<br>Slurry can be deposited into onsite temporary concrete washout facilities.<br>Liquid to be decanted and reused until end of useful life; then taken to non-sewage waste treatment facility.<br>Solid CGR can be incorporated in embankment | Remove CGR immediately by vacuum; not to flow onto lanes or into drainage facilities/gutters.<br>Slurry can be deposited into onsite temporary concrete washout facilities.<br>Liquid to be decanted and reused until end of useful life; then taken to non-sewage waste treatment facility.<br>Solid CGR can be incorporated in embankment | CGR to be removed by vacuum and disposed at approved facility<br>Solid CGR can be incorporated in embankment.<br>Slurry can be placed in impoundment<br>Liquid to be decanted and reused until end of useful life; then taken to non-sewage waste treatment facility. |
| Colorado (CDOT 2011) | HOS to be handled, stockpiled, & disposed without discharge to state waters.<br>Contractor to submit pollutant containment plan. | CGR to be handled, stockpiled, & disposed without discharge to state waters.<br>Contractor to submit pollutant containment plan. | CGR to be handled, stockpiled, & disposed without discharge to state waters.<br>Contractor to submit pollutant containment plan. |
| Connecticut (ConnDOT 2011) | Contractor to submit plan for filtration, containment, and disposal of HOS.<br>No residual release to the environment. | Contractor to submit plan for filtration, containment, and disposal of CGR.<br>Solids settled in sedimentation basin; removed at end of work. | All residuals to be removed in an environmentally friendly manner. |
| Delaware | NA | NA | NA |
| District of Columbia | NA | NA | NA |
| Florida (FDOT 2010) | Control & maintain all residuals throughout.<br>Measure residuals for safe contaminant levels before discharge. | Solids removed before re-opening lane<br>Slurry not to flow onto lanes, or into drainage facilities/sewers.<br>No residuals to enter bodies of water. | NA |

| State | Hydrodemolition | Grinding | Grooving |
|---|---|---|---|
| Georgia<br>(GDOT 2013) | NA | Self-propelled equipment<br>Remove CGR immediately; not to flow onto lanes or into drainage facilities/gutters.<br>Waste not to enter any bodies of water<br>Transport residuals without leaks/spills<br>Regulated solid waste deposited in C&D landfill. | Self-propelled equipment<br>Remove CGR immediately; not to flow onto lanes or into drainage facilities/gutters.<br>Waste not to enter any bodies of water<br>Transport residuals without leaks/spills<br>Regulated solid waste deposited in C&D landfill. |
| Hawaii<br>(CCHDES 2011) | Remove HOS immediately by vacuum; not to flow onto lanes or into drainage facilities/gutters.<br>Allow liquids to dry in a sedimentation pit, or pump water to sanitary sewer.<br>Solids from HOS can be incorporated in embankment. | Remove CGR immediately by vacuum; not to flow onto lanes or into drainage facilities/gutters.<br>Allow liquids to dry in a sedimentation pit, or pump water to sanitary sewer<br>Solid CGR can be incorporated in embankment. | Remove CGR immediately by vacuum; not to flow onto lanes or into drainage facilities/gutters.<br>Allow liquids to dry in a sedimentation pit, or pump water to sanitary sewer<br>Solid CGR can be incorporated in embankment. |
| Idaho<br>(IDT 2012) | All residuals collected and disposed by land application off-site.<br>May store in lined collection pond. | NA | NA |
| Illinois<br>(IDOT 2012) | Liquid not to flow onto lanes or into drainage facilities.<br>Solids used in fills or embankments<br>Solids may be disposed in licensed landfill. | CGR to be disposed of in a licensed landfill, or otherwise recycled/reused.<br>Continuously remove all CGR from surface; must not flow into drainage structures or onto lanes. | Residuals removed continuously by vacuum.<br>Surfaces flushed with water.<br>Liquids to be held in facilities. |
| Indiana<br>(INDOT 2014) | Water must be potable. Not allowed to be discharged into bodies of water. | Continuously remove all CGR from surface; must not flow into drainage structures or onto lanes.<br>Removed from site in tanker truck. | Remove residue immediately from surface using vacuum/brooms. |
| Iowa<br>(IowaDOT 2012b; IowaDOT 2012a) | NA | All CGR removed from surface continuously; kept from flowing onto lanes, or into drainage facilities.<br>CGR may be spread on foreslopes for disposal. | All CGR removed from surface continuously; kept from flowing onto lanes, or into drainage facilities.<br>CGR may be spread on foreslopes for disposal. |

| State | Hydrodemolition | Grinding | Grooving |
|---|---|---|---|
| Kansas (KDOT 2007b; KDOT 2007a) | Submit protected area map, and wastewater handling plan. | CGR removed continuously by vacuum; not to flow onto lanes, into drainage facilities, or bodies of water. | Reside removed continuously by vacuum; not to flow onto lanes, into drainage facilities, or bodies of water. |
| Kentucky (KYTC 2012) | NA | CGR to be cleaned from surface; not to flow onto lanes, or into drainage structures.<br>Submit wastewater treatment plan. | CGR to be cleaned from surface; not to flow onto lanes, or into drainage structures.<br>Submit wastewater treatment plan. |
| Louisiana | N/A | N/A | N/A |
| Maine | N/A | N/A | N/A |
| Maryland | N/A | N/A | N/A |
| Massachusetts | N/A | N/A | N/A |
| Michigan (MDOT 2011) | NA | Develop residual management and disposal plan.<br>Disposal may take place on roadway side slopes. | Develop residual management and disposal plan.<br>Disposal may take place on roadway side slopes. |
| Minnesota (Druschel et al. 2012; MPCA 2012) | NA | In rural areas. CGR may be deposited on vegetated side slopes.<br>CGR must be vacuumed continuously<br>May place in settlement pond; water to evaporate, while solids to be used as fill material or recycled aggregate. | In rural areas. CGR may be deposited on vegetated side slopes.<br>CGR must be vacuumed continuously<br>May place in settlement pond; water to evaporate, while solids to be used as fill material or recycled aggregate. |
| Mississippi (MDOT 2004) | NA | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures. | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures. |
| Missouri (Wenzlick 2002) | Slurry may be dispersed inside ROW<br>No HOS to be discharged into state waters | CGR slurry is allowed to be discharged onto vegetated side slopes.<br>Slurry can be pumped into tankers and hauled offsite.<br>Solid CGR can be used as fill in embankments. | CGR slurry is allowed to be discharged onto vegetated side slopes.<br>Slurry can be pumped into tankers and hauled offsite.<br>Solid CGR can be used as fill in embankments. |
| Montana | NA | NA | NA |

| State | Hydrodemolition | Grinding | Grooving |
|---|---|---|---|
| Nebraska (NDOR 2007) | NA | CGR to be removed from surface before it spreads. | CGR to be removed from surface before it spreads. |
| Nevada (NVDOT 2014) | NA | CGR to be disposed of in authorized Class I or II landfill or permitted Class III landfill. | CGR to be disposed of in authorized Class I or II landfill or permitted Class III landfill. |
| New Hampshire | NA | NA | NA |
| New Jersey (NJDOT 2007) | NA | CGR disposed/recycled according to Solid Waste Management Act.<br>CGR is a Class B recyclable material; must be approved before storage, processing, and transferring to recycle center. | CGR disposed/recycled according to Solid Waste Management Act.<br>CGR is a Class B recyclable material; must be approved before storage, processing, and transferring to recycle center. |
| New Mexico (NMDOT 2014) | NA | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures. | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures. |
| New York (NYSDOT 2014) | Must develop comprehensive plan for filtration and disposal of HOS.<br>HOS not to enter bodies of water. | | |
| North Dakota (NDDOT 2014) | NA | CGR continually removed; disposed through beneficial use.<br>Disposed at permanent waste management facility; may be disposed as an inert waste. | CGR continually removed; disposed through beneficial use.<br>Disposed at permanent waste management facility; may be disposed as an inert waste. |
| Ohio (ODOT 2012) | Wastewater pH not to exceed 11.5<br>Wastewater must be recycled at an appropriate facility.<br>If pH adjusted to 5-9, may dispense residuals on side of road. | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures. | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures. |
| Oklahoma (ODOT 2009) | NA | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures. | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures. |

| State | Hydrodemolition | Grinding | Grooving |
|---|---|---|---|
| Oregon<br>(ODOT 2015) | NA | CGR must be recycled/reused; solids can be used as beneficial fill or in base layers. | CGR must be recycled/reused; solids can be used as beneficial fill or in basements. |
| Pennsylvania<br>(PennDOT 2014) | NA | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures. | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures. |
| Rhode Island<br>(RIDOT 2010) | HOS will be collected in containment system; either lined pit or man-made container.<br>Liquid to be removed/discharged after settling period; not to enter drainage facilities.<br>Solids to be collected from bottom of basin and disposed of properly. | NA | NA |
| South Carolina | NA | NA | NA |
| South Dakota<br>(SDDOT 2001) | NA | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures.<br>Slurry must be filtered; can use sedimentation basin. | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures.<br>Slurry must be filtered; can use sedimentation basin. |
| Tennessee<br>(TDOT 2006) | NA | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures.<br>CGR may be disposed on roadway slopes; if vegetative cover and slopes conditions are met. | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures.<br>CGR may be disposed on roadway slopes; if vegetative cover and slopes conditions are met. |
| Texas | NA | NA | NA |
| Utah<br>(UDOT 2012) | HOS is to be collected in retention basins/sediment traps.<br>All water used is to be cleaned before being returned to streams. | NA | NA |

| State | Hydrodemolition | Grinding | Grooving |
| --- | --- | --- | --- |
| Vermont | NA | NA | NA |
| Virginia (VDOT 2007) | NA | CGR to be disposed in sanitary landfill, or licensed industrial landfill. Liquid material is to be taken to a POTW. | CGR to be disposed in sanitary landfill, or licensed industrial landfill. Liquid material is to be taken to a POTW. |
| Washington (Yonge et al. 2005; WSDOT 2014) | NA | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures. | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures. |
| West Virginia (WVDOH 2010) | NA | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures. | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures. |
| Wisconsin | NA | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures. CGR to be disposed of at authorized disposal site. | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures. CGR to be disposed of at authorized disposal site. |
| Wyoming (WYDOT 2010) | NA | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures. CGR to be disposed of at authorized disposal site. | CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures CGR to be disposed of at authorized disposal site. |

# APPENDIX B – SURVEY QUESTIONS FOR CONTRACTORS

**Types of material**

1. What types of materials do you have experience of disposing?
2. What kinds of projects did these material come from? (hydrodemolition/grinding/grooving/road/bridge)
3. Describe the methods and equipment used for collecting and storing these material. Please provide any pictures you have.
    a. How many of each equipment?
    b. Types of equipment?
    c. Capacity of equipment?
4. Who performed the work for grinding/grooving/hydrodemolition?
    a. Types of contract was used? Were there any pre-bid qualifications considered?
    b. What was included in the work? (Please provide all phases and steps)
    c. What were the responsibilities of each party involved? (Available contracts?)
5. What were the risks associated with performing the work? Storage of the material?
    a. How was that risk mitigated?
    b. What precautionary measures did you take?
    c. Were there any extra cost items associated?
6. What options did you consider for disposing of the materials?
7. What did you end up deciding to do?

**Tests Performed (Paint Filter Test)**

1. Were the tests performed?
2. Who performed the paint filter test?
3. How was it performed?
4. How many tests were performed?
5. What are the costs associated with the tests?

**Disposal of Solids**

1. For the solids associated with the disposal in your project, what method of disposal/reuse did you decide to use?
2. Why did you make that choice?
3. Where was it disposed?
4. How were the solids transported? Who transported them?
    a. Additional associated safety costs?
5. Rates of generation of debris? Volume per area of hydrodemolition?
6. Who performed the disposal?
7. What was the costs/benefits realized from disposal?
8. Can the transportation logs be obtained?
9. Were there any unforeseen costs that surfaced?
10. Any attempts to amend the original contract for the DOT with change orders?

**Solids (Beneficial Use)**

1. What beneficial use did you decide to use?
2. Why did you make that choice?
3. What were the costs/benefits associated with these disposal methods?
4. What was the hauling distance? Where were they disposed? Who transported the material?
5. Who performed the disposal?
6. Were there any other hidden costs?

**Alternate Daily Cover (ADC)**

1. What ADC performed?
2. How was it performed?
3. Where did that happen?
4. Who transported the material?
5. Were there any acceptance costs for using as ADC?

**Land Application**

1. Tests Performed (Who? / How many? / How often?):
    a. Nitrates
    b. Agronomic rates
    c. Set back
    d. pH Tests
    e. Corrosivity
    f. Chemical Oxygen Demand (COD)
2. Any other tests?
3. Legal fees?
4. Hidden Costs?
5. Costs Associated with the Spill Control Plan?
    a. Measures taken to perform spill control plan
    b. Risks associated with spill control plan
    c. Is the spill control plan product specific?
6. Are there any other factors that influence costs in Land Application?
7. Are there any other risks associated with Land Application?
8. Are there costs associated with reporting of information and tests?
9. Were there any costs associated with the creation and submission of the annual report?

**Disposal of Liquids**

<u>Publicly Owned Treatment Works/Wastewater Treatment Plant (POTW/WWTP)</u>

1. Did you have any materials disposed of at POTW's/WWTP's?
2. Why did you choose this option?
3. Who performed the disposal?
4. How was the material transported?
5. What are our costs factors associated with this disposal method?
6. What are the risks associated with this disposal method, if so how were these risks mitigated?

Beneficial Use – Reclaimed Water

1. Effluent Standards
    a. How many tests were performed?
    b. Who performs the tests?
    c. How frequent were the tests?
    d. Are there any other costs factors associated with the tests?
2. How was the material stored at the site?
    a. Any costs associated with storage?
    b. Any risks associated with storage? Risk mitigation?
3. Were there any setback requirements
4. Operations & Maintenance Plan
    a. Are there costs to certification?
    b. Any other costs?
    c. Any other costs due to weather or other delays?
5. Monitoring requirements?
6. Safety Requirements?
7. Any other risks? Mitigation techniques?

# APPENDIX C – INFORMATION COLLECTED FROM INTERVIEWS/SURVEYS

This appendix displays all the information that was collected from disposal facilities and was used to develop the probability definition functions used in the CBA Model.

**LCID Facilities**

Piedmont Region LCID Facilities: Collection Costs per TON and Beneficial Use Alternatives for Concrete Materials

| Clean - LCID - Piedmont Region (By Ton) | | | | | | |
|---|---|---|---|---|---|---|
| Location ID | Cost Data | | | Beneficial Reuse | | |
| | $/TON | County Regulation | Out County Price $/TON | Road Base | Alternative Daily Cover (ADC) | Resell |
| 1 | 0 | | | x | x | |
| 2 | 0 | x | | x | | |
| 3 | 0 | x | 15 | x | x | |
| 4 | 0 | | | x | | |
| 5 | 0 | | | x | | |
| 6 | 0 | | | x | | |
| 7 | 0 | | | x | | |
| 8 | 0 | | | x | | |
| 9 | 0 | | | x | | |
| 10 | 5 | | | x | | |
| 11 | 5 | | | x | | |
| 12 | 6 | | | x | | |
| 13 | 9.75 | | | | | |
| 14 | 9.75 | | | x | | |
| 15 | 10 | | | x | | x |
| 16 | 29.5 | | | | | |
| 17 | 30 | | | | | |
| 18 | 31 | | | | | |
| 19 | 39 | | | | | |
| 20 | 46 | | | | | |

Piedmont Region LCID Facilities: Collection Costs by Axle

| Clean LCID - Piedmont Region (By Truck Volume) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Location ID | Truck Size | | | | | | | | Beneficial Reuse |
| | 1 Axle | Tandem | 3 Axle | 4 Axle | Tractor Trailer | Dump Truck | Extended Tractor Trailer | Liquid (2500gal) | Road Base |
| 1 | 5 | | | | | | | | x |
| 2 | 10 | 10 | 45 | 45 | | | | | |
| 3 | 42 | 47 | 52 | 57 | | | | | |
| 4 | 45 | 55 | 55 | 65 | 85 | | 110 | | |
| 5 | | 40 | 60 | 60 | | | | | |
| 6 | | 50 | 60 | 70 | | 90 | | 200 | |
| 7 | | 50 | 60 | | | | | | |
| 8 | | 50 | | 55 | 60 | | | | |
| 9 | | 60 | 63 | 66 | | | | | |
| 10 | | 60 | 70 | | | | | | |
| 11 | | 65 | 65 | 65 | | | | | |
| 12 | | 70 | 80 | 90 | | | | | |

Coastal Region LCID Facilities: Collection Costs per TON and Beneficial Use Alternatives for Concrete Materials

| Clean - LCID – Coastal Region (By Ton) | | | |
|---|---|---|---|
| Location ID | TON | Beneficial Reuse | |
| | | Road Base | ADC |
| 1 | 0 | | |
| 2 | 0 | x | |
| 3 | 0 | x | |
| 4 | 0 | | |
| 5 | 7.5 | | |
| 6 | 10 | x | x |
| 7 | 15 | | |
| 8 | 19 | | |
| 9 | 20 | | |
| 10 | 52 | | |
| 11 | 65 | | |

Mountain Region LCID Facilities: Collection Costs per TON and Beneficial Use Alternatives for Concrete Materials

| Clean - LCID - Mountian Region (By Ton) | | | |
|---|---|---|---|
| Location ID | TON | Beneficial Reuse | |
| | | Road Base | ADC |
| 1 | 0 | x | x |
| 2 | 0 | x | |
| 3 | 10 | x | |
| 4 | 20 | | |
| 5 | 30 | | |
| 6 | 42 | | |

**MSW Facilities**

Piedmont Region MSW Facilities: Collection Costs per TON and Beneficial Use Alternatives for Concrete Materials

| MSW - Piedmont Region (By Ton) | | | |
|---|---|---|---|
| Location ID | TON | County Regulation | Out of County Price |
| 1 | 22 | x | |
| 2 | 23 | | |
| 3 | 32 | | |
| 4 | 33 | | |
| 5 | 34.4 | x | 43 |
| 6 | 35 | | |
| 7 | 36 | x | 41 |
| 8 | 41 | | |

Piedmont Region MSW Facilities: Collection Costs by Axle

| MSW - Piedmont Region (By Truck Volume) | | | |
|---|---|---|---|
| Location ID | Truck Size | | |
| | Tandem | 3 Axle | 4 Axle |
| 1 | 20 | 20 | 20 |

Coastal Region MSW Facilities: Collection Costs per TON and Beneficial Use Alternatives for Concrete Materials

| MSW – Coastal Region (By Ton) | |
|---|---|
| **Location ID** | **$/TON** |
| 1 | 7 |
| 2 | 39 |
| 3 | 40 |

Mountain Region MSW Facilities: Collection Costs per TON

| MSW - Mountain Region (By Ton) | |
|---|---|
| **Location ID** | **TON** |
| 1 | 43 |
| 2 | 43 |
| 3 | 57 |
| 4 | 57 |
| 5 | 62 |
| 6 | 66 |

Mountain Region MSW Facilities: Collection Costs by Axle

| MSW - Mountain Region (By Truck Volume) | | |
|---|---|---|
| **Location ID** | **Truck Size** | |
| | **1 Axle** | **Tandem** |
| 1 | 15 | 20 |

**C&D Facilities**

Piedmont Region C&D Facilities: Collection Costs per TON

| C&D - Piedmont Region (By Ton) | | | |
|---|---|---|---|
| Location ID | $/TON | County Regulation | Outside of County Price |
| 1 | 5 | | |
| 2 | 20 | | |
| 3 | 21.55 | | |
| 4 | 23 | | |
| 5 | 24 | | |
| 6 | 26 | | |
| 7 | 29.5 | | |
| 8 | 29.93 | | |
| 9 | 29.93 | | |
| 10 | 30 | | |
| 11 | 31 | | |
| 12 | 31 | | |
| 13 | 32 | | |
| 14 | 34 | | |
| 15 | 36 | | |
| 16 | 39 | | |
| 17 | 40 | | |
| 18 | 40 | x | 42 |
| 19 | 45.31 | | |
| 20 | 46 | | |

Piedmont Region C&D Facilities: Collection Costs by Axle

| C&D - Piedmont Region (By Truck Volume) | | | | | | |
|---|---|---|---|---|---|---|
| Location ID | Truck Size | | | | | |
| | 1 Axle | Tandem | 3 Axle | 4 Axle | Tractor Trailer | Extended Tractor Trailer |
| 1 | 10 | 10 | 45 | 45 | | |
| 2 | | 35 | 35 | 35 | | |
| 3 | 45 | 55 | 55 | 65 | 85 | 110 |
| 4 | | 80 | 83 | 86 | | |

Coastal Region C&D Facilities: Collection Costs per TON

| C&D – Coastal Region (By Ton) | |
|---|---|
| **Location ID** | **TON** |
| 1 | 34 |
| 2 | 34 |
| 3 | 40 |
| 4 | 41 |
| 5 | 52 |
| 6 | 59 |
| 7 | 65 |
| 8 | 68 |

Coastal Region C&D Facilities: Collection Costs by Axle

| C&D – Coastal Region (By Truck Volume) | | | | |
|---|---|---|---|---|
| **Location ID** | **Truck Size** | | | |
| | **1 Axle** | **Tandem** | **3 Axle** | **4 Axle** |
| 1 | 10 | 10 | 10 | 10 |

Mountain Region C&D Facilities: Collection Costs per TON

| C&D – Mountain Region (By Ton) | |
|---|---|
| **Name** | **TON** |
| Burke County C&D Landfill | 31 |
| Transylvania County LCID Landfill | 52 |
| Henderson County Transfer Facility | 57 |

# APPENDIX D – EQUATIONS USED IN COST MODEL

In this Appendix, information on calculations and assumptions that were used to create the Benefit Cost Model are presented, as described in the flowchart shown in Figure 34.

The Equations used to calculate the project information outputs are outlined below:

## Section 1 – Calculating the volume and weight of the concrete residuals generated

### *Slurry Generation*

$$Slurry\ Gen = Area\ \times SGR \qquad \text{(Eq. D.1)}$$

Where,

- Slurry Gen. = Quantity of Slurry Generated (gallons)
- Area = Area of Pavement to Grind (square yards)
- SGR = Rate at which Slurry is Generated from Grinding (gallons/square yard)

The SGR values were obtained from contractor interviews. The actual number varies, and the probability definition functions (PDF) for these values are shown in Figure 18 through Figure 33.

### *Volume of Solids*

$$Vol.Solids\ = Slurry\ Gen.\times \left(\frac{1\ CY}{201.974\ Gallons}\right) \times \%Solids \qquad \text{(Eq. D.2)}$$

Where,

- Vol. Solids = Quantity of Solids Residuals Produced (cubic yards)
- Slurry Gen. = Quantity of Slurry Generated (gallons)
- % Solids = Percentage of Solids in Residual Slurry

### *Weight of Solids*

$$Wt.Solids = Vol.Solids\ \times 150\,\frac{lbs}{ft^3}\ \times 27\,\frac{ft^3}{yd^3} \times \frac{1\ Ton}{2000\ lbs} \qquad \text{(Eq. D.3)}$$

Where,

- Wt. Solids = Quantity of Solids Residuals Produced (tons)
- Vol. Solids = Quantity of Solids Residuals Produced (cubic yards)

### *Volume of Liquids*

$$Liquid\ Vol. = Slurry\ Gen. \times (1 - \%Solids) \quad \text{(Eq. D.4)}$$

Where,

- Liquid Vol. = Quantity of Liquid Residual Produced (gallons)
- Slurry Gen. = Quantity of Slurry Generated (gallons)
- % Solids = Percentage of Solids in Residual Slurry

**Section 2 – Initial Slurry Handling**

Initial Slurry Handling consists of two methods for handling slurry generated from these operations; Decanting pond, and Frac Tank Rental.

**1st Option - Decanting Pond**

The first option (Decanting Pond) involves the creation of a decanting pond built on site to deposit slurry generated from grinding/grooving/hydrodemolition operations. This phase is split up into four different operations that will affect the overall price of construction. These operations are:

- Excavation,
- Geosynthetic Layering,
- Backfilling, and
- Compaction.

**Decanting Pond – Excavation**

The first item for consideration is the size of the planned excavation for the decanting pond. Caltrans (2004) states that the decanting ponds constructed for the purpose of slurry handling from concrete operations are not to exceed 75% capacity, suggesting a safety factor of 1.33 to be included when sizing the decanting pond.

The soil at the site for excavation is a factor for consideration since the work-ability of the soil will affect the productivity of the equipment. For this model two types of soil were considered; common earth, and sandy clay & loam.

The excavation equipment considered within the model included the following equipment with varying load capacity in cubic yards (cy):

- Hydraulic excavators
  - Crawler mounted
    - 1 CY, 1.5 CY, 2 CY, 3 CY, and 3.5 CY
  - Wheel mounted
    - 0.5 CY, and 0.75 CY
- Front-end Loader
  - Track mounted
    - 1.5 CY, 2.5 CY, 3 CY, and 5 CY.
  - Wheel mounted
    - 0.75 CY, 1.5 CY, 2.25 CY, 3 CY, and 5 CY.

Regarding labor requirements for the excavation operation, R.S. Means (2009) recommended that a crew consisting of a laborer and an operator be used. However in the model created for the analysis, it is possible to choose more personnel and equipment.

Using the information described above, the production rates, total time required to complete the decanting pond excavation, and the excavation cost can be calculated. The equations used to calculate excavation production and cost are described below:

***Volume of Excavation***

$$Exc.Size = Vol.Solids \times F.S. \qquad \text{(Eq. D.5)}$$

Where,
- Exc. Size = Size of Excavation to be completed (cubic yards)
- Vol. Solids = Quantity of Solids Residuals Produced (cubic yards)
- F.S. = Factor of Safety $\left(\frac{1}{0.75}\right)$

***Excavation Time***

$$Exc.Time = \frac{Exc.Size}{Exc.Output} \qquad \text{(Eq. D.6)}$$

Where,
- Exc. Time = Time to Complete Excavation (hours)
- Exc. Size = Size of Excavation to be completed (cubic yards)
- Exc. Output = Hourly Output of Excavator (cubic yards/hour)

***Excavation Cost - Equipment***

$$EEC = EHR \times Exc.Time \qquad \text{(Eq. D.7)}$$

Where,
- EEC = Total Cost of Excavation Equipment ($)
- EHR = Excavation Equipment Hourly Rate ($/hour)
- Exc. Time = Time to Complete Excavation (hours)

***Excavation Cost - Laborers***

$$ELC = LHR \times Exc.Time \times \#L \qquad \text{(Eq. D.8)}$$

Where,
- ELC = Total Cost of labor used during excavation ($)
- LHR = Labor Hourly Rate ($/hour)
- Exc. Time = Time to Complete Excavation (hours)
- #L = Number of Laborers Used for Excavation (#)

***Excavation Cost - Operators***

$$EOC = EOHR \times Exc.Time \times \#O \qquad \text{(Eq. D.9)}$$

Where,

- EOC = Total Cost of Excavation Equipment Operators ($)
- EOHR = Excavation Equipment Operator Hourly Rate ($/hour)
- Exc. Time = Time to Complete Excavation (hours)
- #O = Number of Operators Used for Excavation (#)

***Excavation Cost - Total***

$$TCE = EEC + ELC + EOC \qquad \text{(Eq. D.10)}$$

Where,

- TCE = Total Cost of Excavation ($)
- EEC = Total Cost of Excavation Equipment ($)
- ELC = Total Cost of labor used during excavation ($)
- EOC = Total Cost of Excavation Equipment Operators ($)

**Decanting Pond – Geosynthetic Layering**

The second step in constructing the decanting pond is to layer the excavated area with a geosynthetic layer to keep the slurry from leaching out of the pond. R.S. Means (2009) suggested that a crew of two laborers be used for the task, however the model created for analysis allows the use of more personnel. The area of the excavation is based on an excavation pond that is one yard deep. The equations used to calculate the cost of placing the geosynthetic layer are described below:

***Excavation Area***

$$Exc.Area = \frac{Exc.\ Size}{Exc.Height} \qquad \text{(Eq. D.11)}$$

(Note: Height of excavation assumed to be 1 yard)

Where,

- Exc. Area = Geosynthetic Layering Area (Square Yards)
- Exc. Size = Size of Excavation to be completed (Cubic Yards)
- Exc. Height = Height of Excavation (yards)

***Geosynthetic Layer Productivity Rate***

$$GLPR = 1250\frac{SY}{hr.} \times \#L \qquad \text{(Eq. D.12)}$$

Where,

- GLPR = Geosynthetic Labor Productivity Rate (Square Yards/hour)
- #L = Number of Laborers Used for Geosynthetic Layering (#)

***Geosynthetic Layer Placement Time***

$$GLT = \frac{GLA}{GLPR} \qquad \text{(Eq. D.13)}$$

Where,
- GLT = Time to Place Geosynthetic Layer (hours)
- GLA = Geosynthetic Layering Area (Square Yards)
- GLPR = Geosynthetic Labor Productivity Rate (Square Yards/hour)

***Geosynthetic Layer Cost - Labor***

$$GLC = GLHR \times GLT \times \#L \qquad \text{(Eq. D.14)}$$

Where,
- GLC = Cost of Labor for Geosynthetic Layering ($)
- GLHR= Hourly Rate for Geosynthetic Laying Laborers ($/hour)
- GLT = Time to Place Geosynthetic Layer (hours)
- #L = Number of Laborers Used for Geosynthetic Layering (#)

***Geosynthetic Layer Cost - Materials***

$$GMC = GUC \times GLA \qquad \text{(Eq. D.15)}$$

Where,
- GMC = Cost of Geosynthetic Materials ($)
- GUC = Unit Cost of Geosynthetic Material ($/Square Yard)
- GLA = Geosynthetic Layering Area (Square Yards)

***Geosynthetic Layer Cost - Total***

$$TGC = GMC + GLC \qquad \text{(Eq. 4.16)}$$

Where,
- TGC = Total Cost of Geosynthetic Layering ($)
- GMC = Cost of Geosynthetic Materials ($)
- GLC = Cost of Labor for Geosynthetic Layering ($)

**Backfilling and Compaction**

This portion of the decanting pond operation occurs when the liquid and solids have been taken out of the decanting pond, and it involves backfilling the excavated earth back into the emptied decanting pond. This phase is required by the state to bring the site conditions back to its previous condition.

The equipment considered within the model for the backfilling operation included the following equipment with varying load capacity in cubic yards (cy):
- Front-end Loader
    - Wheel Mounted
        - 0.75 CY, 1.5 CY, 3 CY, and 5 CY.

The equipment considered for compaction are the following:

- Riding
  - Sheepsfoot
  - Vibrating Roller

- Walk behind
  - Vibrating Plate
  - Vibrating Roller

The model created allows for compaction lifts of either 6in or 12in, as well between two and four compaction equipment passes.

Using the information described above, the production rates, total time required to complete the backfill, and the backfill cost can be calculated, using the following equations:

***<u>Time to Backfill</u>***

$$BFT = \frac{Exc.Size}{BFEO} \times 8 \left(\frac{hr}{day}\right) \quad \text{(Eq. D.17)}$$

Where,
- BFT = Time to Backfill Excavation (hours)
- Exc. Size = Size of Excavation to be completed (Cubic Yards)
- BFEO = Output of Backfill Equipment (CY/day)

***<u>Cost to Backfill - Equipment</u>***

$$BFEC = BFT \times BFEHR \quad \text{(Eq. D.18)}$$

Where,
- BFEC = Cost of Backfill Equipment ($)
- BFT = Time to Backfill Excavation (hours)
- BFEHR = Backfill Equipment Hourly Rate ($/hour)

***<u>Cost to Backfill - Operator</u>***

$$BFOC = BFT \times BFOHR \quad \text{(Eq. D.19)}$$

Where,
- BFOC = Cost of Backfill Operator ($)
- BFT = Time to Backfill Excavation (hours)
- BFOHR = Backfill Operator Hourly Rate ($/hour)

***Total Cost to Backfill***

$$TBFC = BFEC + BFOC \qquad \text{(Eq. D.20)}$$

Where,

- TBFC = Total Cost of Backfill ($)
- BFEC = Cost of Backfill Equipment ($)
- BFOC = Cost of Backfill Operator ($)

***Compaction time***

$$CT = \left(\frac{Exc.Area}{CEO}\right) \times 8\ \frac{hr}{day} \qquad \text{(Eq. D.21)}$$

Where,

- CT = Time to Complete Compaction of Excavation (hours)
- Exc. Area = Area of Excavation (Square Yards)
- CEO = Compaction Equipment Output (Square Yards/Day)

***Compaction Cost - Equipment***

$$CEC = CEHR \times CT \qquad \text{(Eq. D.22)}$$

Where,

- CEC = Compaction Equipment Cost ($)
- CEHR = Compaction Equipment Hourly Rate ($/hour)
- CT = Time to Complete Compaction of Excavation (hours)

***Compaction Cost - Operator***

$$COC = COHR \times CT \qquad \text{(Eq. D.23)}$$

Where,

- COC = Compaction Operator Cost ($)
- COHR = Compaction Operator Hourly Rate ($/hour)
- CT = Time to Complete Compaction of Excavation (hours)

***Compaction Cost – Total***

$$TCC = CEC + COC \qquad \text{(Eq. D.24)}$$

Where,

- TCC = Total Compaction Cost ($)
- CEC = Compaction Equipment Cost ($)
- COC = Compaction Operator Cost ($)

***Total Cost for Decanting Operation***

$$DPC = TCE + TGC + TBFC + TCC \qquad \text{(Eq. D.25)}$$

Where,

- DCP = Total Cost of Decanting Pond
- TCE = Total Cost of Excavation ($)
- TGC = Total Cost of Geosynthetic Layering ($)
- TBFC = Total Cost of Backfill ($)
- TCC = Total Compaction Cost ($)

**2nd Option – Frac Tank**

The second option for initial material handling involves the renting of Frac and liquid storage tanks to manage the slurry generated from the construction operations. The purpose of the Frac tank is to deposit the slurry into which will filter the material and separate the solids and liquids. The solids can then be put aside to dry and the liquids can be placed into the liquid storage tank for pH testing. The liquid residuals must be neutralized below the hazardous waste designation before it can be transported.

***Frac & Liquid Storage Tank - Outputs***

The equations used to calculate the costs of using a Frac and liquid storage tank for slurry handling and management can be seen below.

$$TRC = TDR \times \#days \qquad \text{(Eq. D.26)}$$

Where,

- TRC = Tank Rental Cost ($)
- TDR = Daily Rate of Tank Rental ($/day)

$$TDC = TDR \times \#miles \qquad \text{(Eq. D.27)}$$

Where,

- TDC = Tank Delivery Cost ($)
- TDR = Tank Delivery Rate ($/mile)

$$TTC = TRC + TDC \qquad \text{(Eq. D.28)}$$

Where,

- TTC = Total Tank Cost ($)
- TRC = Tank Rental Cost ($)
- TDC = Tank Delivery Cost ($)

**Section 3 – Liquid Management**

There are two methods for liquid residual management. These are either to deposit the liquid residual at a WWTP/POTW or choose to land apply the liquid residuals at a NCDOT certified land application site. Both of these liquid residual management options include at least one pH test performed by a certified operator/tester. If this test is performed in house then the cost to the contractor is minimum. If the pH is under the hazardous waste designation, (pH<12.5), it is available for transportation. The model allows for multiple sizes of vehicles to be used in the analysis with capacities ranging from 2000 to 4000 gallons.

**1st Option – WWTP/POTW**

The selection of water tank size determines the number of trips that must be performed. The cost of the truck driver and the truck are added together and multiplied by the distance to the disposal site. The total cost of the liquid delivery cost is computed by multiplying the number of trips by the cost per trip. The cost of liquid residual disposal is computed by multiplying the quantity of gallons of liquid residual generated by the cost of disposal at the WWTP/POTW. This figure is then added to the cost of liquid delivery to find the total cost of liquid management.

The equations used to calculate the costs of disposing the liquid residual materials in a POTW or WWTP can be seen below.

***Cost of pH test(s)***

$$pHTC = pHTR \times \#Tests \qquad \text{(Eq. D.29)}$$

Where,

- pHTC = Cost of pH Tesing ($)
- pHTR = Rate for Conducting pH Test Rate ($/Test)

***Number of trips***

$$LTT = \frac{Liquid\,Volume}{LTTS} \qquad \text{(Eq. D.30)}$$

Where,

- LTT = Number of Trips for Liquid Transportation
- Liquid Volume= Quantity of Liquid Residual Produced (Gallons)
- LDTS = Size of Liquid Delivery Tank (Gallons)

***Truck Operator Costs***

$$TTOC = DTS \times \left(\frac{1\,year}{2000\,hrs}\right) \times \left(\frac{1\,hr}{40\,miles}\right) \qquad \text{(Eq. D.31)}$$

Where,

- TTOC = Transportation Truck Operator Cost ($/mile)
- DTS = Delivery Truck Operator Salary ($/year)

***Cost of Truck***

$$TTC = TTHR \times (\frac{1\,hr}{40\,miles}) \quad \text{(Eq. D.32)}$$

Where,

- TTC = Cost of Transportation Truck ($/mile)
- TTHR = Transportation Truck Hourly Rate ($/hour)

***Cost of one trip***

$$LTTC = (TTOC + TTC) \times \#miles \quad \text{(Eq. D.33)}$$

Where,

- LTTC = Liquid Transportation Trip Cost ($/trip)
- TTOC = Transportation Truck Operator Cost ($/mile)
- TTC = Cost of Transportation Truck ($/mile)

***Total Cost of Transportation***

$$LTC = LTTC \times \#Trips \quad \text{(Eq. D.34)}$$

Where,

- LTC = Liquid Transportation Cost
- LTTC = Liquid Transportation Trip Cost ($/trip)

***Cost of Liquid Disposal***

$$LDC = Vol\,Liquid \times LDR \quad \text{(Eq. D.35)}$$

Where,

- LDC = Liquid Disposal Cost ($)
- Liquid Volume= Quantity of Liquid Residual Produced (Gallons)
- LDR = Liquid Disposal Rate ($/Gallon)

***Total Cost of Liquid Disposal***

$$TLDC = LTC + LDC \quad \text{(Eq. D.36)}$$

Where,

- TLDC = Total Cost of Liquid Disposal ($)
- LTC = Liquid Transportation Cost ($)
- LDC = Liquid Disposal Cost ($)

## 2nd Option – Land Application

The cost of land application of liquid residual is determined by multiplying the cost at which the land application site would accept and pick up liquid residuals. The certified land application sites that were contacted said that they would come to pick up the residuals within a reasonable distance. The equations used to calculate the costs of beneficially reusing liquid residual material via land application can be seen below.

$$LAC = Liquid\ Vol. \times LADR \qquad \text{(Eq. D.37)}$$

Where,

- LAC = Land Application Cost ($)
- Liquid Vol. = Volume of Liquid Residuals (Gallons)
- LADR = Land Application Disposal Rate ($/Gallons)

## Section 4 – Solids Management

Each method of solid residual management stars with conducting a Paint Filter Test on the solids to determine the absence of free liquids. This test is to be performed by a qualified employee of the contractor. The cost of this test, and the price of an environmental consultant is taken into account with all methods of solid residual management. If the solid residual material is to be used as a beneficial fill, then the contractor has to provide at least one TCLP test from a representative sample. The options of solid residual management are:

- MSW Landfill,
- LCID Landfill,
- C&D Landfill,
- Beneficial Fill Onsite, and
- Beneficial Fill Offsite.

The solids are delivered to the solids residual sites using dump trucks, and the cost of transportation is based on the weight in tons. The cost of disposal depends on the type of landfill facility and regional location of the site. The sizes of dump trucks that were considered were:

- 7.5 CY,
- 8.9 CY,
- 10 CY,
- 13.6 CY, and
- 20 CY.

The size of the truck determines the number of trips needed to be taken from the jobsite to the disposal site. The total cost of disposal is based on the PDF's previously used to estimate the cost for disposal at these facilities.  The distance to all disposal sites was assumed to be 50 miles. The equations used to calculate the costs of beneficially reusing liquid residual material via land application can be seen below:

***Cost of Paint Filter Test***

$$PFTC = PFTR \times \#T \quad \text{(Eq. D.38)}$$

Where,

- PFTC = Paint Filter Testing Costs ($)
- PFTR = Paint Filter Test Rate ($/Test)
- #T = Number of Paint Filter Tests Ran

***Cost of Disposal of Solids***

$$SDC = Wt.Solids \times SDR \quad \text{(Eq. D.39)}$$

Where,

- SDC= Cost of Disposing Solids ($)
- Weight Solids = Quantity of Solids Residuals Produced (Tons)
- SDR = Solid Disposal Rate ($/ton)

***Number of Trips Required***

$$STT = \frac{Vol.Solids}{SSTT} \quad \text{(Eq. D.40)}$$

Where,

- STT = Solid Transportation Trips (#)
- Volume Solids = Quantity of Solid Residuals (Cubic Yards)
- SSTT = Size of Solid Transportation Truck (Cubic Yards)

***Transportation Cost per Trip***

$$STTC = (STOC + STTC) \times Dist. \quad \text{(Eq. D.41)}$$

Where,

- STTC = Solid Transportation Trip Cost ($/Trip)
- STOC = Solid Transportation Operator Cost ($/mile)
- STTC = Solid Transportation Truck Cost ($/mile)
- Dist. = Number of Miles of Transportation

***Solids Transportation Cost***

$$STC = STTC \times \#Trips \quad \text{(Eq. D.42)}$$

Where,

- STC = Solid Transportation Cost ($)
- STTC = Solid Transportation Truck Cost ($/mile)

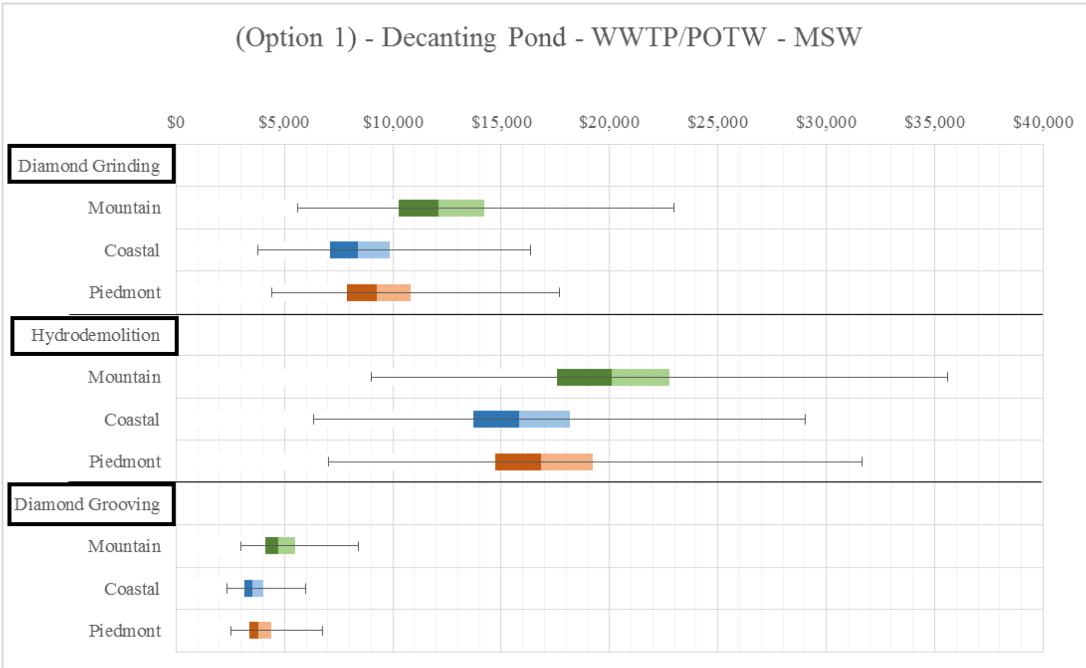
***Total Cost of Solids Disposal***

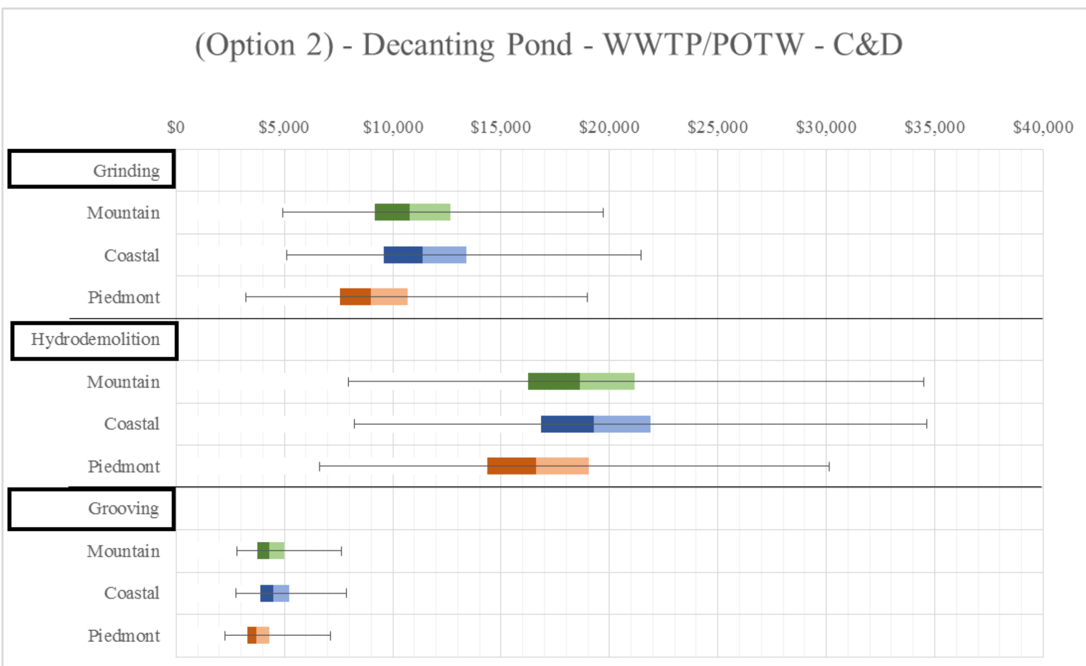
$$TSDC = PFTC + STC + SDC \quad \text{(Eq. D.43)}$$

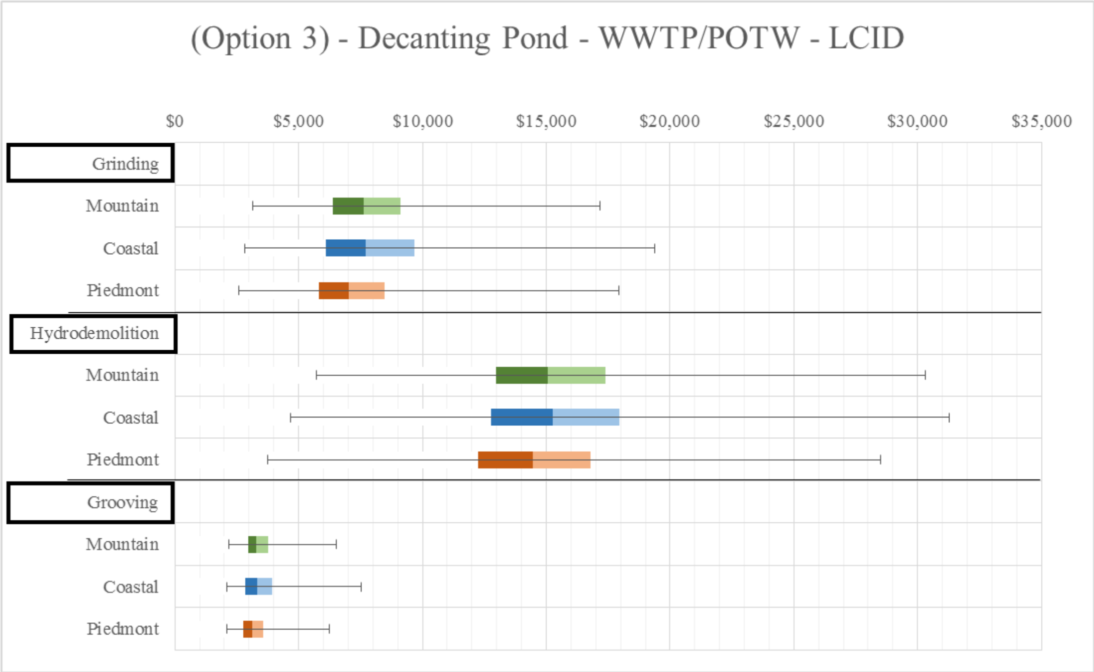
Where,

- TSDC = Total Solid Disposal Cost ($)
- PFTC = Paint Filter Test Cost ($)
- STC = Solid Transportation Cost ($)
- SDC= Cost of Disposing Solids ($)

# APPENDIX E – DISPOSAL/REUSE OPTION COMPARISONS




(Option 3) - Decanting Pond - WWTP/POTW - LCID
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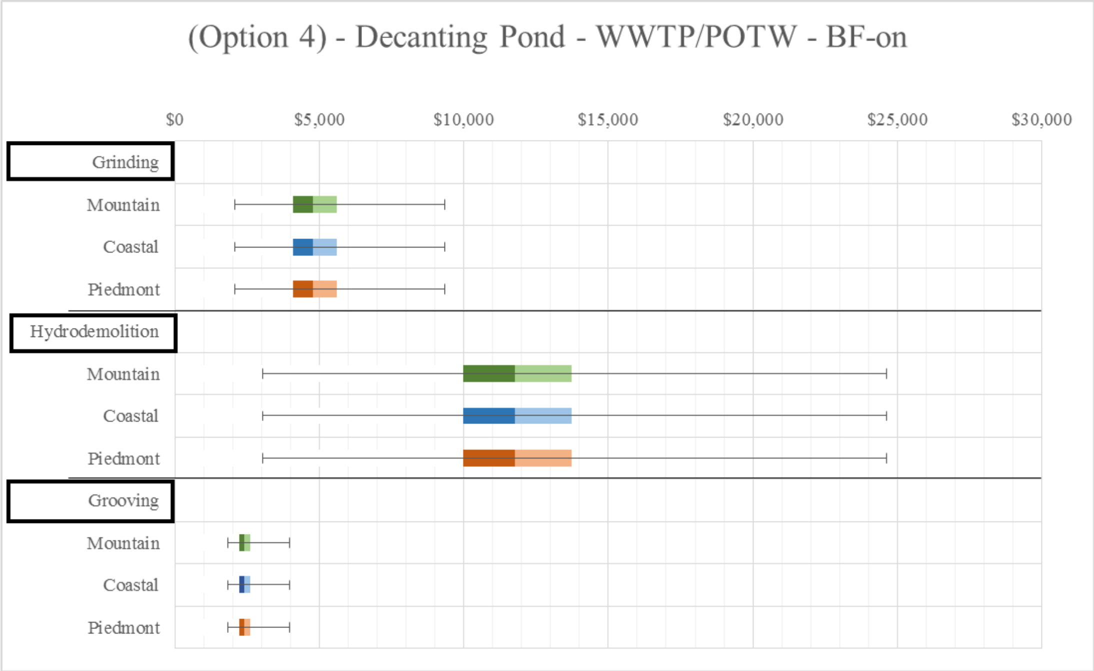
$10,000
$15,000
$20,000
$25,000
$30,000
$35,000
Grinding
Mountain
Coastal
Piedmont
Hydrodemolition
Mountain
Coastal
Piedmont
Grooving
Mountain
Coastal
Piedmont


(Option 4) - Decanting Pond - WWTP/POTW - BF-on
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$20,000
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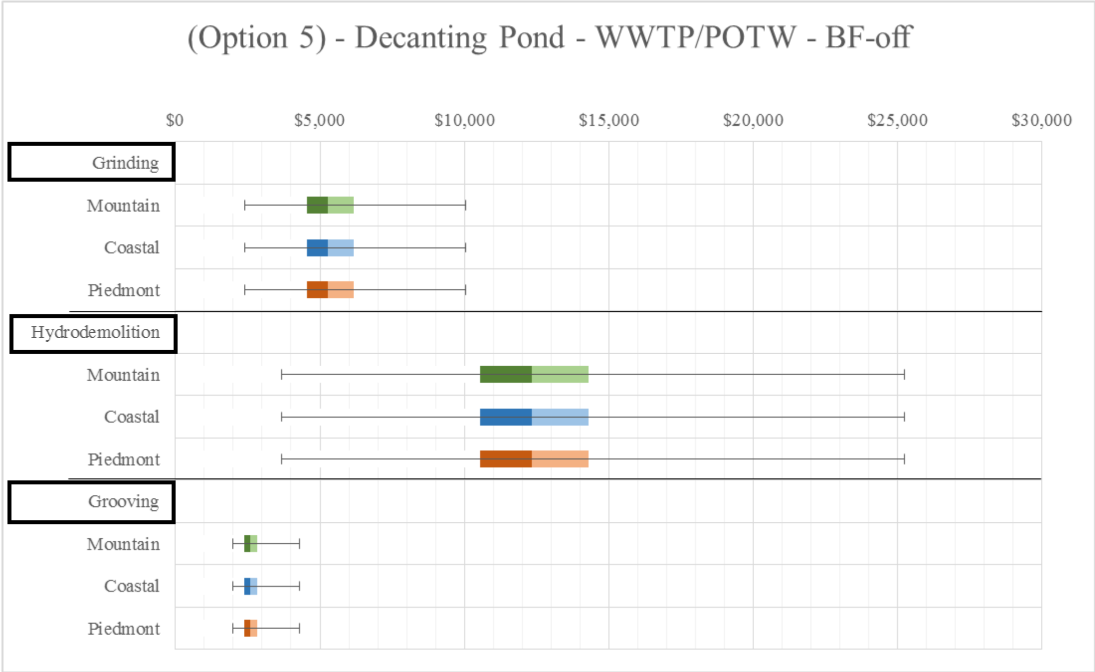
Coastal
Piedmont
Hydrodemolition
Mountain
Coastal
Piedmont
Grooving
Mountain
Coastal
Piedmont


(Option 5) - Decanting Pond - WWTP/POTW - BF-off
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Coastal
Piedmont
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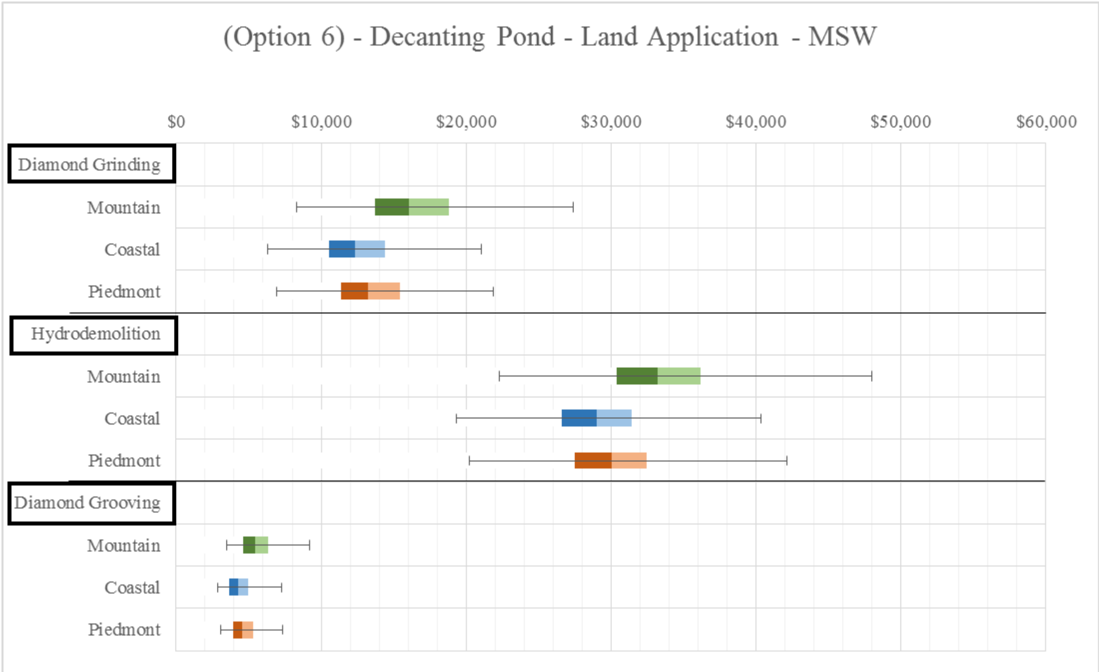
Mountain
Coastal
Piedmont
Grooving
Mountain
Coastal
Piedmont


(Option 6) - Decanting Pond - Land Application - MSW
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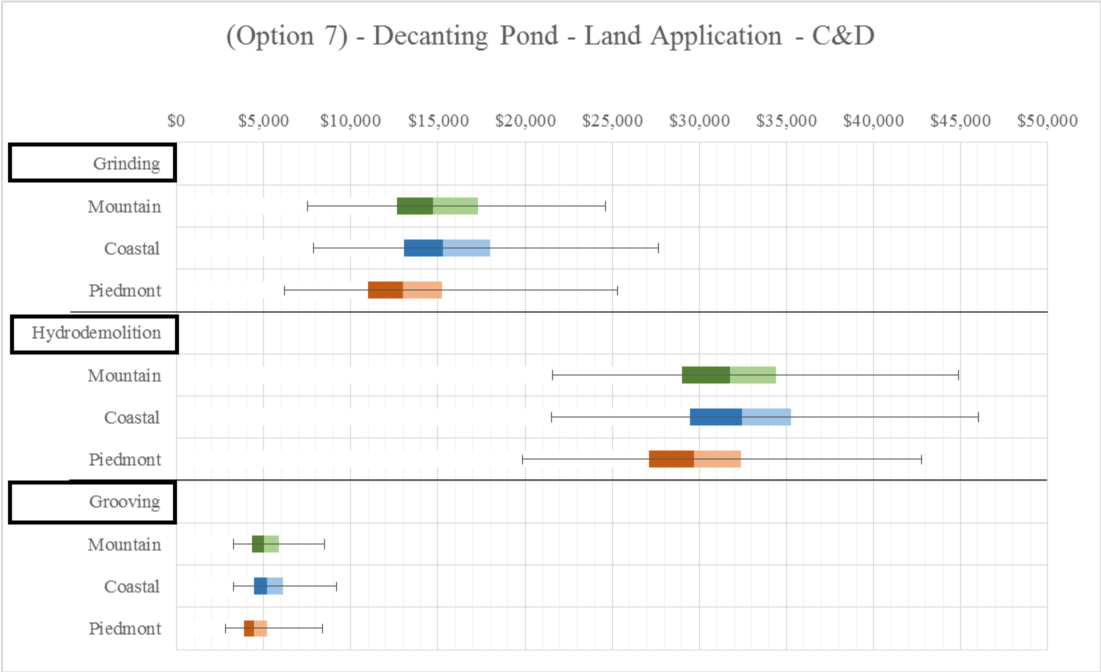
$20,000
$30,000
$40,000
$50,000
$60,000
Diamond Grinding
Mountain
Coastal
Piedmont
Hydrodemolition
Mountain
Coastal
Piedmont
Diamond Grooving
Mountain
Coastal
Piedmont


(Option 7) - Decanting Pond - Land Application - C&D
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$10,000
$15,000
$20,000
$25,000
$30,000
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$40,000
$45,000
$50,000
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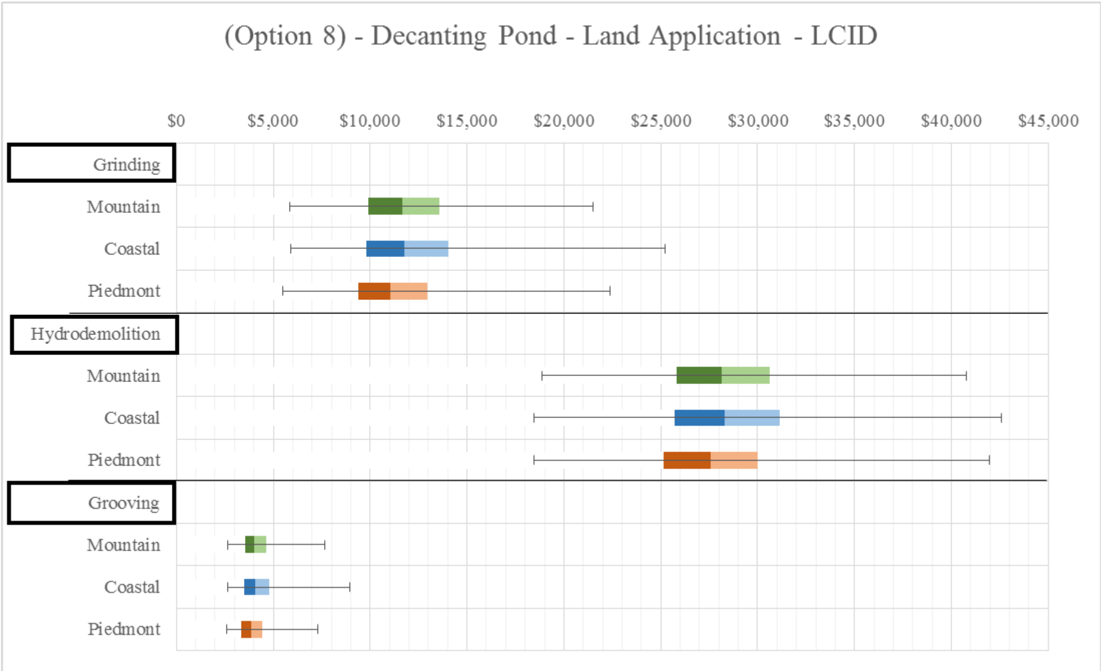
Mountain
Coastal
Piedmont
Hydrodemolition
Mountain
Coastal
Piedmont
Grooving
Mountain
Coastal
Piedmont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$40,000
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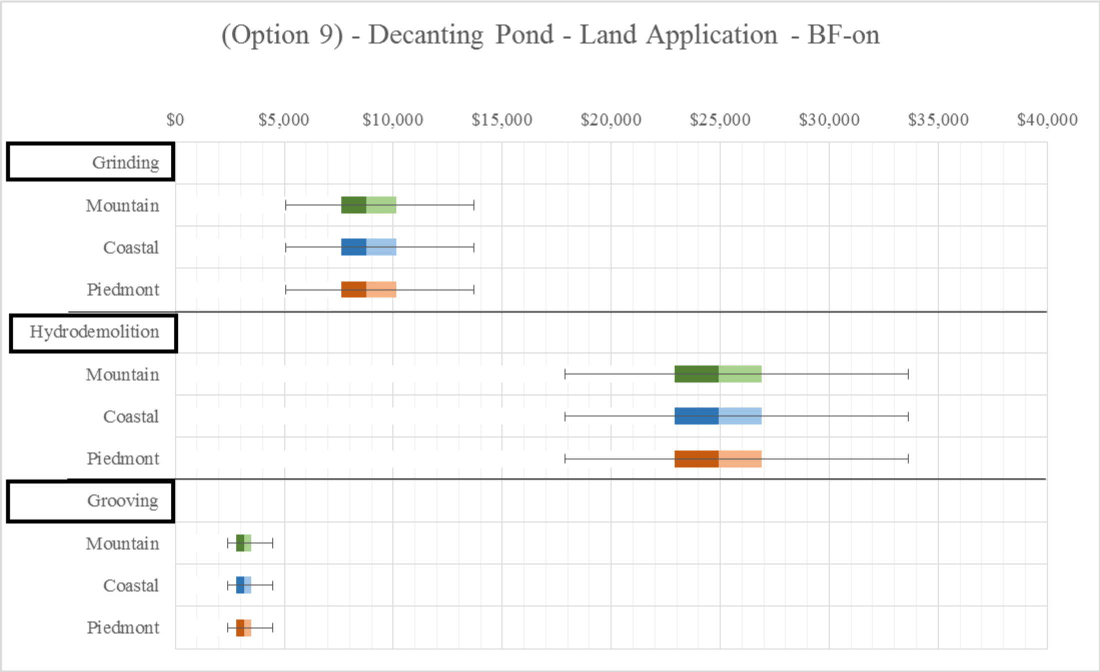
Coastal
Piedmont
Hydrodemolition
Mountain
Coastal
Piedmont
Grooving
Mountain
Coastal
Piedmont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Coastal
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Coastal
Piedmont
Grooving
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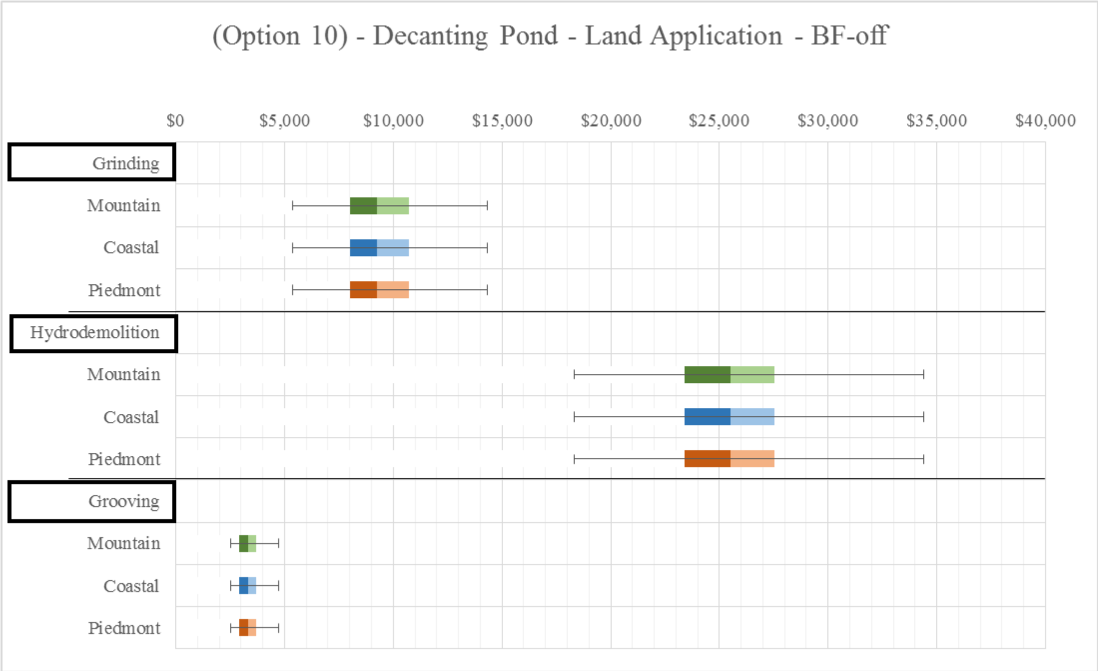
Coastal
Piedmont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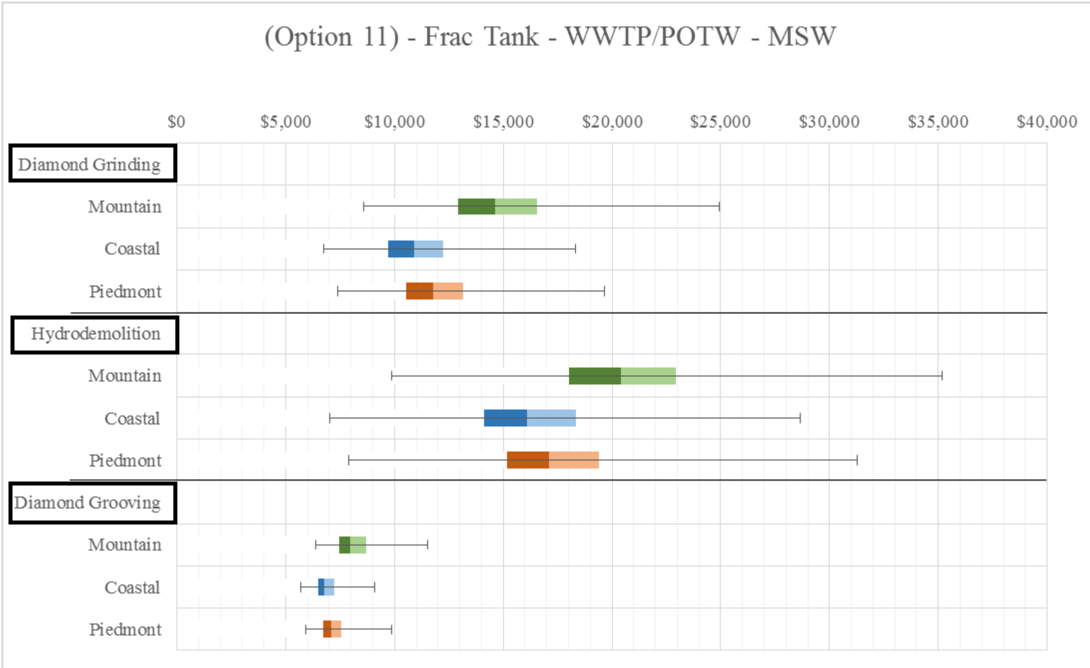
Coastal
Piedmont



(Option 11) - Frac Tank - WWTP/POTW - MSW
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$40,000
Diamond Grinding
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Coastal
Piedmont
Hydrodemolition
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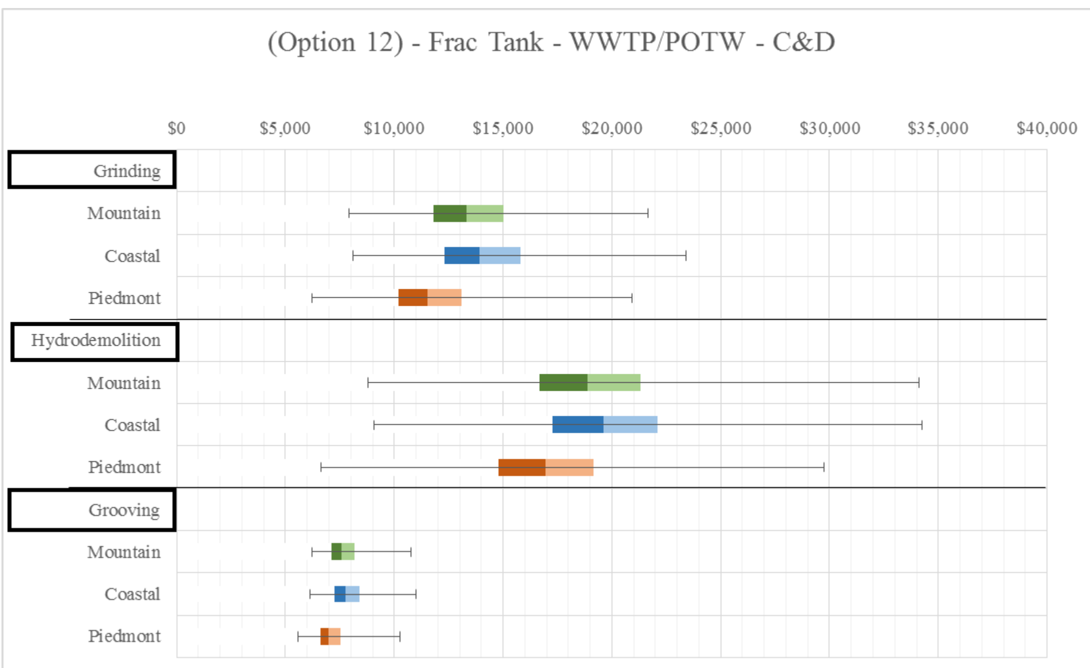
Coastal
Piedmont
Diamond Grooving
Mountain
Coastal
Piedmont

(Option 12) - Frac Tank - WWTP/POTW - C&D
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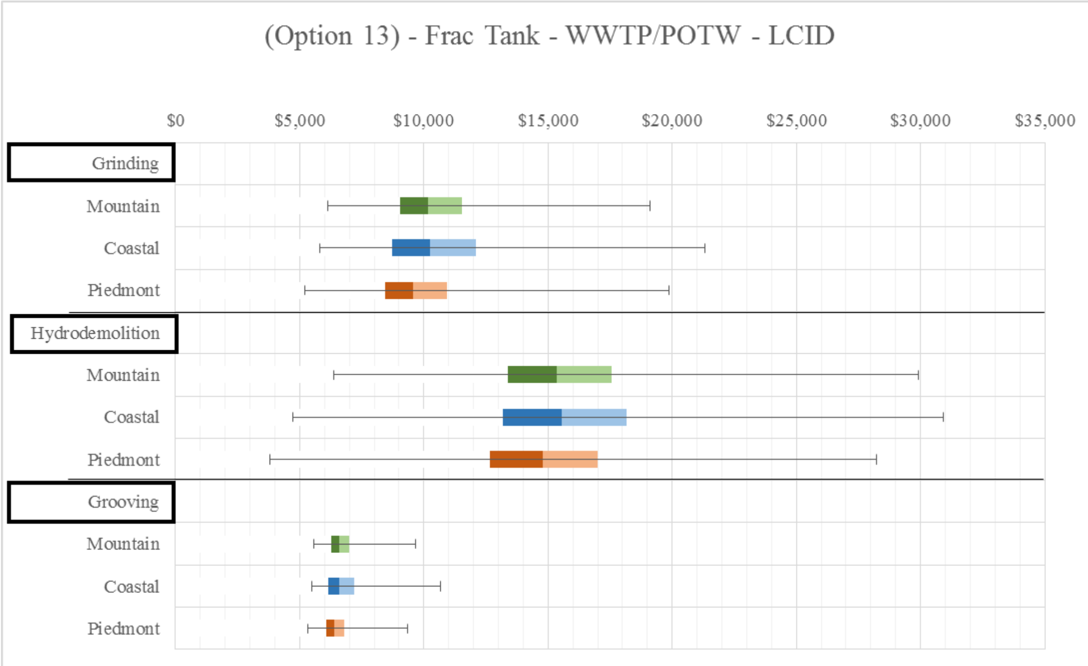
Mountain
Coastal
Piedmont


(Option 13) - Frac Tank - WWTP/POTW - LCID
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Coastal
Piedmont
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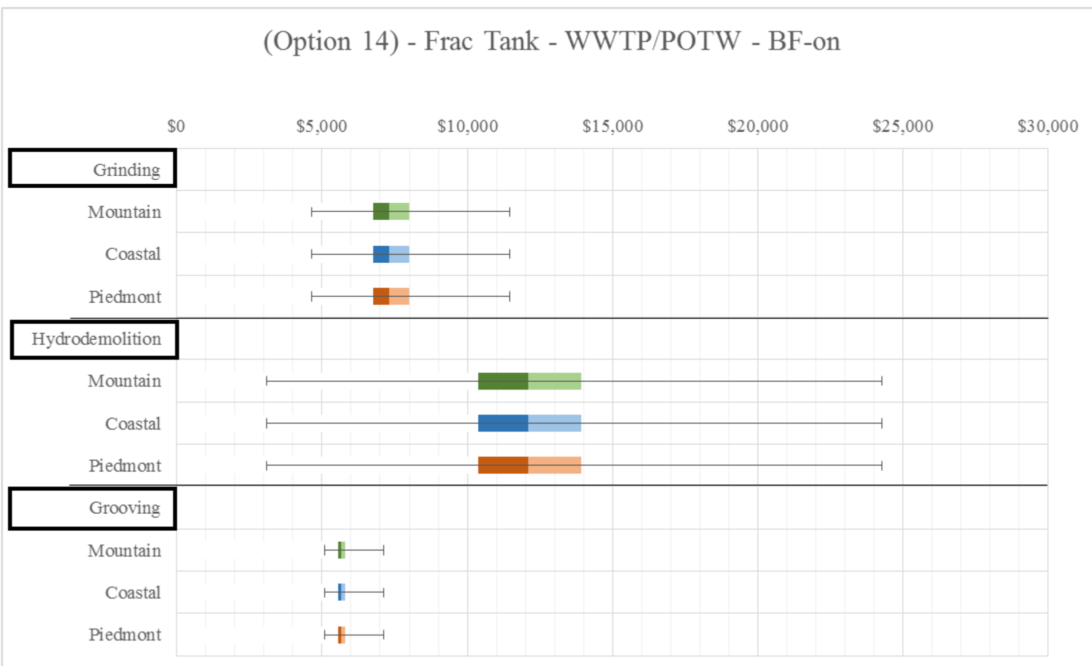
Coastal
Piedmont


(Option 14) - Frac Tank - WWTP/POTW - BF-on
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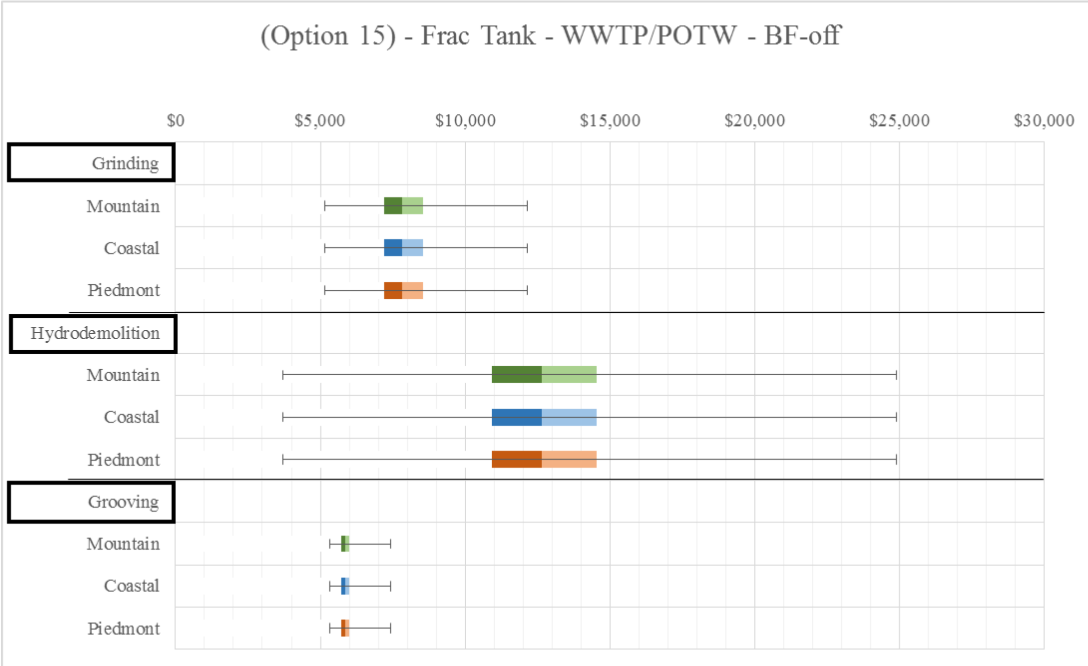

(Option 15) - Frac Tank - WWTP/POTW - BF-off
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Coastal
Piedmont
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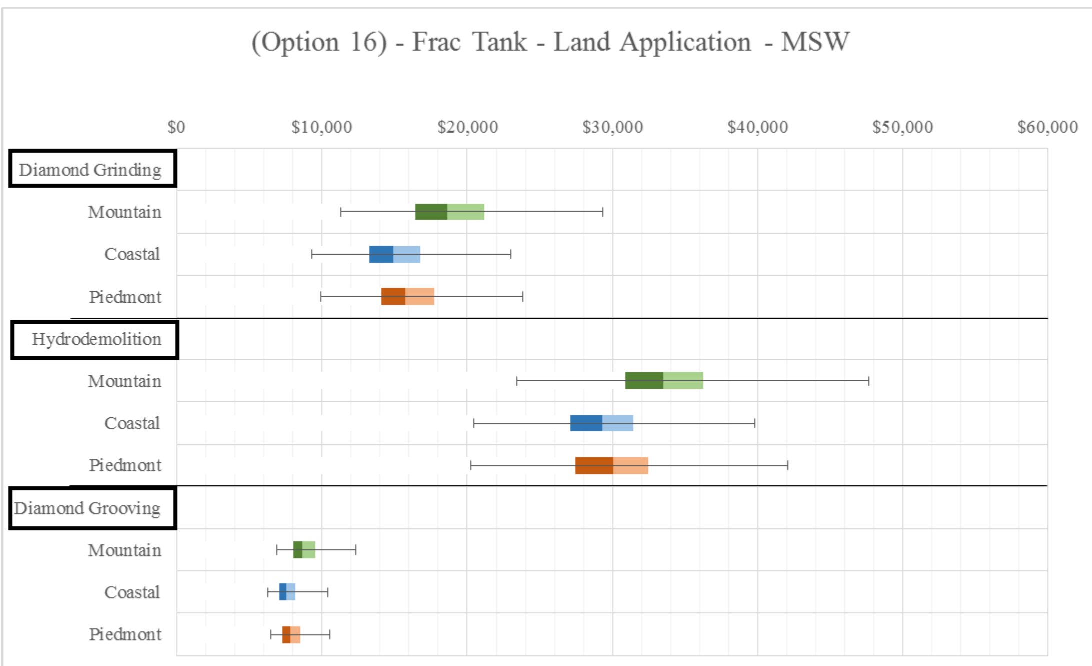
Mountain
Coastal
Piedmont

(Option 16) - Frac Tank - Land Application - MSW
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$60,000
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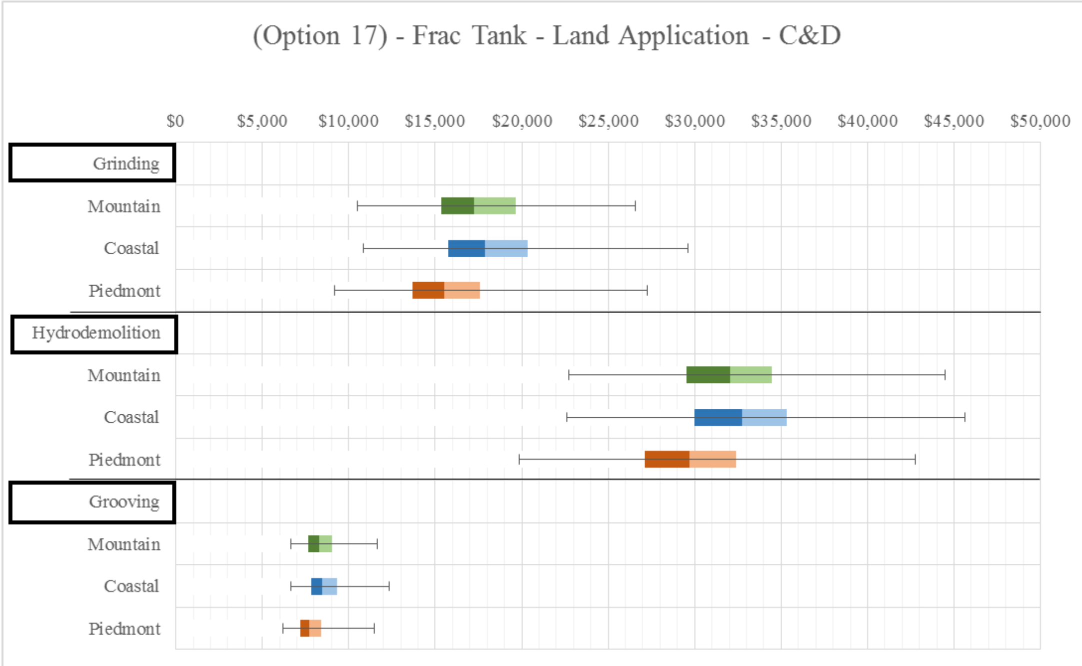
Mountain
Coastal
Piedmont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Grooving
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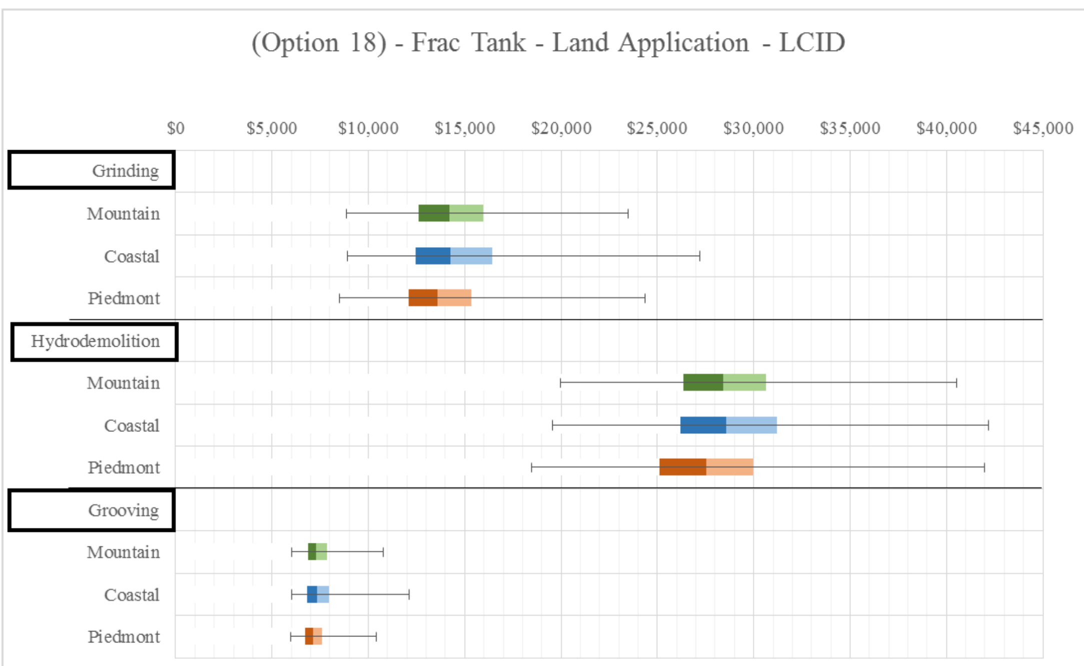
Piedmont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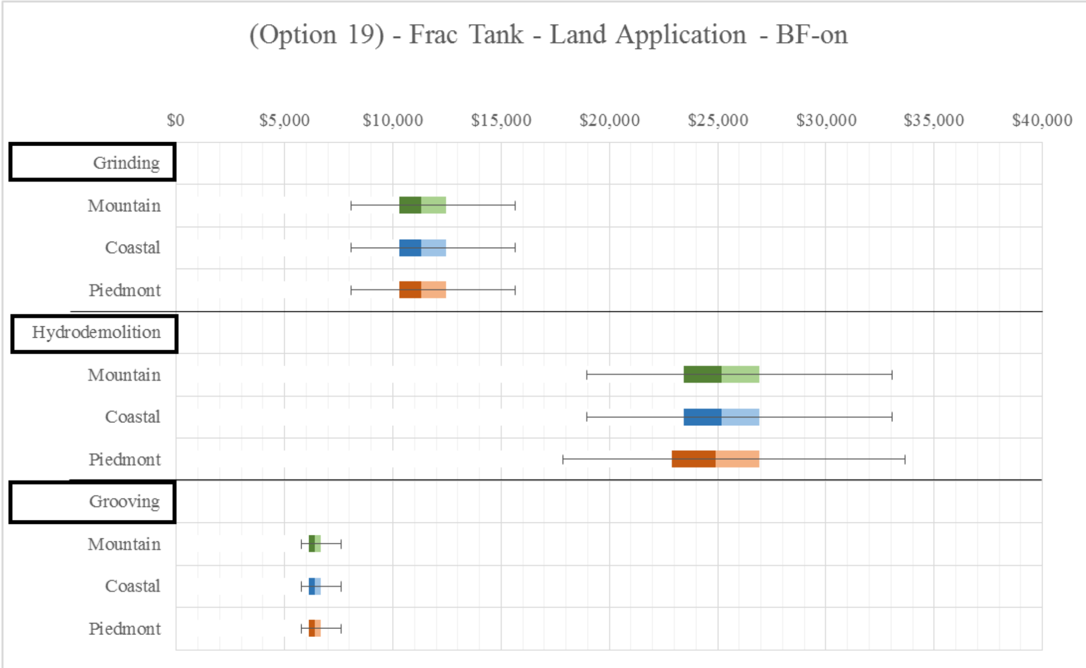
Coastal
Piedmont



(Option 19) - Frac Tank - Land Application - BF-on
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$20,000
$25,000
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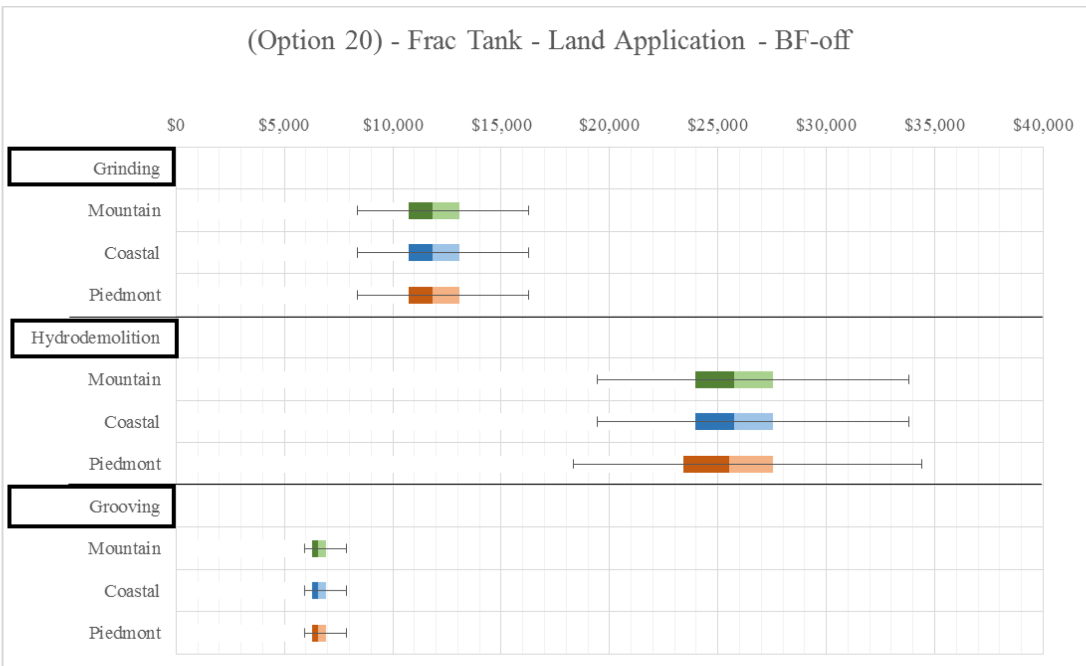
Mountain
Coastal
Piedmont

(Option 20) - Frac Tank - Land Application - BF-off
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$40,000
Grinding
Mountain
Coastal
Piedmont
Hydrodemolition
Mountain
Coastal
Piedmont
Grooving
Mountain
Coastal
Piedmont

# APPENDIX F – ONLINE TOOL FOR DISPOSAL DISTANCE CALCULATIONS

**Introduction:**

On online tool, using google maps, was created to allow contractors to estimate driving distances between their project location and the possible disposal facilities that can accept solid and water waste from hydrodemolition, diamond grinding and diamond grooving operations. The following steps will demonstrate the use of this tool.

**1. Website Location**

Note: The final website location will be determined after coordination with NCDOT personnel.

At the time of publication of this report, the location of the map is: http://nick.tymvios.com/

**2. Website Set-up**

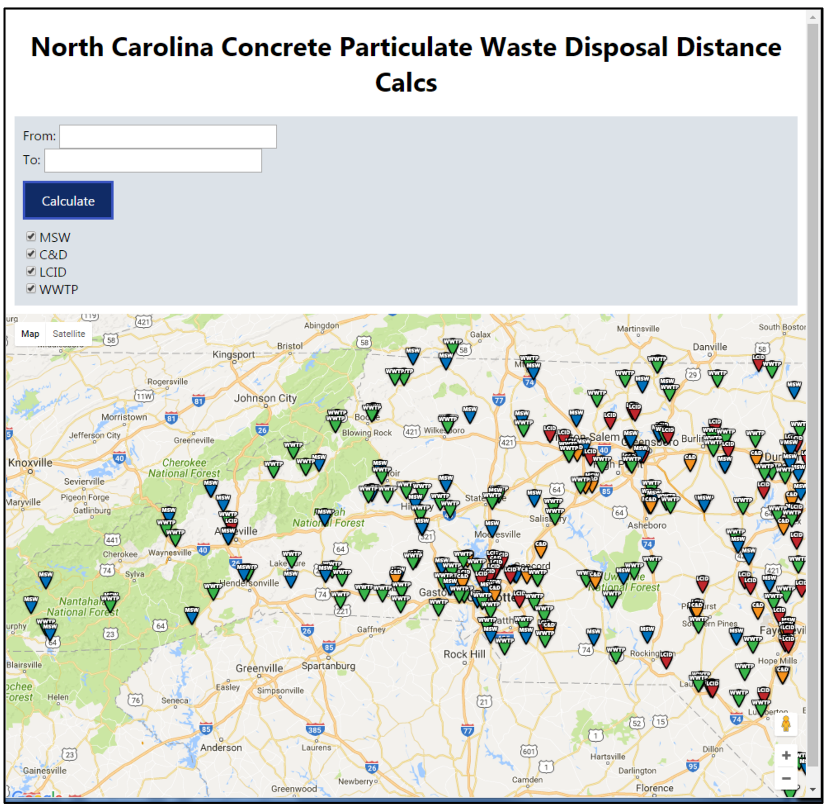



**Figure F 1: Website setup for calculating distances**

Figure F 1 shows the set-up of the website. A user can insert the location of the project that generates the waste material “From:”, Can select a disposal facility, “To:”, and select the types of facilities that are displayed on the map.

## 3. Identifying the location of the project

To select a project location, a user needs to “right click” on the map at the approximate location to the project. In the following image, a project is selected close to the intersection of I-85 with I-485 north of Charlotte. The map tool automatically fills (Figure F 2) the “From:” text box with the latitude and longitude of the location.

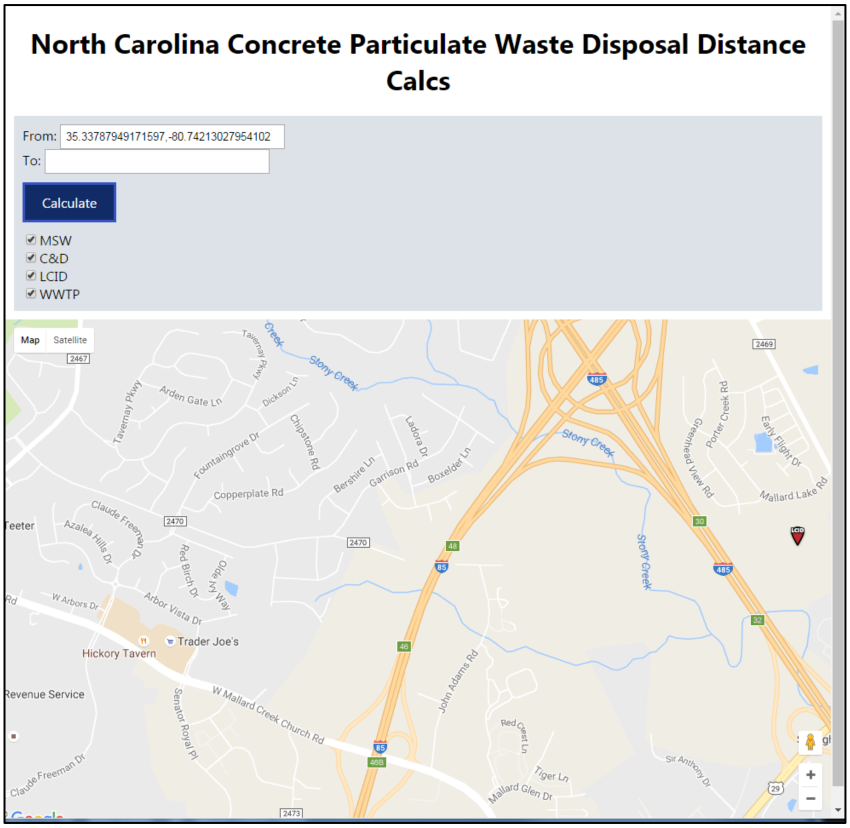



**Figure F 2: GPS coordinates with the “From” location**

## 3. Identifying the disposal facility

If the user would like to find the distance to an LCID facility, in this case the one close to the Charlotte Speedway, the user would then have to “left-click” on the facility. The map immediately displays available contact information for the facility and populates the latitude and longitude of that facility in the “To:” text box, as is shown in Figure F 3.

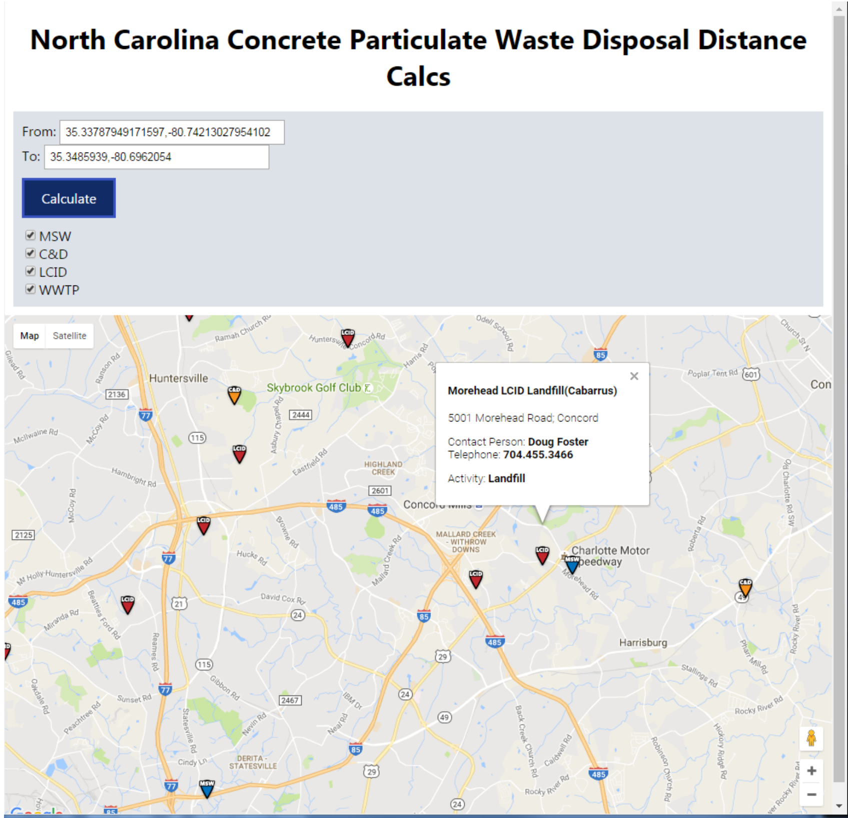



**Figure F 3: Information available after a facility is chosen**

## 4. Calculating the distance between project and disposal facility

Once the selected disposal location is selected, the user can click on the "Calculate" button and the distance as well as the shortest route is then determined (Figure F 4).

Right below the map, directions are displayed showing the origin and destination, as well as the travel distance and time for such a trip Figure F 5.

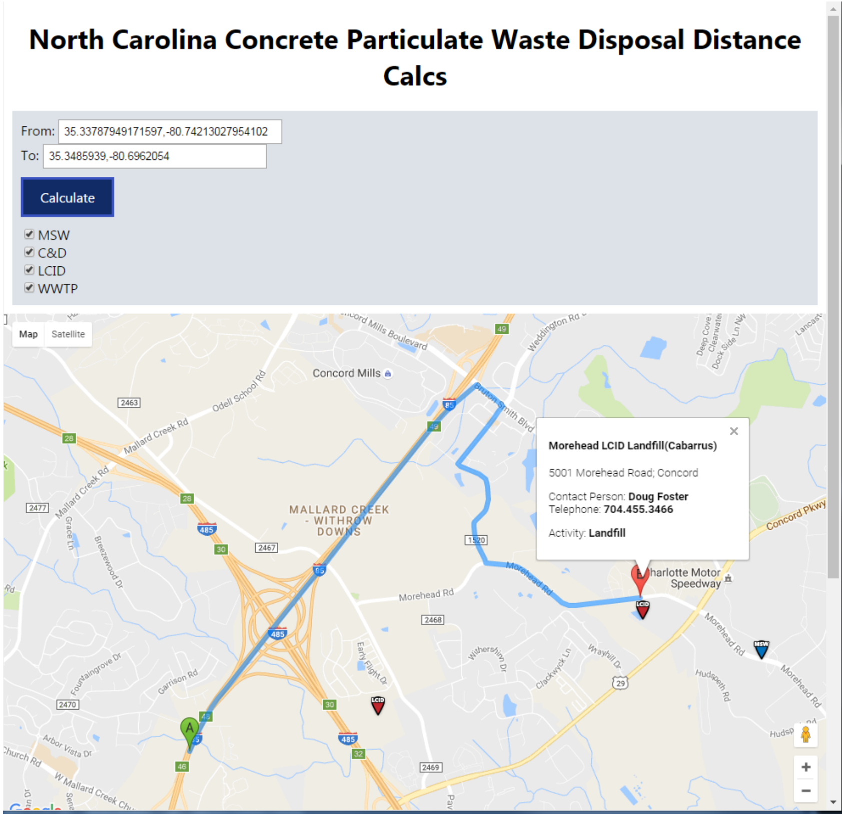



Figure F 4: Route between locations

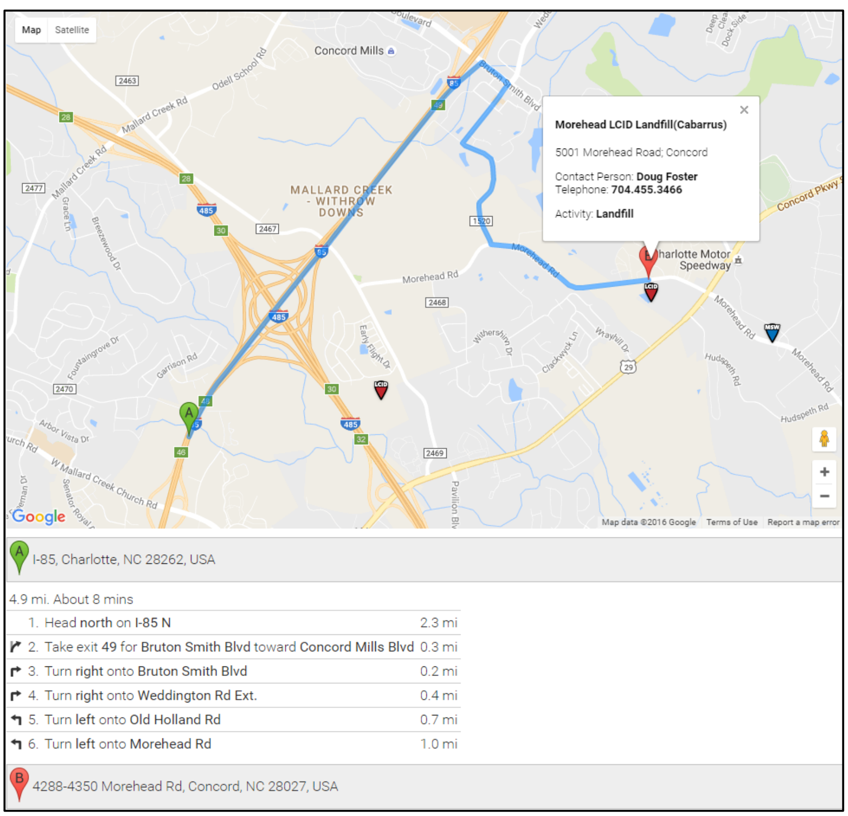



Figure F 5: Directions between locations

## 5. Editing the content of the map tool

It is possible to edit all the content of the map tool, through the administration page. Note at the moment that administration page is at: http://nick.tymvios.com/login.php . The final location of that site will be determined after coordination with NCDOT personnel Figure F 6.

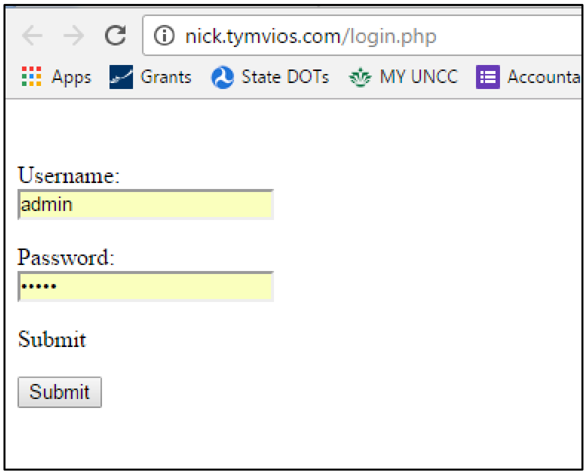



**Figure F 6: Admin site**

Once the login and password have been entered, the map tool's administrator can then perform the following functions (Figure F 7):

a. Manage Administrators – "Manage Admins"
b. Add new Administrators – "New Admins"
c. Manage Locations – "Manage Locations"
d. Add New Locations – "New Location"

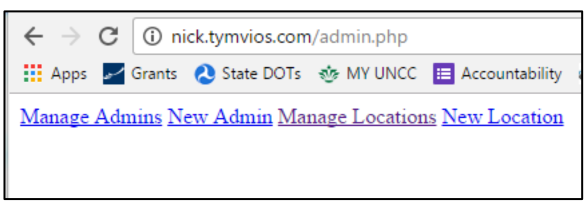



**Figure F 7: Admin options**

Once "Manage Locations" is clicked, the database for all the facilities is visible. A portion of that page is shown below in Figure F 8:

| # | ID | Name | Address | Waste | Activity | Person | Phone | Latitude | Longitude | Active | Actions |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 692 | A-1 Sandrock C&D Landfill | 2091 Bishop Road; Greensboro | CD | LF | Ronald Petty | 336.207.6052 | 35.993474 | -79.852266 | 1 | Edit |
| 2 | 648 | AAA Hauling Of NC Inc | 1171 S Eastern Blvd; Fayetteville | CD | Trans | Kenneth Hardin | 910.321.6037 | 35.0275099 | -78.8864555 | 1 | Edit |
| 3 | 674 | Abbey Green, Inc | 5030 Overdale Rd; Winston-Salem | CD | Trans | Randall Baker | 336.785.2130 | 36.0322623 | -80.2363353 | 1 | Edit |
| 4 | 775 | Albemarle, City Of, CDLF | 40592B Stony Gap Road; Albemarle | CD | LF* | Darren Preslar | 704.984.9674 | 35.3148124 | -80.1552556 | 1 | Edit |

**Figure F 8: Facilities list**

Once “Edit” is pressed for one of these facilities, it is possible to edit all the information concerning that facility as shown in Figure F 9:


**Figure F 9: Editing facility information**

If the option “New Location” is clicked, information for a new facility not already in the database can be entered, and the administrator for the site can enter all the necessary information as shown in Figure F 10.

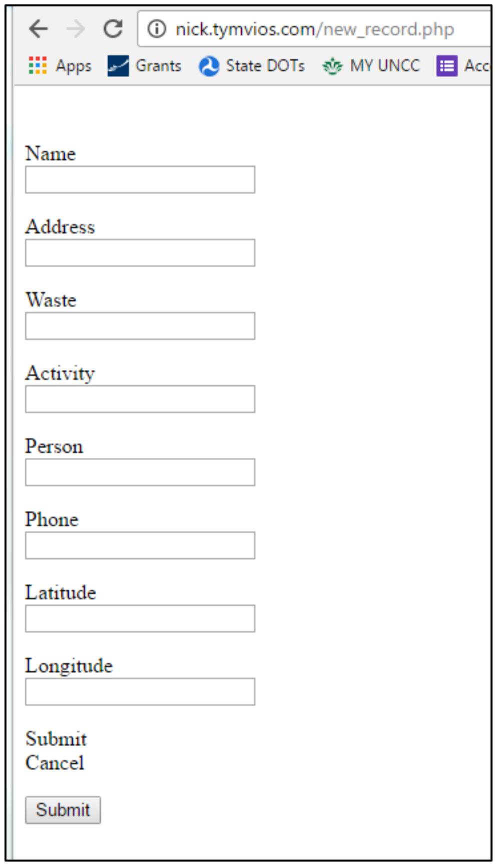



**Figure F 10: Inserting information for new facility**

# APPENDIX G – SIMPLIFIED MODEL

**Introduction:**

A simplified version of the model was developed into an Excel spreadsheet tool that can be utilized by project stakeholders. Utilizing the model approach developed as part fo this research project, the spreadsheet tool allows a contractor to enter cost information on the processes for concrete disposal and reuse, and then compare between the different options by considering the environmental benefits and the risks associated with them. The spreadsheet tool consists of three different pages as follows:

- The first page allows a user to enter information and calculate a cost for selected options for recycling and reuse of concrete residuals
- The second page allows the user to compare between the 20 different options and assign relative weights to the risk and environmental benefits associated with each option
- The third page allows the user to compare Cost, Risk, and Potential Environmental Benefit analysis results for the 20 options, aiding the user in making a decision regarding the option to utilize.

The process for the model is described in detail below. Highlighted green in each of the figures is each of the user inputs supporting the model.

**Page 1 - Project Information and Estimate**

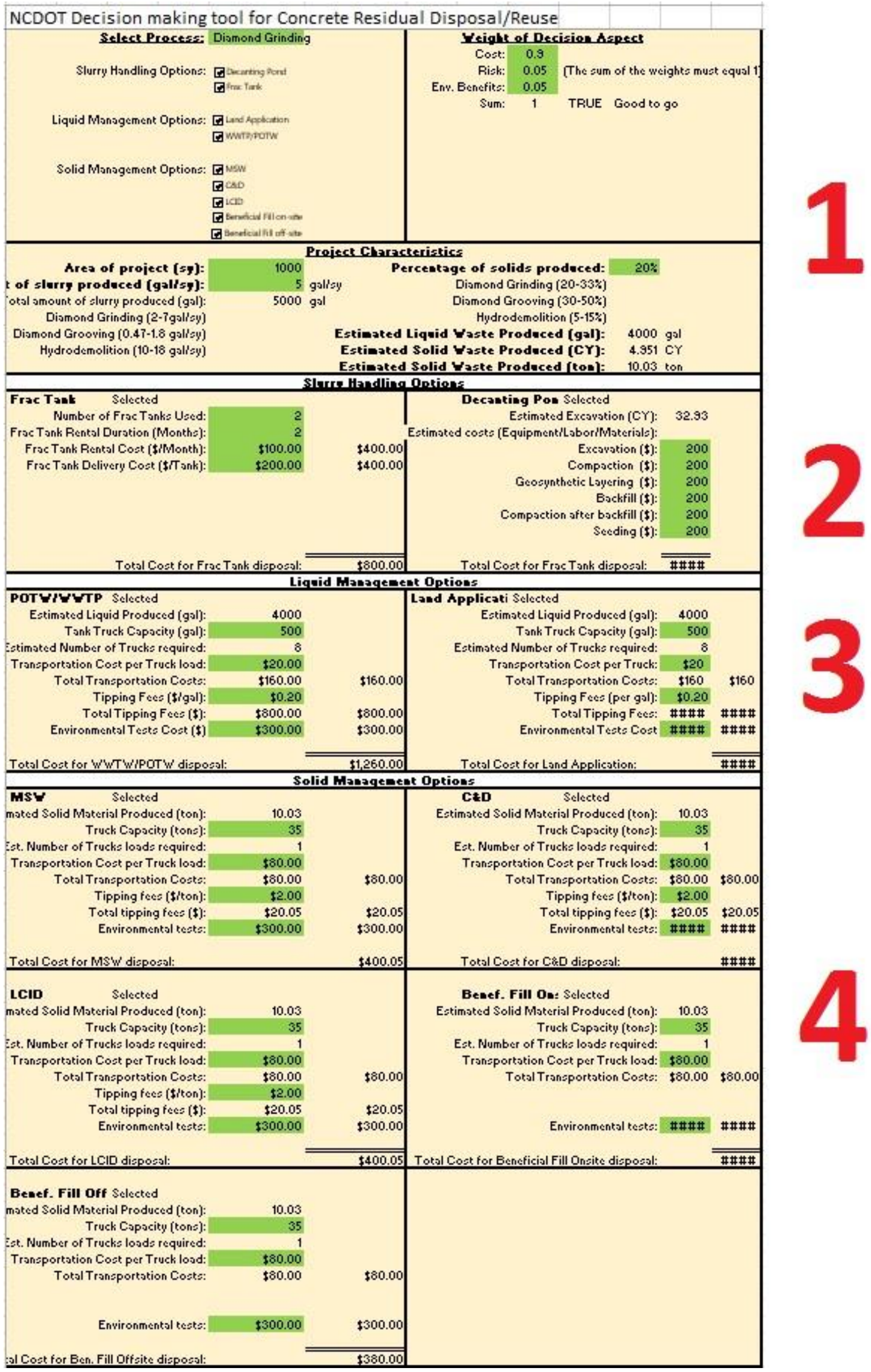
The project information and cost estimate portion of the spreadsheet can be divided into four different sections as shown in Figure G 1 on the next page. Because of the length of this section, an overview of the spreadsheet is shown first in Figure G 1, with details for each of the remaining four sections shown in subsequent Figures G 2, G 3, and G 4. The four sections are as follows:

Section 1: Project characteristics – In this section, the user can select the options that are to be considered for slurry handling, liquid management, and solid management. The user also inputs the project estimates for slurry generation, as well as the percentage of solids produced.

Section 2: In this section, the user can input the costs associated with the slurry handling processes. These include the Frac Tank rental and the construction and backfill of the decanting pond.

Section 3: In this section, the user can input the estimates for the costs associated with the liquid management options, which include the disposal at a WWTP/POTW or the diversion of the liquid material to a land application facility.

Section 4: In this section, the user is asked to input the estimates for the costs associate with solid disposal and reuse, which includes MSW, C&D, LCID facilities, as well as the diversion of the solid material for beneficial fill on-site and off-site.



NCDOT Decision making tool for Concrete Residual Disposal/Reuse

| | | | | | |
|---|---|---|---|---|---|
| **Select Process:** | Diamond Grinding | | **Weight of Decision Aspect** | | |
| Slurry Handling Options: | Decanting Pond | | Cost: | 0.9 | |
| | Frac Tank | | Risk: | 0.05 | (The sum of the weights must equal 1) |
| Liquid Management Options: | Land Application | | Env. Benefits: | 0.05 | |
| | WWTP/POTW | | Sum: | 1 | TRUE Good to go |
| Solid Management Options: | MSW | | | | |
| | C&D | | | | |
| | LCID | | | | |
| | Beneficial Fill on-site | | | | |
| | Beneficial Fill off-site | | | | |

**Project Characteristics**

| | | | | | |
|---|---|---|---|---|---|
| **Area of project (sy):** | 1000 | | **Percentage of solids produced:** | 20% | |
| **t of slurry produced (gal/sy):** | 5 | gal/sy | Diamond Grinding (20-33%) | | |
| otal amount of slurry produced (gal): | 5000 | gal | Diamond Grooving (30-50%) | | |
| Diamond Grinding (2-7gal/sy) | | | Hydrodemolition (5-15%) | | |
| Diamond Grooving (0.47-1.8 gal/sy) | | | **Estimated Liquid Waste Produced (gal):** | 4000 | gal |
| Hydrodemolition (10-18 gal/sy) | | | **Estimated Solid Waste Produced (CY):** | 4.951 | CY |
| | | | **Estimated Solid Waste Produced (ton):** | 10.03 | ton |

**Slurry Handling Options**

| | | | | | |
|---|---|---|---|---|---|
| **Frac Tank** Selected | | | **Decanting Pon** Selected | | |
| Number of Frac Tanks Used: | 2 | | Estimated Excavation (CY): | 32.93 | |
| Frac Tank Rental Duration (Months): | 2 | | Estimated costs (Equipment/Labor/Materials): | | |
| Frac Tank Rental Cost ($/Month): | $100.00 | $400.00 | Excavation ($): | 200 | |
| Frac Tank Delivery Cost ($/Tank): | $200.00 | $400.00 | Compaction ($): | 200 | |
| | | | Geosynthetic Layering ($): | 200 | |
| | | | Backfill ($): | 200 | |
| | | | Compaction after backfill ($): | 200 | |
| | | | Seeding ($): | 200 | |
| Total Cost for Frac Tank disposal: | | $800.00 | Total Cost for Frac Tank disposal: | #### | |

**Liquid Management Options**

| | | | | | |
|---|---|---|---|---|---|
| **POTW/WWTP** Selected | | | **Land Applicati** Selected | | |
| Estimated Liquid Produced (gal): | 4000 | | Estimated Liquid Produced (gal): | 4000 | |
| Tank Truck Capacity (gal): | 500 | | Tank Truck Capacity (gal): | 500 | |
| Estimated Number of Trucks required: | 8 | | Estimated Number of Trucks required: | 8 | |
| Transportation Cost per Truck load: | $20.00 | | Transportation Cost per Truck: | $20 | |
| Total Transportation Costs: | $160.00 | $160.00 | Total Transportation Costs: | $160 | $160 |
| Tipping Fees ($/gal): | $0.20 | | Tipping Fees (per gal): | $0.20 | |
| Total Tipping Fees ($): | $800.00 | $800.00 | Total Tipping Fees: | #### | #### |
| Environmental Tests Cost ($) | $300.00 | $300.00 | Environmental Tests Cost | #### | #### |
| Total Cost for WWTW/POTW disposal: | | $1,260.00 | Total Cost for Land Application: | | #### |

**Solid Management Options**

| | | | | | |
|---|---|---|---|---|---|
| **MSW** Selected | | | **C&D** Selected | | |
| mated Solid Material Produced (ton): | 10.03 | | Estimated Solid Material Produced (ton): | 10.03 | |
| Truck Capacity (tons): | 35 | | Truck Capacity (tons): | 35 | |
| Est. Number of Trucks loads required: | 1 | | Est. Number of Trucks loads required: | 1 | |
| Transportation Cost per Truck load: | $80.00 | | Transportation Cost per Truck load: | $80.00 | |
| Total Transportation Costs: | $80.00 | $80.00 | Total Transportation Costs: | $80.00 | $80.00 |
| Tipping fees ($/ton): | $2.00 | | Tipping fees ($/ton): | $2.00 | |
| Total tipping fees ($): | $20.05 | $20.05 | Total tipping fees ($): | $20.05 | $20.05 |
| Environmental tests: | $300.00 | $300.00 | Environmental tests: | #### | #### |
| Total Cost for MSW disposal: | | $400.05 | Total Cost for C&D disposal: | | #### |
| **LCID** Selected | | | **Benef. Fill On:** Selected | | |
| mated Solid Material Produced (ton): | 10.03 | | Estimated Solid Material Produced (ton): | 10.03 | |
| Truck Capacity (tons): | 35 | | Truck Capacity (tons): | 35 | |
| Est. Number of Trucks loads required: | 1 | | Est. Number of Trucks loads required: | 1 | |
| Transportation Cost per Truck load: | $80.00 | | Transportation Cost per Truck load: | $80.00 | |
| Total Transportation Costs: | $80.00 | $80.00 | Total Transportation Costs: | $80.00 | $80.00 |
| Tipping fees ($/ton): | $2.00 | | | | |
| Total tipping fees ($): | $20.05 | $20.05 | | | |
| Environmental tests: | $300.00 | $300.00 | Environmental tests: | #### | #### |
| Total Cost for LCID disposal: | | $400.05 | Total Cost for Beneficial Fill Onsite disposal: | | #### |
| **Benef. Fill Off** Selected | | | | | |
| mated Solid Material Produced (ton): | 10.03 | | | | |
| Truck Capacity (tons): | 35 | | | | |
| Est. Number of Trucks loads required: | 1 | | | | |
| Transportation Cost per Truck load: | $80.00 | | | | |
| Total Transportation Costs: | $80.00 | $80.00 | | | |
| Environmental tests: | $300.00 | $300.00 | | | |
| al Cost for Ben. Fill Offsite disposal: | | $380.00 | | | |



**Figure G 1: Overview of project information and estimate portion of simplified model (page 1 of spreadsheet tool)**

Section 1:

This first section of the spreadsheet (shown in Figure G.2) allows the user to select the slurry the slurry, liquid, and solid handling options to be considered for comparison. In addition, the user can also input the weights for the three aspects of the selection process (Cost, Risk, and Environmental Benefits). The sum of the weights should add up to 1, as described in Section 2 of this report, according to the user's perception of the importance of each section. In addition, the user can enter the possible slurry production. Guidance is provided for possible slurry production rates.

| | | | |
|---|---|---|---|
| **Select Process:** | Diamond Grinding | **Weight of Decision Aspect** | |
| | | Cost: | 0.9 |
| Slurry Handling Options: | ☑ Decanting Pond | Risk: | 0.05 (The sum of the weights must equal 1) |
| | ☑ Frac Tank | Env. Benefits: | 0.05 |
| | | Sum: | 1 TRUE Good to go |
| Liquid Management Options: | ☑ Land Application | | |
| | ☑ WWTP/POTW | | |
| Solid Management Options: | ☑ MSW | | |
| | ☑ C&D | | |
| | ☑ LCID | | |
| | ☑ Beneficial Fill on-site | | |
| | ☑ Beneficial Fill off-site | | |

| **Project Characteristics** | | | |
|---|---|---|---|
| **Area of project (sy):** | 1000 | **Percentage of solids produced:** | 20% |
| **Amount of slurry produced (gal/sy):** | 5 gal/sy | Diamond Grinding (20-33%) | |
| Total amount of slurry produced (gal): | 5000 gal | Diamond Grooving (30-50%) | |
| Diamond Grinding (2-7gal/sy) | | Hydrodemolition (5-15%) | |
| Diamond Grooving (0.47-1.8 gal/sy) | | **Estimated Liquid Waste Produced (gal):** | 4000 gal |
| Hydrodemolition (10-18 gal/sy) | | **Estimated Solid Waste Produced (CY):** | 4.951132 CY |
| | | **Estimated Solid Waste Produced (ton):** | 10.02604 ton |

**Figure G 2: Overview of section 1 of page 1 of spreadsheet tool – Process Options, Decision Aspect Weighting, and Project Characteristics**

Section 2:

This section of the spreadsheet (shown in Figure G.3) allows the user to input values for the parameters for the slurry handling options considered. Parameters for the frac tank option include the number of frac tanks rented, the duration of the rental in months, the rental rate, and the tank delivery cost. For the decanting pond option, the estimated volume of the pond is provided, according to the calculations provided in Appendix D. The user is asked to estimate the costs for excavation, compaction geosynthetic layering, backfill, and seeding.

| **Slurry Handling Options** | | | | |
|---|---|---|---|---|
| **Frac Tank** Selected | | | **Decanting Pond** Selected | |
| Number of Frac Tanks Used: | 2 | | Estimated Excavation (CY): | 32.92503 |
| Frac Tank Rental Duration (Months): | 2 | | Estimated costs (Equipment/Labor/Materials): | |
| Frac Tank Rental Cost ($/Month): | $100.00 | $400.00 | Excavation ($): | 200 |
| Frac Tank Delivery Cost ($/Tank): | $200.00 | $400.00 | Compaction ($): | 200 |
| | | | Geosynthetic Layering ($): | 200 |
| | | | Backfill ($): | 200 |
| | | | Compaction after backfill ($): | 200 |
| | | | Seeding ($): | 200 |
| Total Cost for Frac Tank disposal: | | $800.00 | Total Cost for Frac Tank disposal: | $1,200.00 |

**Figure G 3: Overview of section 2 of page 1 of spreadsheet tool – Slurry Handling Options**

Section 3:

In this section of the spreadsheet (shown in Figure G 4), the user is asked to enter the values for the parameters for the liquid handling options considered. Parameters for both the POTW/WWTW and Land Application options include the capacity of the truck carrying the liquid, the transportation costs, per truck load, the tipping fees per gallon, and the cost of any environmental tests that need to be performed.

**Liquid Management Options**

| POTW/WWTP Selected | | | Land Application Selected | | |
|---|---|---|---|---|---|
| Estimated Liquid Produced (gal): | 4000 | | Estimated Liquid Produced (gal): | 4000 | |
| Tank Truck Capacity (gal): | 500 | | Tank Truck Capacity (gal): | 500 | |
| Estimated Number of Trucks required: | 8 | | Estimated Number of Trucks required: | 8 | |
| Transportation Cost per Truck load: | $20.00 | | Transportation Cost per Truck: | $20 | |
| Total Transportation Costs: | $160.00 | $160.00 | Total Transportation Costs: | $160 | $160 |
| Tipping Fees ($/gal): | $0.20 | | Tipping Fees (per gal): | $0.20 | |
| Total Tipping Fees ($): | $800.00 | $800.00 | Total Tipping Fees: | $800.00 | $800.00 |
| Environmental Tests Cost ($) | $300.00 | $300.00 | Environmental Tests Cost | $300.00 | $300.00 |
| Total Cost for WWTW/POTW disposal: | | $1,260.00 | Total Cost for Land Application: | | $1,260.00 |

**Figure G 4: Overview of section 3 of page 1 of spreadsheet tool – Liquid Management Options**

Section 4:

In this section of the spreadsheet (shown in Figure G 5), the user is asked to enter the values for the parameters for the solid handling options considered. For the MSW, C&D, and LCID options, the information that is required is the capacity of the trucks, the cost for each truck load, the tipping fees, and the cost of any environmental tests. For the beneficial fill options, the information that is required includes the capacity of the trucks and the transportation costs per truck load.

**Solid Management Options**

| MSW Selected | | | C&D Selected | | |
|---|---|---|---|---|---|
| Estimated Solid Material Produced (ton): | 10.03 | | Estimated Solid Material Produced (ton): | 10.03 | |
| Truck Capacity (tons): | 35 | | Truck Capacity (tons): | 35 | |
| Est. Number of Trucks loads required: | 1 | | Est. Number of Trucks loads required: | 1 | |
| Transportation Cost per Truck load: | $80.00 | | Transportation Cost per Truck load: | $80.00 | |
| Total Transportation Costs: | $80.00 | $80.00 | Total Transportation Costs: | $80.00 | $80.00 |
| Tipping fees ($/ton): | $2.00 | | Tipping fees ($/ton): | $2.00 | |
| Total tipping fees ($): | $20.05 | $20.05 | Total tipping fees ($): | $20.05 | $20.05 |
| Environmental tests: | $300.00 | $300.00 | Environmental tests: | $300.00 | $300.00 |
| Total Cost for MSW disposal: | | $400.05 | Total Cost for C&D disposal: | | $400.05 |
| **LCID** Selected | | | **Benef. Fill Onsite** Selected | | |
| Estimated Solid Material Produced (ton): | 10.03 | | Estimated Solid Material Produced (ton): | 10.03 | |
| Truck Capacity (tons): | 35 | | Truck Capacity (tons): | 35 | |
| Est. Number of Trucks loads required: | 1 | | Est. Number of Trucks loads required: | 1 | |
| Transportation Cost per Truck load: | $80.00 | | Transportation Cost per Truck load: | $80.00 | |
| Total Transportation Costs: | $80.00 | $80.00 | Total Transportation Costs: | $80.00 | $80.00 |
| Tipping fees ($/ton): | $2.00 | | | | |
| Total tipping fees ($): | $20.05 | $20.05 | | | |
| Environmental tests: | $300.00 | $300.00 | Environmental tests: | $300.00 | $300.00 |
| Total Cost for LCID disposal: | | $400.05 | Total Cost for Beneficial Fill Onsite disposal: | | $380.00 |
| **Benef. Fill Offsite** Selected | | | | | |
| Estimated Solid Material Produced (ton): | 10.03 | | | | |
| Truck Capacity (tons): | 35 | | | | |
| Est. Number of Trucks loads required: | 1 | | | | |
| Transportation Cost per Truck load: | $80.00 | | | | |
| Total Transportation Costs: | $80.00 | $80.00 | | | |
| Environmental tests: | $300.00 | $300.00 | | | |
| Total Cost for Ben. Fill Offsite disposal: | | $380.00 | | | |

**Figure G 5: Overview of section 4 of page 1 of spreadsheet tool – Solid Management Options**

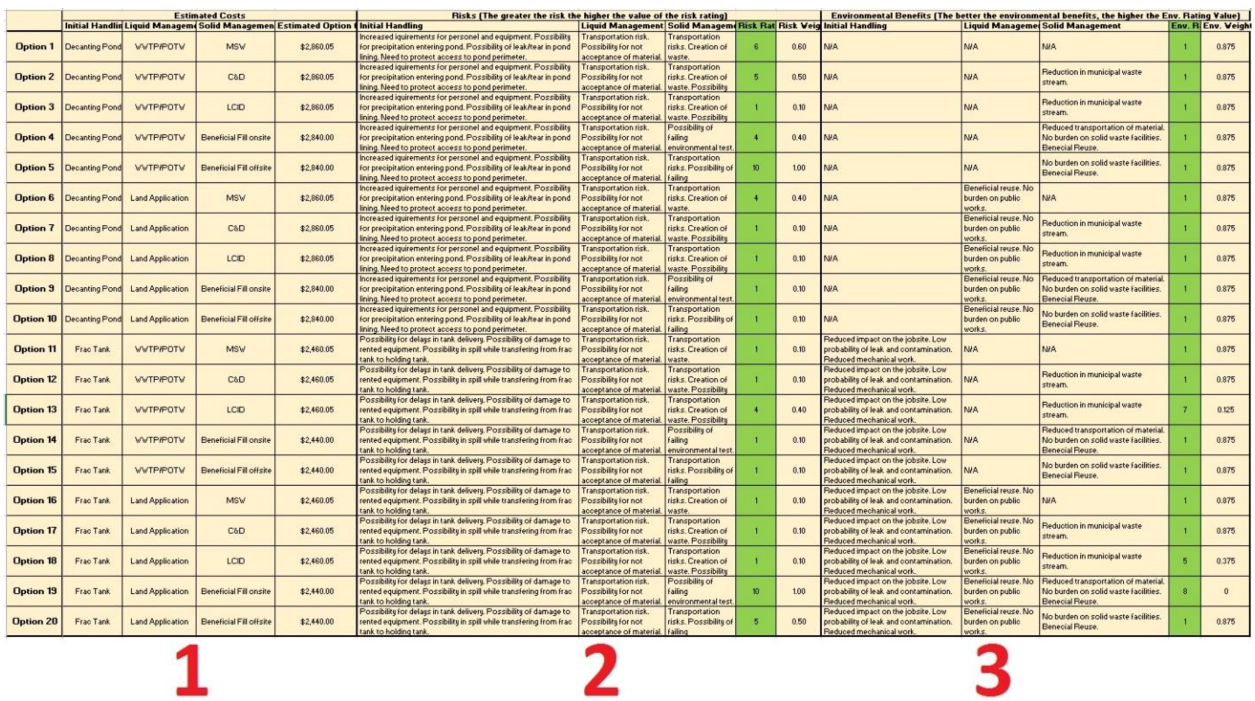
## Page 2 - Option Comparisons

The Options Comparisons page of the spreadsheet can be divided into 3 different sections as shown in Figure G 6. Because of the length of this page of the simplified model spreadsheet tool, an overview of this page of the spreadsheet is shown first (Figure G 6), and then in enlarged in Figures G 7 through G 9) to show detail for each of the 3 sections. The three sections are as follows:

Section 1: Cost Estimate – This section gathers the cost information calculated in the first page of the spreadsheet, and displays the estimated cost for each option.

Section 2: Risk Comparison – This section displays the identified risks for each option, and asks the user to rate the combinations on a scale from 1 to 10.

Section 3: Potential Environmental Benefits Comparison – This section displays the identified environmental benefits for each option, and asks the user to rank the combinations on a scale from 1 to 10.



| | Estimated Costs | | | | Risks (The greater the risk the higher the value of the risk rating) | | | | | Environmental Benefits (The better the environmental benefits, the higher the Env. Rating Value) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Initial Handlin | Liquid Managem | Solid Managemen | Estimated Option ( | Initial Handling | Liquid Management | Solid Managem | Risk Rat | Risk Weig | Initial Handling | Liquid Manageme | Solid Management | Env. R | Env. Weight |
| Option 1 | Decanting Pond | WWTP/POTW | MSW | $2,860.05 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of material. | Transportation risks. Creation of waste. | 6 | 0.60 | N/A | N/A | N/A | 1 | 0.875 |
| Option 2 | Decanting Pond | WWTP/POTW | C&D | $2,860.05 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of material. | Transportation risks. Creation of waste. Possibility | 5 | 0.50 | N/A | N/A | Reduction in municipal waste stream. | 1 | 0.875 |
| Option 3 | Decanting Pond | WWTP/POTW | LCID | $2,860.05 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of material. | Transportation risks. Creation of waste. Possibility | 1 | 0.10 | N/A | N/A | Reduction in municipal waste stream. | 1 | 0.875 |
| Option 4 | Decanting Pond | WWTP/POTW | Beneficial Fill onsite | $2,840.00 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of material. | Possibility of failing environmental test. | 4 | 0.40 | N/A | N/A | Reduced transportation of material. No burden on solid waste facilities. Benecial Reuse. | 1 | 0.875 |
| Option 5 | Decanting Pond | WWTP/POTW | Beneficial Fill offsite | $2,840.00 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of material. | Transportation risks. Possibility of failing | 10 | 1.00 | N/A | N/A | No burden on solid waste facilities. Benecial Reuse. | 1 | 0.875 |
| Option 6 | Decanting Pond | Land Application | MSW | $2,860.05 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of material. | Transportation risks. Creation of waste. | 4 | 0.40 | N/A | Beneficial reuse. No burden on public works. | N/A | 1 | 0.875 |
| Option 7 | Decanting Pond | Land Application | C&D | $2,860.05 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of material. | Transportation risks. Creation of waste. Possibility | 1 | 0.10 | N/A | Beneficial reuse. No burden on public works. | Reduction in municipal waste stream. | 1 | 0.875 |
| Option 8 | Decanting Pond | Land Application | LCID | $2,860.05 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of material. | Transportation risks. Creation of waste. Possibility | 1 | 0.10 | N/A | Beneficial reuse. No burden on public works. | Reduction in municipal waste stream. | 1 | 0.875 |
| Option 9 | Decanting Pond | Land Application | Beneficial Fill onsite | $2,840.00 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of material. | Possibility of failing environmental test. | 1 | 0.10 | N/A | Beneficial reuse. No burden on public works. | Reduced transportation of material. No burden on solid waste facilities. Benecial Reuse. | 1 | 0.875 |
| Option 10 | Decanting Pond | Land Application | Beneficial Fill offsite | $2,840.00 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of material. | Transportation risks. Possibility of failing | 1 | 0.10 | N/A | Beneficial reuse. No burden on public works. | No burden on solid waste facilities. Benecial Reuse. | 1 | 0.875 |
| Option 11 | Frac Tank | WWTP/POTW | MSW | $2,460.05 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of material. | Transportation risks. Creation of waste. | 1 | 0.10 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | N/A | N/A | 1 | 0.875 |
| Option 12 | Frac Tank | WWTP/POTW | C&D | $2,460.05 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of material. | Transportation risks. Creation of waste. Possibility | 1 | 0.10 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | N/A | Reduction in municipal waste stream. | 1 | 0.875 |
| Option 13 | Frac Tank | WWTP/POTW | LCID | $2,460.05 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of material. | Transportation risks. Creation of waste. Possibility | 4 | 0.40 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | N/A | Reduction in municipal waste stream. | 7 | 0.125 |
| Option 14 | Frac Tank | WWTP/POTW | Beneficial Fill onsite | $2,440.00 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of material. | Possibility of failing environmental test. | 1 | 0.10 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | N/A | Reduced transportation of material. No burden on solid waste facilities. Benecial Reuse. | 1 | 0.875 |
| Option 15 | Frac Tank | WWTP/POTW | Beneficial Fill offsite | $2,440.00 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of material. | Transportation risks. Possibility of failing | 1 | 0.10 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | N/A | No burden on solid waste facilities. Benecial Reuse. | 1 | 0.875 |
| Option 16 | Frac Tank | Land Application | MSW | $2,460.05 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of material. | Transportation risks. Creation of waste. | 1 | 0.10 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | Beneficial reuse. No burden on public works. | N/A | 1 | 0.875 |
| Option 17 | Frac Tank | Land Application | C&D | $2,460.05 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of material. | Transportation risks. Creation of waste. Possibility | 1 | 0.10 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | Beneficial reuse. No burden on public works. | Reduction in municipal waste stream. | 1 | 0.875 |
| Option 18 | Frac Tank | Land Application | LCID | $2,460.05 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of material. | Transportation risks. Creation of waste. Possibility | 1 | 0.10 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | Beneficial reuse. No burden on public works. | Reduction in municipal waste stream. | 5 | 0.375 |
| Option 19 | Frac Tank | Land Application | Beneficial Fill onsite | $2,440.00 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of material. | Possibility of failing environmental test. | 10 | 1.00 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | Beneficial reuse. No burden on public works. | Reduced transportation of material. No burden on solid waste facilities. Benecial Reuse. | 8 | 0 |
| Option 20 | Frac Tank | Land Application | Beneficial Fill offsite | $2,440.00 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of material. | Transportation risks. Possibility of failing | 5 | 0.50 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | Beneficial reuse. No burden on public works. | No burden on solid waste facilities. Benecial Reuse. | 1 | 0.875 |



**Figure G 6: Overview of options comparisons portion of simplified model (page 2 of spreadsheet tool)**

Section 1:

This section of the spreadsheet, shown in Figure G.7, displays the cost information for each combination that is considered. The user is not required to insert any new information here. This table allows the user to compare the different options on the basis of cost alone.

| | Estimated Costs | | | |
|---|---|---|---|---|
| | Initial Handlin | Liquid Managem | Solid Managemen | Estimated Option C |
| Option 1 | Decanting Pond | WWTP/POTW | MSW | $2,860.05 |
| Option 2 | Decanting Pond | WWTP/POTW | C&D | $2,860.05 |
| Option 3 | Decanting Pond | WWTP/POTW | LCID | $2,860.05 |
| Option 4 | Decanting Pond | WWTP/POTW | Beneficial Fill onsite | $2,840.00 |
| Option 5 | Decanting Pond | WWTP/POTW | Beneficial Fill offsite | $2,840.00 |
| Option 6 | Decanting Pond | Land Application | MSW | $2,860.05 |
| Option 7 | Decanting Pond | Land Application | C&D | $2,860.05 |
| Option 8 | Decanting Pond | Land Application | LCID | $2,860.05 |
| Option 9 | Decanting Pond | Land Application | Beneficial Fill onsite | $2,840.00 |
| Option 10 | Decanting Pond | Land Application | Beneficial Fill offsite | $2,840.00 |
| Option 11 | Frac Tank | WWTP/POTW | MSW | $2,460.05 |
| Option 12 | Frac Tank | WWTP/POTW | C&D | $2,460.05 |
| Option 13 | Frac Tank | WWTP/POTW | LCID | $2,460.05 |
| Option 14 | Frac Tank | WWTP/POTW | Beneficial Fill onsite | $2,440.00 |
| Option 15 | Frac Tank | WWTP/POTW | Beneficial Fill offsite | $2,440.00 |
| Option 16 | Frac Tank | Land Application | MSW | $2,460.05 |
| Option 17 | Frac Tank | Land Application | C&D | $2,460.05 |
| Option 18 | Frac Tank | Land Application | LCID | $2,460.05 |
| Option 19 | Frac Tank | Land Application | Beneficial Fill onsite | $2,440.00 |
| Option 20 | Frac Tank | Land Application | Beneficial Fill offsite | $2,440.00 |

**Figure G 7: Overview of section 1 of page 2 of spreadsheet tool – Estimated Costs**

Section 2:

This section of the spreadsheet, shown in Figure G 8, allows the user to evaluate the risks associated with each option, and ranks these risks on a scale from 1 (least risk) to 10 (highest risk). This rating allows the user to compare the combinations in accordance to the RAHP method described in Chapter 2 of this report.

| | Risks (The greater the risk the higher the value of the risk rating) | | | | |
|---|---|---|---|---|---|
| | Initial Handling | Liquid Management | Solid Manageme | Risk Rati | Risk Weig |
| Option 1 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of | Transportation risks. Creation of waste. | 6 | 0.60 |
| Option 2 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of | Transportation risks. Creation of waste. Possibility | 5 | 0.50 |
| Option 3 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of | Transportation risks. Creation of waste. Possibility | 1 | 0.10 |
| Option 4 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of | Possibility of failing environmental test. | 4 | 0.40 |
| Option 5 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of | Transportation risks. Possibility of failing | 10 | 1.00 |
| Option 6 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of | Transportation risks. Creation of waste. | 4 | 0.40 |
| Option 7 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of | Transportation risks. Creation of waste. Possibility | 1 | 0.10 |
| Option 8 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of | Transportation risks. Creation of waste. Possibility | 1 | 0.10 |
| Option 9 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of | Possibility of failing environmental test. | 1 | 0.10 |
| Option 10 | Increased iquirements for personel and equipment. Possibility for precipitation entering pond. Possibility of leak/tear in pond lining. Need to protect access to pond perimeter. | Transportation risk. Possibility for not acceptance of | Transportation risks. Possibility of failing | 1 | 0.10 |
| Option 11 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of | Transportation risks. Creation of waste. | 1 | 0.10 |
| Option 12 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of | Transportation risks. Creation of waste. Possibility | 1 | 0.10 |
| Option 13 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of | Transportation risks. Creation of waste. Possibility | 4 | 0.40 |
| Option 14 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of | Possibility of failing environmental test. | 1 | 0.10 |
| Option 15 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of | Transportation risks. Possibility of failing | 1 | 0.10 |
| Option 16 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of | Transportation risks. Creation of waste. | 1 | 0.10 |
| Option 17 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of | Transportation risks. Creation of waste. Possibility | 1 | 0.10 |
| Option 18 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of | Transportation risks. Creation of waste. Possibility | 1 | 0.10 |
| Option 19 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of | Possibility of failing environmental test. | 10 | 1.00 |
| Option 20 | Possibility for delays in tank delivery. Possibility of damage to rented equipment. Possibility in spill while transfering from frac tank to holding tank. | Transportation risk. Possibility for not acceptance of | Transportation risks. Possibility of failing | 5 | 0.50 |

**Figure G 8: Overview of section 2 of page 2 of spreadsheet tool – Risk Comparison**

Section 3:

This section allows the user to evaluate the environmental benefits associated with each combination, and rate these benefits on a relative scale from 1 (lowest potential for environmental benefits) to 10 (greatest potential for environmental benefits). An example of such comparison is shown in Figure G 9. To be consistent with the other two measures (cost and risk), where a high value is undesirable, the environmental weight for each option, is calculated by the following equation:

$$Env\ Benefit\ Weight\ for\ option\ i = 1 - \left(\frac{option\ i\ env.rating}{maximum\ environmental\ rating}\right)$$

| | Environmental Benefits (The better the environmental benefits, the higher the Env. Rating Value) | | | | |
|---|---|---|---|---|---|
| | Initial Handling | Liquid Manageme | Solid Management | Env. Ra | Env. Weight |
| Option 1 | N/A | N/A | N/A | 1 | 0.875 |
| Option 2 | N/A | N/A | Reduction in municipal waste stream. | 1 | 0.875 |
| Option 3 | N/A | N/A | Reduction in municipal waste stream. | 1 | 0.875 |
| Option 4 | N/A | N/A | Reduced transportation of material. No burden on solid waste facilities. Benecial Reuse. | 1 | 0.875 |
| Option 5 | N/A | N/A | No burden on solid waste facilities. Benecial Reuse. | 1 | 0.875 |
| Option 6 | N/A | Beneficial reuse. No burden on public works. | N/A | 1 | 0.875 |
| Option 7 | N/A | Beneficial reuse. No burden on public works. | Reduction in municipal waste stream. | 1 | 0.875 |
| Option 8 | N/A | Beneficial reuse. No burden on public works. | Reduction in municipal waste stream. | 1 | 0.875 |
| Option 9 | N/A | Beneficial reuse. No burden on public works. | Reduced transportation of material. No burden on solid waste facilities. Benecial Reuse. | 1 | 0.875 |
| Option 10 | N/A | Beneficial reuse. No burden on public works. | No burden on solid waste facilities. Benecial Reuse. | 1 | 0.875 |
| Option 11 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | N/A | N/A | 1 | 0.875 |
| Option 12 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | N/A | Reduction in municipal waste stream. | 1 | 0.875 |
| Option 13 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | N/A | Reduction in municipal waste stream. | 7 | 0.125 |
| Option 14 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | N/A | Reduced transportation of material. No burden on solid waste facilities. Benecial Reuse. | 1 | 0.875 |
| Option 15 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | N/A | No burden on solid waste facilities. Benecial Reuse. | 1 | 0.875 |
| Option 16 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | Beneficial reuse. No burden on public works. | N/A | 1 | 0.875 |
| Option 17 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | Beneficial reuse. No burden on public works. | Reduction in municipal waste stream. | 1 | 0.875 |
| Option 18 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | Beneficial reuse. No burden on public works. | Reduction in municipal waste stream. | 5 | 0.375 |
| Option 19 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | Beneficial reuse. No burden on public works. | Reduced transportation of material. No burden on solid waste facilities. Benecial Reuse. | 8 | 0 |
| Option 20 | Reduced impact on the jobsite. Low probability of leak and contamination. Reduced mechanical work. | Beneficial reuse. No burden on public works. | No burden on solid waste facilities. Benecial Reuse. | 1 | 0.875 |

**Figure G 9: Overview of section 3 of page 2 of spreadsheet tool – Potential Environmental Benefits Comparison**

**Page 3 - Decision Matrix**

This final page of the spreadsheet tool (shown in Figure G 10), summarizes the information collected by the user and compares each of the 20 options, weighted using the inputs provided on page 1. Always in accordance to the RAHP described in chapter 2 of this report, the weighted scores for each measure (cost, risk, and potential environmental benefits) are added together. Based on the model computations, a higher score represents a more undesirable option (formatted to show in red in the spreadsheet tool). Lower scores (shown in green) are the more preferable options. The "best" option, with the lowest value, is selected and highlighted by the spreadsheet tool beneath the decision matrix. In this case shown below in Figure G 10, Option 18 (frac tank / land application / LCID) was predicted by the model to be the most optimum option, based on the user inputs.

| | | | | Cost | | Risk | | Environmental Benefit | | Score |
|---|---|---|---|---|---|---|---|---|---|---|
| Option | **Initial Handling** | **Liquid Management** | **Solid Management** | Cost Weight | 0.9 | Risk Weight | 0.05 | EB Weight | 0.05 | |
| 1 | Decanting Pond | WWTP/POTW | MSW | 1.000 | 0.90 | 0.600 | 0.030 | 0.875 | 0.044 | 0.9738 |
| 2 | Decanting Pond | WWTP/POTW | C&D | 1.000 | 0.90 | 0.500 | 0.025 | 0.875 | 0.044 | 0.9688 |
| 3 | Decanting Pond | WWTP/POTW | LCID | 1.000 | 0.90 | 0.100 | 0.005 | 0.875 | 0.044 | 0.9488 |
| 4 | Decanting Pond | WWTP/POTW | Beneficial Fill onsite | 0.993 | 0.89 | 0.400 | 0.020 | 0.875 | 0.044 | 0.9574 |
| 5 | Decanting Pond | WWTP/POTW | Beneficial Fill offsite | 0.993 | 0.89 | 1.000 | 0.050 | 0.875 | 0.044 | 0.9874 |
| 6 | Decanting Pond | Land Application | MSW | 1.000 | 0.90 | 0.400 | 0.020 | 0.875 | 0.044 | 0.9638 |
| 7 | Decanting Pond | Land Application | C&D | 1.000 | 0.90 | 0.100 | 0.005 | 0.875 | 0.044 | 0.9488 |
| 8 | Decanting Pond | Land Application | LCID | 1.000 | 0.90 | 0.100 | 0.005 | 0.875 | 0.044 | 0.9488 |
| 9 | Decanting Pond | Land Application | Beneficial Fill onsite | 0.993 | 0.89 | 0.100 | 0.005 | 0.875 | 0.044 | 0.9424 |
| 10 | Decanting Pond | Land Application | Beneficial Fill offsite | 0.993 | 0.89 | 0.100 | 0.005 | 0.875 | 0.044 | 0.9424 |
| 11 | Frac Tank | WWTP/POTW | MSW | 0.860 | 0.77 | 0.100 | 0.005 | 0.875 | 0.044 | 0.8229 |
| 12 | Frac Tank | WWTP/POTW | C&D | 0.860 | 0.77 | 0.100 | 0.005 | 0.875 | 0.044 | 0.8229 |
| 13 | Frac Tank | WWTP/POTW | LCID | 0.860 | 0.77 | 0.400 | 0.020 | 0.125 | 0.006 | 0.8004 |
| 14 | Frac Tank | WWTP/POTW | Beneficial Fill onsite | 0.853 | 0.77 | 0.100 | 0.005 | 0.875 | 0.044 | 0.8166 |
| 15 | Frac Tank | WWTP/POTW | Beneficial Fill offsite | 0.853 | 0.77 | 0.100 | 0.005 | 0.875 | 0.044 | 0.8166 |
| 16 | Frac Tank | Land Application | MSW | 0.860 | 0.77 | 0.100 | 0.005 | 0.875 | 0.044 | 0.8229 |
| 17 | Frac Tank | Land Application | C&D | 0.860 | 0.77 | 0.100 | 0.005 | 0.875 | 0.044 | 0.8229 |
| 18 | Frac Tank | Land Application | LCID | 0.860 | 0.77 | 0.100 | 0.005 | 0.375 | 0.019 | 0.7979 |
| 19 | Frac Tank | Land Application | Beneficial Fill onsite | 0.853 | 0.77 | 1.000 | 0.050 | 0.000 | 0.000 | 0.8178 |
| 20 | Frac Tank | Land Application | Beneficial Fill offsite | 0.853 | 0.77 | 0.500 | 0.025 | 0.875 | 0.044 | 0.8366 |
| | | | | | | The Optimum option has the lowest value: | | | | 0.797878 |

**Figure G 10: Example of a Decision Matrix**