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# Vulnerability of Waste Infrastructure to Climate Induced Impacts in Coastal Communities

Office of Research and Development

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Office of Research and Development
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# Executive Summary

A recent report by the U.S. Global Change Research Program (USGCRP) states that "Global average sea levels are expected to continue to rise, by at least several inches in the next 15 years and by 1-4 feet by 2100" (USGCRP, 2017). These levels are even higher than the projected ranges estimated by an earlier report by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2001). USGCRP (2017) states expected sea-level rise (SLR) would be higher than the global average on the East and Gulf Coast of the United States (U.S.). This projected SLR coupled with other climate-induced impacts such as more frequent and intense heavy precipitation events, hurricanes and resulting storm surges, and increase in number of tidal floods (nuisance floods) may increase recurring damage to municipal infrastructure, including waste management facilities. The potential for climate-induced impacts thus creates an immediate concern for the security and resiliency of communities, specifically coastal communities.

The goal for this project was to devise a methodology for communities to utilize in understanding the effects of climate-induced extreme weather events and their impacts (e.g., SLR, storm surge, flooding, tidal flooding) on waste management facilities and their operation. The methodology included (1) mapping and other analytic/statistical methods to identify community characteristics at multiple spatial scales and evaluate locations and site-specific characteristics, (2) U.S. Environmental Protection Agency's (EPA's) Incident Waste Decision Support Tool (I-WASTE) tool to identify the locations of waste management facilities, and (3) U.S. EPA's Municipal Solid Waste Decision Support Tool (MSW DST) to understand life-cycle impacts of waste management operations and demonstrate how plans can be modified to robustly incorporate resilience to climate change. These tools further advanced the understanding of future uncertainty of the extent and impact of these events into long term waste management planning. The methodology is illustrated for City of Norfolk, Virginia and surrounding area; however, the methods and the data sources can be utilized in other communities.

Climate-induced impacts on communities could be categorized into three components: 1) temperature, 2) precipitation, and 3) sea level rise (SLR) (Zimmerman, 2010) related impacts. Temperature impacts include long-term changes in mean annual temperatures as well as changes in frequency, duration, and intensity of heat waves. Precipitation impacts include long-term changes in mean annual precipitation as well as intensity and frequency of these events. SLR impacts include inundation and extent of storm surge. The report focuses on impacts of precipitation (Chapter 4) and SLR (Chapter 5). Chapter 4 presents the data available for historic precipitation events and approaches to project the risk associated with precipitation events. Chapter 5 presents the literature characterizing the effects of SLR on tidal flooding, groundwater levels and salinity. The study evaluates each of these climate-induced risks for landfills (Chapter 6), transportation infrastructure (Chapter 7) and other supporting infrastructure (Chapter 8). For instance, Chapter 6 outlines a risk assessment procedure for contaminant release in the event of a climate-induced impact. It will be important to estimate potential contaminant releases from landfills and other waste facilities that are impacted by extreme weather events and estimate the transport of such pollutants in the groundwater to nearby populations. A tiered approach has been adopted or used by numerous state and federal agencies to evaluate risks associated with exposures to pollutants in the environment. As described in Chapter 6, the approach begins with a Tier 1 screening level assessment that includes a simplified conceptual model of the environmental releases and exposure. If unacceptable risks are identified (predicted exposure is greater than the threshold screening value), then a Tier 2 assessment is implemented by refining the release-exposure scenario to include more realism to reflect key sensitive scenario and site-specific conditions. If unacceptable risks persist, then a detailed site-specific conceptual model is developed and evaluated under a Tier 3 analysis.

The City of Norfolk, Virginia was selected as the project site based on its coastal location, availability of data, and proximity to a varied set of waste facilities. The coastal region of Virginia is the second most vulnerable area to impacts of climate change such as SLR, tidal flooding and extreme precipitation in the U.S., behind New Orleans, and is currently being impacted by SLR (City of Virginia Beach, 2009). Intensified by land subsidence in the region, SLR is happening at a fast rate in Norfolk. Sea levels have increased approximately 18 inches since 1900 and 8.79 inches in the past 45 years (Connolly, 2015) in Norfolk, primarily due to subsidence. Old Dominion University scientists predict a 2- to 5-foot rise in Norfolk's sea level by 2100 (Center for Sea Level Rise, 2015).

The City of Norfolk's waste collection programs include the collection of more than 95,000 tons of waste per year for households and businesses in the city (City of Norfolk Division of Waste Management, 2016). Once collected, waste is hauled to the city's transfer station or directly to one of the regional management facilities such as the Tidewater Fibre Corporation (TFC) recycling facility, Wheelabrator waste-to-energy (WTE) plant, or Southeastern Public Service Authority of Virginia (SPSA) landfill.

***Figure ES-1*** shows the location of the City of Norfolk's waste management facilities mapped to hurricane storm surge boundaries. As shown on the map, all but the SPSA landfill appear to be vulnerable to inundation. Identifying the alternative MSW management facilities that would be used should the city's current facilities be inundated is not straightforward. The city does not have a formal plan to identify alternative sites in case of emergencies. Rather, the approach is to determine which facilities have the capability/capacity to handle waste at the time of the emergency. Therefore, reasonable and likely alternative facilities were identified using I-WASTE, SPSA plans, and proximity to the city.

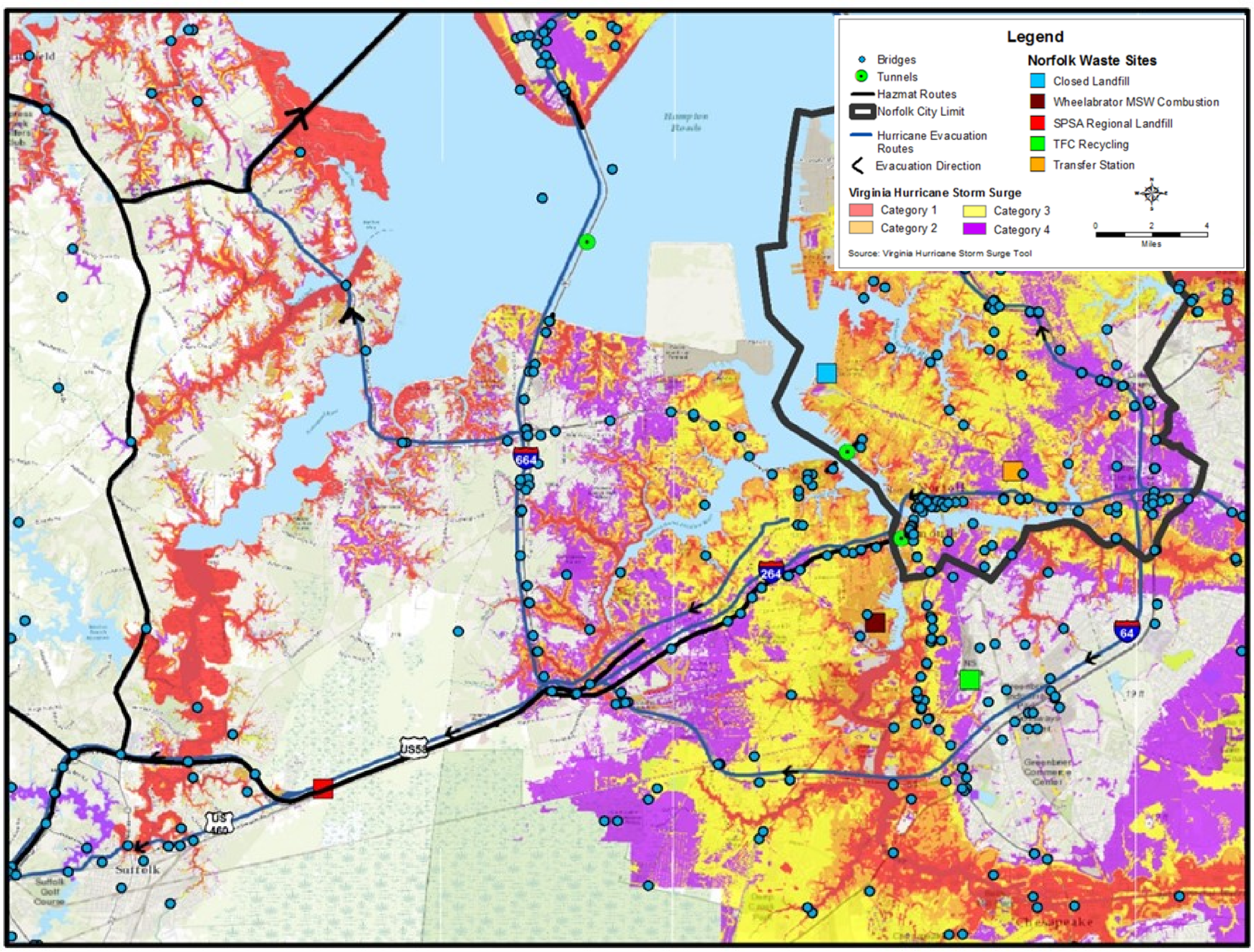



Figure ES-1. Norfolk Waste Facilities with Hurricane Storm Surge Categories

Three degrees of flood-induced impact—low, medium, and high—were used to gauge impacts to waste facilities that would result in the facility being taken off-line and the alternative facility employed. As shown in ***Table ES-1***, moving from the base case to Alternative 1 assumes low impact and only the transfer station is affected. Alternative 2 assumes medium impact where the transfer station, recycling facility and WTE plant are affected. Alternative 3 assumes high impact where all facilities are affected by flood-induced impacts and taken offline. Since the SPSA landfill is far inland, it was projected that the SPSA landfill will not be inundated, even at the highest SLR estimate. So, all cases include SPSA landfill as a disposal alternative. However, the SPSA landfill was taken offline in Alternatives 3 and 4 in the interest of evaluation of alternatives. For Alternative 4, it was assumed that the recycling level would remain the same, but no WTE is employed. Rather, all waste typically sent to WTE instead would be sent to a landfill. A simplifying assumption was made that the low-medium-high level of impact equated to a 10-20-30 percent increase in collection route distance, respectively. The distances between collection routes and the alternative transfer station and alternative landfill are assumed to be the same as per the current facilities. The distances between collection routes and the alternative materials recovery facility (MRF) and WTE facility are 70 and 140 miles, respectively, which are significantly different from the distances to current facilities. The current and alternative MRF, WTE, and landfill facilities assume the same design and performance.

U.S. EPA's MSW DST was used to model the cost, energy consumption, and environmental releases for base case and alternative scenarios. Groups of scenarios modeled include:

1. Non-optimized (current mass flow of waste to different facility types is maintained as shown in ***Table ES-1***)
2. Least cost (MSW DST is set to find the minimum cost solution through optimization of waste flows through waste management facilities)
3. Greenhouse gas (GHG)-optimized (MSW DST is set to find a solution to achieve the minimum GHG emissions through optimization of waste flows through waste management facilities)

**Table ES-1. Base Case and Alternative MSW Flow and Management Facilities**

| Scenario | Transfer Station | Recycling | WTE | Landfill |
|---|---|---|---|---|
| ***Mass Flow (Base Case, Alt 1-3)*** | ***77,874 tons*** | ***31,065 tons*** | ***20,324 tons*** | ***43,611 tons*** |
| Base Case (current) | SPSA – Norfolk | TFC – Norfolk | Wheelabrator – Portsmouth | SPSA – Norfolk |
| Alternative 1 (low impact) | SPSA – Chesapeake | TFC – Norfolk | Wheelabrator – Portsmouth | SPSA – Norfolk |
| Alternative 2 (med. impact) | SPSA – Chesapeake | TFC – Chester | Covanta – Alexandria | SPSA – Norfolk |
| Alternative 3 (high impact) | SPSA – Chesapeake | TFC – Chester | Covanta – Alexandria | USA Waste – Bethel |
| ***Mass Flow (Alt4)*** | ***77,874 tons*** | ***31,065 tons*** | ***0 tons*** | ***63,935 tons*** |
| Alternative 4 (high, no WTE) | SPSA – Chesapeake | TFC – Chester | NA | USA Waste – Bethel |

Based on available data and information about current and alternative facilities, the alternative facilities are assumed to be identical in terms of design and operating parameters. The differences between alternative scenario results and the base case results are primarily caused by the differences in collection and transportation distances. Key findings from the modeling results (presented in Chapter 5) are as follows:

- For the non-optimized scenarios, the cost, energy consumption, and emissions generally follow an increasing trend from the base case to Alternative 3 (high impact), primarily due to the increase in transportation distance from the point of waste collection to the alternative management facilities. The cost and environmental performance for the city's current base case was found to fall generally between the results of the cost- and GHG-optimized cases.
- Least-cost (i.e., cheapest) scenario (optimized) results pointed to MSW collection and landfill disposal as being least costly. Sensitivity analysis was performed on the recycling rate for the cost-optimized scenarios, and it was found that a 5 percent change in the recycling rate corresponds to an approximately 5 percent change in cost.
- GHG-optimized scenarios showed that significant reductions in GHG emissions (and energy consumption) could be achieved by greater levels of materials and energy recovery, but the cost of such a scenario increased significantly as well.
- For scenarios in which WTE was excluded (Alternative 4), cost generally decreased but environmental impacts increased due to the subsequent removal of energy and materials recovery benefits associated with WTE.

A thorough discussion of the cost and environmental tradeoffs of moving to alternative waste facilities should existing facilities be inundated and closed is presented in Chapter 9. A scenario-based approach was taken to understand and incorporate future uncertainty of the extent and impact of these events into the long- term waste management planning. There are some caveats to this analysis. For example, the storm surge and SLR scenarios looked at individual facility flooding however, other factors might influence the availability of the waste management facility such as inundation of access roads, or worker availability in the event of a storm. These aspects of waste management could be covered under emergency management planning process. The study is not intended for emergency management or analysis of options during an event.

The results from this project can help communities in gaining a better understanding of the nature of climate-induced impacts, and how those impacts can affect waste management infrastructure and long-term planning needs. The methodology evaluates environmental impacts and cost implications of alternative waste management options available for municipalities. The insights gathered from illustrative scenario analysis for Norfolk, VA revealed that there can be opportunities to be leveraged if intensity and frequency of precipitation events continue to increase for the region. Solid waste management planners could utilize these opportunities to better design the system to be more resilient and responsive at cheaper costs, and in some cases resulting in better environmental outcomes (e.g., reduced air emissions).

# 1. Introduction

Climate change creates an immense challenge to the security and resilience of coastal communities (U.S. Global Change Research Program (USGCRP), 2014). More frequent and intense disruptive events including hurricanes and storm surges may increase the frequency and extent of damage to municipal infrastructure, including waste sector facilities. Impacts to supporting infrastructure such as transportation routes, energy supplies, and water supply and treatment can also significantly affect waste facility operations. Potentially large amounts of debris and the release of pollutants and contaminants to the environment can have cascading effects such as the failure of additional facilities triggered by the failure of the initial one. The impacts of changing climate on waste facilities and their operations is an immediate concern for coastal communities. Extreme events may result in exposure to contaminants from treatment, storage and disposal facilities, non-hazardous and hazardous waste sites, municipal recycling facilities, or other relevant facilities or sites.

## 1.1. Project Goal

The overall goal for this project was to develop an approach to evaluate vulnerability of solid waste management infrastructure and adaptation strategies to increase its resilience to climate change. Vulnerability of waste management infrastructure to acute and extreme weather events needs to be analyzed to identify those for which siting, treatment and disposal of hazardous, municipal wastes and mixed wastes will be affected. The study utilized (1) mapping and other analytic/statistical methods to identify community characteristics at multiple spatial scales and evaluate locations and site-specific characteristics, (2) U.S. Environmental Protection Agency's (EPA's) Incident Waste Decision Support Tool (I-WASTE) tool to identify the locations of waste management facilities, and (3) U.S. EPA's Municipal Solid Waste Decision Support Tool (MSW DST) to understand life-cycle impacts of waste management plans and demonstrate how plans can be modified to robustly incorporate resilience to climate change. The resulting information is intended for use in better understanding the nature of climate-related impacts on coastal communities and how those impacts can affect waste management facilities and plans, options available for minimizing environmental impacts, and cost implications for municipalities. This report will enable U.S. EPA's Office of Land and Emergency Management (OLEM) to provide support in the form of guidance, training, and technical assistance to communities in need.

Climate-induced impacts on communities could be categorized into three components: 1) temperature, 2) precipitation, and 3) sea level rise (SLR) (Zimmerman, 2010) related impacts. Temperature impacts include long-term changes in mean annual temperatures as well as changes in frequency, duration, and intensity of heat waves. Precipitation impacts include long-term changes in mean annual precipitation as well as intensity and frequency of these events. SLR impacts include inundation and extent of storm surge. In this report, our focus is on precipitation and SLR impacts. In the following chapters, we will discuss impacts of these changes on the waste infrastructure.

## 1.2. Coastal Community Case Study Site

The City of Norfolk was selected as the project site based on its coastal location, availability of data, and proximity to a varied set of waste facilities. The City of Norfolk's population was 242,803 in 2010. Since 2000, the population has grown 3.6 percent, whereas the region (i.e., Hampton Roads region) has grown 7.8 percent (City of Norfolk, 2014). The Intergovernmental Panel on Climate Change (IPCC) estimated that by 2100, global warming will cause sea levels to rise approximately 0.5 to 3 feet (IPCC, 2001). The IPCC estimates have since been updated, and the 2100 predictions now range from 0.66 to 6.6 feet (USGCRP, 2014). Virginia's coastal region is the second most climate-vulnerable area in the U. S., behind

New Orleans, and is currently being impacted by SLR (City of Virginia Beach, 2009). Intensified by land subsidence in the region, the sea level is rising quickly in Norfolk and the surrounding Hampton Roads area. Sea levels have risen approximately 18 inches since 1900 and 8.79 inches in the past 45 years in Norfolk (Connolly, 2015), primarily due to subsidence. Old Dominion University scientists project a 2- to 5-foot SLR at Norfolk by 2100 (Center for Sea Level Rise, 2015). The city is responsible for waste management, and thus our primary spatial boundary is the city proper. Waste management facilities in the surrounding region are also captured, since the potential impacts and solutions are regional in nature.

## 1.3. Climate Resiliency Studies in The Norfolk Area

Numerous climate resiliency analyses and reports have been prepared for Norfolk and the surrounding region. In this section, studies identified to date that contain potentially relevant information are identified and briefly summarized. In general, while these studies provide good information about the context for potential climate impacts and mitigation/adaptation strategies, most point to the same government data sources already identified. Few studies present additional or detailed datasets that contain useful supplemental data for this project.

#### *The Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Planning Pilot Project*

Old Dominion University's Center for Sea Level Rise in Norfolk conducted a two-year pilot study called The Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Planning Pilot Project. The project combined the efforts being conducted at all levels of government with researchers and businesses to achieve a "whole of government, whole of community" approach. The aim of this collaboration was to reduce the negative impacts from climate change and SLR. (Steinhilber, E. et al., 2015)

#### *Vulnerability of Hampton Roads, Virginia, to Storm-Surge Flooding and Sea-Level Rise*

This study mapped the locations of vulnerable sub-populations and compared them to flood-risk exposure zones. For this project, overlays with Geographical Information Systems (GIS) could be performed to evaluate where the locations of the waste facilities lie in relation to these flood-risk exposure zones. (Kleinosky, L.R., et al., 2007)

#### *Sea Level Rise and Flooding Risk in Virginia*

This study found that SLR in the Hampton Roads region occurs twice as fast (2 inches every 10 years) as it does globally because of the ocean circulation and subsidence in the area. The U.S. National Oceanic and Atmospheric Administration's (NOAA's) tide gauge data were used to determine the number of hours per year that streets within neighborhoods were flooded. (Atkinson, L. P. et al., 2012)

#### *The Potential Economic Impact of Hurricanes on Hampton Roads*

The study by the Hampton Roads Planning District Commission (2006) provides the dollar amount of damage to residential, commercial, and industrial sectors in the Hampton Roads area that resulted from hurricanes.

#### *Recurrent Flooding Study for Tidewater Virginia*

For various coastal localities in Virginia, this project calculated the number of road miles and the total area with potential flooding using GIS. The elevation generated from this study has the highest resolution of any available as of 2014. (Mitchell, M. et al., 2013)

***Coastal Resiliency: Adapting to Climate Change in Hampton Roads***

GIS tools were used to evaluate potential vulnerability of the Hampton Roads region to one meter of SLR through identification of the impacts for population, housing, property, roads, businesses, and natural resources. Maps were created that showed the inundation of areas under various scenarios at Mean Higher High Water by 2100. Mean Higher High Water is defined as the average of the Higher High Water height of each tidal day observed over the National Tidal Datum Epoch. (McFarlane, B., 2013*)*

***Street-Level Inundation Modeling***

Dr. Harry Wang of the Virginia Institute of Marine Sciences (VIMS) has led research that involves street-level inundation modeling. The model uses Light Detection and Ranging (LiDAR) data, which allows for the Chesapeake Bay's shoreline to be simulated more accurately, thereby allowing for modeling at the street level. The researchers validated the model with a pilot study that predicted flood levels within a few centimeters of the actual levels observed in the Potomac River during Hurricane Isabel. (Virginia Institute of Marine Science, 2008)

# 2. Models

This study utilized (1) mapping and other analytic/statistical methods to identify community characteristics at multiple spatial scales and evaluate locations and site-specific characteristics; (2) U.S. EPA's I-WASTE tool to identify the locations of waste management facilities, and (3) U.S. EPA's MSW DST to understand life-cycle impacts of waste management plans and demonstrate how plans can be modified to robustly incorporate resilience to climate change.

In addition, we characterized infrastructure related to waste management systems including transportation and utilities infrastructure, as well as historic climate driven events such as precipitation, temperature, and SLR.

## 2.1. Incident Waste Decision Support Tool (I-WASTE)

U.S. EPA's I-WASTE tool provides a framework for planning and response decision-making and consists of calculators to generate waste quantity estimates; databases of treatment and disposal facilities; and a quick reference to technical information, regulations, and guidance to work through the complicated series of decisions needed to assure safe and efficient removal, transport, and management of waste materials (U.S. EPA, 2017). The objective of I-WASTE is to help reduce restoration time and expense by providing quick access to information that will inform the decision-making process for incident waste management. I-WASTE includes:

1. Information on characteristics of waste, debris, and potential contaminants, as well as characteristics of decontamination agents that could be used and may be present as residuals in the waste;
2. Databases of treatment, disposal, and recycling facilities (e.g., hazardous waste incinerators, landfills, medical waste autoclaves), including locations, contact information, permits, and capacities for the different types of waste;
3. A waste quantity estimator that allows end-users to generate order-of-magnitude estimates of volumes and masses of waste and debris from events involving a variety of types of single buildings or several structures over a wide area;

4. A water systems module with information from different geographical areas to support the unique considerations involved in the management of waste (e.g., filter media, piping) generated because of decontaminating water treatment and distribution systems;
5. Agricultural biomass disposal guidelines including training modules developed by the U.S. Department of Agriculture;
6. Natural disaster debris disposal guidelines including case studies organized by disaster type (e.g., hurricanes, tornadoes, earthquakes, floods);
7. Debris transportation, packaging, and staging information;
8. Radiological waste management information and guidelines; and
9. Worker protection information.

## 2.2. Municipal Solid Waste Decision Support Tool (MSW DST)

The MSW DST was developed through a competed cooperative agreement between U.S. EPA's Office of Research and Development (ORD) and Research Triangle Institute (RTI) International to provide a credible and quantitative framework to identify sustainable solutions for managing municipal solid waste (MSW), while considering carbon emissions, energy, air criteria pollutants, waterborne pollutants, and cost. Across the U.S., strategies are being implemented to reduce waste and encourage recycling and composting without the benefit of understanding the environmental tradeoffs. Optimal strategies can differ depending on population density, infrastructure, energy grid mix, waste composition, and transportation distances for hauling waste to and from facilities for processing, recovery, or disposal. The MSW DST considers all waste management activities and the inherent differences among materials (e.g., food waste, glass, metals, paper, plastics, yard debris) that can affect energy recovery and life-cycle environmental tradeoffs. Options can be interrelated, and it can be unclear how best to manage MSW considering total emissions over time. For example, what may be more environmentally advantageous in a rural region may be different from urban or suburban communities. Another factor to consider is that most carbon inventories consider annual emissions and not total emissions over the life-cycle. For most unit processes, emissions are instantaneous. However, if waste is buried in a landfill, then total emissions can occur over many decades and depending upon the time horizon, carbon storage may occur. The MSW-DST provides a systematic approach to evaluating total life-cycle emissions for hauling, processing, and disposal of MSW, while factoring in offsets for materials and energy recovery.

In addition to the U.S. EPA and RTI, the research team also included North Carolina State University, which had a major role in the development of the life-cycle inventory databases for process and cost models as well as the prototype MSW DST. The MSW DST includes many process models that represent the operation of each waste management unit including options for collection, sorting, processing, transport, and disposal of waste. In addition, there are process models to account for the emissions associated with the production and consumption of fuels, electricity, and conversion of recyclables into new products. An offset analysis is used to calculate the environmental benefits or added burdens from the conversion of recycled materials to new products and from the generation of electricity from landfill gas and waste-to-energy (WTE). All unit processes are integrated, and the mass balance is represented by a series of waste flow equations that may be solved for the minimum value of cost, net energy consumption, or emissions of selected pollutants. The functional unit in each process model is 1 ton of waste item set out for collection. Each process model can track and report 32 life-cycle parameters, including energy consumption, carbon dioxide ($CO_2$), carbon monoxide (CO), nitrogen oxides ($NO_x$), sulfur oxides ($SO_x$), carbon dioxide equivalents ($CO_2e$), particulate matter (PM), methane ($CH_4$), water pollutants, and solid wastes. The MSW DST reports out emission factors per ton of waste item handled in that process along with cost.

The MSW DST is available through https://mswdst.rti.org/index.htm (*last accessed 5/16/2018*). The website includes tutorials and downloadable resources to provide background life-cycle assessments and process model documentation.

# 3. Data Availability and Limitations

This section summarizes the data available for characterizing waste management systems and climate-induced risks for the Norfolk region along with key gaps in the data reviewed to date. Available data are presented for (1) waste infrastructure, (2) transportation and utilities infrastructure, (3) historic precipitation events, and (4) SLR.

## 3.1. Waste Infrastructure

The primary source for waste infrastructure data was I-WASTE, which is a tool used to help decision makers in managing waste materials that result from accidents, natural disasters, and terrorist attacks. A list of waste facilities in the Norfolk, VA, study area was obtained from I-WASTE and mapped using a GIS. These sites are listed in ***Table 1*** and displayed in ***Figure 1***.


**Figure 1. Map of Waste Facilities Available from I-WASTE**

**Table 1. List of Waste Facilities in the Norfolk Region from I-WASTE**

| Name | Type |
|---|---|
| Hampton- NASA Steam Plant | Combustion/MSW Combustion Facilities |
| Wheelabrator Portsmouth, Inc. | Combustion/MSW Combustion Facilities |
| York County Transfer Station | Compost Facility |
| Marpol | Decontaminated Wastewater/Centralized Waste Treatment |
| Petrochem Recovery Services Inc. | Decontaminated Wastewater/Centralized Waste Treatment |
| Hampton Roads Sanitation District– Army Base Sewage Treatment | Decontaminated Wastewater/ POTW |
| HRSD – Boat Harbor Sewage Treatment | Decontaminated Wastewater/POTW |
| HRSD – Nansemond Sewage Treatment Plant | Decontaminated Wastewater/POTW |
| HRSD – Virginia Initiative Sewage Treatment Plant | Decontaminated Wastewater/POTW |
| HRSD – York River Sewage Treatment | Decontaminated Wastewater/POTW |
| Virginia Department of Transportation (VDOT) Interstate 64 Goochland Rest Area | Decontaminated Wastewater/POTW |
| Naval Base Norfolk | Government-Owned Land/Facilities |
| Portsmouth City – Craney Island Landfill | Landfills/Inert or Construction and Demolition (C and D) Landfills |
| Virginia Beach Landfill No. 2 | Landfills/Inert or Construction and Demolition (C and D) Landfills |
| USA Waste of Virginia Landfills – Bethel Landfill | Landfills/ MSW Landfills |
| Virginia Beach Landfill No. 2 | Landfills/MSW Landfills |
| Huntington Ingalls Incorporated – NN Shipbldg. Div. | Other/Electric Arc Furnaces |
| HRSD - James River Sewage Treatment | POTW; Other/Electric Arc Furnaces |
| Area Container Services Inc. | Transfer Station |
| Waste Management, Inc./Recycle America Hampton Rds. | Transfer Station |
| Browning-Ferris Industries/Chesapeake Transcyclery | Transfer Station |
| Craney Island Materials Recovery Facility | Transfer Station |
| Newport News Materials Recovery Facility | Transfer Station |
| Safety-Kleen/Chesapeake County | Transfer Station |
| Southeastern Public Service Authority of Virginia (SPSA)/Chesapeake Transfer Station | Transfer Station |
| SPSA/Landstown Transfer Station | Transfer Station |
| Virginia Peninsula Public Service Authority - King William County Transfer Station | Transfer Station |

## 3.2. Transportation and Utilities Infrastructure

The transportation infrastructure in an area is particularly vulnerable to the impacts from SLR. GIS can be used to identify infrastructure that may be vulnerable to storm surge and SLR and was used in this study of the Norfolk area. Spatial analyses can be performed with the infrastructure and weather data to assess the duration of flooding on roads and bridges in the study area. Mitchell et al. (2013) concluded that in 2012, Norfolk had 119 road miles that are vulnerable to flooding.

***Table 2*** shows the data sources that were used to assess the potential impacts on transportation for the study. Several datasets, including primary and secondary roads, bridges, railroads, and hazardous material routes were obtained from the U.S. Department of Transportation (DOT) National Transportation Atlas Database. Annual average daily traffic data were obtained from the VDOT. This dataset was used to evaluate heavily traveled roads and help identify places where traffic problems could occur in severe flooding events.

**Table 2. List of Transportation Data Sources**

| Dataset | Source | Year |
|---|---|---|
| Primary & Secondary Roads | U.S. DOT National Transportation Atlas Database | 2013 |
| National Bridge Inventory | U.S. DOT National Transportation Atlas Database | 2012 |
| Railroad Bridges | U.S. DOT National Transportation Atlas Database | 2012 |
| Railway Crossings | U.S. DOT National Transportation Atlas Database | 2012 |
| Railway Network | U.S. DOT National Transportation Atlas Database | 2012 |
| Hazardous Material Routes | U.S. DOT National Transportation Atlas Database | 2012 |
| VDOT Annual Average Daily Traffic | VDOT | 2015 |

Detailed data and information about potential street-level inundation within the city was not found. However, VIMS has conducted research that involves street-level inundation modeling (VIMS, 2008). The modeling uses LiDAR data, which allow for the Chesapeake Bay shoreline to be simulated more accurately, thereby allowing for modeling at the street level. This, or a similar model, may provide a means for Norfolk to analyze street-level inundation.

The U.S. Department of Energy (DOE) Transportation Routing Analysis Geographic Information System (TRAGIS) model was also reviewed to the extent possible as it requires a sponsor to get full access. While DOT sources provide adequate data for identifying transportation routes and infrastructure, the TRAGIS model may be useful for determining options for alternative routing scenarios.

Spatial data for locating utility infrastructure (namely, electricity and water) were not found from online sources for the City of Norfolk, possibly due to homeland security concerns.

## 3.3. Natural Weather Events

Climate change will have an impact on the frequency and intensity of storms in the Norfolk region. ***Table 3*** lists the identified and reviewed weather-related data sources. An analysis of historic storm and hurricane data was performed using publicly available meteorological data. Geospatial data representing past Atlantic storm tracks were downloaded from the National Weather Service (NWS). Tabular data containing information about storm events are provided by NOAA going back to 1951. In addition to the locations, the duration of the event, number of injuries, and dollar amount of damage are also included.

The City of Norfolk has published maps showing approximate tidal flooding at 2, 4, 6, and 8 feet. The tidally influenced flood-prone areas are shown on maps with streets within the city that get flooded at each of those four levels. The extent of the flooding could be combined with other variables (i.e., areas where utility service outages occur) to show areas at the census block group level that would have the highest likelihood for being affected by storm surge and SLR. The locations of the city and regional waste facilities could be part of this analysis, and those that fall within these high-risk block groups could be identified.

**Table 3. List of Weather-Related Data Sources**

| Dataset | Source | Year |
|---|---|---|
| Storm Events | NOAA | 2000–2015 |
| Past Atlantic Storm Tracks | NWS | 2015 |
| Flood Frequency | NOAA | 2015 |
| Tidally-influenced Flood Prone Areas | City of Norfolk | 2012 |

## 3.4. Sea Level Rise

***Table 4*** lists data sources available for analyzing SLR in the Norfolk region. The City of Norfolk provides flood zone data that is updated regularly. NOAA's SLR web mapping application allows users to download the data used in the program. From the NOAA website, geospatial datasets were obtained that represent SLR inundation for various feet above mean high water (0, 1, 2, 3, 4, 5, and 6). A digital elevation model (DEM) was also obtained, as well as flood frequency data for the study area.

NOAA also has four tide gauge stations in the Norfolk area at Sewell's Point, Money Point, Chesapeake Bay Bridge Tunnel, and at the U.S. Coast Guard (USCG) Training Center. Water levels are available on an hourly basis. Sea level trends and tide prediction data are also available hourly at some of these sites.

**Table 4. List of Data Sources for Sea Level Rise Analysis**

| Dataset | Source | Year |
|---|---|---|
| Flood Zone | Norfolk | 2015 |
| SLR inundation above mean higher high water for 0–6 feet of SLR | NOAA | 2015 |
| Hydrologically unconnected inundation areas for 0–6 feet of SLR | NOAA | 2015 |
| DEM | NOAA | 2015 |
| Flood Frequency | NOAA | 2015 |
| Water Levels | NOAA | 2015 |
| NOAA Tide Predictions | NOAA | 2015 |
| Sea Level Trends | NOAA | 2015 |

## 3.5. Identified Gaps in the Existing Data and Information

In this section, available data and key data gaps that will need to be addressed to complete an assessment of waste infrastructure vulnerability to climate-induced events are summarized.

### 3.5.1. Waste Infrastructure

For the purposes of this study, we rely on I-WASTE to identify waste management infrastructure within the study area. The facilities represented in I-WASTE are based mostly on facilities listed in the EnviroFacts database (U.S. EPA, 2017) and primarily focus on waste transfer stations, combustion units, and landfill disposal units for hazardous and nonhazardous solid wastes. I-WASTE (and EnviroFacts) is more limited in its representation of recycling, composting, and other small-scale waste facilities. This is a consequence of recycling and composting facility information being contained in proprietary databases.

I-WASTE captures both public and private facilities. The tool does include some information about the types of materials accepted at each facility and the current facility capacity. Key gaps in the waste infrastructure data available from I-WASTE includes the following:

- Closed facilities (e.g., old disposal units); note that EnviroFacts does provide information about facilities that have been closed,
- Recycling and composting facilities, and
- Composting and chip/grind facilities.

To help fill gaps in facilities information available from I-WASTE, city officials and waste facility managers were contacted.

### 3.5.2. Climate-Related Impacts

Many tools, models, and applications on the web map SLR, storm surge, and flooding in the Norfolk area under various scenarios. These tools were evaluated to make sure the most recent, highest resolution data were being used and that analyses that have already been carried out were not being repeated as part of this project. With respect to key data gaps, our review of the weather-related information that is publicly available did not yield much data related to duration of inundation. Detailed climate models with a variety of data inputs are required to estimate this variable.

# 4. Climate-Induced Risks: Precipitation

Precipitation impacts include long-term changes in mean annual precipitation as well as intensity, frequency of these events. USGCRP's Climate Science Special Report (2017), part of the 4$^{th}$ National Climate Assessment, focused on climate change science and related physical impacts in the U.S. According to the report, heavy rainfall is increasing in intensity and frequency across the U.S. and globally and is expected to continue to increase. The largest changes have been observed in the Northeast. Still, translating this summary to actual quantitative projections of future hurricane frequencies and strengths in the North Atlantic basin (where Norfolk is located) will be difficult. Landfalling major hurricanes are a relatively rare event in the U.S., happening on average once every three years. Up until August 2017, it had been more than 12 years since a major hurricane (Category 3 or higher) has made landfall in the U.S., exceeding the major hurricane draught record of eight years set from 1861 through 1868 (NOAA National Centers for Environmental Information, 2016). However, the 2017 Atlantic hurricane season ended up being a hyperactive active season with six major hurricanes, including Hurricanes Harvey, Irma, and Jose. These hurricanes resulted in major infrastructure damage and serious health outcomes in the impacted communities.

The purpose of this section is to detail the data available and approach used for projecting risk associated with the potential future frequency, intensity, and tracks for precipitation events and hurricanes that may impact waste management infrastructure in the Norfolk region. We gathered the following data specific to the Norfolk area:

- Frequency of tropical storms,
- Intensity of tropical storms,
- Storm surge levels caused by storms of different intensities,
- Locations of the waste handling units (especially elevation above sea level), and
- Projected future SLR.

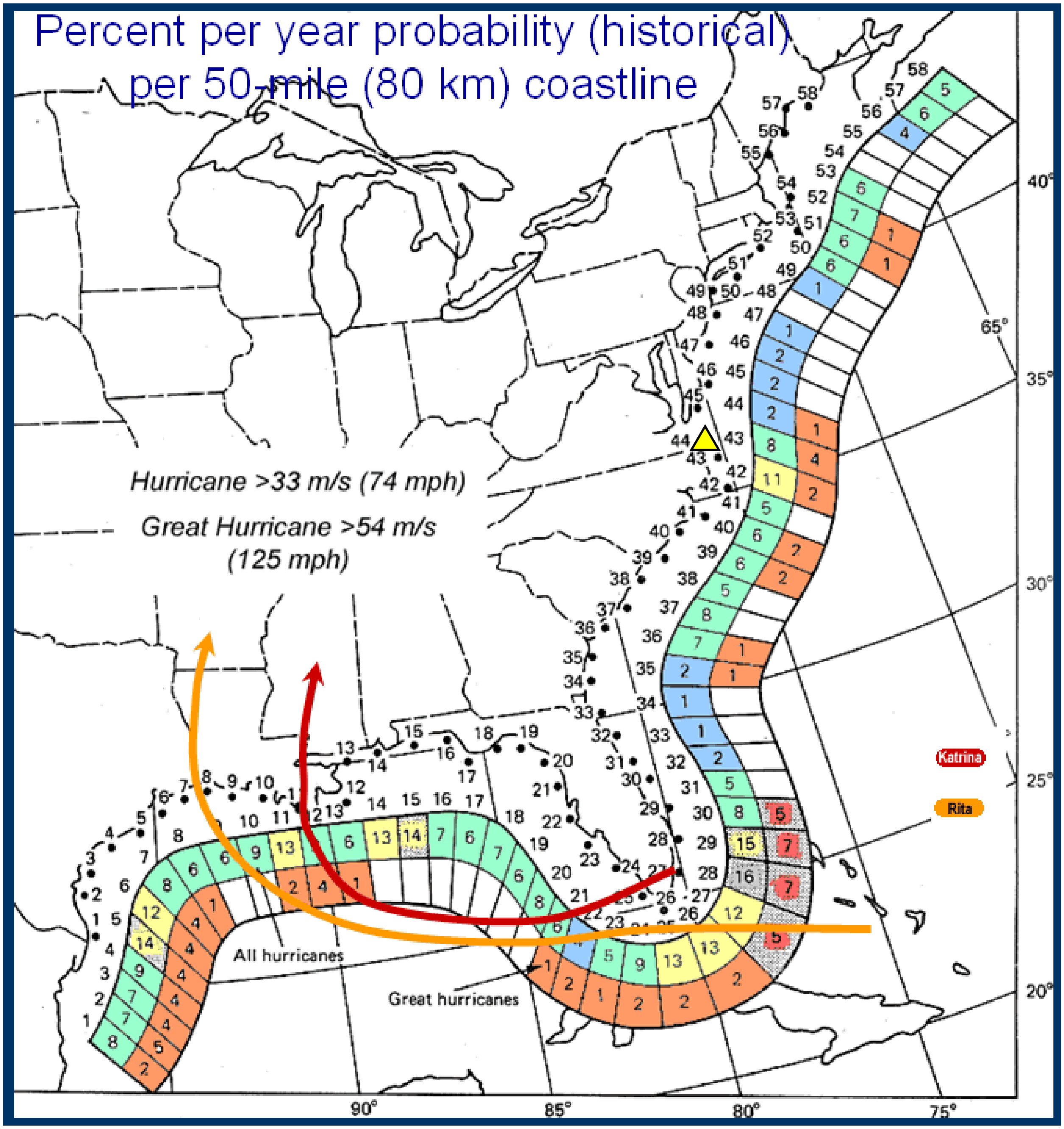
## 4.1. Frequency of Tropical Storms

Historical data regarding tropical storm landfalls in the United States have been used to generate ***Figure 2***, which shows the annual percentage probability of a hurricane making landfall along each 50 miles of the U.S. Gulf Coast and East Coast (Locke, 2005).[1] ***Figure 2*** contains two sets of probability values. The set of values closest to the coastline is the probability of any hurricane (i.e., wind speed greater than 33 m/s or 74 mph) making landfall on each 50-mile segment of U.S. coast. The other set of probability values is for "great" hurricanes with wind speeds greater than 54 m/s (125 mph), approximately a high Category 3 hurricane or greater.

***Figure 2*** indicates that for Norfolk, VA (segment number 44, located at approximately 37N, 77W on the map) the probability of a hurricane landfall is two percent per year, and the probability of a "great" hurricane is one percent per year. Note that these probability estimates are based on 1900–1996 historical data and do not consider potential changes in hurricane frequency or intensity due to climate change.

***Figure 2*** provides the possible landfall location frequency for hurricanes. However, a hurricane might make landfall in North Carolina or another East Coast state and travel up the coast to Norfolk. This situation would generate a storm surge in Norfolk, even if the hurricane did not make landfall at Norfolk. For example, Hurricane Isabel in 2003 made landfall in Pamlico Sound, NC, and crossed the North Carolina-Virginia border approximately 75 miles west-southwest of Norfolk (NOAA, 2015), but this storm produced the largest storm surge of any hurricane at the Sewell's Point storm surge measuring station near Norfolk at 7.9 feet (Weather Underground, 2018).

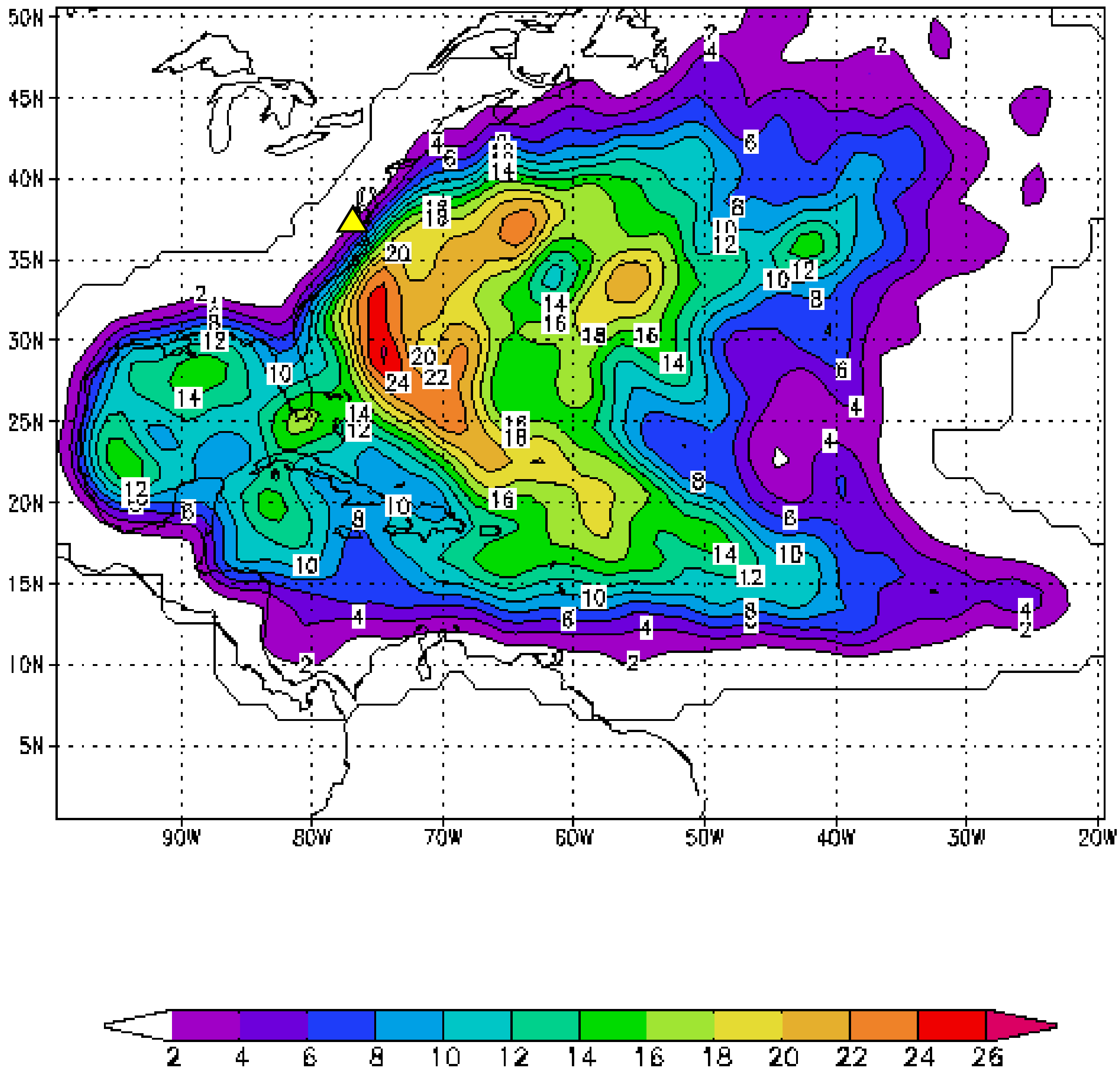
[1] Figure 2 appears to be originally to be from the National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center (NHC), but the NOAA/NHC website cited by Locke, 2005 no longer contains that figure.




Note: The triangle and #44 represents Norfolk, VA; Source: Locke, 2005

**Figure 2. Hurricane landfall probabilities for U.S. Gulf and East Coast, based on historical data**

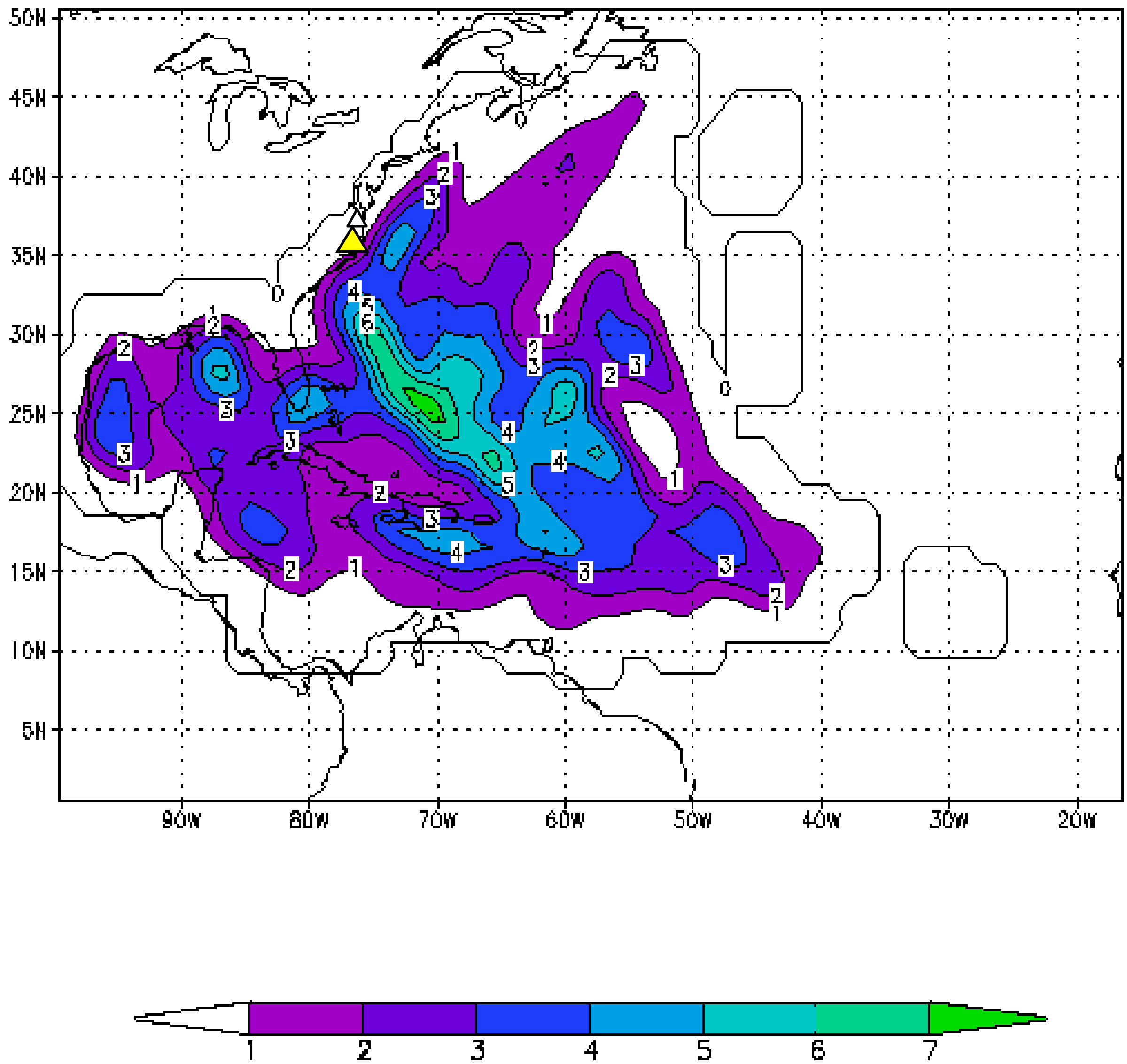
***Figure 3*** shows the probability of a hurricane or named storm coming within approximately 60 miles of any location in any year, from June to November, based on data from 1944 to 1999. It is difficult to discern the exact value for Norfolk, VA from ***Figure 3*** (located at approximately 37N, 77W on the grid), but it appears that the probability of a hurricane or named storm coming within approximately 60 miles of Norfolk, VA, in a year appears to be between 4 and 6 percent, so this analysis uses a value of 5 percent.




Note: The triangle represents Norfolk, VA; Source: NOAA, 2014a

**Figure 3. Probability (%) per year of a hurricane coming within 60 miles of any point in the North Atlantic**

***Figure 4*** presents the probability of a major hurricane (Category 3 or higher) coming within 30 miles of any point in the North Atlantic. It appears from this figure that the probability of an intense hurricane coming within 30 miles of Norfolk is less than 1 percent annually.




Note: The triangle represents Norfolk, VA; Source: NOAA, 2014a

**Figure 4. Probability (%) per year of a major hurricane coming within 30 miles of any point in the North Atlantic**

***Table 5*** summarizes the results from ***Figure 2*** through ***Figure 4*** for Norfolk, VA, and shows that there is approximately a 2 percent per year chance of a hurricane of any intensity making landfall within the 50 miles of coastline that includes Norfolk and approximately a 5 percent chance of a hurricane of any intensity passing within 60 miles of Norfolk.

**Table 5. Summary of Annual Probabilities for Hurricanes at Norfolk, VA**

| Scenario | Annual Probability of the Event Occurring (Percent) | |
|---|---|---|
| | Any Hurricane | "Great" or "Intense" Hurricane |
| Landfall within 50 miles of coastline that includes Norfolk, VA | 2 | 1 |
| Pass within 60 miles of any point in Norfolk, VA | 5 | <1 |

## 4.2. Intensity of Tropical Cyclones

A tropical cyclone is a generic term used by meteorologists to describe a rotating, organized system of clouds and thunderstorms that originates over tropical or subtropical waters and has closed, low-level circulation (NOAA, 2018). As may be expected, strong tropical cyclones are less frequent than weaker tropical cyclones. This fact is illustrated in both ***Figure 2*** and in a comparison of ***Figure 3*** to ***Figure 4***. Thus, it is useful to develop additional resolution between hurricane categories than is available in ***Figure 2*** and in comparing ***Figure 3*** to ***Figure 4***.

***Table 6*** presents an analysis of data for U.S. landfalling hurricanes from 1900 to 2015 (NOAA, 2017).[2] In the table, the Saffir-Simpson hurricane wind speed ratings for all 192 landfalling hurricanes from 1900 to 2015 are summarized. Of the 192 landfalling hurricanes, 79, or 41 percent, were Category 1. Similarly, 49, or 26 percent, were Category 2. The fractional values from ***Table 6*** can be used in conjunction with the values in ***Figure 2*** and ***Figure 3*** for all hurricanes to come up with probabilities for hurricanes within all five Saffir-Simpson hurricane categories. For example, from ***Figure 3***, there is a 5 percent probability of a hurricane of any intensity passing within 60 miles of any point in Norfolk in any year. Combining that five percent annual probability with the fractions for various hurricane categories in ***Table 6*** yields the following fractional annual probabilities for various hurricane categories:

- Category 1 = 2.1% = 0.021 (i.e., 0.05 x 0.41)
- Category 2 = 1.3% = 0.013 (i.e., 0.05 x 0.26)
- Category 3 = 1.1% = 0.011 (i.e., 0.05 x 0.22)
- Category 4 = 0.45% = 0.0045 (i.e., 0.05 x 0.09)
- Category 5 = 0.10% = 0.0010 (i.e. 0.05 x 0.02).

**Table 6. Frequency of Occurrence for Category 1 to 5 Landfalling Hurricanes**

| Saffir-Simpson Category | Wind Speed | Number of Occurrences | Fraction of Total |
|---|---|---|---|
| 1 | 74–95 mph | 79 | 0.41 |
| 2 | 96–110 mph | 49 | 0.26 |
| 3 | 111–129 mph | 43 | 0.22 |

[2] Data from NOAA, (2017) extend back to 1851, but only data from 1900 onward were analyzed, because the earlier data may be less accurate with regard to hurricane strength estimates at landfall.

| | | | |
|---|---|---|---|
| 4 | 130–156 mph | 18 | 0.09 |
| 5 | 157 mph or higher | 3 | 0.02 |
| Total, all categories | 74 mph or higher | 192 | 1.00 |

It is possible to use annual probabilities of occurrence to calculate the cumulative probability of a hurricane in the future. For example, if the annual chance of a hurricane making landfall at Norfolk, VA is 2 percent, the chance that a hurricane will not make landfall at Norfolk, VA is 98 percent (i.e., a fractional value of 0.98), and the chance that a hurricane will not make landfall over 10 years is 82 percent (i.e., 0.98 raised to the $10^{th}$ power). Therefore, the probability that a hurricane will make landfall at Norfolk, VA in 10 years is 18 percent. The formula for calculating the cumulative probability based on annual probability is:

$$CP = 1 - (1 - AP)^n$$

where:

CP = fractional cumulative probability over n years

AP = fractional annual probability of occurrence

n = number of years into the future.

For example, if the annual probability of occurrence of a hurricane landfall at Norfolk, VA, is 2 percent (fractional value of 0.02), the cumulative fractional probability of a hurricane making landfall in the 35 years from 2015 to 2050 is approximately 0.51, or 51 percent (i.e., $1 - (1 - 0.02)^{35}$).

## 4.3. Summary of Frequency and Intensity Data for Norfolk, VA

The previous frequency and intensity discussions are combined and summarized in ***Table 7***. The first two columns in ***Table 7*** contain the cumulative probabilities for landfalling hurricanes at Norfolk, based on ***Figure 2***. The next two columns contain the cumulative probabilities for hurricanes passing within approximately 60 miles of Norfolk, based on ***Figures 3*** and ***4. Table 7*** then has five columns with the cumulative probability of landfalling hurricanes of Saffir-Simpson categories 1 through 5, based on ***Figure 2*** and the hurricane intensity data in ***Table 6***. The final five columns in ***Table 7*** show the expected probability of hurricanes with different intensities passing within approximately 60 miles of Norfolk, based on data from ***Figure 3*** and ***Table 6***.

It is instructive to examine cumulative probabilities to the year 2050 (i.e., the next 35 years from 2015). For example, the Wheelabrator WTE plant commenced operations in 1988, so 2050 would represent a conservative 62-year lifetime for the facility. From ***Table 3***, there is a cumulative fractional probability of 0.21 (i.e., 21 percent) for a Category 1 hurricane making landfall at Norfolk by 2050, but only a 0.05 (5 percent) cumulative chance for a Category 4 hurricane making landfall in the same time frame. Similarly, there is a cumulative fractional probability of 0.34 (34 percent) for a Category 1 hurricane passing within approximately 60 miles of Norfolk by 2050,

## Table 7. Cumulative Probability of Different Hurricane Intensities at Norfolk, VA

| Year | Cumulative probability for landfalling hurricane through this year | Cumulative probability for landfalling "great" hurricane (roughly, Category 4 and 5) through this year | Cumulative probability hurricane will pass within 60 miles through this year | Cumulative probability major (Category 3 or greater) hurricane will pass within 30 miles through this year | Cumulative probability will have a landfalling hurricane through this year | | | | | Cumulative probability will have a hurricane pass within 60 miles | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Cat 1 | Cat 2 | Cat 3 | Cat 4 | Cat 5 | Cat 1 | Cat 2 | Cat 3 | Cat 4 | Cat 5 |
| 2016 | 0.02 | 0.01 | 0.05 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.02 | 0.01 | 0.01 | 0.00 | 0.00 |
| 2017 | 0.04 | 0.02 | 0.10 | 0.01 | 0.02 | 0.01 | 0.01 | 0.00 | 0.00 | 0.04 | 0.02 | 0.02 | 0.01 | 0.00 |
| 2018 | 0.06 | 0.03 | 0.14 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 | 0.00 | 0.06 | 0.04 | 0.03 | 0.01 | 0.00 |
| 2019 | 0.08 | 0.04 | 0.19 | 0.02 | 0.03 | 0.02 | 0.02 | 0.01 | 0.00 | 0.08 | 0.05 | 0.04 | 0.02 | 0.00 |
| 2020 | 0.10 | 0.05 | 0.23 | 0.02 | 0.04 | 0.02 | 0.02 | 0.01 | 0.00 | 0.09 | 0.06 | 0.05 | 0.02 | 0.00 |
| 2021 | 0.11 | 0.06 | 0.26 | 0.02 | 0.05 | 0.03 | 0.03 | 0.01 | 0.00 | 0.11 | 0.07 | 0.06 | 0.02 | 0.00 |
| 2022 | 0.13 | 0.07 | 0.30 | 0.03 | 0.05 | 0.03 | 0.03 | 0.01 | 0.00 | 0.12 | 0.08 | 0.07 | 0.03 | 0.00 |
| 2023 | 0.15 | 0.08 | 0.34 | 0.03 | 0.06 | 0.04 | 0.03 | 0.01 | 0.00 | 0.14 | 0.09 | 0.08 | 0.03 | 0.01 |
| 2024 | 0.17 | 0.09 | 0.37 | 0.04 | 0.07 | 0.04 | 0.04 | 0.02 | 0.00 | 0.15 | 0.09 | 0.08 | 0.03 | 0.01 |
| 2025 | 0.18 | 0.10 | 0.40 | 0.04 | 0.08 | 0.05 | 0.04 | 0.02 | 0.00 | 0.17 | 0.10 | 0.09 | 0.04 | 0.01 |
| 2026 | 0.20 | 0.10 | 0.43 | 0.04 | 0.08 | 0.05 | 0.04 | 0.02 | 0.00 | 0.18 | 0.11 | 0.10 | 0.04 | 0.01 |
| 2027 | 0.22 | 0.11 | 0.46 | 0.05 | 0.09 | 0.05 | 0.05 | 0.02 | 0.00 | 0.19 | 0.12 | 0.10 | 0.04 | 0.01 |
| 2028 | 0.23 | 0.12 | 0.49 | 0.05 | 0.10 | 0.06 | 0.05 | 0.02 | 0.00 | 0.20 | 0.12 | 0.11 | 0.05 | 0.01 |
| 2029 | 0.25 | 0.13 | 0.51 | 0.05 | 0.10 | 0.06 | 0.06 | 0.02 | 0.00 | 0.21 | 0.13 | 0.11 | 0.05 | 0.01 |
| 2030 | 0.26 | 0.14 | 0.54 | 0.06 | 0.11 | 0.07 | 0.06 | 0.02 | 0.00 | 0.22 | 0.14 | 0.12 | 0.05 | 0.01 |
| 2031 | 0.28 | 0.15 | 0.56 | 0.06 | 0.11 | 0.07 | 0.06 | 0.03 | 0.00 | 0.23 | 0.14 | 0.13 | 0.05 | 0.01 |
| 2032 | 0.29 | 0.16 | 0.58 | 0.07 | 0.12 | 0.07 | 0.07 | 0.03 | 0.00 | 0.24 | 0.15 | 0.13 | 0.05 | 0.01 |
| 2033 | 0.30 | 0.17 | 0.60 | 0.07 | 0.13 | 0.08 | 0.07 | 0.03 | 0.00 | 0.25 | 0.15 | 0.13 | 0.06 | 0.01 |
| 2034 | 0.32 | 0.17 | 0.62 | 0.07 | 0.13 | 0.08 | 0.07 | 0.03 | 0.00 | 0.26 | 0.16 | 0.14 | 0.06 | 0.01 |
| 2035 | 0.33 | 0.18 | 0.64 | 0.08 | 0.14 | 0.08 | 0.07 | 0.03 | 0.01 | 0.26 | 0.16 | 0.14 | 0.06 | 0.01 |
| 2036 | 0.35 | 0.19 | 0.66 | 0.08 | 0.14 | 0.09 | 0.08 | 0.03 | 0.01 | 0.27 | 0.17 | 0.15 | 0.06 | 0.01 |
| 2037 | 0.36 | 0.20 | 0.68 | 0.08 | 0.15 | 0.09 | 0.08 | 0.03 | 0.01 | 0.28 | 0.17 | 0.15 | 0.06 | 0.01 |
| 2038 | 0.37 | 0.21 | 0.69 | 0.09 | 0.15 | 0.09 | 0.08 | 0.03 | 0.01 | 0.28 | 0.18 | 0.16 | 0.06 | 0.01 |
| 2039 | 0.38 | 0.21 | 0.71 | 0.09 | 0.16 | 0.10 | 0.09 | 0.04 | 0.01 | 0.29 | 0.18 | 0.16 | 0.07 | 0.01 |
| 2040 | 0.40 | 0.22 | 0.72 | 0.10 | 0.16 | 0.10 | 0.09 | 0.04 | 0.01 | 0.30 | 0.18 | 0.16 | 0.07 | 0.01 |
| 2041 | 0.41 | 0.23 | 0.74 | 0.10 | 0.17 | 0.10 | 0.09 | 0.04 | 0.01 | 0.30 | 0.19 | 0.16 | 0.07 | 0.01 |
| 2042 | 0.42 | 0.24 | 0.75 | 0.10 | 0.17 | 0.11 | 0.09 | 0.04 | 0.01 | 0.31 | 0.19 | 0.17 | 0.07 | 0.01 |
| 2043 | 0.43 | 0.25 | 0.76 | 0.11 | 0.18 | 0.11 | 0.10 | 0.04 | 0.01 | 0.31 | 0.19 | 0.17 | 0.07 | 0.01 |
| 2044 | 0.44 | 0.25 | 0.77 | 0.11 | 0.18 | 0.11 | 0.10 | 0.04 | 0.01 | 0.32 | 0.20 | 0.17 | 0.07 | 0.01 |
| 2045 | 0.45 | 0.26 | 0.79 | 0.11 | 0.19 | 0.12 | 0.10 | 0.04 | 0.01 | 0.32 | 0.20 | 0.18 | 0.07 | 0.01 |
| 2046 | 0.47 | 0.27 | 0.80 | 0.12 | 0.19 | 0.12 | 0.10 | 0.04 | 0.01 | 0.33 | 0.20 | 0.18 | 0.07 | 0.01 |
| 2047 | 0.48 | 0.28 | 0.81 | 0.12 | 0.20 | 0.12 | 0.11 | 0.04 | 0.01 | 0.33 | 0.21 | 0.18 | 0.08 | 0.01 |
| 2048 | 0.49 | 0.28 | 0.82 | 0.12 | 0.20 | 0.12 | 0.11 | 0.05 | 0.01 | 0.34 | 0.21 | 0.18 | 0.08 | 0.01 |
| 2049 | 0.50 | 0.29 | 0.83 | 0.13 | 0.20 | 0.13 | 0.11 | 0.05 | 0.01 | 0.34 | 0.21 | 0.18 | 0.08 | 0.01 |
| 2050 | 0.51 | 0.30 | 0.83 | 0.13 | 0.21 | 0.13 | 0.11 | 0.05 | 0.01 | 0.34 | 0.21 | 0.19 | 0.08 | 0.01 |

but only an 0.08 (8 percent) cumulative probability of a Category 4 hurricane passing within the same area.

## 4.4. Hurricane Intensity versus Flooding Probability

The NOAA/ NWS National Hurricane Center (NHC) Storm Surge Unit has calculated storm surge flooding levels for hurricane categories 1 through 5 for the East Coast and Gulf Coast of the U.S. (NOAA, 2014b). The calculations are based on the Sea, Lake and Overland Surges from Hurricanes (SLOSH) computer program, using "Maximum of Maximums (MOM)" values. MOM values choose maximum surge heights for a given category of hurricane, for a range of storm scenarios, and the surge values are calculated at high tides. Storm surge predictions from the NOAA/NWS/NHC/Storm Surge Unit website were reviewed for four waste handling facilities in the Norfolk area.

## 4.5. Key Findings and Observations

***Table 3*** presented cumulative probabilities for hurricanes of varying intensity making landfall at Norfolk or passing near Norfolk, based on average data from the 20th century. The cumulative fractional probabilities from the years 2015 to 2050 are presented in ***Table 8***.

**Table 8. Hurricane Scenarios for Norfolk, VA**

| Scenario | Cumulative Fractional Probability of Occurrence, 2015–2050 | | | | |
|---|---|---|---|---|---|
| | Category 1 | Category 2 | Category 3 | Category 4 | Category 5 |
| Landfall in 50 miles coastal segment for Norfolk | 0.21 | 0.13 | 0.11 | 0.05 | 0.01 |
| Pass within approximately 60 miles of Norfolk | 0.34 | 0.21 | 0.19 | 0.08 | 0.01 |

The results of an assessment of the NOAA (2014b) probabilities for flooding are presented for the four main Norfolk, VA waste facilities in ***Table 9***. It is extremely unlikely (less than 1 percent chance) that any of the four waste sites would be flooded in a Category 1 hurricane. In contrast, the Portsmouth WTE plant would be very likely (greater than 90 percent chance) to flood in a Category 4 storm, whereas it would still be very unlikely (less than 10 percent chance) that the TFC recycling facility would flood, even in a Category 4 storm. Note that the NOAA/NWS/NHC Storm Surge Unit analysis does not consider Category 5 storms north of the North Carolina and Virginia border, so there is no analysis for Category 5 storms presented in ***Table 9***.

The results of ***Table 8*** and ***Table 9*** can be combined to get an overall cumulative storm surge flooding probability for the four waste sites in the Norfolk area for the years 2015–2050. The most likely facility to flood appears to be the Portsmouth WTE plant; the Portsmouth WTE plant appears very likely to flood in a Category 4 hurricane. However, from ***Table 4***, there is only about a 5 percent chance that a Category 4 hurricane will make landfall at Norfolk within the 2015–2050 period, and only an 8 percent chance that a hurricane will pass within approximately 60 miles of Norfolk in the 2015–2050 period. Therefore, the overall chance that even the Portsmouth WTE plant will be flooded by a storm surge in the 2015–2050 period is low (less than 20 percent).

**Table 9. Flooding Probabilities at Norfolk Waste Sites, for Various Hurricane Categories**

| Waste Handling Location | Meters above Sea Level [a] | Probability [b] the Site Will Be Flooded, MOM [c] Conditions, High Tide | | | |
|---|---|---|---|---|---|
| | | Category 1 | Category 2 | Category 3 | Category 4 |
| Portsmouth WTE plant | 4 | 0–0.01 | 0–0.33 | 0.66–1.00 | 0.90–1.00 |
| SPSA Regional Landfill | 5 | 0–0.01 | 0–0.01 | 0–0.33 | 0.33–0.66 |
| SPSA Norfolk Transfer Station | 7 | 0–0.01 | 0–0.10 | 0.33–0.66 | 0.66–1.00 |
| TFC Recycling | 7 | 0–0.01 | 0–0.01 | 0–0.01 | 0–0.10 |

[a] From Google Earth, using lowest elevation at each location.
[b] Using NOAA, 2014b.
[c] MOM = "Maximum of Maximums;" uses the maximum surge values for a range of storm simulations.

The overall chance of storm surge flooding in the 2015–2050 period for the SPSA Regional Landfill - Suffolk and the SPSA Norfolk Transfer Station is less than 10 percent, and the chance of storm surge flooding for TFC Recycling is less than 1 percent. However, it is important to note that these flooding probability estimates do not consider possible changes in the frequency and intensity of hurricanes from 2015 to 2050 as well as flooding of access roads that might impact the availability of the facility.

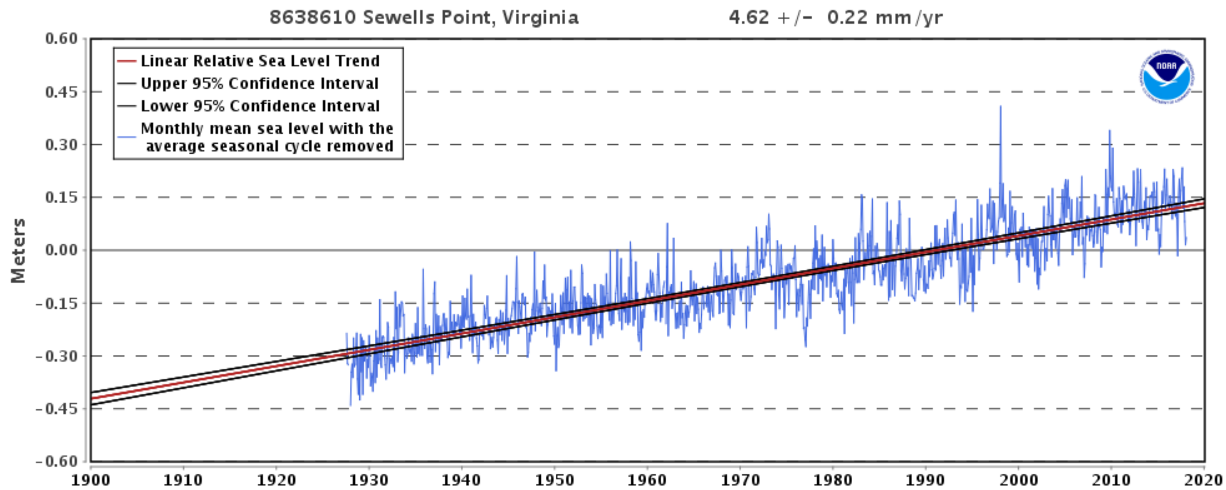
# 5. Climate-Induced Risks: Sea Level Rise

This chapter summarizes some of the literature characterizing the effects of SLR on tidal floods, groundwater levels and salinity and the impact of those changes on landfills located in Virginia's southern coastal plain and presents historic coastal inundation.

Wuebbles et al. (2017) states with very high confidence that SLR has caused the number of tidal floods each year -also called "nuisance floods"- to increase 5- to 10- fold since the 1960s in several U.S. coastal cities. Specifically, the rate has been accelerating in over 25 Atlantic and Gulf Coast cities. In addition, SLR is one of the contributors to increase in the frequency and extent of extreme flooding associated with coastal storms (Wuebbles et al., 2017).

In addition to nuisance floods, SLR will impact groundwater levels, specifically aquifers located near the coast, which could lead to groundwater emergence and shoaling during high precipitation events (Hoover et al., 2017).

The closest tidal gauge to Norfolk that has sea level data to 2010 is Sewells Point, VA. ***Figure 5*** shows the results from monitoring at that station from approximately 1928 to 2015. The relative sea level trend is 4.62 millimeters/year with a 95 percent confidence interval of +/- 0.22 mm/yr based on monthly mean sea level data from 1927 to 2017, which is equivalent to a change of 1.52 feet in 100 years (NOAA, 2018). Assuming the rise rate remains roughly constant, the SLR from 2015 to 2050 would be approximately 6 inches (0.5 feet). This level would not significantly change the results of the analyses.




Source: NOAA, 2018

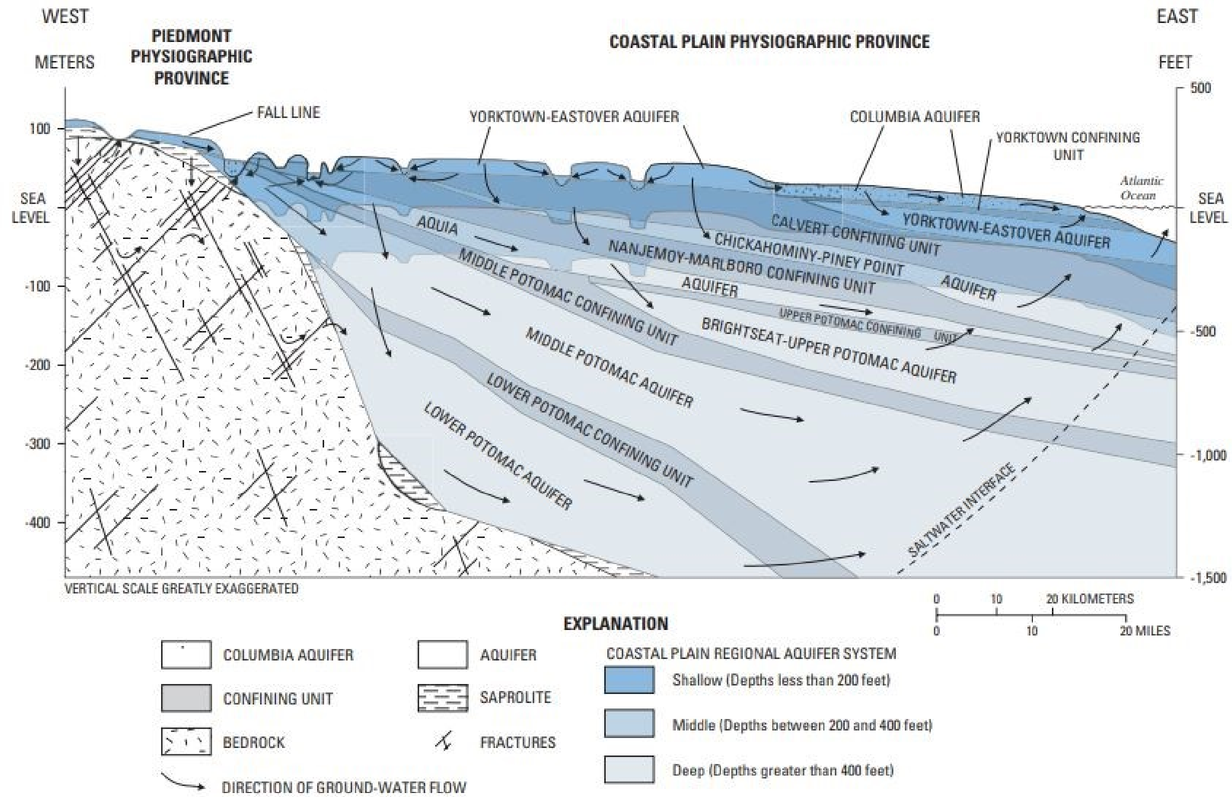
**Figure 5. Sea Level Trend at Sewell's Point, VA**

Approaches have also been identified that have previously been used to analyze the effects of SLR changes on groundwater levels and aquifer salinity.

## 5.1. Geological Characteristics of the Virginia Coastal Plain

The geological characteristics of a region influence potential impacts on groundwater due to SLR. The Coastal Plain Region of Virginia is generally underlain by a thick sequence of mostly unconsolidated sand and gravel aquifer units that are gently dipping seaward from the Piedmont region. Generally fossiliferous forms of limestone layers also occur within the sequence of coastal aquifer units. The aquifer units are generally separated by beds of clay and silt, or occasionally layers of cemented sands. The transmissivity of the confining clay and silt beds between sand and gravel aquifers is very low, compared to the aquifer formations, and to varying degrees restricts groundwater flow between the aquifer layers. The thickness of sediments that underlay the Virginia coastal plain over the basement rock ranges from approximately 8,000 feet to 10,000 feet (McFarland and Bruce, 2006).

A hydrogeologic cross-section showing the Coastal Plain aquifer system that is characteristic of the Norfolk and Hampton Roads area is shown in ***Figure 6*** (USGS, 2003). The Columbia aquifer is the shallowest aquifer in the Norfolk area (Smith, 2003; McFarland and Bruce, 2006) and can be tens of feet thick (McFarland and Bruce, 2006). The Columbia aquifer is used primarily for domestic groundwater supplies (McFarland and Bruce, 2006) and is directly recharged by rainfall. The base of the Columbia surficial aquifer is in contact with the top of the Yorktown confining unit. Overall, the Columbia aquifer and the Yorktown confining unit generally contain freshwater, although higher concentrations of chloride can occur locally. The deeper Yorktown-Eastover aquifer that underlies the Yorktown confining unit is also a potential source of freshwater in the region but can contain higher concentrations of dissolved solids and be somewhat saline in some areas. More significant supplies of fresh groundwater are obtained from the deeper Potomac aquifer. In 2010, Norfolk used approximately 3.38 million gallons per day of fresh groundwater for public supplies (City of Norfolk, 2013), but gets most of its freshwater supply from surface water sources.




Source: USGS, 2003

**Figure 6. Generalized Hydrogeologic Section and Direction of Groundwater Flow in the Virginia Coastal Plain Groundwater Changes Resulting from Sea Level Rise**

A Columbia Water Center study suggests that groundwater levels have been on the decline throughout the U.S. over the last several decades because of over-pumping (Russo et al., 2014). SLR may cause some of the groundwater levels in the area to rebound because water tables rise with increases in sea levels, saturating the soil and impacting the ability of surface water to drain (Rotzoll and Fletcher, 2013). This rise in the water table could potentially inundate infrastructure (including waste management facilities) in low-lying areas. Groundwater inundation will start sporadically but when it does happen, it will be most likely to occur at high tide and heavy rainfall (Rotzoll and Fletcher, 2013).

***Figure 7*** shows the sites where the City of Norfolk sends its waste and includes locations of USGS groundwater wells in the area. The groundwater depths at the USGS monitoring wells in the Norfolk area range from roughly 77 to 90 feet below the land surface. The city sends its waste to the SPSA landfill in Suffolk, which is adjacent to the Great Dismal Swamp National Wildlife Refuge. The bottom of the waste cells at this landfill are pyramid shaped. At their deepest points, they are 48 feet below existing grade, or -48 feet mean sea level. The center is at -10 feet mean sea level. Coastal wetlands, such as the Great Dismal Swamp, will undoubtedly be impacted by climate change and SLR.

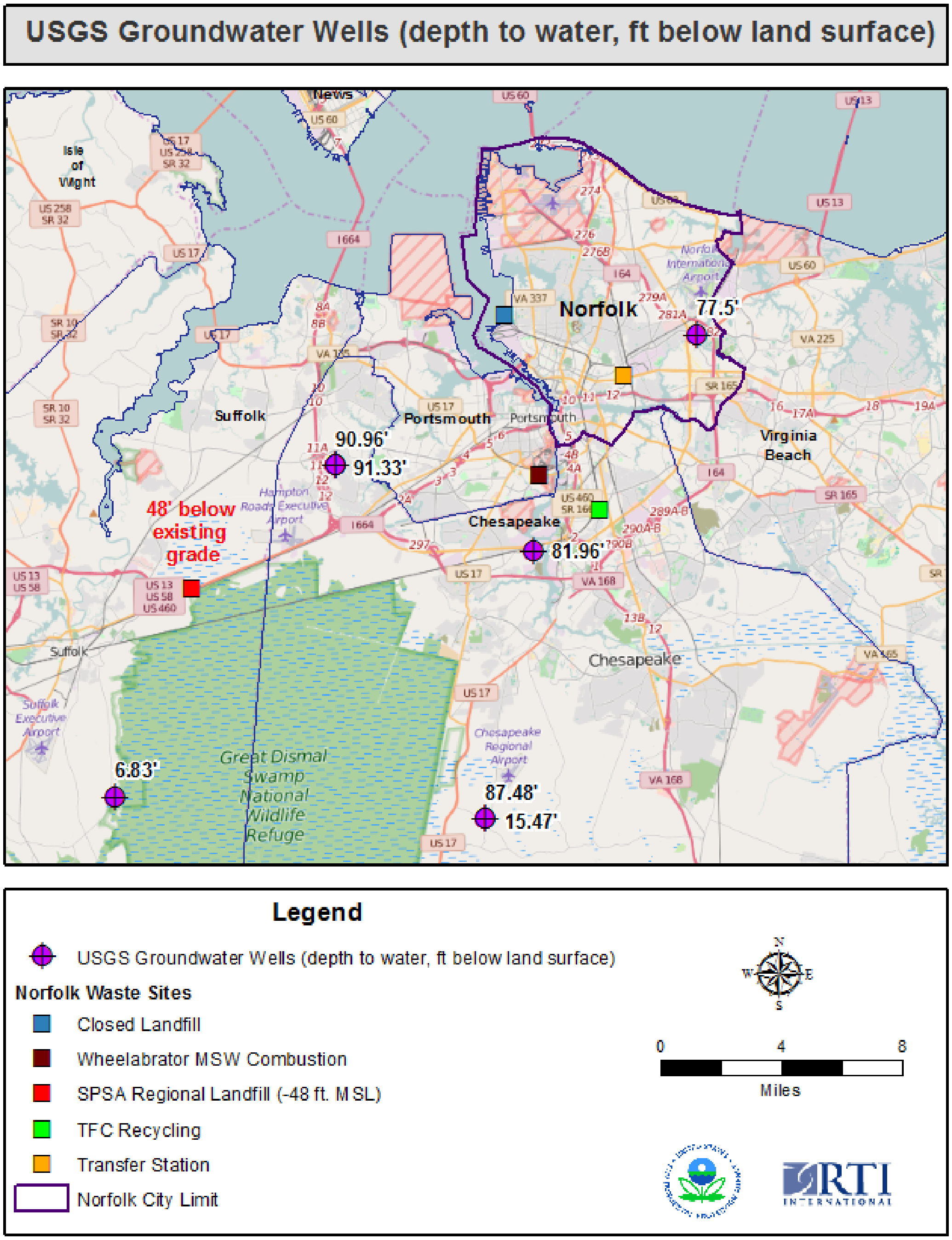



**Figure 7. USGS Groundwater Wells (depth to water, feet below land surface)**

***Figure 8*** shows shallow coastal flooding areas in red. These are areas where flooding occurs, usually in the form of ponding, with an average depth ranging from 1 to 3 feet. None of the sites where the City of Norfolk sends its waste appear to fall within these shallow flooding areas. Two monitoring stations are shown on the map. The Sewells Point NOAA Tide Gauge station is expected to see approximately 2.5 feet of rise by 2100 (Atkinson et al., 2012). This increase in mean sea level will also lead to an increase in saltwater intrusion into freshwater aquifers as the mixing zone between fresh water and saline water moves farther inland. It should also be noted that there is a closed landfill in the City of Norfolk that is located right at the coast in a flood zone. Although this site has been converted to a golf course, the wastes buried there are still subject to being released into the environment because of the impacts associated with flooding and storm surges, and possibly from groundwater rise.

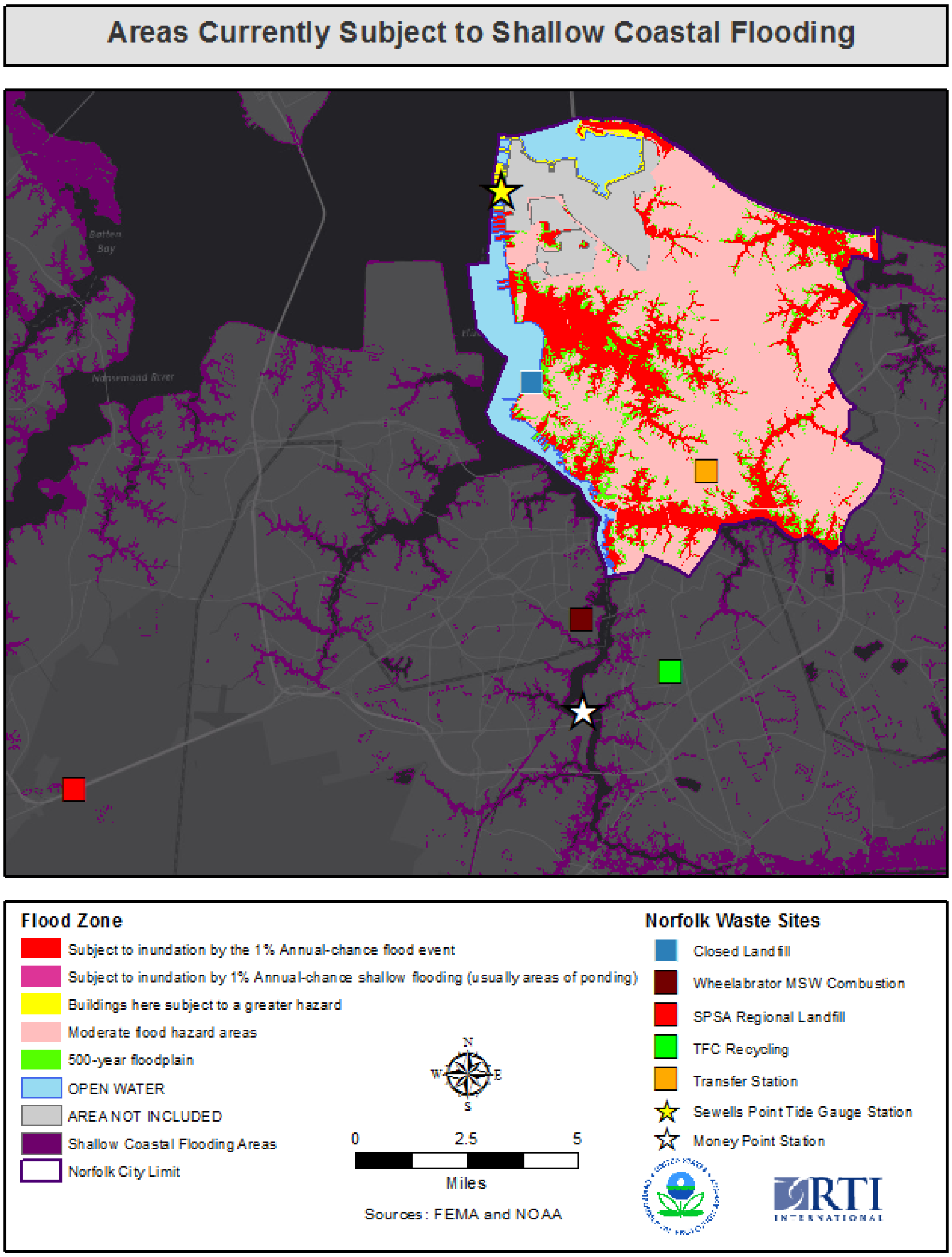



**Figure 8. Areas Currently Subject to Shallow Coastal Flooding**

***Figure 9*** shows the Sewells Point Tide Gauge station current frequency of coastal flood events and durations, due to coastal storm events, as compared to hypothetical 0.5 m (1.6 ft) and 1 m (3.3 ft) SLR scenarios (NOAA, 2013). Flooding begins at 4.5 ft mean lower low water (MLLW). With 0.5 m of SLR, nearly 400 flood events (which could occur twice a day at both high tide and low tide, based on a 3-

year average) can be expected at this station. The duration of flooding would be less than 100 days per year at 0.5 m of SLR. At 1 m of SLR, this station would experience 600 flood events each year (3-year average, high tide and low tide) and would be inundated by flooding for a little more than 200 days per year.

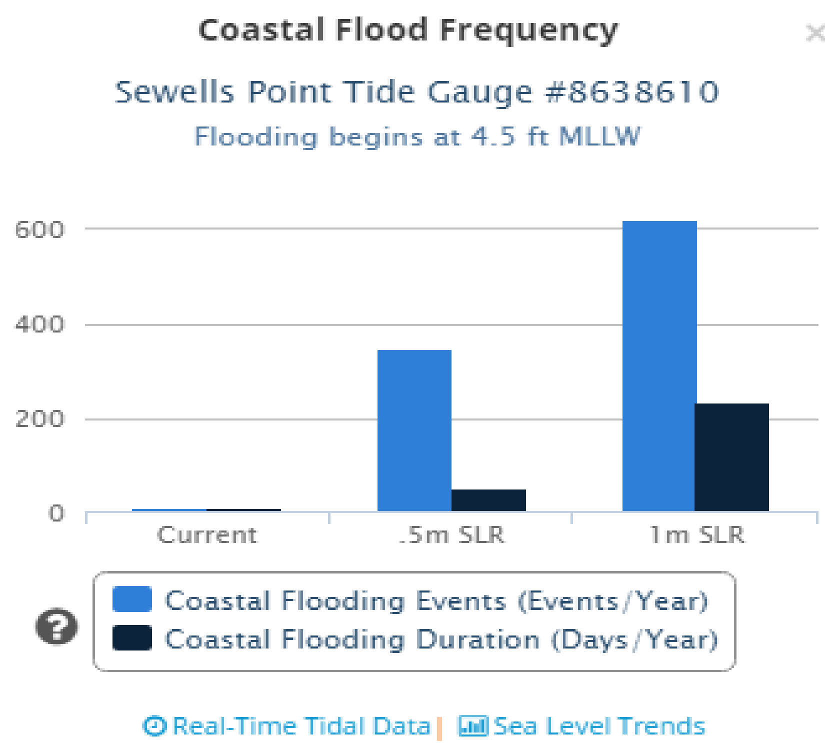



**Figure 9. Coastal Flood Frequency at Sewells Point Tide Gauge (Source: NOAA)**

One of the consequences of climate-induced coastal flooding will be salt water inundating coastal groundwater. This process is dependent upon various hydraulic, geometric, and transport parameters. Coastal aquifers that are deep with mild hydraulic gradients are more vulnerable to climate change and SLR (Sherif and Singh, 1999). The Hampton Roads Planning District Commission (2014) found chloride concentrations to be 250 mg/L at the top of the aquifer where the City of Norfolk lies. An increase in salinity levels due to SLR can lead to corrosion of subsurface water and sewer pipes and a high water table may mean a rise in evaporation and groundwater discharge (Rotzoll and Fletcher, 2013).

## 5.2. Approaches for Analyzing the Effects of Sea Level Rise on Groundwater

In this section, approaches and models that have been used to analyze the effects of SLR on groundwater are summarized. In general, few studies have been identified that directly address the issue. Two models that were identified that may be useful tools for supporting such analyses are MODFLOW and PRISM2-DSS. These two models and examples of their applications are summarized in the following sub-sections.

### 5.2.1 Use of MODFLOW to Simulate Current and Future Groundwater Levels

MODFLOW is a proven, open-source model developed by USGS. It is used to simulate and predict groundwater conditions and groundwater/surface-water interactions. Bjerklie et al. (2012) used

MODFLOW to do two different simulations of groundwater levels in New Haven, Connecticut. The first simulation involved an assessment of future groundwater levels from a 3-foot rise in sea level. The second simulation also included a 3-foot rise in sea level combined with a 12 percent increase in groundwater recharge. The output from the first simulation yielded a 3-foot rise in groundwater levels near the coast, which tapered off closer to a discharge area at a non-tidal stream in the study area. Water levels were affected even where the pre-simulation water table was 17–24 feet above the current sea level. When combined with a 12 percent recharge, groundwater levels were as much as a foot higher in some locations.

### 5.2.2 Use of the Pee Dee River and Atlantic Intracoastal Waterway Salinity Model-Decision Support System (PRISM2-DSS)

A study prepared by Carolinas Integrated Sciences and Assessments (2012) analyzed how climate change is affecting and will affect the Yadkin-Pee Dee River basin. It particularly focused on investigating the frequency and duration of saltwater intrusion events due to SLR. The inputs for the saltwater intrusion model include tidal range, mean water level, and streamflow data inputs, which are used to estimate specific conductance, and in return, salinity responses of water discharge under various scenarios.

A secondary component of the study included enhancing a decision support system (DSS) that can be used by resource managers, industry, and water and sewer districts to plan for future coastal climate change. Scenarios for how SLR may impact the inland penetration and duration of saltwater intrusion events can be adjusted with this DSS. The DSS can also be used to help stakeholders prepare for severe events to plan for things like repositioning freshwater intakes and treatment facilities and to help determine ways to handle increased treatment costs.

# 6. Understanding Impacts on Landfills

## 6.1. Precipitation related

Flooding risks should be taken into consideration in the long-term management of landfills, both during operation, post-closure and monitoring phases. A review paper outlines existing and needed practices for better management of landfills to minimize the risks posed by precipitation events or other types of impacts to avoid adverse effects on human health and the environment. The paper reviews practices and case studies conducted in Europe, U.S., Canada and Japan. Closure management practices contribute to outcomes on human health and the environment (Laner et al., 2012).

Quantitative methodologies were developed to assess potential of risks posed by landfill flooding using metrics such as proximity to flood plains, frequency and extent of precipitation events, chemical load in the landfills etc. Laner et al. (2009) presents a case study to evaluate vulnerability of landfills in Austria due to flooding. A quantitative methodology is developed to quantify likelihood of flooding and release of pollutants through leachate. Neuhold et al. (2011) builds on the Laner study to develop a quantitative approach to assess flood risk associated with flood-prone waste disposal sites determined in the Laner study.

There are no case studies conducted for Norfolk, VA related to precipitation impacts on landfills, however the above-mentioned studies and methods can be applied to understand the risks. The SPSA landfill serving Norfolk, VA is rather inland and far away from the coastal flooding zones (***Figure 8***).

## 6.2. Sea Level Rise

Even under extreme SLR scenarios, landfills in the Norfolk VA are not projected to inundate. However, potential changes in water tables could threaten wastes stored in landfills. The risk of contaminants or pollutants leaching through liners could increase as salt water permeates through clay liners that are impervious to fresh water (Flynn et al., 1984). The primary landfill, the SPSA landfill in Suffolk, used by the City of Norfolk, is adjacent to the Great Dismal Swamp National Wildlife Refuge, where the water table would be very close to the surface. As described earlier, the bottom of the waste cells at the SPSA landfill are pyramid-shaped with their deepest points at 48 feet below existing grade (or -48 feet mean sea level) with the center at 10 feet below existing grade (or -10 feet mean sea level).

Although groundwater may be impacted in the region, there is not enough data and information to ascertain if and how the SPSA landfill would be impacted by groundwater changes. The hydrogeology beneath the landfill may be multilayered and complex. There are both shallow and deep groundwater levels in the nearby USGS monitoring wells, as shown in ***Figure 7***, and the USGS 7.5-minute quadrangle map of Suffolk, VA, shows that the landfill is surrounded by wetland areas. The wetlands are, at least in part, an extension of the Great Dismal Swamp National Wildlife Refuge located along the border of the landfill site. The water level of the shallow groundwater (6 feet below ground surface), as shown in ***Figure 7***, is also evidence that the base of the landfill is likely below the water table. The permit for the landfill indicates that hydraulic control is required to keep the waste from being buoyant. The elevation of groundwater beneath the landfill is not known but the depth of sumps used for groundwater control is between elevation 30 to 18 feet below sea level, and the land surface is approximately 20 feet above mean sea level; therefore, the water table is lower near the base of the landfill, and the deepest points of the site base are 48 feet below the land surface.

The areas along streams and wetlands near the SPSA landfill location are also subject to flooding (see ***Figure 8***). Flooding is currently addressed in the landfill's Emergency Management Plan (SPSA, 2015), but not in response to anticipated SLR. Any storm event in association with SLR would increase the flooding potential of the landfill area. Given research into potential SLR–induced impacts to coastal groundwater (e.g., Bjerklie et al., 2012), it appears that there is a potential for direct impacts on the SPSA landfill site.

One of the impacts to the SPSA landfill complex could be loss of waste buoyancy control. Current plans (HDR Engineering, Inc., 2011) in the landfill permit indicate that monitoring of the sumps used for hydraulic control will not be necessary after adequate ballast is in place. SLR could change the ballast requirement and result in increased costs for monitoring, maintaining, and potentially expanding the system. It is also possible that a rise in groundwater levels could complicate hydraulic control if sumps were flooded above the drainage head, and pumping wells were necessary. Although an unlikely scenario, there is a possibility that the pumping wells or sump systems would need to be maintained indefinitely, either to avoid buoyancy issues or to isolate waste types. In addition to complications of hydraulic control beneath the landfill, there could be indirect impacts to supporting infrastructure and utilities that affect site operations such as interruption of electricity or sewer service.

As sea levels rise, there is also greater likelihood for standing pools of brackish water, maximized at high tide, because the ability for groundwater drainage is impacted. Waste infrastructure in low-lying coastal areas, where withdrawal is not substantial, should plan properly to minimize the impacts of SLR on groundwater.

It is important to estimate potential contaminant releases from climate-impacted landfills and the transport of such pollutants in the groundwater to nearby populations. In addition, other climate impacts such as flooding and washout from extreme precipitation events could transport contaminants to downstream receptor populations. Resources should also be appropriately allocated to evaluate potential climate-related releases based on anticipated changes in the hydrogeological setting of a landfill. More resources could and should be assigned to address complicated and significant situations rather than to address situations considered routine and relatively minor.

A tiered approach has been adopted or used by numerous state and federal agencies to evaluate risks associated with exposures to pollutants in the environment in a conservative manner. For example, the Illinois EPA uses a tiered approach to support remediation objectives for cleanup of contaminated soil and groundwater[3]. To be successful, tiered approaches need to have clearly defined and measurable endpoints between tiers. In general, a tiered approach begins with a Tier 1 screening level assessment that includes a simplified conceptual model of the environmental setting and pollutant release mechanisms combined with conservative exposure assumptions for humans and habitats. If unacceptable risks are identified (predicted exposure > threshold screening value), then a Tier 2 assessment is implemented using a more realistic release-exposure scenario to reflect key sensitive scenario and site-specific conditions. If unacceptable risks persist, then a detailed site-specific conceptual model is developed and evaluated under a Tier 3 analysis.

A possible Tier 1 scenario for climate-impacted landfills would be to assume direct contact and failure of the liner system with the water table, resulting in groundwater exposures equal to measurements or estimates of landfill leachate concentrations, which are then compared to screen levels corresponding to specific receptors and exposure pathways. Alternatively, if water table elevations are not expected to rise to that extent, national groundwater dilution-attenuation factors (DAFs) available in U.S. EPA tools (e.g., U.S. EPA Region 5 Delisting Risk Assessment Software [DRAS][4]) can be applied to expected leachate concentrations for screening comparisons. Tier 2 analyses consisting of deterministic or probabilistic fate and transport simulations can be conducted using existing U.S. EPA tools (e.g., Industrial Waste Management Evaluation Model [IWEM][5]) that require a minimum of key site- or location-specific data to predict potential landfill releases subject to changes in water table elevations.

As mentioned above, established open source groundwater flow and transport software (e.g., USGS MODFLOW[6] and SEAWAT[7]) for detailed Tier 3 site-specific investigations are available. Existing U.S. EPA OLEM and ORD models specific to sources (land disposal units) and fate and transport pathways (groundwater, air, surface water) with supporting data can be combined and customized to address conditions specific to climate-impacted landfills (i.e., no unsaturated zone). For example, existing U.S. EPA's OLEM and ORD solid/hazardous waste models and data—including the Science Advisory Board-reviewed Multimedia, Multi-pathway, Multi-receptor Exposure and Risk Assessment technology (3MRA, U.S. EPA, 2003) modules (***Figure 10***) and the next generation of these models currently being developed within the HE$^2$RMES (Human and Ecological Exposure & Risk in Multimedia Systems) (Babendreier et al., 2012) domain within U.S. EPA's FRAMES v 2 (Framework for Risk Analysis in Multimedia Environmental Systems, version 2)—can be adopted or adapted to investigate exposures to populations and ecosystems from flood-impacted landfills (and other land disposal units). To support such modeling efforts, comprehensive physical and chemical properties, human and ecological benchmarks, and the

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[3] See http://www.epa.illinois.gov/topics/cleanup-programs/taco/index (Last accessed October 2017)

[4] Available at https://www.epa.gov/hw/hazardous-waste-delisting-risk-assessment-software-dras (Last accessed October 2017)

[5] Available at https://www.epa.gov/smm/industrial-waste-management-evaluation-model-version-31 (Last accessed October 2017)

[6] Available at http://water.usgs.gov/ogw/modflow/MODFLOW.html (Last accessed October 2017)

[7] Available at http://water.usgs.gov/ogw/seawat/ (Last accessed October 2017)

U.S. EPA exposure factors are necessary for modeling waterborne (and airborne) contaminant exposures. These modeling systems could also be modified and leveraged to estimate potential impacts from flood-related power loss.

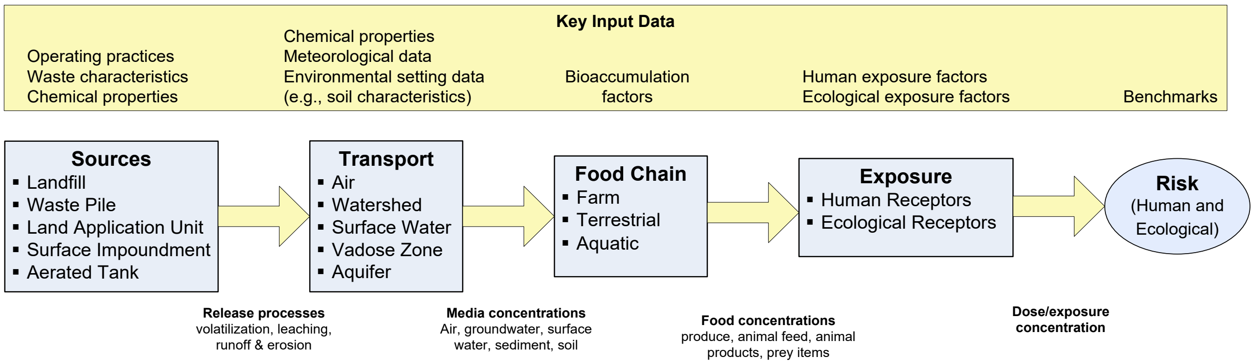



**Figure 10. Overview of OLEM 3MRA Modules to Model Releases, Fate and Transport, Exposures, and Risks from Waste Management Units**

# 7. Understanding Impacts on Transportation Infrastructure

The purpose of this chapter is to detail data available for characterizing potential climate-induced impacts to transportation infrastructure and durations of route disruptions. Infrastructure systems are made up of interconnected networks that transport goods and services and provide the foundation for a myriad of functions that occur within a populated area. When natural weather disasters occur, there could be widespread damage to transportation infrastructure (and utilities) that support waste management. Waste collection from residences and businesses can be delayed or suspended. Flooding and debris on the roads causing narrowing or complete impassability for collection vehicles as well as deterioration or damage to roads and bridges could severely impact waste collection.

Transporting waste from transfer stations to waste management facilities could also be temporarily halted. Again, transportation routes may have to be altered as roads and streets are flooded, narrowed, or blocked and supporting transportation infrastructure (bridges and tunnels) is damaged or unsafe for passage. Low-lying transfer, recycling, treatment, and disposal facilities could be cut off from normal routes or damaged from flooding, necessitating planning for alternative routing and possibly alternative facilities.

Transportation infrastructure-related data and information that would be appropriate to support an assessment of vulnerability to climate impacts (and determine adaptation measures) include:

1. Information about roads, bridges, and other features of the transportation system that may be impacted:

    - Quantities (e.g., lengths of roadway by type, number of bridges and tunnels),
    - Hierarchy (e.g., arterial roads, connectors, collectors, local streets),
    - Elevations of roadways, bridges and tunnels,
    - Locations (mapping), and
    - Characteristics (age, width, surface and subsurface material type, drainage).

2. Data characterizing the extent that transportation infrastructure may be impacted at varying levels of SLR and per other climate-induced impacts.
3. Alternative waste collection and transportation route options with consideration given to other transportation system variables (e.g., traffic patterns, vehicle size and weight restrictions).
4. Geophysical information characterizing areas where waste collection routes and transfer and processing facilities could potentially be rerouted or relocated.

GIS can be used to quantify and measure the impacts because it provides a platform to compile and present transportation data that cover the Norfolk area. Roads that are used to support waste management infrastructure are identified, particularly those that are flooded by tides. Various scenarios of SLR and storm surge could be run to highlight vulnerable areas within the transportation network.

To complete this task, available data and information for characterizing transportation-related impacts from storms and hurricanes were reviewed. Hurricane Sandy in 2012 provided the most recent and relevant information as the storm tracked up the east coast of the U.S. In Norfolk, Hurricane Sandy resulted in closures of major tunnels to the city including Midtown, Brooklyn-Battery, Holland and Queens Tunnels as well as more than 100 secondary roads due to flooding (Preston et al, 2012). In New York City, Hurricane Sandy caused severe traffic gridlock for three days (Kaufman et al., 2012), and infrastructure systems were damaged by the breach of seawater (U.S. Department of Housing and Urban Development, 2014). In preparation for flooding and winds, all bridges and tunnels in New York City were closed before the storm. However, taking this precautionary measure did not prepare transportation authorities for flooding in the city's tunnels. Coastal flooding and storm surge during Hurricane Sandy led to dune and beach erosion as well as "inundation of wetland habitats, removal of or erosion to coastal dunes, destruction of coastal lakes, and new inlet creation" (U.S. Department of Housing and Urban Development, 2014).

In both Norfolk and New York, waste management departments responded within a day after the storm to remove storm debris and collect waste (AltDaily, 2012; Discard Studies, 2014). One of the recommendations made after Hurricane Sandy was to develop and apply infrastructure resilience guidelines nationally. These guidelines would entail making risk-based decisions that incorporate potential climate change impacts and development patterns throughout the life cycle of the infrastructure.

## 7.1. Transportation Infrastructure Supporting Waste Management

Major roads, bridges, and tunnels near Norfolk that support waste management that have been identified (Hampton Roads Planning District Commission, 2011) as being vulnerable to hurricanes and storm surge inundation are listed in ***Table 10***. ***Figure 11*** shows state-maintained roads in the City of Norfolk that have been categorized by their annual average daily traffic counts. There are 189 existing arterial miles in Norfolk. There are also 22 miles of freeway, plus a seven-mile reversible high-occupancy vehicle (HOV) lane on I-64 (City of Norfolk, 2015). Interstate 64 and U.S. Highways 58 and 60 are the major routes that go from east to west. U.S. Highway 13 and Highway 460 are the major connectors between the north and south. The Hampton Roads Beltway includes I-64, I-264, I-464, and I-664 and forms a loop around Norfolk and other cities in the region.

**Table 10. Major Roads, Bridges, and Tunnels Supporting Waste Management in and around Norfolk**

| Major Roads | Major Bridges | Tunnels |
|---|---|---|
| I-64, I-264, I-464, I-664 | Berkley Bridge | Hampton Roads Bridge Tunnel |
| US-13, US-58, US-60, US-460 | High Rise Bridge | Downtown Tunnel, Midtown Tunnel |

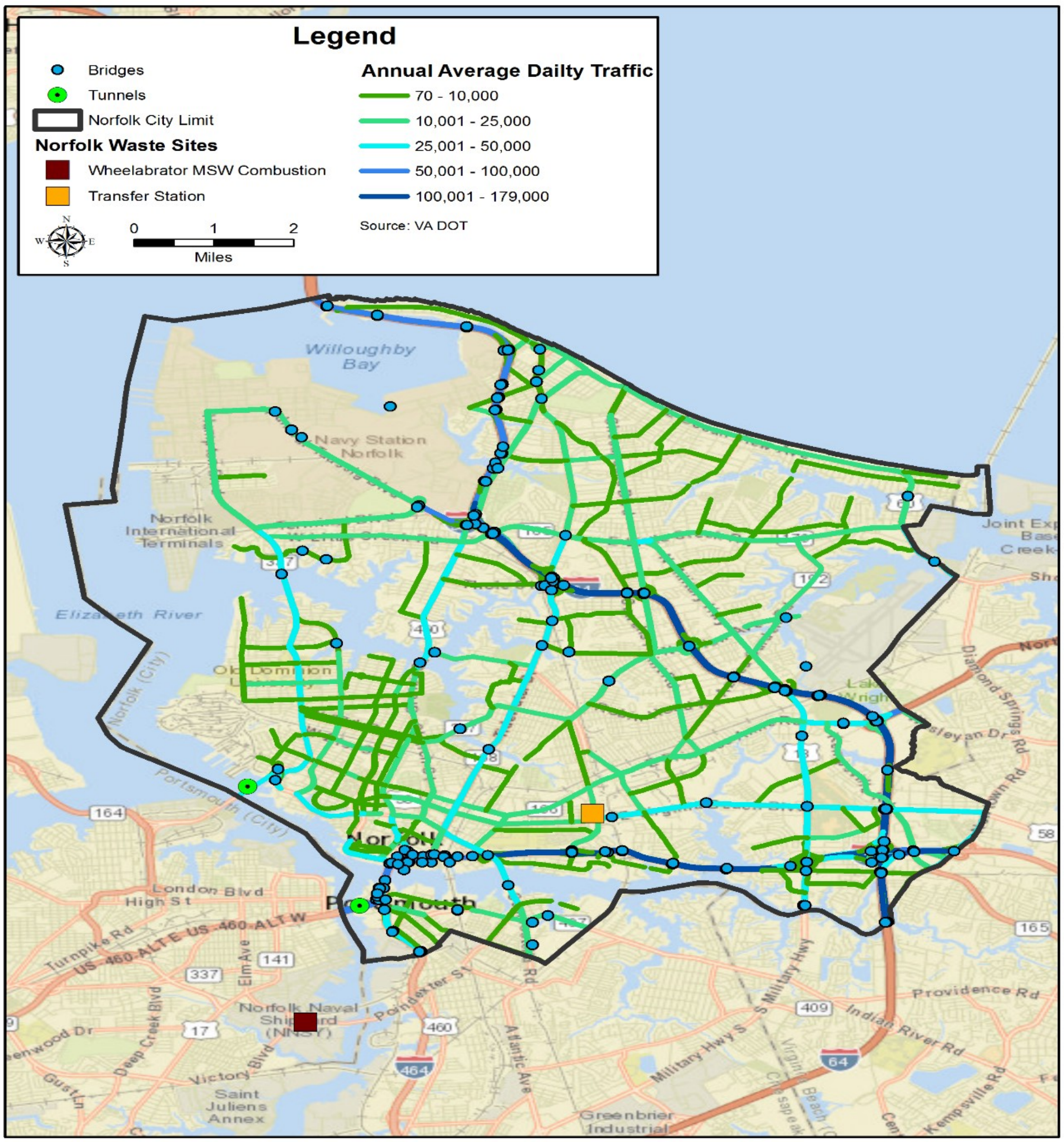


**Figure 11. Annual Average Daily Traffic Counts for Major Roads in Norfolk**

Norfolk's transportation network also includes several bridges and tunnels. Major bridges in the city are the Berkley Bridge and High-Rise Bridge. Heavily traveled tunnels include the Hampton Roads Bridge Tunnel and the Downtown and Midtown Tunnels. During severe weather events, these bridges and tunnels may be closed to restrict their use, becoming a major hindrance to waste collection and transportation service.

Interstate 64 is the only route that has a reversal plan, which means the eastbound lanes will be reserved so that additional traffic can travel west towards Richmond (Virginia Department of Transportation, 2012). This plan will only be enacted during the most extreme weather events.

***Figure 12*** shows regional arterial roads and the City of Norfolk's waste management facilities along with inundation areas from a hurricane storm surge. The storm surge elevations displayed, which come from a tool created by the Virginia Department of Emergency Management that utilizes NOAA's SLOSH model "presents 'worst-case' combinations of direction, forward speed, landfall point, and astronomical tide for each Saffir-Simpson scale of hurricane category" (Virginia Department of Emergency Management, 2014). The map also shows evacuation directions that go south and west away from the city's waste operation sites towards the regional landfill.

As shown in ***Figure 12***, many of the city's roadways, bridges and tunnels appear to fall within Category 1–4 hurricane storm surge levels. According to Mitchell et al. (2013), Norfolk currently has 119 road miles that are vulnerable to flooding. In addition, the *Norfolk Flooding Strategy Overview* (City of Norfolk, 2017) estimated that 17 percent of the city's road miles require drainage and roadway improvements.

Detailed data and information about potential street-level inundation within the city were not found. However, VIMS has conducted research that involves street-level inundation modeling (VIMS, 2008). The modeling uses LiDAR data, which allows for the Chesapeake Bay's shoreline to be simulated more accurately and modeling at the street level. This or a similar model may provide a means for Norfolk to analyze street-level inundation. The U.S. DOT's National Transportation Atlas Database is a source of data for primary and secondary roads and bridges. VDOT also collects average daily traffic data. These datasets may be useful for evaluating heavily traveled roads and identifying places where traffic problems could occur during severe flooding events.

Although the SPSA regional landfill is in a location that is free from hurricane storm surge, the WTE plant, transfer station, and recycling center could be impacted by strong hurricanes. The closed landfill site included on the map is also in a vulnerable location.

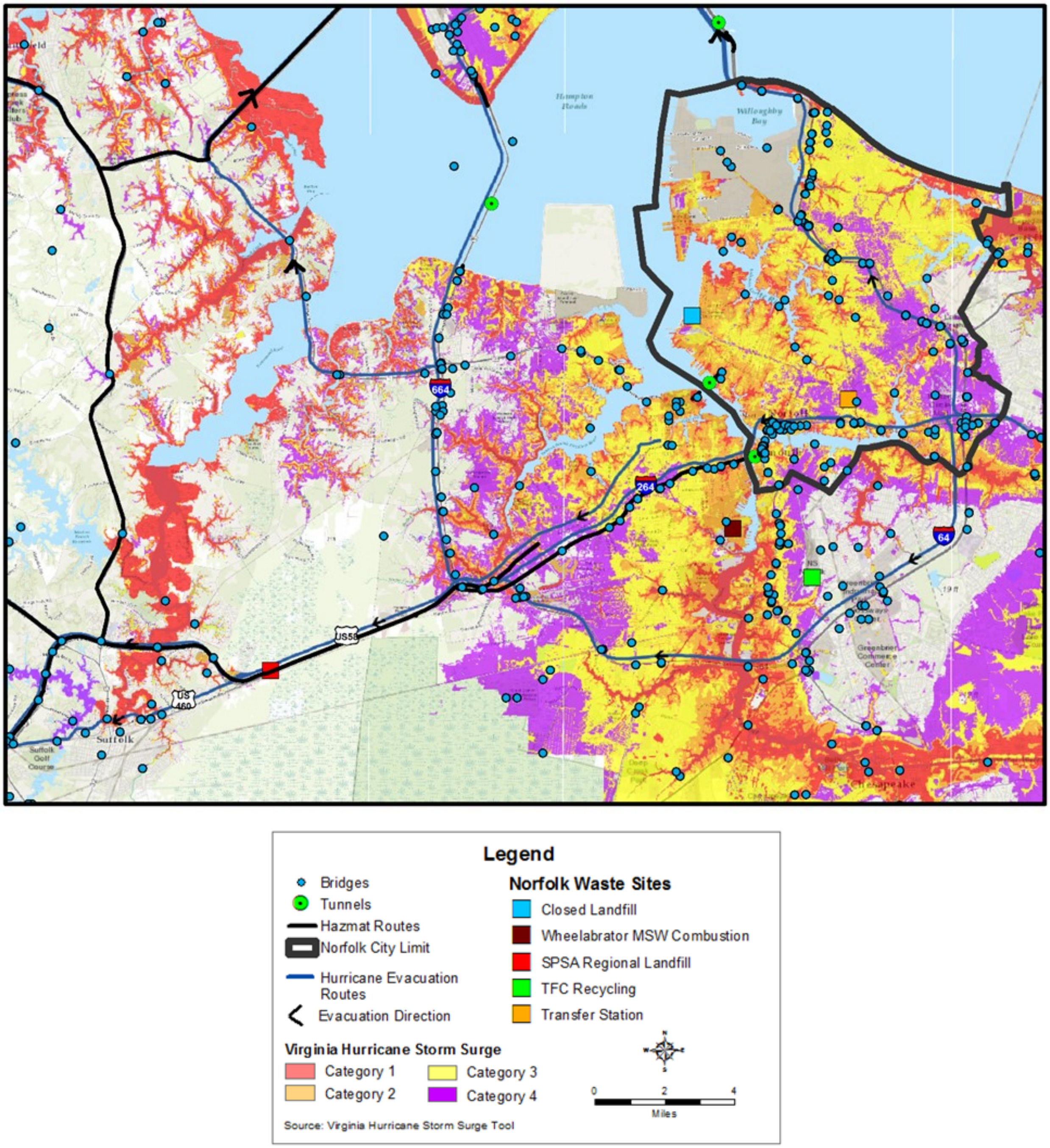



**Figure 12. Norfolk Waste Management Facilities with Hurricane Storm Surge Categories**

## 7.2. Disruptions-Duration, Recovery Times, and Alternative Options

Hurricanes and storms can cause disruptions in waste collection and management. When Hurricane Ike struck Houston in 2008, city services were disrupted for "weeks" (Centers for Disease Control and Prevention, 2009). To glean information about the duration of disruptions, time until recovery, and alternative options for handling disruptions, several documents in the public domain were reviewed including city and regional studies, emergency management and resiliency plans from VIMS, SPSA, and the Hampton Roads Planning District Commission. Electronic communications and phone calls were also made to the City of Norfolk's GIS and Public Works Department, but responses were not returned.

Transportation infrastructure is a significant target for the city's *Norfolk Flooding Strategy Overview* (City of Norfolk, undated), which includes increasing the elevation of buildings and roadways. A "roadway and intersection improvement" project is under way at Brambleton and Colley Avenue which involves raising the westbound lanes to reduce the frequency of flooding.

SPSA manages the landfill that serves the greater Hampton Roads region. The *SPSA Disaster Response Plan* (2015) describes their implementation and emergency response procedures. The authority empties its transfer stations prior to the onset of an anticipated weather event because there often is an increase in disposal of waste from residents before the arrival of a storm. They may elect to suspend residential disposal if it is negatively impacting their ability to handle municipal and commercial solid waste (SPSA, 2015). There is no additional capacity to handle large amounts of storm debris, even from a Category 1 hurricane, and SPSA may contract out this work to private companies that specialize in disaster debris management.

When winds are greater than 40 mph, hauling operations are likely to be suspended to and from SPSA facilities. According to SPSA's Disaster Response Plan, normal operations are resumed as soon as conditions allow. The decision to reopen facilities is based on the time of day, quantities of waste that are currently at their facilities, duration of the storm, and the ability to continue to receive waste at the city's transfer station.

According to the city, trash collection is rarely delayed, and when trash collection is delayed, all plans stipulate that personnel be back on the job as soon as possible to resume the collection of refuse (City of Norfolk, 2016). Factors that may impact waste collection transportation efficiency for storm debris and other wastes include:

- Well-defined transportation network,
- Hauling times,
- Debris volume,
- Accumulation of debris at temporary accumulation sites,
- Destination linkage of highways and disposal sites, and
- Number of disposal sites (Solis et al., 1995).

The City of Norfolk uses the Verizon Network fleet electronic system to track and monitor their waste collection and transportation vehicles. The city is knowledgeable of the roads that are prone to flooding and will adjust collection routes based on the timing of events. No information was available from the city at the time of this report about the frequency of collection route adjustment. Traffic congestion is another significant factor in the challenges associated with the transport of waste, both under normal conditions and under conditions that could arise during a hurricane or over the years because of SLR. In addition to the roads used to collect and transfer waste, bridges and tunnels in the area are often congested and can present significant constraints that impact waste management systems (Hampton Roads Planning District Commission, 2011).

Concerns raised by stakeholders in the area has hindered the selection of temporary disposal sites and the modification and configuration of transportation routes. Previous proposals have been considered that involved using railways and barging in waste from out-of-state. However, these alternative options were rejected for political reasons (Hampton Roads Planning District Commission, 2011). Norfolk's complex geography with peninsulas connected by bridges and tunnels creates few alternative routes (Mitchell et al., 2013).

### 7.3. Sea Level Rise and Groundwater

Although direct impacts of groundwater level and quality changes are not likely to affect roads, indirect impacts can occur when the capacity for soil infiltration is reduced or when storm water drainage systems become impaired, in turn possibly leading to flooding on roads and leading to road closures and roadway deterioration. Roads may need to be elevated to abate the effects of SLR.

## 8. Understanding Impacts on Utilities and Other Supporting Infrastructure

SLR and potential changes to groundwater levels and salinity can impact urban infrastructure and utilities. In this section, potential impacts of SLR on utilities and roads are summarized.

### 8.1. Water Supply

In the areas around Norfolk, some homeowners rely on wells for their drinking water. If the salinity in these wells increases, additional treatment may be necessary to make the water usable. An increase in the salinity of wells will also likely result in greater stress on surface water sources. Saltwater intrusion into groundwater wells may also reduce the amount of water that comes from surface water intakes, which in turn could put pressure on groundwater resources and lead to higher treatment costs that would be passed on to the public.

### 8.2. Electric Utilities

Many of Norfolk's utilities are located not too far underground and could easily be impacted by increased flooding and SLR. According to the City of Norfolk, Department of Utilities *Standard Design Criteria Manual* (2005), the water mains are installed 6 feet underground or less. The minimum cover depth for all sewer lines is 3 feet (36 inches).

The National Electrical Safety Code (IEEE, 1999) requires driven rods to be at least 8 feet deep, unless rock bottom is encountered. Bare wires and strips of metal are buried only at a minimum of 18 inches deep. The minimum depth for metal plates is only 5 feet. Supply cables and conductors that are 0–600 Volts (V) can be placed only 24 inches deep. Those that are 601V–50,000V are buried at least 30 inches and those that are greater than 50,000V must be buried at least 42 inches.

Pipe and electrical equipment are often designed to withstand corrosive subsurface conditions and may not be affected as much by inundation by saline groundwater. The age of the system would likely be an important factor in the level of impact that would occur.

## 9. Assessing Cost and Environmental Impacts of Alternative Waste Management Scenarios

The purpose of this chapter is to detail the approach, assumptions, and outcomes from the assessment of alternative MSW waste management scenarios should the City of Norfolk waste management infrastructure be inundated via climate-related impacts. U.S. EPA's MSW DST was utilized to estimate the cost and environmental impacts for predefined MSW management scenarios.

## 9.1. Scenarios Analyzed Using the MSW DST

The City of Norfolk's current MSW management system includes collection of MSW, recyclables, and bulk waste for a 2010 population of approximately 242,803 (SPSA, 2016). Once collected, waste is hauled to the city's transfer station or directly to one of the regional management facilities including the TFC recycling facility, Wheelabrator WTE plant, or SPSA landfill. This management system serves as the baseline for purposes of the scenario analysis exercise.

Specific waste flow data for the City of Norfolk were not found; rather, data are presented at the SPSA-level (SPSA, 2016). Using data for waste generated and amount sent to the Norfolk transfer station per SPSA (2016) and the SPSA-regional estimates for the percentage of waste that is sent to recycling, WTE, and landfill disposal per SPSA (2016), the mass flow of MSW for the City of Norfolk was calculated. The results are shown in ***Table 11***, and these values are used for the scenario modeling exercise using the MSW DST.

**Table 11. Mass Flows of MSW for Simulation Scenarios including Base Case**

| Process | Percentage | Tonnage | Source |
|---|---|---|---|
| Collection | 100% | 95,000 tons | Reported (SPSA, 2016) |
| Transfer | 82% (of collected) | 77,874 tons | Reported (SPSA, 2016) |
| Recycling | 33% (of collected) | 31,065 tons | Calculated (based on SPSA, 2016) |
| WTE* | 21% (of collected) | 20,324 tons | Calculated (based on SPSA, 2016) |
| Landfill | 46% (of collected) | 43,611 tons | Calculated (based on SPSA, 2016) |

* No waste is sent to WTE in Alternative 4 and the 20,324 tons is instead sent to landfill.

Identifying alternative MSW management scenarios based on probable future climate-induced impacts in the Norfolk region is not straightforward. Determining which facilities would be impacted and taken off-line was informed by inundation estimates and maps detailing flood boundaries and facility locations but should be considered hypothetical. The city does not have a formal plan or set alternative sites in case of emergencies. Rather, their approach is to determine which facilities have the capability/capacity to handle waste at the time of the emergency. I-WASTE and SPSA (2016) are then used to identify waste facilities outside the Norfolk region that might serve as alternative sites should the facilities that service the City of Norfolk be inundated. Reasonable and likely alternatives for each facility have been identified and assumed.

***Table 12*** lists, and ***Figure 13*** illustrates on a map, the current (base case) facilities that service the City of Norfolk and assumed alternative facilities should any base case facilities be inundated or otherwise taken off-line. Three degrees of climate-induced impact—low, medium, and high—were used to provide a range of base case facilities that may be taken off-line, and alternative facilities employed. As shown in ***Table 12***, moving from the base case to Alternative 1 assumes low impact and only the transfer station is affected. Alternative 2 assumes medium impact where the transfer station, materials recovery facility (MRF), and WTE plant are affected. Alternative 3 assumes high impact where all facilities are impacted. In no case was it projected that the SPSA landfill would be inundated, even at the highest SLR estimate. However, the SPSA landfill was taken offline in Alternatives 3 and 4 for illustrative purposes. For Alternative 4, it is assumed that the recycling level remains the same all waste sent to WTE would instead be sent to the Bethel landfill.

**Table 12. Facilities and Tonnages Used for Base Case and Alternative MSW Management Scenarios**

| Scenario | Transfer Station | Recycling | WTE | Landfill |
|---|---|---|---|---|
| **Base Case (current)** | SPSA – Norfolk | TFC – Norfolk | Wheelabrator – Portsmouth | SPSA – Norfolk |
| 95,000 tons | 77,874 tons | 31,065 tons | 20,324 tons | 43,611 tons |
| **Alternative 1 (low impact)** | SPSA – Chesapeake | TFC – Norfolk | Wheelabrator – Portsmouth | SPSA – Norfolk |
| 95,000 tons | 77,874 tons | 31,065 tons | 20,324 tons | 43,611 tons |
| **Alternative 2 (med impact)** | SPSA – Chesapeake | TFC – Chester | Covanta – Alexandria | SPSA – Norfolk |
| 95,000 tons | 77,874 tons | 31,065 tons | 20,324 tons | 43,611 tons |
| **Alternative 3 (high impact)** | SPSA – Chesapeake | TFC – Chester | Covanta – Alexandria | USA Waste – Bethel |
| 95,000 tons | 77,874 tons | 31,065 | 20,324 tons | 43,611 tons |
| **Alternative 4 (high, no WTE)** | SPSA – Chesapeake | TFC – Chester | NA | USA Waste – Bethel |
| 95,000 tons | 77,874 tons | 31,065 tons | 0 tons | 63,935 tons |

Key information and assumptions employed by waste management activity or process for the scenario analysis are provided in ***Table 13***. With respect to waste collection and potential climate-induced impacts to collection service and routing, Norfolk's complex geography with peninsulas connected by bridges and tunnels creates few alternative routes (Mitchell, 2013). In lieu of having quantitative estimates of collection routing changes that may result from routes being flooded or otherwise impacted, an assumption was made that the low, medium, and high levels of impact equated to a 10, 20, and 30 percent increase in collection route distance, respectively.

The distance between collection and the alternative transfer station and landfill are assumed to be the same as the current facilities. The distance between collection and the alternative MRF is 70 miles, and WTE is 140 miles, which are significantly different from the distances to current facilities. The current and alternative MRF, WTE, and landfill facilities assume the same design and performance.

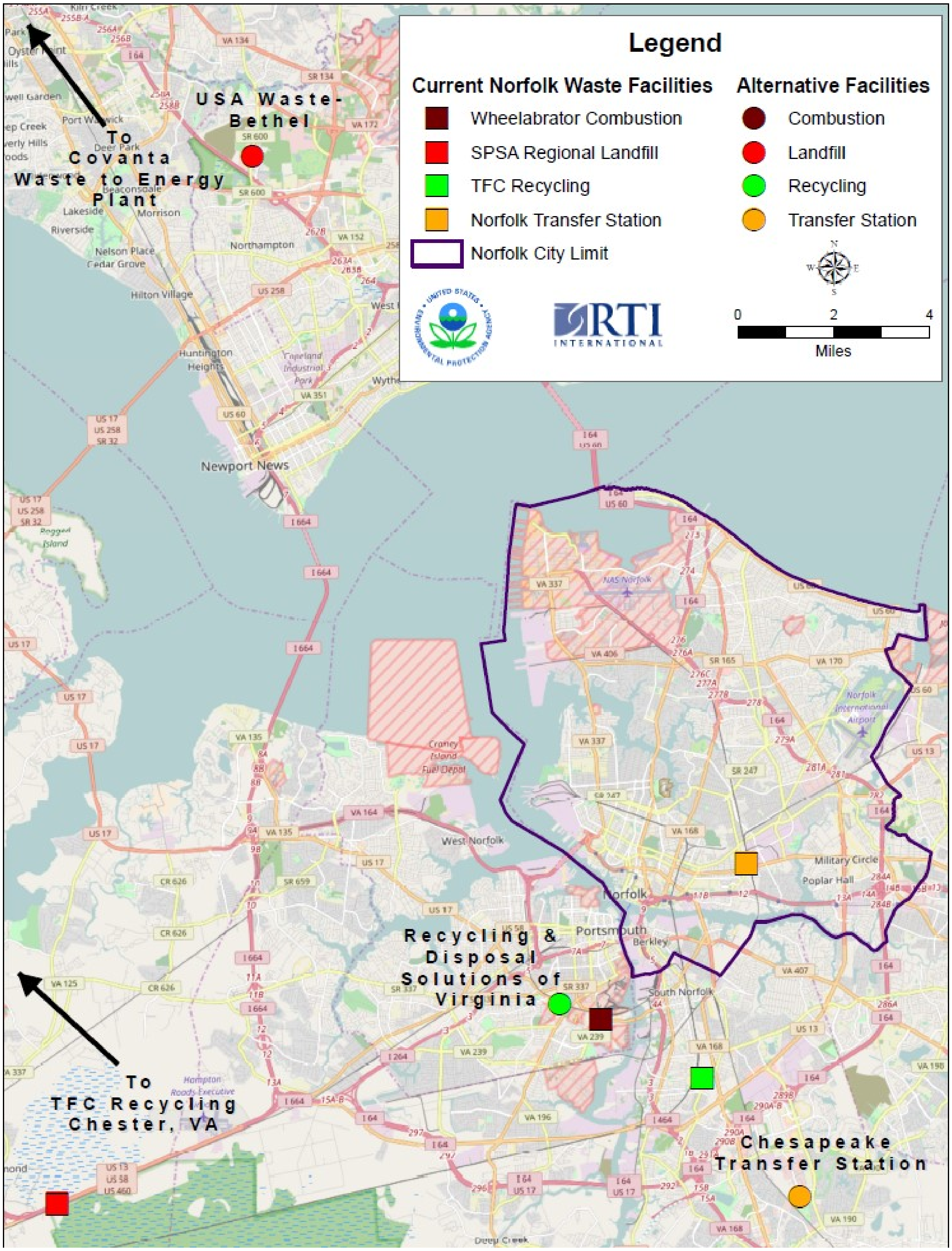



**Figure 13. Location of Base Case and Assumed Alternative MSW Management Facilities**

**Table 13. Key Assumptions Used in the Scenario Analysis**

| Parameter | Current Case | Alternative Cases |
|---|---|---|
| ***General*** | | |
| Waste Generation | 95,000 tons | 95,000 tons |
| Waste Composition | U.S. Average (***Table 14***) | U.S. Average (***Table 14***) |
| Waste Collection Frequency | 1 time per week | 1 time per week |
| | | |
| ***Transportation Distances**** | | |
| Collection to Transfer Station | 10 miles one way | 10 miles one way |
| Collection to MRF | 10 miles one way | 70 miles one way |
| Collection to WTE | 10 miles one way | 140 miles one way |
| Collection to Landfill | 10 miles one way | 10 miles one way |
| | | |
| ***Recycling (MRF)*** | | |
| Basic Design | Single-stream; semi-automated | Single-stream; semi-automated |
| Assumed Offset | Average utility grid mix of fuels | Average utility grid mix of fuels |
| | | |
| ***WTE*** | | |
| Basic Design | Mass-burn | Mass-burn |
| Plant Efficiency | 17,500 Btu/kWh | 17,500 Btu/kWh |
| Metals Recovery | Ferrous only; 95% from ash | Ferrous only; 95% from ash |
| Assumed Electricity Offset | Regional average (***Table 15***) | Regional average (***Table 15***) |
| | | |
| ***Landfill*** | | |
| Basic Design | Conventional, Subtitle D Type | Conventional, Subtitle D Type |
| Landfill Gas Collection Average Efficiency | 75% | 75% |
| Landfill Gas Management | Energy recovery | Energy recovery |
| Assumed Electricity Offset | Regional average (***Table 15***) | Regional average (***Table 15***) |

*The distances to the facilities in the current case are in the 10-14 miles range from the centroid of the city. We assumed 10 miles one way in our analysis. Transportation distances are assumed to increase in 10 percent increments per the base-low-med-high impact cases. For example, base case collection cost, energy, and emission results are increased 10 percent in the low impact case to account for an assumed 10 percent increase in transportation distance due to route flooding and subsequent rerouting.

**Table 14. Assumed Waste Composition Based on U.S. Average**

| Waste Item | Percent (by mass) |
|---|---|
| Leaves | 4.0% |
| Grass | 5.4% |
| Branches | 4.0% |
| Newspaper | 4.7% |
| Corrugated Cardboard | 12.4% |
| Office Paper | 5.7% |
| Phone Books | 0.7% |
| Books | 1.1% |
| Magazines | 1.3% |
| 3rd Class Mail | 2.5% |
| High-density polyethylene (HDPE) - Translucent | 1.9% |
| HDPE - Pigmented | 1.9% |
| Polyethylene terephthalate (PET) | 8.6% |
| Ferrous Cans | 0.9% |
| Ferrous Metal | 5.9% |
| Aluminum | 1.4% |
| Glass - Clear | 2.7% |
| Glass - Brown | 0.9% |
| Glass - Green | 1.0% |
| Food Waste | 14% |
| Miscellaneous Combustible | 15% |
| Miscellaneous Non-Combustible | 4.0% |

**Table 15. Regional Average Electricity Grid Mix of Fuels Used in the Scenario Analysis**

| Fuel | Percent |
|---|---|
| Coal | 46.6% |
| Oil | 5.9% |
| Natural gas | 3.8% |
| Nuclear | 41.7% |
| Hydro | 2.0% |
| Wood | 0.0% |
| Other | 0.0% |

Source: Mid-Atlantic Area Council of the National Electric Reliability Council.

## 9.2. Scenario Results

In this section, the results from the modeling exercise using the MSW DST are presented. Summary-level results representing net totals for the scenarios modeled (see Section 5.1) using the MSW DST are presented in ***Table 16***. Detailed results by scenario are provided in ***Attachment A***.

***Figures 14, 15, and 16*** display the results for each scenario on a bar chart. The tabular and charted results are grouped as follows:

1. Non-optimized (simulated mass flow according to ***Table 11***)
2. Cost-optimized (no mass flow constraints and MSW DST set to find minimum cost solution)
3. GHG-optimized (no mass flow constraints and MSW DST set to find minimum GHG solution)

Since the alternative facilities are assumed to be identical in terms of design and operating parameters, based on the available data and information about the current and alternative facilities, the difference in alternative scenario results from the base case results are primarily due to the differences in collection and transportation distances. Some other findings/observations are as follows:

- For the non-optimized scenarios, the cost and environmental impacts generally follow an increasing trend from the base case to Alternative 3 (high impact).
- For all cases, the unconstrained cost-optimized (i.e., cheapest) solution was found to be MSW collection and landfill disposal.
- For scenarios in which WTE was excluded, cost generally decreased but environmental impacts increased due to the subsequent removal of energy and materials recovery benefits associated with WTE.
- Level of diversion varied from one scenario set to another. For example, in the simulation scenarios, the recycling rate was 32%, in the cost-optimization scenarios, there was no recycling as disposing MSW to landfill is the cheapest option. However, in the GHG-optimization scenarios, except for Alt 4, the recycling rate decreased to 27%, with increased utilization of the WTE facility. these scenarios resulted in utilization of landfill to dispose WTE ash, and broken glass from the Material Recovery Facility. In the case of Alt 4, the recycling rate increased to 48%, while the rest of the MSW is disposed to landfills as this scenario prohibit the use of WTE facility.

### 9.2.1. Cost

Net total cost results (reported in 2017 dollars) for each scenario are charted in ***Figure 14*** and include capital, labor, and operating and maintenance (O&M) costs. Revenue from the recovery and sale of energy and recyclable materials is netted out of the cost results. The non-optimized results display an increase in cost for waste management as the level of climate-induced impact increases from the base case through the alternative (low-medium-high impact) cases. The net difference in cost between the base case and the alternative scenarios increases as collection and transportation distances increase, moving from low to high impact. In the Alternative 4 results, there is a slight decrease in net cost as compared to the base case due to the exclusion of WTE and instead sending that tonnage of MSW to the alternative landfill. 100% utilization of landfill leads to least-expensive option.

For the cost-optimized scenarios—where all cases found MSW collection and landfill disposal to be cheapest—the results as shown in ***Figure 14*** display the significant decrease in cost when recycling and WTE are not utilized.

For the GHG-optimized scenarios, recycling and energy recovery (via WTE) were maximized and only residual waste resulting from recycling and WTE was landfilled. As shown in ***Figure 14***, the GHG-optimized results exhibit significant increases in cost. As shown in ***Figures 15*** and ***16***, however, the GHG-optimized results provide significant increases in environmental benefits per energy consumption and GHG emissions reductions. Also shown in Figure 14, when WTE is excluded from the analysis (per Alternative 4), cost for the GHG-optimized case is significantly lower, but carbon emission reductions are also lower (as shown in ***Figure 16***). This differential represents the higher cost of WTE in terms of electricity but also the tradeoff between that higher cost and reduction in energy consumption and GHG emissions that can result from WTE.

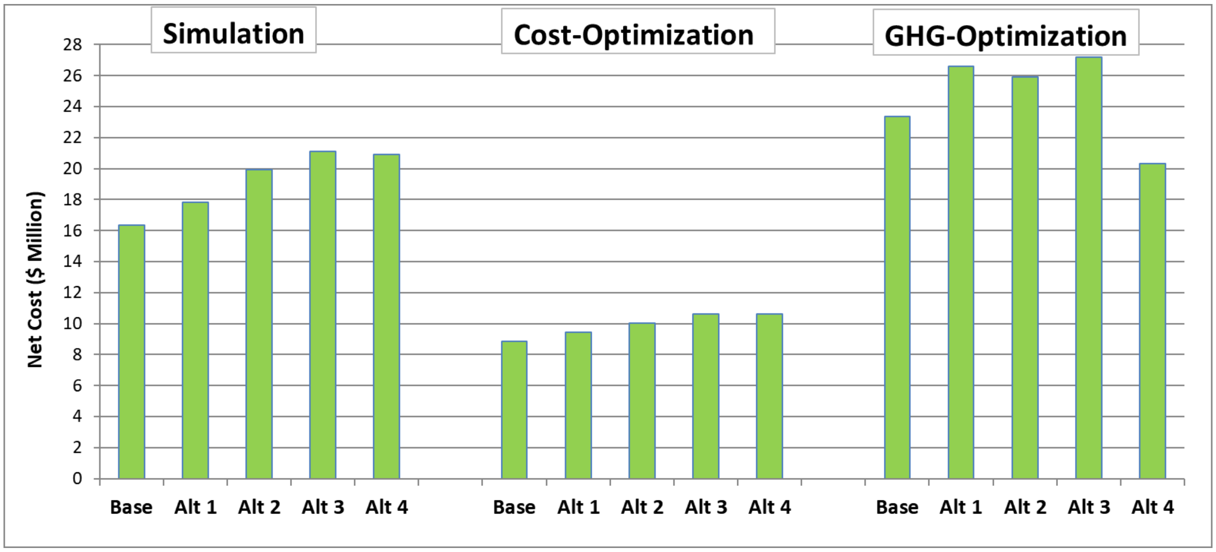
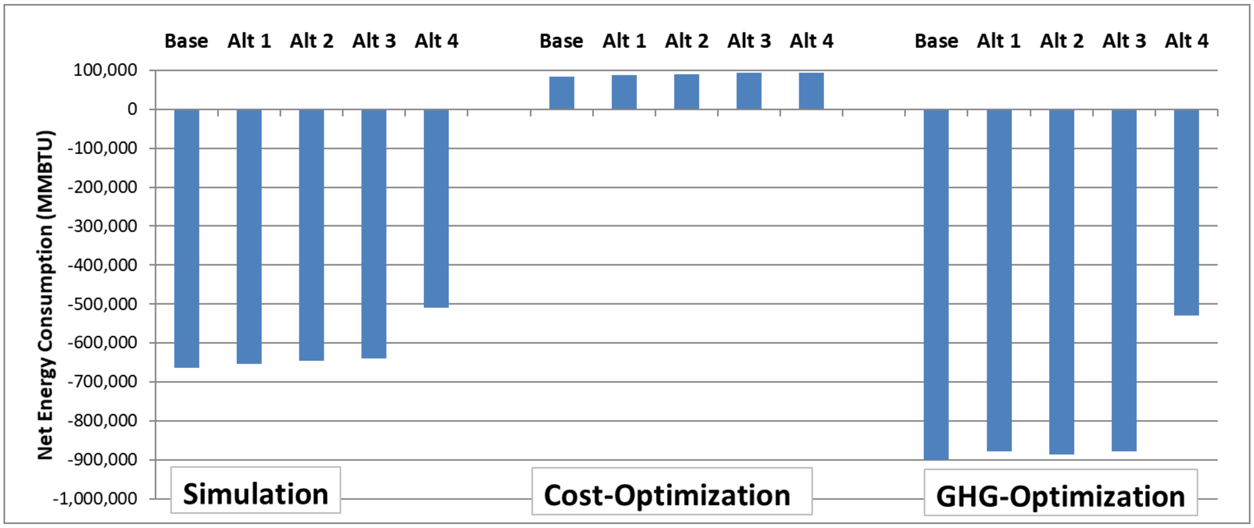



**Figure 14. Net Total Cost Results for Scenarios Modeled**

### 9.2.2. Energy Consumption

Net total energy consumption results for each scenario are charted in ***Figure 15***. The non-optimized results display an increase in energy consumption for waste management as the level of climate-induced impact increases from the base case through the alternative (low-medium-high impact) cases. Changes in energy consumption were not found to be as significant, as non-transportation activities (e.g., landfill gas, energy, materials recovery) tend to drive these results. However, in the Alternative 4 results, there is a more significant net increase in energy consumption as compared to the base case due to the exclusion of WTE (and forgoing significant energy recovery) and instead sending that tonnage of MSW to the alternative landfill.




Note: Negative energy consumption indicates that more life cycle energy is saved via recycling, WTE, and landfill gas-to-energy activities than is required to collect, transport, and manage the MSW.

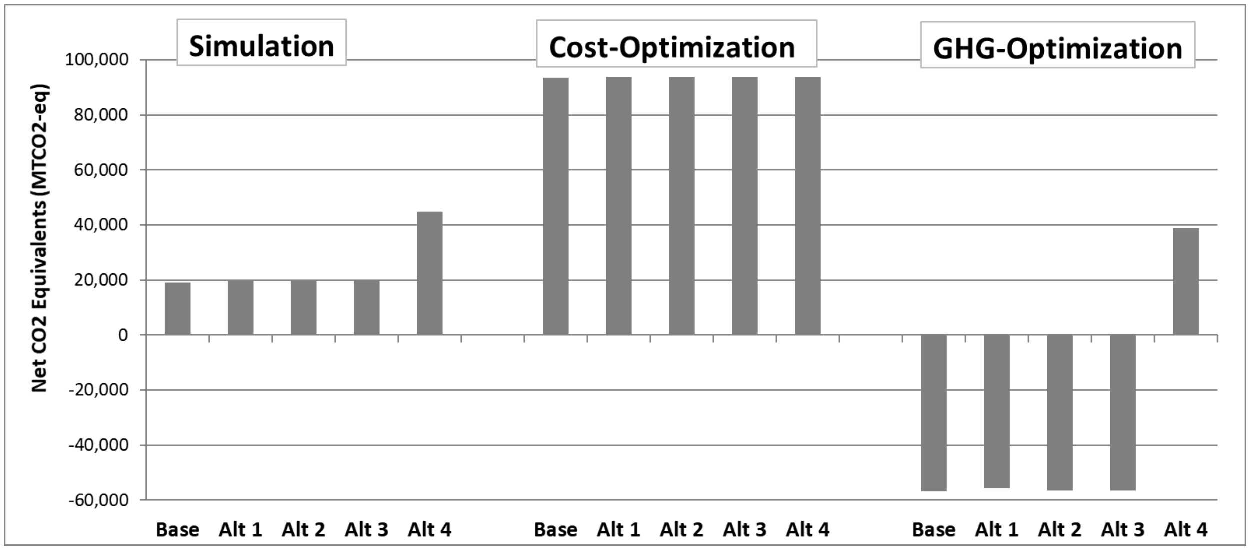
**Figure 15. Net Total Energy Consumption Results for Scenarios Modeled in Million BTUs**

For the cost-optimized scenarios—where all cases found MSW collection and landfill disposal to be cheapest—the results as shown in ***Figure 15*** display the significant increase in energy consumption when recycling and WTE are not utilized.

For the GHG-optimized scenarios, recycling and energy recovery (via WTE) were maximized and only residual waste resulting from recycling and WTE was landfilled. As shown in ***Figure 15***, significant reductions in energy consumption can be achieved but as shown in ***Figure 14***, a tradeoff is a corresponding significant increase in cost. Also shown in ***Figure 15***, when WTE is excluded from the analysis (per Alternative 4), energy consumption is significantly greater for the non-optimized and GHG-optimized cases. This differential represents the energy potential of WTE in terms of electricity energy generation as well as energy savings associated with metals recovery for recycling.

### 9.2.3. Carbon Emissions

Net total carbon emission results for each scenario are charted in ***Figure 16***. The non-optimized results display an increase in cost for waste management as the level of climate-induced impact increases from the base case through the alternative (low-medium-high impact) cases. Changes in GHG emissions, though, were not found to be as significant, as non-transportation activities (e.g., landfill gas, energy and materials recovery) tend to drive these results. However, in the Alternative 4 results, there is a more significant net increase in carbon emissions as compared to the base case due to the exclusion of WTE (and forgoing significant energy and metals recovery and associated GHG emission reduction benefits) and instead sending that tonnage of MSW to the alternative landfill.




Note: negative carbon emission indicates that more life cycle carbon is saved via recycling, WTE, and landfill gas-to-energy activities than is required to collect, transport, and manage the MSW.

**Figure 16. Net Total Carbon Emission Results for Scenarios Modeled in Metric Tons of CO2 equivalent**

For the cost-optimized scenarios—where all cases found MSW collection and landfill disposal to be cheapest—the results as shown in ***Figure 16*** display the significant increase in carbon emissions when recycling and WTE are not utilized.

For the GHG-optimized scenarios, recycling and energy recovery (via WTE) were maximized and only residual waste resulting from recycling and WTE was landfilled. As shown in ***Figure 16***, significant reductions in carbon emissions can be achieved but as shown in ***Figure 14***, a tradeoff is a corresponding significant increase in cost. Also shown in ***Figure 16*** is that when WTE is excluded from the analysis (per Alternative 4), carbon emissions are significantly greater for the nonoptimized and GHG-optimized cases. This differential represents the benefit of WTE in terms of electricity energy generation, metals recovery for recycling, and associated GHG emissions reduction benefits.

## 9.3. Sensitivity Analyses

One limitation of the scenarios as analyzed is that it was assumed that the current mass flow of MSW was adhered to (non-optimize scenarios) or there were no mass flow constraints (the cost and GHG optimized scenarios). Scenarios that maintained part of the current mass flow (e.g., tonnage currently recycled/utilized in WTE) were not analyzed. However, selected sensitivity analyses were performed to address the targeted topics of recycling rates and landfill gas collection efficiency. Results from these sensitivity analyses are presented in ***Table 16***.

A sensitivity analysis was performed on the recycling rate for the cost-optimized scenarios (where the cheapest option was always found to be landfill disposal) to understand its impact on cost and environmental results. Iterations of the MSW DST were run changing the recycling rate in 5 percent increments. A 5 percent change in recycling rate was found to equate to approximately a 5 percent change in net total cost for the cost-optimized scenarios.

A sensitivity analysis was also performed on landfill gas collection efficiency to understand its impact on (in particular) carbon emission results. Iterations of the MSW DST were run changing the landfill gas collection efficiency in 5 percent increments. A 5 percent change in gas collection efficiency was found to equate to an approximate 6 to 7 percent change in landfill carbon (methane and total carbon equivalent emission) results. While landfill carbon emissions are significant in cases where significant amounts of MSW are landfilled, recycling and energy recovery (via WTE) can provide significant carbon emissions reductions. In the non-optimized base case, for example, recycling and WTE reduce total landfill carbon emissions by half.

# 10. Concluding Remarks

This report outlines a methodology to evaluate risks and vulnerabilities on waste management infrastructure due to climate-induced events. The data sources, methods and tools presented can be applied to any other coastal community to evaluate their vulnerabilities. This project intended to provide a guideline for better understanding of risks posed by changing climate (e.g., SLR, storm surge, flooding, tidal flooding) and possible impacts on waste management infrastructure and its operation. We utilized U.S. EPA's I-WASTE and MSW DST for data and scenario building. Climate-related impacts can be categorized into three components, i.e., temperature, precipitation, and SLR. Literature has been focused on precipitation and SLR impacts rather than temperature related impacts. Therefore, the study focused on precipitation and SLR impacts.

The City of Norfolk was selected as a case study site through discussions among the project team based on its coastal location, availability of data, and proximity to a varied set of waste facilities. The coastal region of Virginia is the second most climate-vulnerable area in the U.S., behind New Orleans, and is currently being impacted by SLR (City of Virginia Beach, 2009). Historic precipitation and SLR data were collected and overlaid with the waste management infrastructure (specifically keeping in mind location, access and engineering design). A scenario-based approach was taken to understand and incorporate future uncertainty of the extent and impact of these events into the long- term waste management planning. The results from this project are intended for use in gaining a better understanding of the nature of climate-induced impacts on coastal communities, and how those impacts can affect waste management infrastructure and long-term planning needs. The study presented options available for minimizing impacts and potential cost implications for municipalities. There are some caveats to this analysis. For example, the storm surge and SLR scenarios looked at individual facility flooding however, other factors might influence the availability of the waste management facility such as inundation of access roads, or worker availability in the event of a storm. These aspects of waste management could be covered under emergency management planning process. The study is not intended for emergency management or analysis of options during an event.

The insights gathered from scenario analysis revealed that there can be opportunities to be leveraged if intensity and frequency of precipitation events continue to increase for the region. Planners could utilize these opportunities to better design the system to be more resilient and responsive at cheaper costs, and in some cases resulting in better environmental outcomes (e.g., reduced air emissions).

## Table 16. Summary Level Scenario Results (Net Totals)

| | | Non-Optimized | | | | | Cost-Optimized | | | | | GHG-Optimized | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Parameter** | **Units** | **Basecase** | **Alt 1** | **Alt 2** | **Alt 3** | **Alt 4** | **Basecase** | **Alt 1** | **Alt 2** | **Alt 3** | **Alt 4** | **Basecase** | **Alt 1** | **Alt 2** | **Alt 3** | **Alt 4** |
| **Cost** | $ | 16,360,200 | 17,829,200 | 19,923,240 | 21,110,240 | 20,915,000 | 8,880,000 | 9,459,000 | 10,038,000 | 10,617,000 | 10,617,000 | 23,343,180 | 26,588,680 | 25,891,180 | 27,165,180 | 20,312,686 |
| | | | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 |
| **Energy Consumption** | MMBTU | -663,874 | -653,224 | -646,214 | -640,034 | -510,620 | 84,400 | 87,420 | 90,440 | 93,460 | 93,460 | -899,776 | -879,016 | -886,236 | -879,466 | -529,350 |
| | | | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 |
| **Air Emissions** | | | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 |
| Total Particulate Matter | lb | -213,097 | -212,146 | -211,915 | -211,855 | -185,752 | 4,302 | 4,332 | 4,362 | 4,393 | 4,393 | -237,718 | -234,877 | -237,596 | -237,534 | -206,152 |
| Nitrogen Oxides | lb | -291,204 | -281,074 | -276,054 | -272,124 | -235,500 | 39,000 | 40,960 | 42,920 | 44,880 | 44,880 | -338,980 | -315,700 | -331,040 | -327,070 | -261,410 |
| Hydrocarbons (non CH4) | lb | -290,263 | -287,268 | -286,303 | -285,788 | -312,019 | 8,010 | 8,535 | 9,060 | 9,585 | 9,585 | -677,713 | -669,477 | -676,681 | -676,165 | -322,582 |
| Sulfur Oxides | lb | -655,347 | -653,085 | -652,253 | -651,741 | -492,523 | 7,660 | 7,914 | 8,168 | 8,422 | 8,422 | -855,563 | -849,577 | -854,531 | -854,015 | -500,762 |
| Carbon Monoxide | lb | -661,977 | -654,183 | -651,489 | -649,805 | -627,978 | 21,180 | 22,028 | 22,876 | 23,724 | 23,724 | -483,076 | -462,151 | -479,306 | -477,421 | -648,285 |
| Carbon Dioxide Biogenic | lb | 106,002,107 | 106,002,399 | 106,002,552 | 106,002,671 | 93,003,062 | 71,500,598 | 71,500,658 | 71,500,718 | 71,500,777 | 71,500,777 | 153,402,916 | 153,403,576 | 153,403,159 | 153,403,280 | 89,602,636 |
| Carbon Dioxide Fossil | TC-eq | -52,305,700 | -51,410,300 | -51,088,900 | -50,907,500 | -44,132,800 | 2,470,000 | 2,597,000 | 2,724,000 | 2,851,000 | 2,851,000 | -110,618,990 | -108,185,390 | -110,251,790 | -110,068,190 | -47,203,200 |
| Ammonia | lb | -1,639 | -1,638 | -1,638 | -1,638 | -1,622 | 2 | 2 | 2 | 2 | 2 | -123 | -120 | -123 | -123 | -1,636 |
| Lead | lb | -15 | -15 | -15 | -15 | -14 | 0 | 0 | 0 | 0 | 0 | 5 | 5 | 5 | 5 | -14 |
| Methane | lb | 3,933,598 | 3,933,793 | 3,933,894 | 3,933,975 | 5,817,935 | 8,030,400 | 8,030,440 | 8,030,480 | 8,030,520 | 8,030,520 | -132,366 | -131,927 | -132,204 | -132,122 | 5,429,324 |
| Hydrochloric Acid | lb | -5,741 | -5,740 | -5,739 | -5,738 | -2,027 | 1,893 | 1,893 | 1,894 | 1,894 | 1,894 | -6,755 | -6,752 | -6,754 | -6,753 | -1,801 |
| Carbon Equivalents | lb | 6,244 | 6,368 | 6,412 | 6,437 | 13,817 | 27,674 | 27,691 | 27,709 | 27,726 | 27,726 | -15,565 | -15,231 | -15,514 | -15,489 | 12,091 |
| | | | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 |
| **Ancillary Solid Waste** | lb | -15,280,714 | -15,274,234 | -15,270,804 | -15,268,074 | -11,227,550 | 427,400 | 428,740 | 430,080 | 431,420 | 431,420 | -16,678,860 | -16,664,370 | -16,673,440 | -16,670,730 | -11,082,940 |
| | | | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 |
| **Water Releases** | | | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 |
| Dissolved Solids | lb | -189,413 | -187,749 | -186,885 | -186,201 | -154,569 | 8,040 | 8,383 | 8,726 | 9,069 | 9,069 | -485,379 | -481,613 | -483,987 | -483,291 | -164,412 |
| Suspended Solids | lb | 10,868 | 10,905 | 10,925 | 10,941 | 14,422 | 348 | 356 | 364 | 372 | 372 | -23,544 | -23,458 | -23,512 | -23,496 | 14,172 |
| BOD | lb | 109,595 | 109,601 | 109,605 | 109,607 | 141,367 | 83,213 | 83,214 | 83,215 | 83,217 | 83,217 | 9,548 | 9,562 | 9,554 | 9,556 | 134,459 |
| COD | lb | 97,864 | 97,906 | 97,927 | 97,945 | 187,173 | 232,085 | 232,094 | 232,102 | 232,111 | 232,111 | -5,970 | -5,876 | -5,936 | -5,918 | 177,399 |
| Oil | lb | 9,572 | 9,611 | 9,631 | 9,647 | 13,694 | 19,179 | 19,187 | 19,195 | 19,203 | 19,203 | -2,600 | -2,513 | -2,568 | -2,552 | 12,081 |
| Sulfuric Acid | lb | -643 | -643 | -643 | -642 | -642 | 1 | 1 | 1 | 1 | 1 | -2,054 | -2,054 | -2,054 | -2,054 | -647 |
| Iron | lb | 2,871 | 2,872 | 2,872 | 2,873 | 3,099 | 23 | 23 | 23 | 23 | 23 | -3,248 | -3,246 | -3,247 | -3,247 | 3,131 |
| Ammonia | lb | 546,868 | 546,869 | 546,869 | 546,869 | 798,878 | 127,001 | 127,002 | 127,002 | 127,002 | 127,002 | -835 | -833 | -834 | -834 | 798,878 |
| Copper | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -6 | -6 | -6 | -6 | 0 |
| Cadmium | lb | -7 | -7 | -7 | -7 | -6 | 2 | 2 | 2 | 2 | 2 | -8 | -8 | -8 | -8 | -6 |
| Arsenic | lb | 3 | 3 | 3 | 3 | 5 | 26 | 26 | 26 | 26 | 26 | -2 | -2 | -2 | -2 | 5 |
| Mercury | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Phosphate | lb | 1,130 | 1,130 | 1,130 | 1,131 | 1,678 | 1,700 | 1,700 | 1,700 | 1,700 | 1,700 | -196 | -196 | -196 | -196 | 1,676 |
| Selenium | lb | 2 | 2 | 2 | 2 | 4 | 1 | 1 | 1 | 1 | 1 | -6 | -6 | -6 | -6 | 4 |
| Chromium | lb | 3 | 3 | 3 | 3 | 10 | 23 | 23 | 23 | 23 | 23 | -20 | -20 | -20 | -20 | 8 |
| Lead | lb | 2 | 2 | 2 | 2 | 3 | 4 | 4 | 4 | 4 | 4 | -4 | -4 | -4 | -4 | 3 |
| Zinc | lb | 49 | 49 | 49 | 49 | 51 | 0 | 0 | 0 | 0 | 0 | -23 | -23 | -23 | -23 | 51 |

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# Appendix A: Detailed Scenario Modeling Results

## Table A-1. Base Case Non-optimized MSW DST Results

| Parameter | Units | Rec Collection | MSW Collection | Transfer Station | MRF | WTE | Landfill | Ash-landfill | Transport | Remfg | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| **Cost** | $ | 6,740,000 | 5,130,000 | 224,000 | 3,450,000 | 1,630,000 | 1,420,000 | 42,200 | 244,000 | -2,520,000 | 16,360,200 |
| | | | | | | | | | | | 0 |
| **Energy Consumption** | MBTU | 36,000 | 25,800 | 1,040 | 13,000 | -123,000 | 26,500 | 276 | 5,510 | -649,000 | -663,874 |
| | | | | | | | | | | | 0 |
| **Air Emissions** | | | | | | | | | | | 0 |
| Total Particulate Matter | lb | 311 | 297 | 448 | 5,390 | -17,000 | 2,350 | 17 | 1,090 | -206,000 | -213,097 |
| Nitrogen Oxides | lb | 20,100 | 19,200 | 5,910 | 20,900 | -30,700 | 10,600 | 186 | 7,600 | -345,000 | -291,204 |
| Hydrocarbons (non CH4) | lb | 0 | 5,150 | 736 | 970 | -507 | 1,280 | 48 | 3,060 | -301,000 | -290,263 |
| Sulfur Oxides | lb | 2,620 | 2,500 | 701 | 45,800 | -157,000 | 4,840 | 32 | 2,160 | -557,000 | -655,347 |
| Carbon Monoxide | lb | 9,980 | 6,860 | 1,480 | 2,440 | 2,140 | 6,570 | 63 | 7,490 | -699,000 | -661,977 |
| Carbon Dioxide Biogenic | lb | 612 | 586 | 40 | 654 | 30,800,000 | 38,700,000 | 3 | 212 | 36,500,000 | 106,002,107 |
| Carbon Dioxide Fossil | tons | 574,000 | 1,240,000 | 169,000 | 7,020,000 | -6,520,000 | 912,000 | 13,300 | 886,000 | -56,600,000 | -52,305,700 |
| Ammonia (Air) | lb | 0 | 0 | 0 | 1 | -3 | 1 | 0 | 1 | -1,640 | -1,639 |
| Lead (Air) | lb | 0 | 0 | 0 | 1 | -1 | 0 | 0 | 0 | -14.2 | -15 |
| Methane (CH4) | lb | 412 | 393 | 30 | 8,120 | -28,600 | 4,020,000 | 2 | 141 | -66,900 | 3,933,598 |
| Hydrochloric Acid | lb | 4 | 3 | 1 | 1,760 | -3,290 | 1,130 | 0 | 1 | -5,350 | -5,741 |
| Carbon Equivalents | lb | 80 | 171 | 23 | 984 | -987 | 13,800 | 2 | 121 | -7,950 | 6,244 |
| | | | | | | | | | | | 0 |
| **Ancillary Solid Waste** | lb | 14,000 | 13,300 | 1,260 | 972,000 | -3,460,000 | 374,000 | 96 | 4,630 | -13,200,000 | -15,280,714 |
| | | | | | | | | | | | 0 |
| **Water Releases** | | | | | | | | | | | 0 |
| Dissolved Solids | lb | 3,500 | 3,340 | 229 | 7,120 | -23,900 | 1,070 | 18 | 1,210 | -182,000 | -189,413 |
| Suspended Solids | lb | 80 | 76 | 5 | 648 | -2,280 | 110 | 1 | 28 | 12,200 | 10,868 |
| BOD | lb | 13 | 13 | 1 | 16 | -52 | 69,200 | 0 | 5 | 40,400 | 109,595 |
| COD | lb | 87 | 84 | 6 | 29 | -66 | 192,000 | 94 | 30 | -94,400 | 97,864 |
| Oil | lb | 81 | 78 | 5 | 13 | -8 | 8,770 | 189 | 28 | 416 | 9,572 |
| Sulfuric Acid | lb | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | -646 | -643 |
| Iron | lb | 2 | 2 | 0 | 64 | -223 | 5 | 0 | 1 | 3,020 | 2,871 |
| Ammonia | lb | 1 | 1 | 0 | 3 | -9 | 548,000 | 1 | 0 | -1,130 | 546,868 |
| Copper | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cadmium | lb | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | -8.29 | -7 |
| Arsenic | lb | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3 |
| Mercury | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -0.00474 | 0 |
| Phosphate | lb | 0 | 0 | 0 | 0 | 1 | 1,210 | 0 | 0 | -81.2 | 1,130 |
| Selenium | lb | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| Chromium | lb | 0 | 0 | 0 | 0 | -1 | 12 | 0 | 0 | -8.36 | 3 |
| Lead | lb | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | -0.0368 | 2 |
| Zinc | lb | 0 | 0 | 0 | 0 | -2 | 0 | 0 | 0 | 50 | 49 |

## Table A-2. Alternative 1 Non-Optimized MSW DST Results

| Parameter | Units | Rec Collection | MSW Collection | Transfer Station | MRF | WTE | Landfill | Ash-landfill | Transport | Remfg | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| **Cost** | $ | 7,414,000 | 5,643,000 | 224,000 | 3,450,000 | 1,630,000 | 1,420,000 | 42,200 | 526,000 | -2,520,000 | 17,829,200 |
| | | | | | | | | | 0 | | 0 |
| **Energy Consumption** | MBTU | 39,600 | 28,380 | 1,040 | 13,000 | -123,000 | 26,500 | 276 | 9,980 | -649,000 | -653,224 |
| | | | | | | | | | 0 | | 0 |
| **Air Emissions** | | | | | | | | | 0 | | 0 |
| Total Particulate Matter | lb | 342 | 327 | 448 | 5,390 | -17,000 | 2,350 | 17 | 1,980 | -206,000 | -212,146 |
| Nitrogen Oxides | lb | 22,110 | 21,120 | 5,910 | 20,900 | -30,700 | 10,600 | 186 | 13,800 | -345,000 | -281,074 |
| Hydrocarbons (non CH4) | lb | 0 | 5,665 | 736 | 970 | -507 | 1,280 | 48 | 5,540 | -301,000 | -287,268 |
| Sulfur Oxides | lb | 2,882 | 2,750 | 701 | 45,800 | -157,000 | 4,840 | 32 | 3,910 | -557,000 | -653,085 |
| Carbon Monoxide | lb | 10,978 | 7,546 | 1,480 | 2,440 | 2,140 | 6,570 | 63 | 13,600 | -699,000 | -654,183 |
| Carbon Dioxide Biogenic | lb | 673 | 645 | 40 | 654 | 30,800,000 | 38,700,000 | 3 | 384 | 36,500,000 | 106,002,399 |
| Carbon Dioxide Fossil | tons | 631,400 | 1,364,000 | 169,000 | 7,020,000 | -6,520,000 | 912,000 | 13,300 | 1,600,000 | -56,600,000 | -51,410,300 |
| Ammonia (Air) | lb | 0 | 0 | 0 | 1 | -3 | 1 | 0 | 3 | -1,640 | -1,638 |
| Lead (Air) | lb | 0 | 0 | 0 | 1 | -1 | 0 | 0 | 0 | -14.2 | -15 |
| Methane (CH4) | lb | 453 | 432 | 30 | 8,120 | -28,600 | 4,020,000 | 2 | 255 | -66,900 | 3,933,793 |
| Hydrochloric Acid | lb | 4 | 4 | 1 | 1,760 | -3,290 | 1,130 | 0 | 2 | -5,350 | -5,740 |
| Carbon Equivalents | lb | 88 | 188 | 23 | 984 | -987 | 13,800 | 2 | 220 | -7,950 | 6,368 |
| | | | | | | | | | 0 | | 0 |
| **Ancillary Solid Waste** | lb | 15,400 | 14,630 | 1,260 | 972,000 | -3,460,000 | 374,000 | 96 | 8,380 | -13,200,000 | -15,274,234 |
| | | | | | | | | | 0 | | 0 |
| **Water Releases** | | | | | | | | | 0 | | 0 |
| Dissolved Solids | lb | 3,850 | 3,674 | 229 | 7,120 | -23,900 | 1,070 | 18 | 2,190 | -182,000 | -187,749 |
| Suspended Solids | lb | 88 | 84 | 5 | 648 | -2,280 | 110 | 1 | 50 | 12,200 | 10,905 |
| BOD | lb | 14 | 14 | 1 | 16 | -52 | 69,200 | 0 | 8 | 40,400 | 109,601 |
| COD | lb | 96 | 92 | 6 | 29 | -66 | 192,000 | 94 | 55 | -94,400 | 97,906 |
| Oil | lb | 89 | 85 | 5 | 13 | -8 | 8,770 | 189 | 51 | 416 | 9,611 |
| Sulfuric Acid | lb | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | -646 | -643 |
| Iron | lb | 2 | 2 | 0 | 64 | -223 | 5 | 0 | 1 | 3,020 | 2,872 |
| Ammonia (Water) | lb | 2 | 1 | 0 | 3 | -9 | 548,000 | 1 | 1 | -1,130 | 546,869 |
| Copper | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cadmium | lb | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | -8.29 | -7 |
| Arsenic | lb | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3 |
| Mercury (Water) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -0.00474 | 0 |
| Phosphate | lb | 0 | 0 | 0 | 0 | 1 | 1,210 | 0 | 0 | -81.2 | 1,130 |
| Selenium | lb | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| Chromium | lb | 0 | 0 | 0 | 0 | -1 | 12 | 0 | 0 | -8.36 | 3 |
| Lead (Water) | lb | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | -0.0368 | 2 |
| Zinc | lb | 0 | 0 | 0 | 0 | -2 | 0 | 0 | 0 | 50 | 49 |

## Table A-3. Alternative 2 Non-Optimized MSW DST Results

| Parameter | Units | Rec Collection | MSW Collection | Transfer Station | MRF | WTE | Landfill | Ash-landfill | Transport | Remfg | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| **Cost** | $ | 8,088,000 | 6,156,000 | 224,000 | 3,450,000 | 1,630,000 | 1,420,000 | 42,200 | 1,433,040 | -2,520,000 | 19,923,240 |
| | | | | | | | | | | | |
| **Energy Consumption** | MBTU | 43,200 | 30,960 | 1,040 | 13,000 | -123,000 | 26,500 | 276 | 10,810 | -649,000 | -646,214 |
| | | | | | | | | | | | |
| **Air Emissions** | | | | | | | | | | | |
| Total Particulate Matter | lb | 373 | 356 | 448 | 5,390 | -17,000 | 2,350 | 17 | 2,150 | -206,000 | -211,915 |
| Nitrogen Oxides | lb | 24,120 | 23,040 | 5,910 | 20,900 | -30,700 | 10,600 | 186 | 14,890 | -345,000 | -276,054 |
| Hydrocarbons (non CH4) | lb | 0 | 6,180 | 736 | 970 | -507 | 1,280 | 48 | 5,990 | -301,000 | -286,303 |
| Sulfur Oxides | lb | 3,144 | 3,000 | 701 | 45,800 | -157,000 | 4,840 | 32 | 4,230 | -557,000 | -652,253 |
| Carbon Monoxide | lb | 11,976 | 8,232 | 1,480 | 2,440 | 2,140 | 6,570 | 63 | 14,610 | -699,000 | -651,489 |
| Carbon Dioxide Biogenic | lb | 734 | 703 | 40 | 654 | 30,800,000 | 38,700,000 | 3 | 417 | 36,500,000 | 106,002,552 |
| Carbon Dioxide Fossil | tons | 688,800 | 1,488,000 | 169,000 | 7,020,000 | -6,520,000 | 912,000 | 13,300 | 1,740,000 | -56,600,000 | -51,088,900 |
| Ammonia (Air) | lb | 0 | 0 | 0 | 1 | -3 | 1 | 0 | 3 | -1,640 | -1,638 |
| Lead (Air) | lb | 0 | 0 | 0 | 1 | -1 | 0 | 0 | 0 | -14.2 | -15 |
| Methane (CH4) | lb | 494 | 472 | 30 | 8,120 | -28,600 | 4,020,000 | 2 | 276 | -66,900 | 3,933,894 |
| Hydrochloric Acid | lb | 4 | 4 | 1 | 1,760 | -3,290 | 1,130 | 0 | 2 | -5,350 | -5,739 |
| Carbon Equivalents | lb | 96 | 205 | 23 | 984 | -987 | 13,800 | 2 | 239 | -7,950 | 6,412 |
| | | | | | | | | | | | |
| **Ancillary Solid Waste** | lb | 16,800 | 15,960 | 1,260 | 972,000 | -3,460,000 | 374,000 | 96 | 9,080 | -13,200,000 | -15,270,804 |
| | | | | | | | | | | | |
| **Water Releases** | | | | | | | | | | | |
| Dissolved Solids | lb | 4,200 | 4,008 | 229 | 7,120 | -23,900 | 1,070 | 18 | 2,370 | -182,000 | -186,885 |
| Suspended Solids | lb | 96 | 91 | 5 | 648 | -2,280 | 110 | 1 | 54 | 12,200 | 10,925 |
| BOD | lb | 16 | 15 | 1 | 16 | -52 | 69,200 | 0 | 9 | 40,400 | 109,605 |
| COD | lb | 105 | 100 | 6 | 29 | -66 | 192,000 | 94 | 60 | -94,400 | 97,927 |
| Oil | lb | 98 | 93 | 5 | 13 | -8 | 8,770 | 189 | 55 | 416 | 9,631 |
| Sulfuric Acid | lb | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | -646 | -643 |
| Iron | lb | 2 | 2 | 0 | 64 | -223 | 5 | 0 | 1 | 3,020 | 2,872 |
| Ammonia (Water) | lb | 2 | 2 | 0 | 3 | -9 | 548,000 | 1 | 1 | -1,130 | 546,869 |
| Copper | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cadmium | lb | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | -8.29 | -7 |
| Arsenic | lb | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3 |
| Mercury (Water) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -0.00474 | 0 |
| Phosphate | lb | 0 | 0 | 0 | 0 | 1 | 1,210 | 0 | 0 | -81.2 | 1,130 |
| Selenium | lb | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| Chromium | lb | 0 | 0 | 0 | 0 | -1 | 12 | 0 | 0 | -8.36 | 3 |
| Lead (Water) | lb | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | -0.0368 | 2 |
| Zinc | lb | 0 | 0 | 0 | 0 | -2 | 0 | 0 | 0 | 50 | 49 |

## Table A-4. Alternative 3 Non-Optimized MSW DST Results

| Parameter | Units | Rec Collection | MSW Collection | Transfer Station | MRF | WTE | Landfill | Ash-landfill | Transport | Remfg | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| **Cost** | $ | 8,762,000 | 6,669,000 | 224,000 | 3,450,000 | 1,630,000 | 1,420,000 | 42,200 | 1,433,040 | -2,520,000 | 21,110,240 |
| | | | | | | | | | | | |
| **Energy Consumption** | MBTU | 46,800 | 33,540 | 1,040 | 13,000 | -123,000 | 26,500 | 276 | 10,810 | -649,000 | -640,034 |
| | | | | | | | | | | | |
| **Air Emissions** | | | | | | | | | | | |
| Total Particulate Matter | lb | 404 | 386 | 448 | 5,390 | -17,000 | 2,350 | 17 | 2,150 | -206,000 | -211,855 |
| Nitrogen Oxides | lb | 26,130 | 24,960 | 5,910 | 20,900 | -30,700 | 10,600 | 186 | 14,890 | -345,000 | -272,124 |
| Hydrocarbons (non CH4) | lb | 0 | 6,695 | 736 | 970 | -507 | 1,280 | 48 | 5,990 | -301,000 | -285,788 |
| Sulfur Oxides | lb | 3,406 | 3,250 | 701 | 45,800 | -157,000 | 4,840 | 32 | 4,230 | -557,000 | -651,741 |
| Carbon Monoxide | lb | 12,974 | 8,918 | 1,480 | 2,440 | 2,140 | 6,570 | 63 | 14,610 | -699,000 | -649,805 |
| Carbon Dioxide Biogenic | lb | 796 | 762 | 40 | 654 | 30,800,000 | 38,700,000 | 3 | 417 | 36,500,000 | 106,002,671 |
| Carbon Dioxide Fossil | tons | 746,200 | 1,612,000 | 169,000 | 7,020,000 | -6,520,000 | 912,000 | 13,300 | 1,740,000 | -56,600,000 | -50,907,500 |
| Ammonia (Air) | lb | 0 | 0 | 0 | 1 | -3 | 1 | 0 | 3 | -1,640 | -1,638 |
| Lead (Air) | lb | 0 | 0 | 0 | 1 | -1 | 0 | 0 | 0 | -14.2 | -15 |
| Methane (CH4) | lb | 536 | 511 | 30 | 8,120 | -28,600 | 4,020,000 | 2 | 276 | -66,900 | 3,933,975 |
| Hydrochloric Acid | lb | 5 | 4 | 1 | 1,760 | -3,290 | 1,130 | 0 | 2 | -5,350 | -5,738 |
| Carbon Equivalents | lb | 104 | 222 | 23 | 984 | -987 | 13,800 | 2 | 239 | -7,950 | 6,437 |
| | | | | | | | | | | | |
| **Ancillary Solid Waste** | lb | 18,200 | 17,290 | 1,260 | 972,000 | -3,460,000 | 374,000 | 96 | 9,080 | -13,200,000 | -15,268,074 |
| | | | | | | | | | | | |
| **Water Releases** | | | | | | | | | | | |
| Dissolved Solids | lb | 4,550 | 4,342 | 229 | 7,120 | -23,900 | 1,070 | 18 | 2,370 | -182,000 | -186,201 |
| Suspended Solids | lb | 104 | 99 | 5 | 648 | -2,280 | 110 | 1 | 54 | 12,200 | 10,941 |
| BOD | lb | 17 | 16 | 1 | 16 | -52 | 69,200 | 0 | 9 | 40,400 | 109,607 |
| COD | lb | 113 | 109 | 6 | 29 | -66 | 192,000 | 94 | 60 | -94,400 | 97,945 |
| Oil | lb | 106 | 101 | 5 | 13 | -8 | 8,770 | 189 | 55 | 416 | 9,647 |
| Sulfuric Acid | lb | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | -646 | -642 |
| Iron | lb | 3 | 2 | 0 | 64 | -223 | 5 | 0 | 1 | 3,020 | 2,873 |
| Ammonia (Water) | lb | 2 | 2 | 0 | 3 | -9 | 548,000 | 1 | 1 | -1,130 | 546,869 |
| Copper | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cadmium | lb | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | -8.29 | -7 |
| Arsenic | lb | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3 |
| Mercury (Water) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -0.00474 | 0 |
| Phosphate | lb | 0 | 0 | 0 | 0 | 1 | 1,210 | 0 | 0 | -81.2 | 1,131 |
| Selenium | lb | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| Chromium | lb | 0 | 0 | 0 | 0 | -1 | 12 | 0 | 0 | -8.36 | 3 |
| Lead (Water) | lb | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | -0.0368 | 2 |
| Zinc | lb | 0 | 0 | 0 | 0 | -2 | 0 | 0 | 0 | 50 | 49 |

## Table A-5. Alternative 4 Non-Optimized MSW DST Results

| Parameter | Units | Rec Collection | MSW Collection | Transfer Station | MRF | WTE | Landfill | Ash-landfill | Transport | Remfg | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| **Cost** | $ | 8,762,000 | 6,669,000 | 224,000 | 3,450,000 | | 2,080,000 | | 2,070,000 | -2,340,000 | 20,915,000 |
| | | | | | | | | | | | |
| **Energy Consumption** | MBTU | 46,800 | 33,540 | 1,040 | 13,000 | | 38,900 | | 21,100 | -665,000 | -510,620 |
| | | | | | | | | | | | |
| **Air Emissions** | | | | | | | | | | | |
| Total Particulate Matter | lb | 404 | 386 | 448 | 5,390 | | 3,440 | | 4,180 | -200,000 | -185,752 |
| Nitrogen Oxides | lb | 26,130 | 24,960 | 5,910 | 20,900 | | 15,500 | | 29,100 | -358,000 | -235,500 |
| Hydrocarbons (non CH4) | lb | 0 | 6,695 | 736 | 970 | | 1,880 | | 11,700 | -334,000 | -312,019 |
| Sulfur Oxides | lb | 3,406 | 3,250 | 701 | 45,800 | | 7,070 | | 8,250 | -561,000 | -492,523 |
| Carbon Monoxide | lb | 12,974 | 8,918 | 1,480 | 2,440 | | 9,610 | | 28,600 | -692,000 | -627,978 |
| Carbon Dioxide Biogenic | lb | 796 | 762 | 40 | 654 | | 56,500,000 | | 811 | 36,500,000 | 93,003,062 |
| Carbon Dioxide Fossil | tons | 746,200 | 1,612,000 | 169,000 | 7,020,000 | | 1,330,000 | | 3,390,000 | -58,400,000 | -44,132,800 |
| Ammonia (Air) | lb | 0 | 0 | 0 | 1 | | 1 | | 5 | -1,630 | -1,622 |
| Lead (Air) | lb | 0 | 0 | 0 | 1 | | 0 | | 0 | -14.5 | -14 |
| Methane (CH4) | lb | 536 | 511 | 30 | 8,120 | | 5,870,000 | | 539 | -61,800 | 5,817,935 |
| Hydrochloric Acid | lb | 5 | 4 | 1 | 1,760 | | 1,650 | | 3 | -5,450 | -2,027 |
| Carbon Equivalents | lb | 104 | 222 | 23 | 984 | | 20,200 | | 464 | -8,180 | 13,817 |
| | | | | | | | | | | | |
| **Ancillary Solid Waste** | lb | 18,200 | 17,290 | 1,260 | 972,000 | | 546,000 | | 17,700 | -12,800,000 | -11,227,550 |
| | | | | | | | | | | | |
| **Water Releases** | | | | | | | | | | | |
| Dissolved Solids | lb | 4,550 | 4,342 | 229 | 7,120 | | 1,560 | | 4,630 | -177,000 | -154,569 |
| Suspended Solids | lb | 104 | 99 | 5 | 648 | | 161 | | 105 | 13,300 | 14,422 |
| BOD | lb | 17 | 16 | 1 | 16 | | 101,000 | | 17 | 40,300 | 141,367 |
| COD | lb | 113 | 109 | 6 | 29 | | 281,000 | | 116 | -94,200 | 187,173 |
| Oil | lb | 106 | 101 | 5 | 13 | | 12,900 | | 108 | 462 | 13,694 |
| Sulfuric Acid | lb | 1 | 1 | 0 | 0 | | 0 | | 1 | -645 | -642 |
| Iron | lb | 3 | 2 | 0 | 64 | | 8 | | 3 | 3,020 | 3,099 |
| Ammonia (Water) | lb | 2 | 2 | 0 | 3 | | 800,000 | | 2 | -1,130 | 798,878 |
| Copper | lb | 0 | 0 | 0 | 0 | | 0 | | 0 | 0 | 0 |
| Cadmium | lb | 0 | 0 | 0 | 0 | | 2 | | 0 | -8.03 | -6 |
| Arsenic | lb | 0 | 0 | 0 | 0 | | 5 | | 0 | 0 | 5 |
| Mercury (Water) | lb | 0 | 0 | 0 | 0 | | 0 | | 0 | -0.00472 | 0 |
| Phosphate | lb | 0 | 0 | 0 | 0 | | 1,760 | | 0 | -83.3 | 1,678 |
| Selenium | lb | 0 | 0 | 0 | 0 | | 4 | | 0 | 0 | 4 |
| Chromium | lb | 0 | 0 | 0 | 0 | | 17 | | 0 | -8.12 | 10 |
| Lead (Water) | lb | 0 | 0 | 0 | 0 | | 3 | | 0 | -0.0366 | 3 |
| Zinc | lb | 0 | 0 | 0 | 0 | | 0 | | 0 | 50.1 | 51 |

## Table A-6. Base Case Cost-Optimized MSW DST Results

| Parameter | Units | MSW Collection | Recyclables Collection | Transfer Station | MRF | WTE | Landfill | Ash-landfill | Transport | Remfg | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| **Cost** | $ | 5,790,000 | 0 | 0 | 0 | 0 | 3,090,000 | 0 | 0 | 0 | 8,880,000 |
| | | | | | | | | | | | |
| **Energy Consumption** | MBTU | 30,200 | 0 | 0 | 0 | 0 | 54,200 | 0 | 0 | 0 | 84,400 |
| | | | | | | | | | | | |
| **Air Emissions** | | | | | | | | | | | |
| Total Particulate Matter | lb | 302 | 0 | 0 | 0 | 0 | 4,000 | 0 | 0 | 0 | 4,302 |
| Nitrogen Oxides | lb | 19,600 | 0 | 0 | 0 | 0 | 19,400 | 0 | 0 | 0 | 39,000 |
| Hydrocarbons (non CH4) | lb | 5,250 | 0 | 0 | 0 | 0 | 2,760 | 0 | 0 | 0 | 8,010 |
| Sulfur Oxides | lb | 2,540 | 0 | 0 | 0 | 0 | 5,120 | 0 | 0 | 0 | 7,660 |
| Carbon Monoxide | lb | 8,480 | 0 | 0 | 0 | 0 | 12,700 | 0 | 0 | 0 | 21,180 |
| Carbon Dioxide Biogenic | lb | 598 | 0 | 0 | 0 | 0 | 71,500,000 | 0 | 0 | 0 | 71,500,598 |
| Carbon Dioxide Fossil | tons | 1,270,000 | 0 | 0 | 0 | 0 | 1,200,000 | 0 | 0 | 0 | 2,470,000 |
| Ammonia (Air) | lb | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| Lead (Air) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Methane (CH4) | lb | 400 | 0 | 0 | 0 | 0 | 8,030,000 | 0 | 0 | 0 | 8,030,400 |
| Hydrochloric Acid | lb | 3 | 0 | 0 | 0 | 0 | 1,890 | 0 | 0 | 0 | 1,893 |
| Carbon Equivalents | lb | 174 | 0 | 0 | 0 | 0 | 27,500 | 0 | 0 | 0 | 27,674 |
| | | | | | | | | | | | |
| **Ancillary Solid Waste** | lb | 13,400 | 0 | 0 | 0 | 0 | 414,000 | 0 | 0 | 0 | 427,400 |
| | | | | | | | | | | | |
| **Water Releases** | | | | | | | | | | | |
| Dissolved Solids | lb | 3,430 | 0 | 0 | 0 | 0 | 4,610 | 0 | 0 | 0 | 8,040 |
| Suspended Solids | lb | 78 | 0 | 0 | 0 | 0 | 270 | 0 | 0 | 0 | 348 |
| BOD | lb | 13 | 0 | 0 | 0 | 0 | 83,200 | 0 | 0 | 0 | 83,213 |
| COD | lb | 85 | 0 | 0 | 0 | 0 | 232,000 | 0 | 0 | 0 | 232,085 |
| Oil | lb | 79 | 0 | 0 | 0 | 0 | 19,100 | 0 | 0 | 0 | 19,179 |
| Sulfuric Acid | lb | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Iron | lb | 2 | 0 | 0 | 0 | 0 | 21 | 0 | 0 | 0 | 23 |
| Ammonia (Water) | lb | 1 | 0 | 0 | 0 | 0 | 127,000 | 0 | 0 | 0 | 127,001 |
| Copper | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cadmium | lb | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| Arsenic | lb | 0 | 0 | 0 | 0 | 0 | 26 | 0 | 0 | 0 | 26 |
| Mercury (Water) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Phosphate | lb | 0 | 0 | 0 | 0 | 0 | 1,700 | 0 | 0 | 0 | 1,700 |
| Selenium | lb | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| Chromium | lb | 0 | 0 | 0 | 0 | 0 | 23 | 0 | 0 | 0 | 23 |
| Lead (Water) | lb | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 4 |
| Zinc | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## Table A-7. Alternative 1 Cost-Optimized MSW DST Results

| Parameter | Units | MSW Collection | Recyclables Collection | Transfer Station | MRF | WTE | Landfill | Ash-landfill | Transport | Remfg | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| **Cost** | $ | 6,369,000 | 0 | 0 | 0 | 0 | 3,090,000 | 0 | 0 | 0 | 9,459,000 |
| | | | | | | | | | | | |
| **Energy Consumption** | MBTU | 33,220 | 0 | 0 | 0 | 0 | 54,200 | 0 | 0 | 0 | 87,420 |
| | | | | | | | | | | | |
| **Air Emissions** | | | | | | | | | | | |
| Total Particulate Matter | lb | 332 | 0 | 0 | 0 | 0 | 4,000 | 0 | 0 | 0 | 4,332 |
| Nitrogen Oxides | lb | 21,560 | 0 | 0 | 0 | 0 | 19,400 | 0 | 0 | 0 | 40,960 |
| Hydrocarbons (non CH4) | lb | 5,775 | 0 | 0 | 0 | 0 | 2,760 | 0 | 0 | 0 | 8,535 |
| Sulfur Oxides | lb | 2,794 | 0 | 0 | 0 | 0 | 5,120 | 0 | 0 | 0 | 7,914 |
| Carbon Monoxide | lb | 9,328 | 0 | 0 | 0 | 0 | 12,700 | 0 | 0 | 0 | 22,028 |
| Carbon Dioxide Biogenic | lb | 658 | 0 | 0 | 0 | 0 | 71,500,000 | 0 | 0 | 0 | 71,500,658 |
| Carbon Dioxide Fossil | tons | 1,397,000 | 0 | 0 | 0 | 0 | 1,200,000 | 0 | 0 | 0 | 2,597,000 |
| Ammonia (Air) | lb | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| Lead (Air) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Methane (CH4) | lb | 440 | 0 | 0 | 0 | 0 | 8,030,000 | 0 | 0 | 0 | 8,030,440 |
| Hydrochloric Acid | lb | 3 | 0 | 0 | 0 | 0 | 1,890 | 0 | 0 | 0 | 1,893 |
| Carbon Equivalents | lb | 191 | 0 | 0 | 0 | 0 | 27,500 | 0 | 0 | 0 | 27,691 |
| | | | | | | | | | | | |
| **Ancillary Solid Waste** | lb | 14,740 | 0 | 0 | 0 | 0 | 414,000 | 0 | 0 | 0 | 428,740 |
| | | | | | | | | | | | |
| **Water Releases** | | | | | | | | | | | |
| Dissolved Solids | lb | 3,773 | 0 | 0 | 0 | 0 | 4,610 | 0 | 0 | 0 | 8,383 |
| Suspended Solids | lb | 86 | 0 | 0 | 0 | 0 | 270 | 0 | 0 | 0 | 356 |
| BOD | lb | 14 | 0 | 0 | 0 | 0 | 83,200 | 0 | 0 | 0 | 83,214 |
| COD | lb | 94 | 0 | 0 | 0 | 0 | 232,000 | 0 | 0 | 0 | 232,094 |
| Oil | lb | 87 | 0 | 0 | 0 | 0 | 19,100 | 0 | 0 | 0 | 19,187 |
| Sulfuric Acid | lb | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Iron | lb | 2 | 0 | 0 | 0 | 0 | 21 | 0 | 0 | 0 | 23 |
| Ammonia (Water) | lb | 2 | 0 | 0 | 0 | 0 | 127,000 | 0 | 0 | 0 | 127,002 |
| Copper | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cadmium | lb | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| Arsenic | lb | 0 | 0 | 0 | 0 | 0 | 26 | 0 | 0 | 0 | 26 |
| Mercury (Water) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Phosphate | lb | 0 | 0 | 0 | 0 | 0 | 1,700 | 0 | 0 | 0 | 1,700 |
| Selenium | lb | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| Chromium | lb | 0 | 0 | 0 | 0 | 0 | 23 | 0 | 0 | 0 | 23 |
| Lead (Water) | lb | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 4 |
| Zinc | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## Table A-8. Alternative 2 Cost-Optimized MSW DST Results

| Parameter | Units | MSW Collection | Recyclables Collection | Transfer Station | MRF | WTE | Landfill | Ash-landfill | Transport | Remfg | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| **Cost** | $ | 6,948,000 | 0 | 0 | 0 | 0 | 3,090,000 | 0 | 0 | 0 | 10,038,000 |
| | | | | | | | | | | | |
| **Energy Consumption** | MBTU | 36,240 | 0 | 0 | 0 | 0 | 54,200 | 0 | 0 | 0 | 90,440 |
| | | | | | | | | | | | |
| **Air Emissions** | | | | | | | | | | | |
| Total Particulate Matter | lb | 362 | 0 | 0 | 0 | 0 | 4,000 | 0 | 0 | 0 | 4,362 |
| Nitrogen Oxides | lb | 23,520 | 0 | 0 | 0 | 0 | 19,400 | 0 | 0 | 0 | 42,920 |
| Hydrocarbons (non CH4) | lb | 6,300 | 0 | 0 | 0 | 0 | 2,760 | 0 | 0 | 0 | 9,060 |
| Sulfur Oxides | lb | 3,048 | 0 | 0 | 0 | 0 | 5,120 | 0 | 0 | 0 | 8,168 |
| Carbon Monoxide | lb | 10,176 | 0 | 0 | 0 | 0 | 12,700 | 0 | 0 | 0 | 22,876 |
| Carbon Dioxide Biogenic | lb | 718 | 0 | 0 | 0 | 0 | 71,500,000 | 0 | 0 | 0 | 71,500,718 |
| Carbon Dioxide Fossil | tons | 1,524,000 | 0 | 0 | 0 | 0 | 1,200,000 | 0 | 0 | 0 | 2,724,000 |
| Ammonia (Air) | lb | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| Lead (Air) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Methane (CH4) | lb | 480 | 0 | 0 | 0 | 0 | 8,030,000 | 0 | 0 | 0 | 8,030,480 |
| Hydrochloric Acid | lb | 4 | 0 | 0 | 0 | 0 | 1,890 | 0 | 0 | 0 | 1,894 |
| Carbon Equivalents | lb | 209 | 0 | 0 | 0 | 0 | 27,500 | 0 | 0 | 0 | 27,709 |
| | | | | | | | | | | | |
| **Ancillary Solid Waste** | lb | 16,080 | 0 | 0 | 0 | 0 | 414,000 | 0 | 0 | 0 | 430,080 |
| | | | | | | | | | | | |
| **Water Releases** | | | | | | | | | | | |
| Dissolved Solids | lb | 4,116 | 0 | 0 | 0 | 0 | 4,610 | 0 | 0 | 0 | 8,726 |
| Suspended Solids | lb | 94 | 0 | 0 | 0 | 0 | 270 | 0 | 0 | 0 | 364 |
| BOD | lb | 15 | 0 | 0 | 0 | 0 | 83,200 | 0 | 0 | 0 | 83,215 |
| COD | lb | 102 | 0 | 0 | 0 | 0 | 232,000 | 0 | 0 | 0 | 232,102 |
| Oil | lb | 95 | 0 | 0 | 0 | 0 | 19,100 | 0 | 0 | 0 | 19,195 |
| Sulfuric Acid | lb | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Iron | lb | 2 | 0 | 0 | 0 | 0 | 21 | 0 | 0 | 0 | 23 |
| Ammonia (Water) | lb | 2 | 0 | 0 | 0 | 0 | 127,000 | 0 | 0 | 0 | 127,002 |
| Copper | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cadmium | lb | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| Arsenic | lb | 0 | 0 | 0 | 0 | 0 | 26 | 0 | 0 | 0 | 26 |
| Mercury (Water) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Phosphate | lb | 0 | 0 | 0 | 0 | 0 | 1,700 | 0 | 0 | 0 | 1,700 |
| Selenium | lb | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| Chromium | lb | 0 | 0 | 0 | 0 | 0 | 23 | 0 | 0 | 0 | 23 |
| Lead (Water) | lb | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 4 |
| Zinc | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## Table A-9. Alternative 3 Cost-Optimized MSW DST Results

| Parameter | Units | MSW Collection | Recyclables Collection | Transfer Station | MRF | WTE | Landfill | Ash-landfill | Transport | Remfg | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| **Cost** | $ | 7,527,000 | 0 | 0 | 0 | 0 | 3,090,000 | 0 | 0 | 0 | 10,617,000 |
| | | | | | | | | | | | |
| **Energy Consumption** | MBTU | 39,260 | 0 | 0 | 0 | 0 | 54,200 | 0 | 0 | 0 | 93,460 |
| | | | | | | | | | | | |
| **Air Emissions** | | | | | | | | | | | |
| Total Particulate Matter | lb | 393 | 0 | 0 | 0 | 0 | 4,000 | 0 | 0 | 0 | 4,393 |
| Nitrogen Oxides | lb | 25,480 | 0 | 0 | 0 | 0 | 19,400 | 0 | 0 | 0 | 44,880 |
| Hydrocarbons (non CH4) | lb | 6,825 | 0 | 0 | 0 | 0 | 2,760 | 0 | 0 | 0 | 9,585 |
| Sulfur Oxides | lb | 3,302 | 0 | 0 | 0 | 0 | 5,120 | 0 | 0 | 0 | 8,422 |
| Carbon Monoxide | lb | 11,024 | 0 | 0 | 0 | 0 | 12,700 | 0 | 0 | 0 | 23,724 |
| Carbon Dioxide Biogenic | lb | 777 | 0 | 0 | 0 | 0 | 71,500,000 | 0 | 0 | 0 | 71,500,777 |
| Carbon Dioxide Fossil | tons | 1,651,000 | 0 | 0 | 0 | 0 | 1,200,000 | 0 | 0 | 0 | 2,851,000 |
| Ammonia (Air) | lb | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| Lead (Air) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Methane (CH4) | lb | 520 | 0 | 0 | 0 | 0 | 8,030,000 | 0 | 0 | 0 | 8,030,520 |
| Hydrochloric Acid | lb | 4 | 0 | 0 | 0 | 0 | 1,890 | 0 | 0 | 0 | 1,894 |
| Carbon Equivalents | lb | 226 | 0 | 0 | 0 | 0 | 27,500 | 0 | 0 | 0 | 27,726 |
| | | | | | | | | | | | |
| **Ancillary Solid Waste** | lb | 17,420 | 0 | 0 | 0 | 0 | 414,000 | 0 | 0 | 0 | 431,420 |
| | | | | | | | | | | | |
| **Water Releases** | | | | | | | | | | | |
| Dissolved Solids | lb | 4,459 | 0 | 0 | 0 | 0 | 4,610 | 0 | 0 | 0 | 9,069 |
| Suspended Solids | lb | 102 | 0 | 0 | 0 | 0 | 270 | 0 | 0 | 0 | 372 |
| BOD | lb | 17 | 0 | 0 | 0 | 0 | 83,200 | 0 | 0 | 0 | 83,217 |
| COD | lb | 111 | 0 | 0 | 0 | 0 | 232,000 | 0 | 0 | 0 | 232,111 |
| Oil | lb | 103 | 0 | 0 | 0 | 0 | 19,100 | 0 | 0 | 0 | 19,203 |
| Sulfuric Acid | lb | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Iron | lb | 3 | 0 | 0 | 0 | 0 | 21 | 0 | 0 | 0 | 23 |
| Ammonia (Water) | lb | 2 | 0 | 0 | 0 | 0 | 127,000 | 0 | 0 | 0 | 127,002 |
| Copper | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cadmium | lb | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| Arsenic | lb | 0 | 0 | 0 | 0 | 0 | 26 | 0 | 0 | 0 | 26 |
| Mercury (Water) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Phosphate | lb | 0 | 0 | 0 | 0 | 0 | 1,700 | 0 | 0 | 0 | 1,700 |
| Selenium | lb | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| Chromium | lb | 0 | 0 | 0 | 0 | 0 | 23 | 0 | 0 | 0 | 23 |
| Lead (Water) | lb | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 4 |
| Zinc | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## Table A-10. Alternative 4 Cost-Optimized MSW DST Results

| Parameter | Units | MSW Collection | Transfer Station | MRF | WTE | Landfill | Ash-landfill | Transport | Remfg | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | |
| **Cost** | $ | 7,527,000 | 0 | 0 | 0 | 3,090,000 | 0 | 0 | 0 | 10,617,000 |
| | | | | | | | | | | |
| **Energy Consumption** | MBTU | 39,260 | 0 | 0 | 0 | 54,200 | 0 | 0 | 0 | 93,460 |
| | | | | | | | | | | |
| **Air Emissions** | | | | | | | | | | |
| Total Particulate Matter | lb | 393 | 0 | 0 | 0 | 4,000 | 0 | 0 | 0 | 4,393 |
| Nitrogen Oxides | lb | 25,480 | 0 | 0 | 0 | 19,400 | 0 | 0 | 0 | 44,880 |
| Hydrocarbons (non CH4) | lb | 6,825 | 0 | 0 | 0 | 2,760 | 0 | 0 | 0 | 9,585 |
| Sulfur Oxides | lb | 3,302 | 0 | 0 | 0 | 5,120 | 0 | 0 | 0 | 8,422 |
| Carbon Monoxide | lb | 11,024 | 0 | 0 | 0 | 12,700 | 0 | 0 | 0 | 23,724 |
| Carbon Dioxide Biogenic | lb | 777 | 0 | 0 | 0 | 71,500,000 | 0 | 0 | 0 | 71,500,777 |
| Carbon Dioxide Fossil | tons | 1,651,000 | 0 | 0 | 0 | 1,200,000 | 0 | 0 | 0 | 2,851,000 |
| Ammonia (Air) | lb | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| Lead (Air) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Methane (CH4) | lb | 520 | 0 | 0 | 0 | 8,030,000 | 0 | 0 | 0 | 8,030,520 |
| Hydrochloric Acid | lb | 4 | 0 | 0 | 0 | 1,890 | 0 | 0 | 0 | 1,894 |
| Carbon Equivalents | lb | 226 | 0 | 0 | 0 | 27,500 | 0 | 0 | 0 | 27,726 |
| | | | | | | | | | | |
| **Ancillary Solid Waste** | lb | 17,420 | 0 | 0 | 0 | 414,000 | 0 | 0 | 0 | 431,420 |
| | | | | | | | | | | |
| **Water Releases** | | | | | | | | | | |
| Dissolved Solids | lb | 4,459 | 0 | 0 | 0 | 4,610 | 0 | 0 | 0 | 9,069 |
| Suspended Solids | lb | 102 | 0 | 0 | 0 | 270 | 0 | 0 | 0 | 372 |
| BOD | lb | 17 | 0 | 0 | 0 | 83,200 | 0 | 0 | 0 | 83,217 |
| COD | lb | 111 | 0 | 0 | 0 | 232,000 | 0 | 0 | 0 | 232,111 |
| Oil | lb | 103 | 0 | 0 | 0 | 19,100 | 0 | 0 | 0 | 19,203 |
| Sulfuric Acid | lb | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Iron | lb | 3 | 0 | 0 | 0 | 21 | 0 | 0 | 0 | 23 |
| Ammonia (Water) | lb | 2 | 0 | 0 | 0 | 127,000 | 0 | 0 | 0 | 127,002 |
| Copper | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cadmium | lb | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| Arsenic | lb | 0 | 0 | 0 | 0 | 26 | 0 | 0 | 0 | 26 |
| Mercury (Water) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Phosphate | lb | 0 | 0 | 0 | 0 | 1,700 | 0 | 0 | 0 | 1,700 |
| Selenium | lb | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| Chromium | lb | 0 | 0 | 0 | 0 | 23 | 0 | 0 | 0 | 23 |
| Lead (Water) | lb | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 4 |
| Zinc | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## Table A-11. Base Case GHG-Optimized MSW DST Results

| Parameter | Units | Recyclables Collection | Residuals Collection | Transfer Station | MRF | WTE | Landfill | Ash-landfill | Transport | Remfg | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| **Cost** | $ | 7,490,000 | 5,250,000 | 0 | 5,580,000 | 6,110,000 | 7,680 | 137,000 | 28,500 | -1,260,000 | 23,343,180 |
| | | | | | | | | | | | |
| **Energy Consumption** | MBTU | 41,100 | 26,600 | 0 | 12,700 | -355,000 | 123 | 891 | 6,810 | -633,000 | -899,776 |
| | | | | | | | | | | | |
| **Air Emissions** | | | | | | | | | | | |
| Total Particulate Matter | lb | 317 | 297 | 0 | 3,360 | -27,100 | 2 | 55 | 1,350 | -216,000 | -237,718 |
| Nitrogen Oxides | lb | 20,500 | 19,200 | 0 | 12,500 | -6,200 | 28 | 602 | 9,390 | -395,000 | -338,980 |
| Hydrocarbons (non CH4) | lb | 0 | 5,160 | 0 | 748 | -562 | 7 | 154 | 3,780 | -687,000 | -677,713 |
| Sulfur Oxides | lb | 2,660 | 2,500 | 0 | 27,500 | -255,000 | 5 | 102 | 2,670 | -636,000 | -855,563 |
| Carbon Monoxide | lb | 11,700 | 7,150 | 0 | 3,390 | -5,790 | 10 | 204 | 9,260 | -509,000 | -483,076 |
| Carbon Dioxide Biogenic | lb | 626 | 588 | 0 | 1,430 | 137,000,000 | 0 | 10 | 262 | 16,400,000 | 153,402,916 |
| Carbon Dioxide Fossil | tons | 586,000 | 1,250,000 | 0 | 4,310,000 | -33,700,000 | 2,010 | 43,000 | 1,090,000 | -84,200,000 | -110,618,990 |
| Ammonia (Air) | lb | 0 | 0 | 0 | 4 | -35 | 0 | 0 | 2 | -94 | -123 |
| Lead (Air) | lb | 0 | 0 | 0 | 0 | -1 | 0 | 0 | 0 | 6 | 5 |
| Methane (CH4) | lb | 419 | 393 | 0 | 5,740 | -55,900 | 0 | 8 | 174 | -83,200 | -132,366 |
| Hydrochloric Acid | lb | 3 | 3 | 0 | 916 | -938 | 0 | 0 | 1 | -6,740 | -6,755 |
| Carbon Equivalents | lb | 81 | 171 | 0 | 607 | -4,780 | 0 | 6 | 150 | -11,800 | -15,565 |
| | | | | | | | | | | | |
| **Ancillary Solid Waste** | lb | 14,000 | 13,100 | 0 | 578,000 | -5,690,000 | 11 | 309 | 5,720 | -11,600,000 | -16,678,860 |
| | | | | | | | | | | | |
| **Water Releases** | | | | | | | | | | | |
| Dissolved Solids | lb | 3,590 | 3,370 | 0 | 36,100 | -357,000 | 3 | 58 | 1,500 | -173,000 | -485,379 |
| Suspended Solids | lb | 82 | 77 | 0 | 1,790 | -17,800 | 0 | 2 | 34 | -7,730 | -23,544 |
| BOD | lb | 13 | 13 | 0 | 77 | -761 | 0 | 0 | 6 | 10,200 | 9,548 |
| COD | lb | 89 | 84 | 0 | 134 | -1,250 | 0 | 305 | 37 | -5,370 | -5,970 |
| Oil | lb | 83 | 78 | 0 | 25 | -157 | 47 | 609 | 35 | -3,320 | -2,600 |
| Sulfuric Acid | lb | 1 | 1 | 0 | 0 | 4 | 0 | 0 | 0 | -2,060 | -2,054 |
| Iron | lb | 2 | 2 | 0 | 207 | -2,050 | 0 | 0 | 1 | -1,410 | -3,248 |
| Ammonia (Water) | lb | 1 | 1 | 0 | 14 | -137 | 0 | 4 | 1 | -719 | -835 |
| Copper | lb | 0 | 0 | 0 | 1 | -7 | 0 | 0 | 0 | 0 | -6 |
| Cadmium | lb | 0 | 0 | 0 | 0 | -1 | 0 | 0 | 0 | -8 | -8 |
| Arsenic | lb | 0 | 0 | 0 | 0 | -3 | 0 | 0 | 0 | 0 | -2 |
| Mercury (Water) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Phosphate | lb | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | -199 | -196 |
| Selenium | lb | 0 | 0 | 0 | 1 | -7 | 0 | 0 | 0 | 0 | -6 |
| Chromium | lb | 0 | 0 | 0 | 1 | -14 | 0 | 0 | 0 | -8 | -20 |
| Lead (Water) | lb | 0 | 0 | 0 | 0 | -5 | 0 | 0 | 0 | 0 | -4 |
| Zinc | lb | 0 | 0 | 0 | 2 | -21 | 0 | 0 | 0 | -4 | -23 |

## Table A-12. Alternative 1 GHG-Optimized MSW DST Results

| Parameter | Units | Recyclables Collection | Residuals Collection | Transfer Station | MRF | WTE | Landfill | Ash-landfill | Transport | Remfg | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| **Cost** | $ | 8,239,000 | 5,775,000 | 0 | 5,580,000 | 6,110,000 | 7,680 | 137,000 | 2,000,000 | -1,260,000 | 26,588,680 |
| | | | | | | | | | | | |
| **Energy Consumption** | MBTU | 45,210 | 29,260 | 0 | 12,700 | -355,000 | 123 | 891 | 20,800 | -633,000 | -879,016 |
| | | | | | | | | | | | |
| **Air Emissions** | | | | | | | | | | | |
| Total Particulate Matter | lb | 349 | 327 | 0 | 3,360 | -27,100 | 2 | 55 | 4,130 | -216,000 | -234,877 |
| Nitrogen Oxides | lb | 22,550 | 21,120 | 0 | 12,500 | -6,200 | 28 | 602 | 28,700 | -395,000 | -315,700 |
| Hydrocarbons (non CH4) | lb | 0 | 5,676 | 0 | 748 | -562 | 7 | 154 | 11,500 | -687,000 | -669,477 |
| Sulfur Oxides | lb | 2,926 | 2,750 | 0 | 27,500 | -255,000 | 5 | 102 | 8,140 | -636,000 | -849,577 |
| Carbon Monoxide | lb | 12,870 | 7,865 | 0 | 3,390 | -5,790 | 10 | 204 | 28,300 | -509,000 | -462,151 |
| Carbon Dioxide Biogenic | lb | 689 | 647 | 0 | 1,430 | 137,000,000 | 0 | 10 | 801 | 16,400,000 | 153,403,576 |
| Carbon Dioxide Fossil | tons | 644,600 | 1,375,000 | 0 | 4,310,000 | -33,700,000 | 2,010 | 43,000 | 3,340,000 | -84,200,000 | -108,185,390 |
| Ammonia (Air) | lb | 0 | 0 | 0 | 4 | -35 | 0 | 0 | 5 | -94 | -120 |
| Lead (Air) | lb | 0 | 0 | 0 | 0 | -1 | 0 | 0 | 0 | 6 | 5 |
| Methane (CH4) | lb | 461 | 432 | 0 | 5,740 | -55,900 | 0 | 8 | 532 | -83,200 | -131,927 |
| Hydrochloric Acid | lb | 4 | 3 | 0 | 916 | -938 | 0 | 0 | 3 | -6,740 | -6,752 |
| Carbon Equivalents | lb | 89 | 188 | 0 | 607 | -4,780 | 0 | 6 | 458 | -11,800 | -15,231 |
| | | | | | | | | | | | |
| **Ancillary Solid Waste** | lb | 15,400 | 14,410 | 0 | 578,000 | -5,690,000 | 11 | 309 | 17,500 | -11,600,000 | -16,664,370 |
| | | | | | | | | | | | |
| **Water Releases** | | | | | | | | | | | |
| Dissolved Solids | lb | 3,949 | 3,707 | 0 | 36,100 | -357,000 | 3 | 58 | 4,570 | -173,000 | -481,613 |
| Suspended Solids | lb | 90 | 85 | 0 | 1,790 | -17,800 | 0 | 2 | 104 | -7,730 | -23,458 |
| BOD | lb | 15 | 14 | 0 | 77 | -761 | 0 | 0 | 17 | 10,200 | 9,562 |
| COD | lb | 98 | 92 | 0 | 134 | -1,250 | 0 | 305 | 114 | -5,370 | -5,876 |
| Oil | lb | 91 | 86 | 0 | 25 | -157 | 47 | 609 | 106 | -3,320 | -2,513 |
| Sulfuric Acid | lb | 1 | 1 | 0 | 0 | 4 | 0 | 0 | 1 | -2,060 | -2,054 |
| Iron | lb | 2 | 2 | 0 | 207 | -2,050 | 0 | 0 | 2 | -1,410 | -3,246 |
| Ammonia (Water) | lb | 2 | 1 | 0 | 14 | -137 | 0 | 4 | 2 | -719 | -833 |
| Copper | lb | 0 | 0 | 0 | 1 | -7 | 0 | 0 | 0 | 0 | -6 |
| Cadmium | lb | 0 | 0 | 0 | 0 | -1 | 0 | 0 | 0 | -8 | -8 |
| Arsenic | lb | 0 | 0 | 0 | 0 | -3 | 0 | 0 | 0 | 0 | -2 |
| Mercury (Water) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Phosphate | lb | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | -199 | -196 |
| Selenium | lb | 0 | 0 | 0 | 1 | -7 | 0 | 0 | 0 | 0 | -6 |
| Chromium | lb | 0 | 0 | 0 | 1 | -14 | 0 | 0 | 0 | -8 | -20 |
| Lead (Water) | lb | 0 | 0 | 0 | 0 | -5 | 0 | 0 | 0 | 0 | -4 |
| Zinc | lb | 0 | 0 | 0 | 2 | -21 | 0 | 0 | 0 | -4 | -23 |

## Table A-13. Alternative 2 GHG-Optimized MSW DST Results

| Parameter | Units | Recyclables Collection | Residuals Collection | Transfer Station | MRF | WTE | Landfill | Ash-landfill | Transport | Remfg | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| **Cost** | $ | 8,988,000 | 6,300,000 | 0 | 5,580,000 | 6,110,000 | 7,680 | 137,000 | 28,500 | -1,260,000 | 25,891,180 |
| | | | | | | | | | | | |
| **Energy Consumption** | MBTU | 49,320 | 31,920 | 0 | 12,700 | -355,000 | 123 | 891 | 6,810 | -633,000 | -886,236 |
| | | | | | | | | | | | |
| **Air Emissions** | | | | | | | | | | | |
| Total Particulate Matter | lb | 380 | 356 | 0 | 3,360 | -27,100 | 2 | 55 | 1,350 | -216,000 | -237,596 |
| Nitrogen Oxides | lb | 24,600 | 23,040 | 0 | 12,500 | -6,200 | 28 | 602 | 9,390 | -395,000 | -331,040 |
| Hydrocarbons (non CH4) | lb | 0 | 6,192 | 0 | 748 | -562 | 7 | 154 | 3,780 | -687,000 | -676,681 |
| Sulfur Oxides | lb | 3,192 | 3,000 | 0 | 27,500 | -255,000 | 5 | 102 | 2,670 | -636,000 | -854,531 |
| Carbon Monoxide | lb | 14,040 | 8,580 | 0 | 3,390 | -5,790 | 10 | 204 | 9,260 | -509,000 | -479,306 |
| Carbon Dioxide Biogenic | lb | 751 | 706 | 0 | 1,430 | 137,000,000 | 0 | 10 | 262 | 16,400,000 | 153,403,159 |
| Carbon Dioxide Fossil | tons | 703,200 | 1,500,000 | 0 | 4,310,000 | -33,700,000 | 2,010 | 43,000 | 1,090,000 | -84,200,000 | -110,251,790 |
| Ammonia (Air) | lb | 0 | 0 | 0 | 4 | -35 | 0 | 0 | 2 | -94 | -123 |
| Lead (Air) | lb | 0 | 0 | 0 | 0 | -1 | 0 | 0 | 0 | 6 | 5 |
| Methane (CH4) | lb | 503 | 472 | 0 | 5,740 | -55,900 | 0 | 8 | 174 | -83,200 | -132,204 |
| Hydrochloric Acid | lb | 4 | 4 | 0 | 916 | -938 | 0 | 0 | 1 | -6,740 | -6,754 |
| Carbon Equivalents | lb | 98 | 205 | 0 | 607 | -4,780 | 0 | 6 | 150 | -11,800 | -15,514 |
| | | 0 | 0 | | | | | | | | |
| **Ancillary Solid Waste** | lb | 16,800 | 15,720 | 0 | 578,000 | -5,690,000 | 11 | 309 | 5,720 | -11,600,000 | -16,673,440 |
| | | | | | | | | | | | |
| **Water Releases** | | | | | | | | | | | |
| Dissolved Solids | lb | 4,308 | 4,044 | 0 | 36,100 | -357,000 | 3 | 58 | 1,500 | -173,000 | -483,987 |
| Suspended Solids | lb | 99 | 93 | 0 | 1,790 | -17,800 | 0 | 2 | 34 | -7,730 | -23,512 |
| BOD | lb | 16 | 15 | 0 | 77 | -761 | 0 | 0 | 6 | 10,200 | 9,554 |
| COD | lb | 107 | 101 | 0 | 134 | -1,250 | 0 | 305 | 37 | -5,370 | -5,936 |
| Oil | lb | 100 | 94 | 0 | 25 | -157 | 47 | 609 | 35 | -3,320 | -2,568 |
| Sulfuric Acid | lb | 1 | 1 | 0 | 0 | 4 | 0 | 0 | 0 | -2,060 | -2,054 |
| Iron | lb | 3 | 2 | 0 | 207 | -2,050 | 0 | 0 | 1 | -1,410 | -3,247 |
| Ammonia (Water) | lb | 2 | 2 | 0 | 14 | -137 | 0 | 4 | 1 | -719 | -834 |
| Copper | lb | 0 | 0 | 0 | 1 | -7 | 0 | 0 | 0 | 0 | -6 |
| Cadmium | lb | 0 | 0 | 0 | 0 | -1 | 0 | 0 | 0 | -8 | -8 |
| Arsenic | lb | 0 | 0 | 0 | 0 | -3 | 0 | 0 | 0 | 0 | -2 |
| Mercury (Water) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Phosphate | lb | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | -199 | -196 |
| Selenium | lb | 0 | 0 | 0 | 1 | -7 | 0 | 0 | 0 | 0 | -6 |
| Chromium | lb | 0 | 0 | 0 | 1 | -14 | 0 | 0 | 0 | -8 | -20 |
| Lead (Water) | lb | 0 | 0 | 0 | 0 | -5 | 0 | 0 | 0 | 0 | -4 |
| Zinc | lb | 0 | 0 | 0 | 2 | -21 | 0 | 0 | 0 | -4 | -23 |

## Table A-14. Alternative 3 GHG-Optimized MSW DST Results

| Parameter | Units | Recyclables Collection | Residuals Collection | Transfer Station | MRF | WTE | Landfill | Ash-landfill | Transport | Remfg | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| **Cost** | $ | 9,737,000 | 6,825,000 | 0 | 5,580,000 | 6,110,000 | 7,680 | 137,000 | 28,500 | -1,260,000 | 27,165,180 |
| | | | | | | | | | | | |
| **Energy Consumption** | MBTU | 53,430 | 34,580 | 0 | 12,700 | -355,000 | 123 | 891 | 6,810 | -633,000 | -879,466 |
| | | | | | | | | | | | |
| **Air Emissions** | | | | | | | | | | | |
| Total Particulate Matter | lb | 412 | 386 | 0 | 3,360 | -27,100 | 2 | 55 | 1,350 | -216,000 | -237,534 |
| Nitrogen Oxides | lb | 26,650 | 24,960 | 0 | 12,500 | -6,200 | 28 | 602 | 9,390 | -395,000 | -327,070 |
| Hydrocarbons (non CH4) | lb | 0 | 6,708 | 0 | 748 | -562 | 7 | 154 | 3,780 | -687,000 | -676,165 |
| Sulfur Oxides | lb | 3,458 | 3,250 | 0 | 27,500 | -255,000 | 5 | 102 | 2,670 | -636,000 | -854,015 |
| Carbon Monoxide | lb | 15,210 | 9,295 | 0 | 3,390 | -5,790 | 10 | 204 | 9,260 | -509,000 | -477,421 |
| Carbon Dioxide Biogenic | lb | 814 | 764 | 0 | 1,430 | 137,000,000 | 0 | 10 | 262 | 16,400,000 | 153,403,280 |
| Carbon Dioxide Fossil | tons | 761,800 | 1,625,000 | 0 | 4,310,000 | -33,700,000 | 2,010 | 43,000 | 1,090,000 | -84,200,000 | -110,068,190 |
| Ammonia (Air) | lb | 0 | 0 | 0 | 4 | -35 | 0 | 0 | 2 | -94 | -123 |
| Lead (Air) | lb | 0 | 0 | 0 | 0 | -1 | 0 | 0 | 0 | 6 | 5 |
| Methane (CH4) | lb | 545 | 511 | 0 | 5,740 | -55,900 | 0 | 8 | 174 | -83,200 | -132,122 |
| Hydrochloric Acid | lb | 4 | 4 | 0 | 916 | -938 | 0 | 0 | 1 | -6,740 | -6,753 |
| Carbon Equivalents | lb | 106 | 222 | 0 | 607 | -4,780 | 0 | 6 | 150 | -11,800 | -15,489 |
| | | | | | | | | | | | |
| **Ancillary Solid Waste** | lb | 18,200 | 17,030 | 0 | 578,000 | -5,690,000 | 11 | 309 | 5,720 | -11,600,000 | -16,670,730 |
| | | | | | | | | | | | |
| **Water Releases** | | | | | | | | | | | |
| Dissolved Solids | lb | 4,667 | 4,381 | 0 | 36,100 | -357,000 | 3 | 58 | 1,500 | -173,000 | -483,291 |
| Suspended Solids | lb | 107 | 100 | 0 | 1,790 | -17,800 | 0 | 2 | 34 | -7,730 | -23,496 |
| BOD | lb | 17 | 16 | 0 | 77 | -761 | 0 | 0 | 6 | 10,200 | 9,556 |
| COD | lb | 116 | 109 | 0 | 134 | -1,250 | 0 | 305 | 37 | -5,370 | -5,918 |
| Oil | lb | 108 | 101 | 0 | 25 | -157 | 47 | 609 | 35 | -3,320 | -2,552 |
| Sulfuric Acid | lb | 1 | 1 | 0 | 0 | 4 | 0 | 0 | 0 | -2,060 | -2,054 |
| Iron | lb | 3 | 3 | 0 | 207 | -2,050 | 0 | 0 | 1 | -1,410 | -3,247 |
| Ammonia (Water) | lb | 2 | 2 | 0 | 14 | -137 | 0 | 4 | 1 | -719 | -834 |
| Copper | lb | 0 | 0 | 0 | 1 | -7 | 0 | 0 | 0 | 0 | -6 |
| Cadmium | lb | 0 | 0 | 0 | 0 | -1 | 0 | 0 | 0 | -8 | -8 |
| Arsenic | lb | 0 | 0 | 0 | 0 | -3 | 0 | 0 | 0 | 0 | -2 |
| Mercury (Water) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Phosphate | lb | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | -199 | -196 |
| Selenium | lb | 0 | 0 | 0 | 1 | -7 | 0 | 0 | 0 | 0 | -6 |
| Chromium | lb | 0 | 0 | 0 | 1 | -14 | 0 | 0 | 0 | -8 | -20 |
| Lead (Water) | lb | 0 | 0 | 0 | 0 | -5 | 0 | 0 | 0 | 0 | -4 |
| Zinc | lb | 0 | 0 | 0 | 2 | -21 | 0 | 0 | 0 | -4 | -23 |

**Table A-15. Alternative 4 GHG-Optimized MSW DST Results**

| Parameter | Units | Recyclables Collection | Residuals Collection | Transfer Station | MRF | WTE | Landfill | Ash-landfill | Transport | Remfg | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| **Cost** | $ | 9,737,000 | 6,825,000 | 0 | 4,450,000 | 0 | 1,860,000 | 0 | 686 | -2,560,000 | 20,312,686 |
| | | | | | | | | | | | |
| **Energy Consumption** | MBTU | 53,430 | 34,580 | 0 | 15,700 | 0 | 35,000 | 0 | 6,940 | -675,000 | -529,350 |
| | | | | | | | | | | | |
| **Air Emissions** | | | | | | | | | | | |
| Total Particulate Matter | lb | 412 | 386 | 0 | 6,510 | 0 | 3,160 | 0 | 1,380 | -218,000 | -206,152 |
| Nitrogen Oxides | lb | 26,650 | 24,960 | 0 | 25,300 | 0 | 14,100 | 0 | 9,580 | -362,000 | -261,410 |
| Hydrocarbons (non CH4) | lb | 0 | 6,708 | 0 | 1,180 | 0 | 1,680 | 0 | 3,850 | -336,000 | -322,582 |
| Sulfur Oxides | lb | 3,458 | 3,250 | 0 | 55,300 | 0 | 6,510 | 0 | 2,720 | -572,000 | -500,762 |
| Carbon Monoxide | lb | 15,210 | 9,295 | 0 | 2,960 | 0 | 8,810 | 0 | 9,440 | -694,000 | -648,285 |
| Carbon Dioxide Biogenic | lb | 814 | 764 | 0 | 790 | 0 | 52,500,000 | 0 | 268 | 37,100,000 | 89,602,636 |
| Carbon Dioxide Fossil | tons | 761,800 | 1,625,000 | 0 | 8,470,000 | 0 | 1,220,000 | 0 | 1,120,000 | -60,400,000 | -47,203,200 |
| Ammonia (Air) | lb | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 2 | -1,640 | -1,636 |
| Lead (Air) | lb | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | -15 | -14 |
| Methane (CH4) | lb | 545 | 511 | 0 | 9,790 | 0 | 5,490,000 | 0 | 178 | -71,700 | 5,429,324 |
| Hydrochloric Acid | lb | 4 | 4 | 0 | 2,120 | 0 | 1,520 | 0 | 1 | -5,450 | -1,801 |
| Carbon Equivalents | lb | 106 | 222 | 0 | 1,190 | 0 | 18,900 | 0 | 153 | -8,480 | 12,091 |
| | | | | | | | | | | | |
| **Ancillary Solid Waste** | lb | 18,200 | 17,030 | 0 | 1,170,000 | 0 | 506,000 | 0 | 5,830 | -12,800,000 | -11,082,940 |
| | | | | | | | | | | | |
| **Water Releases** | | | | | | | | | | | |
| Dissolved Solids | lb | 4,667 | 4,381 | 0 | 8,590 | 0 | 1,420 | 0 | 1,530 | -185,000 | -164,412 |
| Suspended Solids | lb | 107 | 100 | 0 | 782 | 0 | 148 | 0 | 35 | 13,000 | 14,172 |
| BOD | lb | 17 | 16 | 0 | 19 | 0 | 93,600 | 0 | 6 | 40,800 | 134,459 |
| COD | lb | 116 | 109 | 0 | 35 | 0 | 261,000 | 0 | 38 | -83,900 | 177,399 |
| Oil | lb | 108 | 101 | 0 | 15 | 0 | 11,500 | 0 | 36 | 321 | 12,081 |
| Sulfuric Acid | lb | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | -649 | -647 |
| Iron | lb | 3 | 3 | 0 | 77 | 0 | 7 | 0 | 1 | 3,040 | 3,131 |
| Ammonia (Water) | lb | 2 | 2 | 0 | 3 | 0 | 800,000 | 0 | 1 | -1,130 | 798,878 |
| Copper | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cadmium | lb | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | -8 | -6 |
| Arsenic | lb | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 5 |
| Mercury (Water) | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Phosphate | lb | 0 | 0 | 0 | 0 | 0 | 1,760 | 0 | 0 | -85 | 1,676 |
| Selenium | lb | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 4 |
| Chromium | lb | 0 | 0 | 0 | 0 | 0 | 16 | 0 | 0 | -8 | 8 |
| Lead (Water) | lb | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3 |
| Zinc | lb | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 50 | 51 |

# Glossary

| | |
|---|---|
| ACE | Air, Climate, and Energy |
| DAF | Dilution-attenuation factor |
| DEM | Digital elevation model |
| DOE | U.S. Department of Energy |
| DOT | U.S. Department of Transportation |
| DSS | Decision Support System |
| DRAS | Delisting Risk Assessment Software |
| EPA | Environmental Protection Agency |
| FRAMES | Framework for Risk Analysis in Multimedia Environmental Systems |
| GHG | Greenhouse gas |
| GIS | Geographic information system |
| HDPE | High-density polyethylene |
| $HE^2RMES$ | Human and Ecological Exposure & Risk in Multimedia Systems |
| HOV | High occupancy vehicle |
| HRSD | Hampton Roads Sanitation District |
| IPCC | Intergovernmental Panel on Climate Change |
| I-WASTE | Incident Waste Decision Support Tool |
| IWEM | Industrial Waste Management Evaluation Model |
| LiDAR | Light Detection and Ranging |
| MLLW | Mean lower low water |
| MOM | Maximum of the maximums |
| MRF | Materials recovery facility |
| MSW | Municipal solid waste |
| MSW DST | Municipal Solid Waste Decision Support Tool |
| NASA | U.S. National Aeronautics and Space Administration |
| NHC | National Hurricane Center |
| NOAA | U.S. National Oceanic and Atmospheric Administration |
| NWS | National Weather Service |
| O&M | Operations and maintenance |
| OLEM | Office of Land and Emergency Management (EPA) |
| ORD | Office of Research and Development (EPA) |
| PET | Polyethylene terephthalate |
| POTW | Publicly owned treatment works |
| RTI | Research Triangle Institute |
| SLOSH | Sea, Lake and Overland Surges from Hurricanes |
| SLR | Sea level rise |
| SPSA | Southeastern Public Service Authority of Virginia |
| TFC | Tidewater Fibre Corporation |
| TRAGIS | Transportation Routing Analysis Geographic Information System |
| U.S. | United States |
| USCG | U.S. Coast Guard |

| | |
|---|---|
| USGCRP | United States Global Change Research Program |
| USGS | United States Geological Survey |
| VDOT | Virginia Department of Transportation |
| VIMS | Virginia Institute of Marine Science |
| WTE | Waste-to-energy |

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