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Environmental and Cost Life Cycle Assessment of Disinfection Options for Municipal Wastewater Treatment

Office of Research and Development
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ENVIRONMENTAL AND COST LIFE CYCLE ASSESSMENT OF DISINFECTION OPTIONS FOR MUNICIPAL WASTEWATER TREATMENT

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ABSTRACT

EPA is evaluating water disinfection technologies in coordination with the Confluence Water Technology Innovation Cluster (WTIC) and EPA's National Risk Management Research Laboratory (NRMRL). EPA is developing an environmental life cycle assessment (LCA) and cost analysis to evaluate the environmental outcomes and costs associated with innovative disinfection technologies. EPA is further interested in establishing an LCA and cost model framework that could be used to study other technologies or changes to drinking water and municipal wastewater treatment systems in the future. For each technology, there are associated differences in pathogen removal, disinfection by-product formation, treatment facility energy use and operating costs, input chemical requirements, and supply chain impacts.

This document summarizes the data collection, analysis, and results for a base case wastewater treatment (WWT) plant reference model. The base case is modeled after the Metropolitan Sewer District of Greater Cincinnati (MSDGC) Mill Creek Plant. The plant has an activated sludge system but is not removing nitrogen or phosphorus and uses sodium hypochlorite for disinfection prior to discharge to the Ohio River. Sludge at the Mill Creek Plant is incinerated in fluidized bed reactors. The Mill Creek plant receives a large amount of industrial waste and UV may not provide sufficient disinfection. MSGDC's reports were the primary data sources for the life cycle inventory of wastewater collection and treatment system.

Results of the base case analysis show normalized WWT results are dominated by eutrophication. Eutrophication impacts are from release of ammonia and phosphorus emissions in wastewater effluent. Sludge incineration makes the largest contribution to global warming potential, much of which is related to biogenic CO_2 emissions from combustion of the sludge. Excluding biogenic carbon dioxide emissions more than halves the overall carbon footprint of treating wastewater in the base case. Aeration is the life cycle stage that consumes the most electricity, making it the largest contributor for many impacts including energy demand, fossil depletion, acidification, blue water use, ozone depletion, human health cancer, and human health criteria. The impacts driven by electricity consumption are sensitive to the electricity usage and electricity grid sensitivity analyses conducted. Overall, primary disinfection with sodium hypochlorite only contributes zero to 6 percent for most impact categories, with the exception of blue water use, ozone depletion, metal depletion, and human health noncancer. Upstream processes associated with production of the sodium hypochlorite have relatively high impacts for these categories. Wastewater collection accounts for 33 percent of the total cost, followed by plant-wide overhead cost, which accounts for 20 percent of the cost, sludge thickening and dewatering, which accounts for 19 percent of the cost, and aeration, which accounts for 14 percent of the cost.

This study provides the US specific life cycle datasets for each unit process of wastewater treatment system. The open-source and process based models built in this study are flexible to incorporate future development of wastewater treatment technologies and associated datasets.

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1. INTRODUCTION AND STUDY GOAL

Municipal wastewater treatment systems in the United States are under increasing pressure to improve performance while maintaining costs, which are amongst the lowest in the developed world.[1] Increasing urbanization, protection of surface waters against increasing nutrient concentrations, and managing stormwater while avoiding overflow events are all drivers for modifications to improve system performance. At the same time, the cost structure of providing municipal wastewater services nationally is shifting from installation of systems to maintenance of existing infrastructure.[2] In 2008, the cost for required improvements to wastewater treatment facilities and collection systems nationally was estimated to be $300 billion.[3] Meanwhile, municipal operators are considering improvements to system performance and efficiency. This study provides a baseline environmental and cost life cycle assessment of municipal wastewater collection and treatment in the Cincinnati Region in coordination with the Confluence Water Technology Innovation Cluster[4] and EPA's National Risk Management Research Laboratory. This baseline study offers context to aid decision-making related to municipal wastewater systems.

Data were collected from the Metropolitan Sewer of Greater Cincinnati (MSDGC) Mill Creek Plant to develop a base case wastewater treatment (WWT) plant life cycle assessment (LCA) model and cost analysis. The base case plant treats 114 million gallons per day (MGD) and discharges 97 MGD of treated water to the Ohio River. Mill Creek uses activated sludge treatment and does not address nutrient removal. The plant uses liquid sodium hypochlorite for disinfection. Incoming and outgoing water metrics reported for this study by MSDGC at the Mill Creek Plant are displayed in Table 1. Sludge at the Mill Creek Plant is incinerated in fluidized bed reactors.

[1] Raftelis. '2012 Water and Wastewater Rate Survey.' Raftelis Financial Consultants, Inc. and the American Water Works Association. Published by the American Water Works Association. 2013. [ISBN: 9781583219003]

[2] U.S. EPA. 'Cost Accounting and Budgeting for Improved Wastewater Treatment.' 1998.

[3] U.S. EPA Clean Watersheds Needs Survey 2008 Report to Congress. 2008.

[4] Confluence is a network of water technology researchers, businesses, utilities, and others in the southwest Ohio, northern Kentucky, and southeast Indiana region. The group was formed in 2011 with help from EPA and the U.S. Small Business Administration. See http://www.watercluster.org and http://www2.epa.gov/clusters-program for more information.

Table 1. Incoming and outgoing water quality metrics for MSDGC Mill Creek Plant (per m^3 water).

	Incoming Water			Outgoing Water			
Water Metrics	Minimum	Maximum	Average	Minimum	Maximum	Average	Unit
Ammonia				2.20	11.4	7.66	g
Dissolved solids				4.90	5.80	5.20	g
pH	5.90	7.60	6.80				pH
Phosphorus				0.22	0.88	0.55	g
Suspended solids	46.0	1,072	208	13.0	32.0	21.5	g
Temperature	8.00	23.0	16.0	13.4	23.8	18.0	ºC
Turbidity				3.40	78.0	9.20	NTU

Source: Primary data collected from MSDGC for the year 2012

Additional details on the base case plant are provided in Sections 2.2 and 3.2. The goals for the base case LCA model and cost analysis are to:

1. Evaluate the base case environmental outcomes and costs to provide a baseline for comparison to alternative disinfection technologies.
2. Establish an LCA and cost framework that could be used to study other technologies or changes to WWT systems.

The study intends to answer the following research questions[5]:

1. What are the net life cycle impacts associated with the collection and treatment of municipal wastewater?
2. What are the contributions of each life cycle stage to the net result for each impact category? What are the contributions of each step in the wastewater management system?
3. What are the contributions of specific environmental releases to the net result for each technology and impact category?
4. What is the effect of plausible parameter variability? What parameters associated with wastewater characteristics have the greatest effect on net greenhouse gas and human health impact results?

The remainder of the report provides details on EPA's analysis and is organized into the following sections:

- Section 2 defines the study scope.

[5] This project requires the collection and use of existing data. EPA developed a Quality Assurance Project Plan (QAPP) which outlines the quality objectives for this project. The plan is entitled Quality Assurance Project Plan for Systems-Based Sustainability and Emerging Risks Performance Assessment of Cincinnati Regional Water Technology Innovations: Comparative Life Cycle Assessment and Cost Analysis of Water Treatment Options, and was prepared by Eastern Research Group, Inc. for U.S. EPA Sustainable Technology Division, National Risk Management Research Laboratory. The plan was approved February 2013.

- Section 3 provides details on the LCA method including a description of the unit processes included in the base case model.
- Section 4 describes the cost analysis.
- Section 5 presents base case results.
- Section 6 presents base case sensitivity results.
- Section 7 discusses overall findings and next steps in the study.
- Section 8 provides the references for the study.

2. SCOPE

The base case model includes wastewater collection, treatment, waste management, and treated water release. The base case establishes the reference case for comparison to alternative wastewater disinfection technologies.

2.1 Functional Unit

The functional unit, which provides the basis for comparison, used in this study is the treatment of a cubic meter of wastewater to meet or exceed the National Pollutant Discharge Elimination System (NPDES) requirements for the MSDGC.

2.2 System Boundaries

Figure 1 illustrates the system boundary for the WWT base case model. The system boundary starts at collection of wastewater and ends at downstream release of wastewater effluent. In addition to the processes shown here, electricity for pumping wastewater at the WWT plant headworks and other miscellaneous pumping is included within the systems boundaries. Consumption of natural gas and mobile fuel such as diesel and gasoline is also included. Sewer pipe infrastructure and capital equipment at the WWT plant is within the system boundaries. Transportation for all inputs to the processes within supply chains, such as transporting waste to landfill, is also included within the system boundaries.

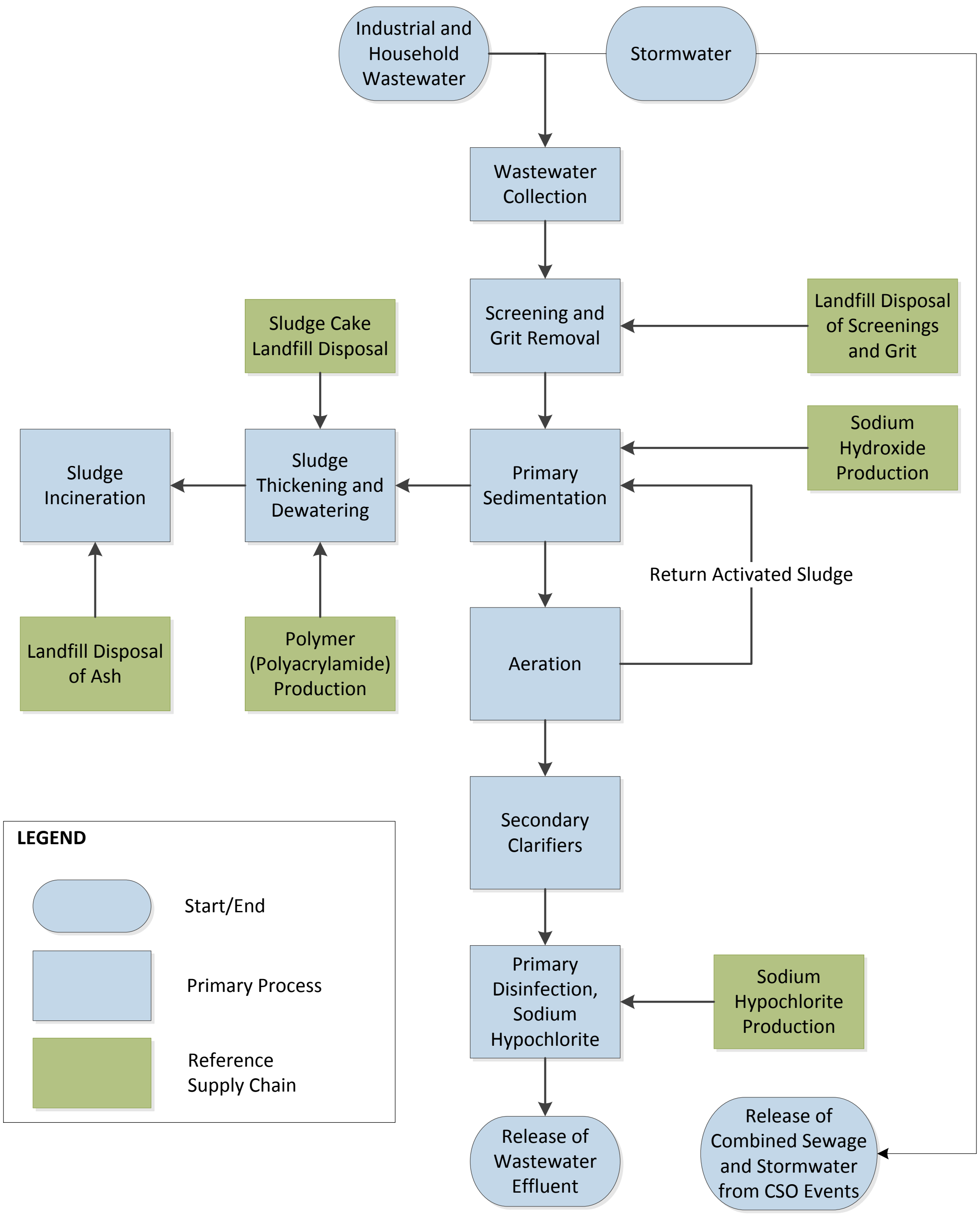

Figure 1. System boundary of the wastewater treatment base case model.

2.3 Impacts and Flows Tracked

The full inventory of emissions generated in an LCA study is lengthy and diverse, making it difficult to interpret emissions profiles in a concise and meaningful manner. Life cycle impact assessment (LCIA) helps with interpretation of the emissions inventory. In the LCIA phase, the inventory of emissions is first classified into categories in which the emissions may contribute to impacts on human health or the environment. Within each impact category, the emissions are then normalized to a common reporting basis, using characterization factors that express the impact of each substance relative to a reference substance.

Table 2 summarizes the complete list of impacts examined for the base case model runs. This study addresses global, regional, and local impact categories. The LCIA method provided by the Tool for the Reduction and Assessment of Chemical and Environmental Impacts (TRACI), version 2.0, developed by the U.S. EPA specifically to model environmental and human health impacts in the U.S., is the primary LCIA method applied in this work.[6] Additionally, the ReCiPe LCIA method is used to characterize fossil fuel, blue water use (i.e. water depletion) and metal depletion.[7] Energy is tracked based on point of extraction using the cumulative energy demand method developed by ecoinvent.[8] The blue water use impact category represents freshwater use from surface water or groundwater sources. The blue water use category includes indirect consumption of water from upstream processes, such as water withdrawals for electricity generation (e.g., evaporative water losses from coal power cooling water and establishment of hydroelectric dams).[9] A companion cost analysis is also conducted.

Table 2. Impact and flow results categories.

Category	Method	Unit	Description
Cost	Cost Analysis	$	Measures total cost in U.S. dollars.
Global Warming	TRACI 2.0	kg CO_2 eq	Represents the potential heat trapping capacity of greenhouse gases.
Energy Demand	ecoinvent	MJ eq	Measures the total energy use from point of extraction.
Fossil Depletion	ReCiPe	kg oil eq	Assesses the potential reduction of fossil fuel energy resources.
Acidification	TRACI 2.0	H+ moles eq	Quantifies the potential acidifying effect of substances on their environment.
Eutrophication	TRACI 2.0	kg N eq	Assesses potential impacts from excessive load of macro-nutrients to the environment.
Blue Water Use	Custom	m^3	Calculates consumptive use of fresh surface or groundwater.
Smog	TRACI 2.0	kg O^3 eq	Determines the potential formation of reactive substances (e.g. tropospheric ozone) that cause harm to human health

6 EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), see: http://www.epa.gov/nrmrl/std/sab/traci/.

7 Goedkoop M.J., Heijungs R, Huijbregts M., De Schryver A.; Struijs J., Van Zelm R, ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; First edition Report I: Characterisation; 6 January 2009, http://www.lcia-recipe.net

8 Ecoinvent Cumulative Energy Demand (CED) Method implemented in ecoinvent data v2.2. 2010. Swiss Centre for Life Cycle Inventories.

9 Pfister, S., Saner, D., Koehler, A. 2011. The environmental relevance of freshwater consumption in global power production. International Journal of Life Cycle Assessment, 16 (6): 580-591.

Category	Method	Unit	Description
			and vegetation.
Ozone Depletion	TRACI 2.0	kg CFC-11 eq	Measures potential stratospheric ozone depletion.
Metal Depletion	ReCiPe	kg Fe eq	Assesses the potential reduction of metal resources.
Human Health, Cancer, Total	TRACI 2.0	CTU	A comparative toxic unit (CTU) for cancer characterizes the probable increase in cancer related morbidity (from inhalation or ingestion) for the total human population per unit mass of a chemical emitted.
Human Health, NonCancer, Total	TRACI 2.0	CTU	A CTU for noncancer characterizes the probable increase in noncancer related morbidity (from inhalation or ingestion) for the total human population per unit mass of a chemical emitted.
Human Health, Criteria	TRACI 2.0	kg PM10 eq	Assesses human exposure to elevated particulate matter less than 10 μm.
Ecotoxicity, Total	TRACI 2.0	CTU	Assesses potential fate, exposure, and effect of chemicals on the environment.

2.3.1 Normalized and Weighted Results

Normalization is an optional step in LCA that aids in understanding the significance of the impact assessment results. Normalization is conducted by dividing the impact category results by a normalized value. The normalized value is typically the environmental burdens of the region of interest either on an absolute or per capita basis. The results presented here are normalized to reflect person equivalents in the U.S. using TRACI v2.1 normalization factors.[10] Only impacts with TRACI normalization factors are shown, some categories like blue water use and energy demand are excluded due to lack of available normalization factors.

Weighting is an additional optional step in LCA that provides a link between the quantitative results and subjective choices of decision makers. This study applies weights to the normalized results described above. The weights utilized here were developed by the National Institute of Standards and technology (NIST) for the BEES (Building for Environmental and Economic Sustainability) software.[11] This weighting set was created specifically for the buildings sector context, which may not be completely compatible with the wastewater treatment sector. However, due to lack of a weighting set specific to the water treatment sector, this NIST weighting set has been utilized.

[10] Ryberg, M., Vieira, M.D.M., Zgola, M., Bare, J., and Rosenbaum, R.K., 2014. Updated US and Canadian normalization factors for TRACI 2.1. Clean Techn Environ Policy, 16: 329-339.

[11] Gloria, T.P., Lippiatt, B.C., and Cooper, J. 2007. Life cycle impact assessment weights to support environmentally preferable purchasing in the United States. Environ. Sci. Technol, 41, 7551-7557.

3. LCA METHOD

Development of an LCA requires significant input data, an LCA modeling platform, and impact assessment methods. This section provides background on the development of the LCA model. Section 3.1 discusses the data collection method and model, Section 3.2 describes the unit processes, Section 3.3 lists the data sources, Section 3.4 covers the infrastructure modeling, and Section 3.5 describes limitations of the LCA model.

In this study, MSDGC provided much of the LCA input data for the unit processes listed in Figure 1 for the Mill Creek plant. EPA supplemented this information with data from two MSDGC reports:

- Metropolitan Sewer District of Greater Cincinnati, *2010 Sustainability Report: Redefining the Future* (Sustainability Report).[12]

- Metropolitan Sewer District, *Mill Creek WWTP Facility Plan* (Facility Plan), Black & Veatch, May 2008.[13]

This study also used publicly accessible and private databases to provide underlying data sets describing the supply chains of inputs to the processes modeled here. For example, in addition to the unit processes described in Section 3.2, an LCA also includes impacts from the production of any materials required in the process.

3.1 Data Collection and Model

Data were collected electronically using Excel templates designed by the project team to be completed by MSDGC Mill Creek. Mill Creek operates separate divisions for the collection system and the WWT plant, and EPA collected data from both divisions to obtain information for the entire system shown in Figure 1. Data collection was an iterative process, whereby the project team asked MSDGC multiple rounds of questions to ensure all necessary life cycle and cost information was being reported and properly interpreted in the assessment. The quality and objectivity of results was ensured by carefully adhering to the data collection protocols and quality procedures laid out in the Quality Assurance Project Plan prior to beginning work on the project.

Each unit process in the life cycle inventory was constructed independently of all other unit processes. This allows objective review of individual data sets before their contribution to the overall life cycle results has been determined. Also, because these data are reviewed individually, assumptions were assessed based on their relevance to the process rather than their effect on the overall outcome of the study.

The model was constructed in OpenLCA, an open-source LCA software package provided by GreenDelta.

[12] Available at http://projectgroundwork.org/sustainability/index.html

[13] Available at http://www.msdgc.org/downloads/wetweather/bundles/Documents_for_LMCPR-Phase_I-EHRT/Mill%20Creek%20WWTP/MSD%20Mill%20Creek%20Facility%20Plan.pdf

3.2 Unit Processes

Figure 1 shows the WWT base case unit processes beginning with wastewater collection and ending at discharge to the Ohio River. The plant has an activated sludge system but is not removing nitrogen or phosphorus and uses sodium hypochlorite for disinfection. Sludge at the Mill Creek Plant is incinerated in fluidized bed reactors. A description of each unit process follows. These unit processes align with the unit processes developed for the OpenLCA model. In the model, infrastructure processes for each of the below unit processes were also developed. This infrastructure is discussed further in Section 3.4.

Wastewater Collection

1. Collect household, commercial, and municipal wastewater, as well as stormwater, and transport by sewer to the WWT facility. The collection system is a combined sewer system, which is designed to collect these different wastewater types (rainwater runoff, domestic sewage, and industrial wastewater) in the same sewer pipe network. Typically, all types of wastewater are treated at the wastewater plant; however, during heavy rainfall/snowmelt, the water volume exceeds the capacity of the sewer system or WWTP, in which case the overflow is discharged directly to nearby surface water. The quantity of combined sewer overflow (CSO) is tracked in the model. The wastewater collection unit process also includes pumping to move raw wastewater through the collection system piping. Pipe infrastructure production, installation and removal, and collection system maintenance are also covered in this process.

Pumping Energy, at Wastewater Plant

2. Electricity used for pumping the wastewater at the headworks of the plant and for any miscellaneous pumping throughout the plant not attributed to any one of the unit processes below.

Mobile Fuel Combustion, at Wastewater Treatment Plant

3. Diesel and gasoline fuel used for maintenance activities at the WWT plant.

Screening and Grit Removal, at Wastewater Treatment Plant

4. Screening removes large debris from the wastewater flow through multiple screens. Grit removal extracts stone, grit, and other settleable debris. Debris from these processes is transported to a landfill for disposal.

Primary Sedimentation, at Wastewater treatment Plant

5. Removes solids by sedimentation in pre-settling basins and mechanical scraping, and oil and grease by mechanical skimming.

Aeration, at Wastewater Treatment Plant

6. Remove organics through conventional aerobic activated sludge process including aeration.

Secondary Clarifiers, at Wastewater Treatment Plant

7. Remove biological solids by gravity settling.

Sludge Thickening and Dewatering, at Wastewater Treatment Plant

8. Sludge is thickened using gravity settling and centrifuges. Sludge is then dewatered by centrifuge. Centrate is returned to primary or secondary sedimentation.

Sludge Incineration, at Wastewater Treatment Plant

9. Sludge is incinerated using fluidized-bed incinerators. Ash from incineration is disposed of in a landfill.

Wastewater Primary disinfection, Sodium Hypochlorite

10. The wastewater effluent is disinfected using sodium hypochlorite as the disinfectant.

Release of Wastewater Effluent

11. The treated wastewater is released to a river.

Municipal Wastewater Treatment

12. This process aggregates the above processes in the OpenLCA model.

3.3 Base Case Data Sources

Table 3 displays the data sources used for the Mill Creek WWT plant base case, which treats approximately 114 MGD of wastewater. In general, data from Mill Creek staff were used where available. EPA supplemented information from Mill Creek staff with information from the Sustainability Report and Mill Creek Facility Report. The data used from these reports are for Mill Creek plant processes and therefore meet the criteria for representativeness in the project Quality Assurance Project Plan.

Mill Creek WWT plant staff provided the total electricity used for the entire plant. EPA distributed the total electricity by unit process by using equipment specification data in the facility report. Table 4 shows the plant electricity distribution used in this analysis. MSDGC provided information on electricity use at the collection system separately.

Table 3. Data sources.

Life Cycle Stage	Unit Process/Process Emission	Required Data	Direct Input from Mill Creek Staff	Sustainability Report	Facility Plan	Literature Source	Other Sources/Notes
Wastewater Collection	Stormwater (from CSO events)	Volume of CSO events	✓				
	Industrial and household water	Volume collected	✓				
	Electricity (collection system pumps)	Quantity used	✓				MSDGC provided the total cost of electricity used by the collection system. The corresponding amount of electricity was calculated using the cost per kilowatt-hour of electricity provided by MSDGC.
	Sewer pipe infrastructure	Length and type of pipe	✓				
	Pipe installation	Length and type of pipe	✓				
Pumping, at WWTP	Electricity[a]	Quantity used	✓ (total quantity)		✓ (percent used)		
Mobile Fuel Combustion	Gasoline-powered equipment	Quantity used	✓	✓			Mill Creek Collection System staff provided amount of gasoline used for collection system activities.
	Diesel-powered equipment	Quantity used		✓			
Screening and Grit Removal	Landfill waste disposal	Quantity generated	✓	✓			
	Electricity[a]	Quantity used	✓ (total quantity)		✓ (percent used)		
Primary Sedimentation	Sodium hydroxide production	Quantity used	✓				
	Electricity	Quantity used	✓ (total quantity)		✓ (percent used)		
	Waste quantity	Quantity generated	✓				
Secondary Clarifiers	Electricity[a]	Quantity used	✓ (total quantity)		✓ (percent used)		
	Waste quantity	Quantity generated					

Life Cycle Stage	Unit Process/Process Emission	Required Data	Direct Input from Mill Creek Staff	Sustainability Report	Facility Plan	Literature Source	Other Sources/Notes
Sludge Thickening and Dewatering	Waste quantity	Quantity generated	✓				
	Polymer (polyacrylamide) production	Quantity used at plant	✓				
	Electricity [a]	Quantity used	✓ (total quantity)		✓ (percent used)		
Aeration	Carbon dioxide, biogenic	Quantity generated				✓	Monteith et al. (2005)[16]
	Electricity [a]	Quantity used	✓ (total quantity)		✓ (percent used)		
Sludge Incineration	Quantity incinerated	Quantity incinerated	✓				
	Electricity [a]	Quantity used	✓ (total quantity)		✓ (percent used)		
	Natural gas	Quantity used	✓				
	Carbon dioxide, biogenic	Quantity generated				✓	IPCC (2006) Chapter 5, pg 5.7 and Table 5.2[17]
	Methane, biogenic	Quantity generated				✓	IPCC (2006) Chapter 5, pg 5.20[17]
	Nitrous oxide	Quantity generated				✓	Suzuki Model from Brown et al. (2010)[14]
Disinfection	Sodium hypochlorite production	Quantity used	✓				
Infrastructure at the WWT Plant	Infrastructure components for all unit processes at the WWT plant	Type and quantity of component			✓		

[a]Mill Creek provided the total plant electricity used. EPA used specifications for individual pieces of equipment from the Mill Creek Facility Plan to develop a percent distribution among the life cycle stages.

Table 4. Percent electricity contribution by life cycle stage.[a]

Life Cycle Stage	Percent Plant Electricity
Screening and grit removal	0.14%
Pumping	17.69%
Primary sedimentation	1.95%
Aeration	62.86%
Secondary clarifiers	2.22%
Primary disinfection	0.00%
Sludge thickening and dewatering	13.64%
Sludge incineration	1.50%

[a]Distribution for plant electricity only. Collection system electricity was presented separately.

Wastewater collection data were obtained from MSDGC for the entire collection system, which serves multiple WWT plants. Therefore, EPA normalized wastewater collection data by the total length of sewer pipes within MSDGC's jurisdiction. These normalized values were then multiplied by the length of sewer pipes that serve the Mill Creek WWT plant to allocate the collection data to only the Mill Creek plant.

As shown in Table 3, EPA also estimated impacts from greenhouse gases (GHG) generated at the treatment plant. The Mill Creek Plant does not perform nutrient removal processes or anaerobic digestion and sludge continuously flows through the sludge thickening processes to the incinerators. Therefore, EPA expects minimal contribution to methane and nitrous oxide emissions from the aeration and sludge thickening processes.[14,15] EPA included biogenic CO_2 emissions from aeration and all biogenic and fossil GHG emissions from the incineration process in the model. EPA estimated biogenic CO_2 emissions from aeration using the method proposed by Monteith et al.[16] MSDGC provided information on volume of aerobic reactor volume, annual volume of influent wastewater, influent and effluent total suspended solids, and solids retention time, while the paper from Monteith et al. supplied the remaining parameters of a typical conventional activated sludge treatment system needed for the calculation.

EPA used the following information to estimate GHG emissions from incineration for the base case:

- For biogenic CO_2 emissions from sludge:

[14] Brown, Beecher, and Carpenter. Calculator Tool for Determining Greenhouse Gas Emissions for Biosolids Processing and End Use. Environmental Science and Technology. 2010, 44 (24), pp 9509–9515.

[15] Foley, J. and P. Lant. Direct Methane and Nitrous Oxide Emissions from Full-Scale Wastewater Treatment Systems. Research by Advanced Water Care Management Center, The University of Queensland Australia for Water Services Association of Australia, http://www.wsaa.asn.au.

[16] Monteith, Sahely, MacLean, and Bagley. A Rational Procedure for Estimation of Greenhouse-Gas Emissions from Municipal Wastewater Treatment Plants. *Water Environment Research;* Jul/Aug 2005; 77, 4; Water Resources Abstracts pg. 390.

- The Intergovernmental Panel on Climate Change (IPCC) 2006 Guidelines for GHG Inventories gives a range of 40 to 50% carbon content in dry sludge.[17] EPA used the average of this range (45%) in calculations.
- The IPCC provides a default oxidation rate of 100%.[17]
- The biogenic CO_2 emissions factor was calculated as 1.65 tons biogenic CO_2 / dry ton of sludge.
- According to MSDGC, the Mill Creek Plant produces 37,811 metric tons of dry sludge and treats 157,615,342 m^3 of wastewater annually.
- EPA calculated that 0.40 kg biogenic CO_2 is released per cubic meter of wastewater treated.

* For CH_4 emissions from sludge:
  - The IPCC 2006 gives a default value of 4.85×10^{-5} kg CH_4 emitted / kg of dry sludge burned, which converts to 12 g CH_4 / m^3 of wastewater treated.[14,15,17]

* For N_2O emissions from sludge:
  - The Suzuki model describes nitrous oxide emissions from continuously operated fluidized bed incinerators using the equation: $\eta = 161.3 - 0.140T_f$, where η is the percent of total N in the sludge that is volatilized as N_2O, and T_f is the average highest freeboard temperature from the fluidized bed facilities.
  - Based on the average highest freeboard temperature of 1,600 degrees F provided by Mill Creek Plant, $\eta = 0.011034$ and emissions of N_2O are 6.936×10^{-4} tons per dry ton of sludge incinerated.
  - The BEAM model uses a default ratio of 0.04 tons nitrogen per ton of dry sludge.[18]
  - Total nitrous oxide emissions were calculated as 0.17 g N_2O per cubic meter of wastewater treated at the plant.

* For fossil GHG emissions from natural gas combustion:
  - Emissions from natural gas combusted in Mill Creek's incinerator are based on LCI data from the National Renewable Energy Laboratory's U.S. Life Cycle Inventory Database (U.S. LCI), a publically available life cycle inventory source.[19]

EPA did not model GHG emissions from the wastewater collection system. Although some studies show that methane can be found in gravity flow sewer systems such as the one used by MSDGC, very little research has been done to determine how much is produced.[15] Thus, there is not enough

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[17] Intergovernmental Panel on Climate Change. Guidelines for National Greenhouse Gas Inventories Volume 5: Waste. Intergovernmental Panel on Climate Change. 2006. Available at http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

[18] The Biosolids Emissions Assessment Model (BEAM): A Method for Determining Greenhouse Gas Emissions from Canadian Biosolids Management Practices (2009) Prepared by SYLVIS for Canadian Council of Ministers of the Environment.

[19] National Renewable Energy Lab. US LCI Database. See: http://www.nrel.gov/lci/database/default.asp.

information available to provide a good estimate of CH_4 generated in the sewer pipes that feed the Mill Creek WWTP.

For upstream processes that would not be known by Mill Creek staff such as information on impacts of chemical production, EPA used information from the U.S. LCI Database.[19] Where data were not available from Mill Creek or the U.S. LCI, ecoinvent v2.2, a private Swiss life cycle inventory (LCI) database with data for many unit processes, was used.[20] For some unit processes, the quantities representative of Mill Creek were used in conjunction with background LCI processes. For example, EPA obtained electricity quantities from Mill Creek and used U.S. LCI data to model the impacts of that quantity of electricity. Table 5 presents the WWT LCI data used in the model on the basis of one cubic meter of wastewater treated. These data represent the operational inputs and outputs; LCI data for infrastructure components are provided in Section 3.4.

[20] Ecoinvent Centre (2010), ecoinvent data v2.2. ecoinvent reports No. 1-25, Swiss Centre for Life Cycle Inventories.

Table 5. WWT LCI model input and output data (per m^3 wastewater treated).

Input	Unit	TOTAL Quantity	Quantity by Life Cycle Stage										
			Wastewater Collection	**Pumping at WWT Plant**	**Screening and Grit Removal**	**Primary Sedimentation**	**Sludge Thickening and Dewatering**	**Sludge Incineration**	**Aeration**	**Secondary Clarifiers**	**Disinfection**	**Mobile Fuel Combustion, at Plant**	**Release of Waste-water Effluent**
Stormwater	m3	**0.24**	0.24										
Industrial and household wastewater	m3	**1.00**	1.00										
Purchased electricity	kWh	**0.45**	0.007	0.078	6.2E-04	0.0086	0.060	0.0066	0.28	0.0097			
Natural gas	m3	**0.023**	3.4E-04					0.023					
Diesel	liters	**0.0018**	7.8E-04									0.001	
Gasoline	liters	**0.0015**	0.0012									3.1E-04	
Sodium hypochlorite	liters	**0.012**									0.012		
Sodium hydroxide	kg	**0.0020**				0.0020							
Polymer (polyacrylamide)	kg	**0.0069**					0.0069						
Output													
Sludge cake (landfill waste disposal)	kg	**0.0045**					0.0045						
Screenings, grit (landfill waste disposal)	kg	**0.029**			0.029								
Ash (landfill waste disposal)	kg	**0.054**						0.054					
Carbon monoxide (air emission)	kg	**5.9E-06**						5.9E-06					
VOC (air emission)	kg	**2.8E-07**						2.8E-07					
$PM_{2.5}$ (air emission)	kg	**3.6E-06**						3.6E-06					
PM_{10} (air emission)	kg	**4.2E-06**						4.2E-06					
Lead (air emissions)	kg	**1.8E-09**						1.8E-09					
Organic compounds (air emission)	kg	**3.1E-06**						3.1E-06					
NOx (air emission)	kg	**8.9E-06**						8.9E-06					
SO_2 (air emission)	kg	**1.1E-06**						1.1E-06					
Biogenic carbon dioxide (air emission)	kg	**0.50**						0.40	0.099				
Methane (air emission)	kg	**1.2E-04**						1.2E-04					
Nitrous oxide (air emission)	kg	**1.7E-04**						1.7E-04					
Phosphorus (water emission)	kg	**5.5E-04**											5.5E-04
Ammonia (water emission)	kg	**0.0077**											0.0077
Suspended solids (water emission)	kg	**0.021**											0.021
Dissolved solids (water emission)	kg	**0.0052**											0.0052
WWT effluent	m3	**0.85**											0.85

[a] Sewer pipe and WWTP infrastructure and installation/removal not displayed in table.

3.4 Infrastructure Modeling

Infrastructure data for the collection system was calculated based on pipe type and length data provided by MSDGC, while infrastructure components at the WWT plant were estimated using the Facility Plan.[13] In the Figure 2 system boundaries, infrastructure components modeled are shown in red. Table 6 through Table 9 display the infrastructure requirements at the plant and for the collection system on the basis of one cubic meter of wastewater treated. It was assumed that the lifetime of the buildings and tanks is 100 years. A shorter lifetime of 25 years was estimated for the pumps and motors. The pipe lifetimes (at the plant and in the collection system) are based on the data shown in Table 11. Infrastructure was normalized by dividing the total infrastructure impact by the total lifetime of the component, and then by the water treated per year. It is assumed that the water treated per year (for every year during the infrastructure component lifetime) is 157,615,342 cubic meters, which is the volume of drinking water treated in 2012.

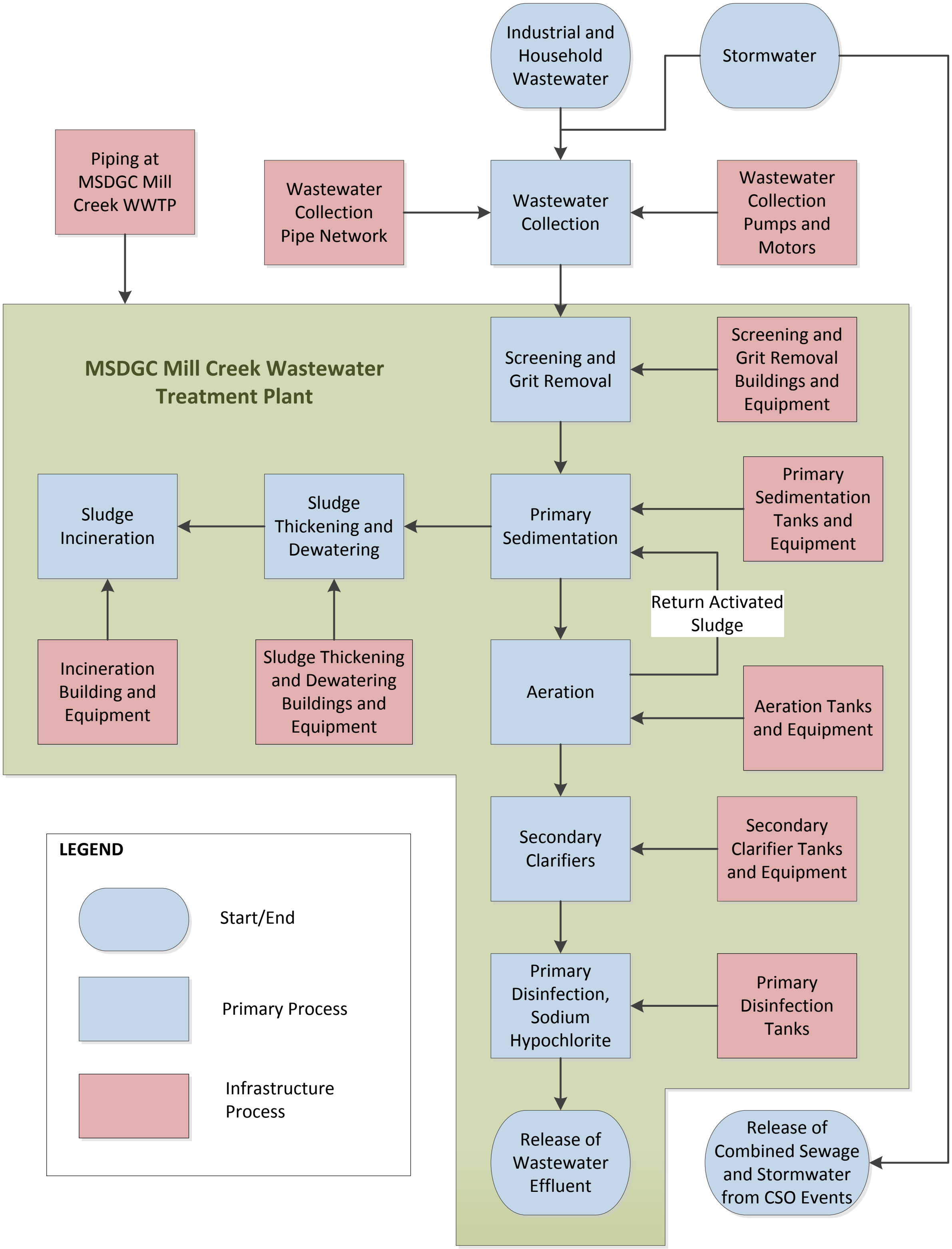


Figure 2. System boundaries of wastewater treatment base case showing infrastructure input.

Table 6. Infrastructure requirements for tanks and buildings at wastewater treatment plant (per m^3 water treated).

	Material Type			
Life Cycle Stage	*Steel (kg)*	*HDPE (kg)*	*Concrete (m3)*	*Earthworks (m3)*
Pumping, at WWT Plant	3.9E-05	0	6.7E-09	2.6E-06
Screening and Grit Removal	9.8E-05	1.2E-06	6.8E-07	2.6E-06
Primary Sedimentation	8.8E-04	5.8E-06	1.0E-05	6.1E-07
Aeration	6.4E-04	0	7.3E-06	2.4E-06
Secondary Clarifiers	2.7E-04	0	3.1E-06	1.5E-06
Sludge Thickening and Dewatering	1.2E-04	1.6E-05	4.7E-07	4.9E-06
Sludge Incineration	5.8E-05	0	5.1E-09	1.9E-06
Primary Disinfection, Sodium Hypochlorite	0	2.2E-06	0	0

Source: MSDGC Facility Plan

Table 7. Infrastructure requirements for motors at wastewater treatment plant (per m^3 water treated).

	Material Type				
Life Cycle Stage	*Electrical Steel (kg)*	*Other Steel (kg)*	*Cast Iron (kg)*	*Aluminum (kg)*	*Copper (kg)*
Pumping, at WWT Plant	3.7E-06	7.9E-07	3.6E-06	2.1E-07	6.4E-07
Screening and Grit Removal	1.3E-08	3.6E-09	1.8E-08	3.9E-09	2.8E-09
Primary Sedimentation	2.4E-08	6.0E-09	1.8E-07	5.4E-09	4.6E-09
Aeration	1.3E-05	2.8E-06	1.3E-05	7.6E-07	2.3E-06
Secondary Clarifiers	5.1E-08	1.4E-08	3.2E-07	1.4E-08	1.1E-08
Sludge Thickening and Dewatering	2.4E-06	5.2E-07	2.6E-06	1.6E-07	4.2E-07
Sludge Incineration	9.5E-08	2.1E-08	1.8E-07	6.4E-09	1.7E-08

Source: MSDGC Facility Plan

Table 8. Infrastructure requirements for pumps at wastewater treatment plant (per m^3 water treated).

	Material Type	
Life Cycle Stage	*Cast Iron (kg)*	*Stainless Steel 18/8 Coil (kg)*
Pumping, at WWT Plant	2.4E-05	2.2E-06
Screening and Grit Removal	5.5E-08	8.4E-09
Primary Sedimentation	1.3E-07	9.1E-08
Secondary Clarifiers	4.6E-06	7.2E-07
Sludge Thickening and Dewatering	2.8E-07	1.9E-07
Sludge Incineration	2.2E-07	5.7E-08

Source: MSDGC Facility Plan

Table 9. Infrastructure requirements for piping at wastewater treatment plant (per m^3 water treated).

		Length by Pipe Type		Installation
Life Cycle Stage	*Diameter (in)*	*Ductile Iron (m)*	*Reinforced Concrete (m)*	*Earthworks (m3)*
Screening and Grit Removal	48	0	7.9E-09	4.2E-08
	72	0	1.7E-09	1.5E-08
	90	0	1.3E-09	1.5E-08
	96	0	2.0E-08	2.5E-07
Primary Sedimentation	8	5.8E-08	0	8.9E-08
	16	0	1.3E-08	2.7E-08
	96	0	2.0E-08	2.5E-07
Aeration	8	6.9E-09	0	1.1E-08
	10	1.4E-08	0	2.4E-08
	12	1.9E-08	0	3.4E-08
	120	0	1.3E-08	2.2E-07
Sludge Thickening and Dewatering	6	7.3E-09	0	1.0E-08
	8	1.1E-07	0	1.7E-07
	10	4.1E-08	0	6.9E-08
	12	2.6E-09	0	4.7E-09
	16	6.4E-08	0	1.3E-07
	20	4.3E-08	0	1.1E-07
	48	1.6E-08	0	8.5E-08
Sludge Incineration	10	2.9E-08	0	4.8E-08
	12	3.1E-08	0	5.6E-08
	16	2.8E-08	0	5.9E-08
Release of Wastewater Effluent	120		1.0E-07	1.8E-06

Source: MSDGC Facility Plan

Table 10. Infrastructure requirements for sewage pipe network (per m^3 water treated).

	Pipe Material					
Diameter (in)	*PVC (m)*	*Vitrified Clay (m)*	*Concrete (m)*	*Reinforced Concrete (m)*	*Cement-Lined Ductile Iron (m)*	Earthworks (m3)
8	1.8E-05	2.4E-05	8.9E-06	2.4E-07	5.4E-07	7.8E-05
10	3.6E-08	2.5E-06	4.6E-07	1.9E-08	3.2E-08	5.1E-06
12	4.7E-06	2.6E-05	4.6E-05	3.8E-06	6.9E-07	1.5E-04
15	1.1E-06	6.3E-06	2.9E-06	5.7E-07	0	2.2E-05
16	0	0	0	0	1.6E-07	3.4E-07
18	9.6E-07	5.1E-06	2.8E-06	6.3E-07	1.1E-07	2.2E-05
20	0	6.0E-07	0	0	4.4E-08	1.6E-06
21	4.3E-07	1.1E-06	9.4E-07	3.6E-07	0	7.1E-06

	Pipe Material					
Diameter (in)	*PVC (m)*	*Vitrified Clay (m)*	*Concrete (m)*	*Reinforced Concrete (m)*	*Cement-Lined Ductile Iron (m)*	Earthworks (m3)
24	1.5E-06	2.7E-06	1.7E-06	4.3E-07	3.1E-07	1.8E-05
27	1.6E-07	2.0E-07	1.8E-07	2.9E-07	0	2.6E-06
30	8.7E-07	2.2E-07	1.7E-06	1.1E-06	3.2E-07	1.4E-05
33	0	8.5E-08	2.3E-07	9.7E-08	0	1.5E-06
36	4.3E-07	2.5E-07	6.7E-07	1.3E-06	2.4E-07	1.2E-05
42	0	6.7E-08	7.7E-07	6.1E-07	0	6.7E-06
48	0	0	4.3E-07	7.3E-07	0	6.2E-06
54	0	0	2.5E-07	5.1E-07	0	4.6E-06
60	0	0	3.8E-07	1.8E-06	0	1.5E-05
66	0	0	5.6E-08	5.8E-07	0	4.9E-06
72	0	0	2.3E-07	5.4E-07	0	6.6E-06
96	0	0	8.4E-08	7.8E-07	0	1.1E-05

Source: Primary data collected from MSDGC for 2012.

Table 11. Generic pipe lifetimes.

	Pipe Material				
	PVC	*Vitrified Clay*	*Concrete*	*Reinforced Concrete*	*Cement-Lined Ductile Iron*
Lifetime (Years)	55	100	105	105	97.5

Source: American Water Works Association. 2012. Buried No Longer: Confronting America's Water Infrastructure Challenge.

3.5 LCA Limitations

While limitations of this study are discussed throughout this paper, some of the main limitations that readers should understand when interpreting the data and findings are as follows:

- **Plant Infrastructure and Capital Equipment.** The energy and wastes associated with the following infrastructure components are included in this analysis:
    - Collection system piping infrastructure specifications (type, size) - Obtained information from Mill Creek facility reports.
    - Installation and removal of collection system infrastructure.
    - Plant infrastructure including buildings, piping, basins, and industrial machinery - Input data based on estimations from the Mill Creek WWTP Facility Plan.[13]
    - Collection system and at plant pipe manufacturing information datasets obtained from Franklin Associates, a Division of ERG.

Infrastructure modeling of buildings, tanks, motors, and pumps included material and installation burdens, but excluded assembly of the components due to lack of available data. Additionally, the infrastructure burdens are normalized over each component's total lifetime assuming that the water treated every year is 157,615,448 cubic meters, which was the volume treated in 2012. In actuality, there would be differences in water delivered per year over time. The lifetimes assumed for each component are estimates based on historical information of the MSDGC facility; however, the study does include a sensitivity analysis to look at a wider range of potential lifetimes of infrastructure components.

- **Support Personnel Requirements.** Support personnel requirements are included in the cost analysis, but excluded from the LCA model. The energy and wastes associated with research and development, sales, and administrative personnel or related activities are not included.

- **Transferability of Results.** While this study is intended to inform decision-making for a wide range of stakeholders, the data presented here relate to one representative facility. Further work is recommended to understand the variability of key parameters across specific situations.

- **Representativeness of Background Data.** Background processes are representative of either U.S. average data (in the case of data from U.S. LCI) or European average (in the case of ecoinvent) data.

- **Data Accuracy and Uncertainty.** In a complex study with literally thousands of numeric entries, the accuracy of the data and how it affects conclusions is truly a difficult subject, and one that does not lend itself to standard error analysis techniques. The reader should keep in mind the uncertainty associated with LCA models when interpreting the results. Comparative conclusions should not be drawn based on small differences in impact results.

4. BASE CASE COST ANALYSIS

The focus of the cost analysis is to understand the contribution of life cycle stages to the overall cost of treating domestic wastewater and, moving forward, to determine how different disinfection alternatives impact final consumer sewer rates.

The remainder of this section provides additional details on the cost analysis data and assumptions.[21]

4.1 Base Case Cost Data

The cost analysis used actual annual costs from 2012 provided by Mill Creek to allocate costs to each WWT stage. EPA used information from Table 3 and Table 4 along with the cost information provided by MSDGC to calculate costs for each WWT life cycle stage. Table 12 summarizes the annual costs by unit process. Many costs, such as operating and maintenance labor, are incurred on a plant-wide basis. Therefore, a separate line item for these plant-wide costs is included in Table 12. EPA normalized the total costs to a cubic meter of influent wastewater in the results presentation in Section 0.

Wastewater collection data were obtained from MSDGC for the entire collection system, which serves multiple WWT plants. Therefore, EPA normalized wastewater collection data by the total length of sewer pipes within MSDGC's jurisdiction. These normalized values were then multiplied by the length of sewer pipes that serve the Mill Creek WWT plant to allocate the collection data to only the Mill Creek plant.

The cost analysis does not include capital costs for infrastructure. Data on initial installation dates, costs, and current capital improvement project funding were not available from MSDGC. Therefore, EPA's cost analysis focuses on the annual operating costs shown in Table 12.

Table 12. Mill Creek plant annual costs.[a]

Life Cycle Stage	Unit Process	Annual Cost ($/year)
Wastewater Collection	Labor	$3,310,000
	Natural gas	$10,100
	Electricity (for pumping)	$54,800
	Gasoline	$199,000
	Other O&M	$1,940,000
Pumping, at WWTP	Electricity[b]	$639,000
Mobile Fuel Combustion, at WWTP	Gasoline and diesel-powered equipment[c]	$307,000
Screening and Grit Removal	Electricity[b]	$5,080
Primary Sedimentation	Sodium hydroxide	$94,500
	Electricity[b]	$70,500
Secondary Clarifiers	Electricity[b]	$80,000
Sludge Thickening and Dewatering	Polymer (polyacrylamide)	$2,600,000
	Electricity[b]	$492,000
Aeration	Electricity[b]	$2,270,000

[21] Data used in the cost analysis is included in the Excel file WWT.BaseCase.Costs.DraftFinal.2014-03-20.xlsx.

Life Cycle Stage	Unit Process	Annual Cost ($/year)
Sludge Incineration	Electricity[b]	$54,100
	Natural gas	$679,000
Disinfection	Sodium hypochlorite	$332,000
	Materials[d]	$17,200
	Service[d]	$23,400
	Labor[d]	$63,300
Plant wide costs (does not include disinfection labor and service)[a]	Materials	$991,000
	Service	$190,000
	Labor	$1,380,000
	Waste disposal	$750,000
Total Costs		**$16,600,000**

[a] All costs were provided by MSDGC unless noted.
[b] EPA used the total plant electricity cost provided by MSDGC and the distribution shown in Table 4 to calculate electricity costs by unit process.
[c] EPA used information on fuel consumption from the Sustainability Report and estimated the amount of fuel used for all MSDGC operations per the volume of treated water by all MSDGC plants. EPA then used the volume of treated water by the Mill Creek plant to estimate the Mill Creek apportioned amount of fuel. EPA used fuel prices from the Department of Energy, Energy Information Administration (EIA) to calculate the total fuel cost for Mill Creek apportioned fuel use (including collection and plant operations). Because MSDGC provided fuel costs for the collection system portion directly, EPA subtracted the collection system fuel use from the total fuel costs to determine the fuel used at the Mill Creek plant.
[d] Maintenance costs for the disinfection unit process were broken out separately to evaluate potential changes for the alternative disinfection technology.

4.2 Cost Data Quality, Assumptions, and Limitations

EPA used data provided by MSDGC for calendar year 2012 where possible. As shown in Table 3, EPA also used the Mill Creek Sustainability Report and Facility Plan to supplement the collected data. EPA also used cost data from the Energy Information Administration, U.S. Gasoline and Diesel Prices, 2012.[22] Wastewater collection costs presented in this study are calculated as portions of the total wastewater collection costs attributed to the Mill Creek WWT plant.

[22] EPA used the weekly, Ohio regular all formulations retail gasoline prices and the weekly Midwest No. 2 diesel retail prices.

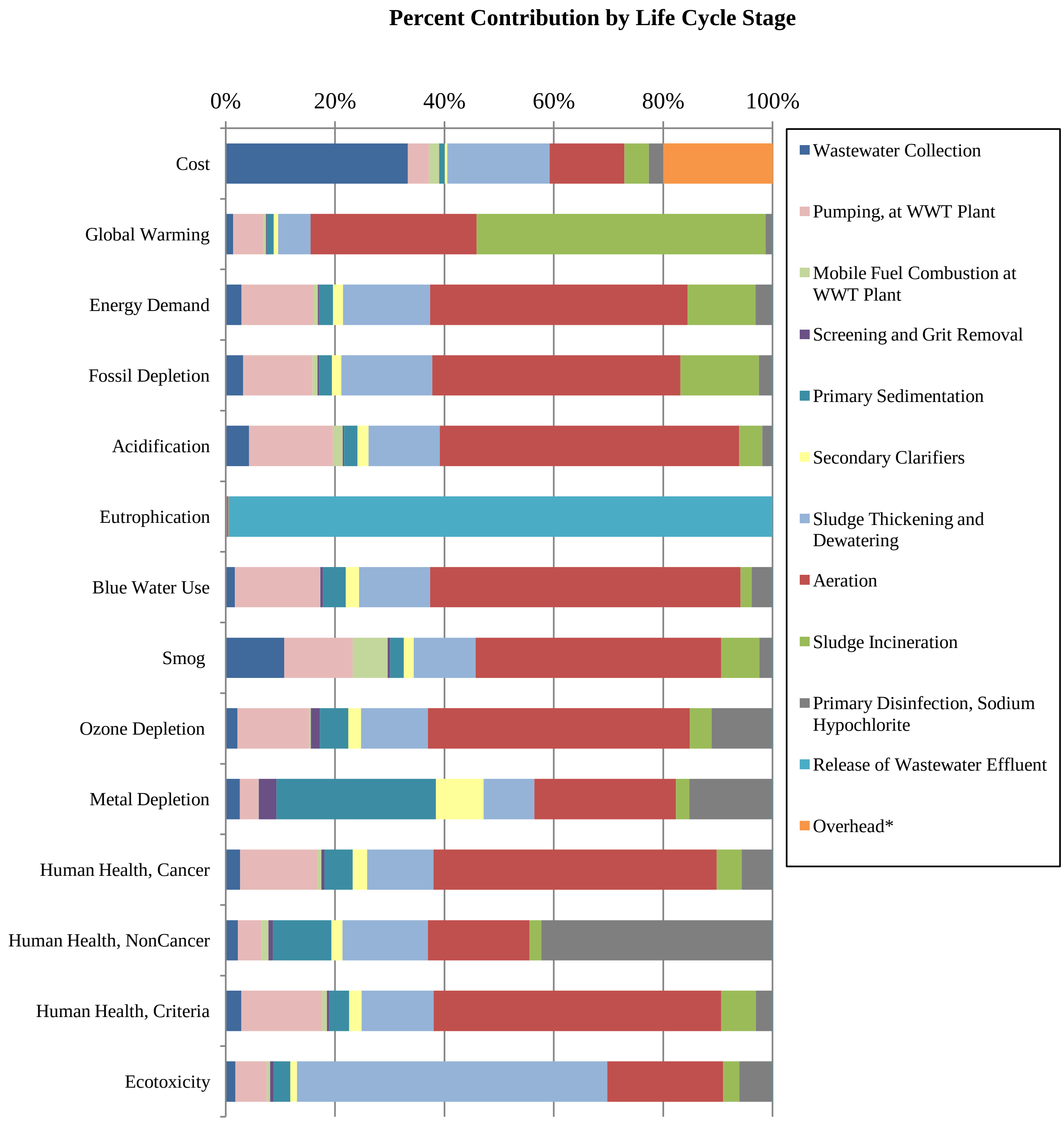
5. BASE CASE RESULTS

Figure 3 displays the Base Case WWT contribution analysis results and Table 13 provides Base Case WWT results per functional unit.[23]

Base case findings of note include:

- Eutrophication impacts are dominated by release of wastewater effluent. This is a result of ammonia and phosphorus water emissions in the effluent.
- Sludge incineration makes the largest contribution to global warming potential. Much of this is related to biogenic CO_2 emissions from combustion of the sludge. Section 5.1 provides a detailed breakdown of the carbon footprint results and includes a discussion of biogenic CO_2 accounting.
- Aeration is the life cycle stage that consumes the most electricity, which is the reason it is the largest contributor for many impacts including energy demand, fossil depletion, acidification, blue water use, ozone depletion, human health cancer, and human health criteria.
- Overall, primary disinfection with sodium hypochlorite only contributed zero to 6 percent for most impact categories, with the exception of ozone depletion, metal depletion, and human health noncancer. Production of the sodium hypochlorite had relatively high impacts for these categories.
- Wastewater collection accounts for 33 percent of the cost, followed by plant-wide overhead cost, which accounts for 20 percent of the cost, sludge thickening and dewatering, which accounts for 19 percent of the cost, and aeration, which accounts for 14 percent of the cost.

[23] The results for the life cycle assessment and cost analysis are presented in a separate Excel file.



*Overhead is only included for the cost results' category

Figure 3. Base Case WWT contribution analysis results.

Table 13. Base Case WWT results per m³ wastewater treated.

Results Category	Unit	Base Case WWT Plant
Cost	*$*	0.11
Global Warming	*kg CO_2 eq*	0.96
Energy Demand	*MJ*	7.79
Fossil Depletion	*kg oil eq*	0.15
Acidification	*kg H+ mole eq*	0.15
Eutrophication	*kg N eq*	0.010
Blue Water Use	*m^3*	3.4E-03
Smog	*kg O^3 eq*	0.026
Ozone Depletion	*kg CFC11 eq*	8.9E-09
Metal Depletion	*kg Fe eq*	0.0099
Human Health, Cancer, Total	*CTU*	1.0E-11
Human Health, NonCancer, Total	*CTU*	9.1E-12
Human Health, Criteria	*kg PM10 eq*	4.5E-04
Ecotoxicity, Total	*CTU*	2.5E-04

5.1 Detailed Carbon Footprint Results

Table 14 displays the detailed carbon footprint results for the base case WWT. Results in this figure are presented by both overall life cycle stage and by specific unit process. Approximately 51.8 percent of the carbon footprint is attributable to biogenic carbon dioxide. This study starts at the collection of wastewater, and does not incorporate the production of the wastewater components. The biogenic carbon dioxide reported here was recently removed from the atmosphere (e.g., through plant or animal production for food, which is later consumed). This biogenic carbon is stored in the wastewater until it is released via aeration or incineration of the sludge back into the atmosphere. Overall, in alignment with the IPCC methodology, there is a net zero impact for wastewater biogenic carbon in the form of CO_2 emissions since the carbon is only temporarily removed from the atmosphere. However, since the original uptake of carbon is outside the system boundaries for this study, the biogenic carbon is included here to show comprehensive carbon accounting. Impacts associated with the emission of biogenic carbon in the form of CH_4 from sludge incineration are included since CH_4 was not removed from the atmosphere and its GWP is 25 times that of CO_2 when applying the IPCC 2007 100a LCIA method. This study found that the carbon footprint of 1 m^3 of wastewater treated excluding biogenic carbon is 0.46 kg CO_2 eq.

Table 14. Detailed carbon footprint results for base case WWT.

Life Cycle Stage	Unit Process/Process Emission	kg CO_2 eq/m^3 water treated	Percent Contribution by Unit Process or Process Emission	Percent Contribution by Life Cycle Stage
Wastewater Collection	Electricity	0.0046	0.48%	1.40%
	Sewer Pipe Infrastructure	0.0024	0.25%	
	Pipe Installation	9.2E-05	0.01%	
	Gasoline Powered Equipment	0.0031	0.32%	
	Diesel Powered Equipment	0.0025	0.26%	
	Natural Gas	7.6E-04	0.08%	
Pumping, at WWT Plant	Electricity	0.053	5.53%	5.55%
	Pumping Infrastructure	1.3E-04	0.01%	
Mobile Fuel Combustion at WWT Plant	Gasoline Powered Equipment	7.9E-04	0.08%	0.42%
	Diesel Powered Equipment	0.0032	0.34%	
Screening and Grit Removal	Landfill Waste Disposal	3.6E-04	0.04%	0.12%
	Electricity	4.2E-04	0.04%	
	Screening and Grit Removal Infrastructure	3.6E-04	0.04%	
Primary Sedimentation	Sodium Hydroxide	0.0022	0.22%	1.27%
	Electricity	0.0059	0.61%	
	Sedimentation Infrastructure	4.2E-03	0.44%	
Secondary Clarifiers	Electricity	0.0066	0.69%	0.83%
	Secondary Clarifiers Infrastructure	1.3E-03	0.14%	
Sludge Thickening and Dewatering	Landfill Waste Disposal	5.5E-05	0.01%	5.94%
	Polymer (polyacrylamide)	0.016	1.63%	
	Electricity	0.041	4.26%	
	Sludge Thickening Infrastructure	3.7E-04	0.04%	
Aeration	Carbon dioxide, biogenic	0.10	10.40%	30.38%
	Electricity	0.19	19.66%	
	Aeration Infrastructure	3.1E-03	0.32%	
Sludge Incineration	Carbon dioxide, biogenic	0.40	41.40%	52.81%
	Methane, biogenic	0.0029	0.30%	
	Nitrous oxide	0.050	5.19%	
	Electricity	0.0045	0.47%	
	Natural Gas	0.051	5.33%	
	Landfill Waste Disposal	0.0011	0.11%	
	Sludge Incineration Infrastructure	1.1E-04	0.01%	
Primary Disinfection	Sodium Hypochlorite	0.012	1.27%	1.27%
	Primary Disinfection Infrastructure	3.8E-06	0.0004%	
Release of Wastewater Effluent	Piping	7.1E-05	0.01%	0.01%

Life Cycle Stage	Unit Process/Process Emission	kg CO_2 eq/m^3 water treated	Percent Contribution by Unit Process or Process Emission	Percent Contribution by Life Cycle Stage
TOTAL (Including biogenic CO_2)		**0.96**	***100%***	***100%***
TOTAL (Excluding biogenic CO_2)		**0.46**		
	% Contribution biogenic CO_2	*51.8%*		

5.2 Detailed Infrastructure Results

Figure 4 and Table 15 display the contribution of infrastructure at the wastewater treatment plant and in the collection system to the base case results. For the majority of impact categories, excluding metal depletion and human health noncancer, infrastructure contributes 8 percent or less to the total impacts. Metal depletion, however, is largely driven by infrastructure, with infrastructure from the wastewater treatment plant and collection system accounting for approximately 70 percent of all metal depletion impacts. The remaining metal depletion impacts are also primarily due to upstream infrastructure impacts, for instance from the construction of plants which produce chemicals used for wastewater treatment. In general, the collection system pipe network and features associated with primary sedimentation and aeration are the infrastructure components with the highest impacts.

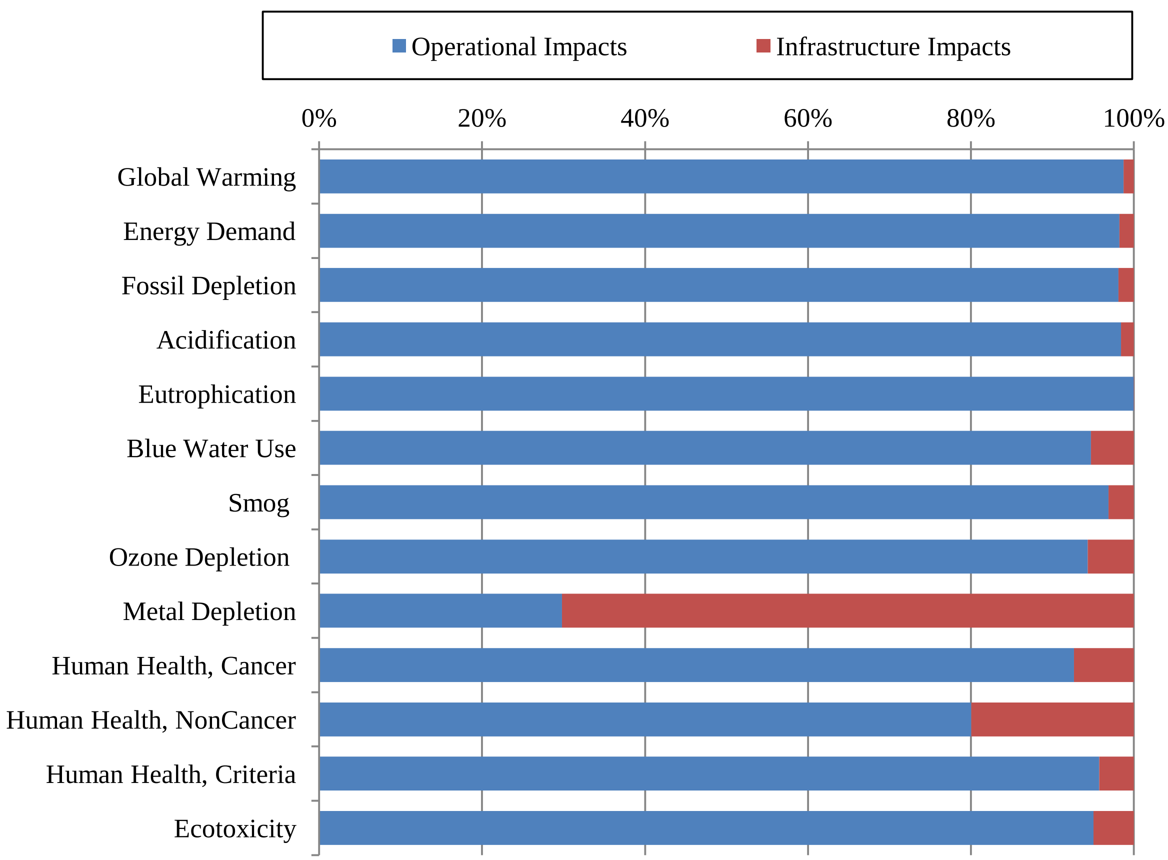


Figure 4. Infrastructure contribution analysis.

Table 15. Contribution of infrastructure to base case results per m^3 wastewater treated.

	Impact Category												
	Global Warming	Energy Demand	Fossil Depletion	Acidification	Eutrophication	Blue Water Use	Smog	Ozone Depletion	Metal Depletion	Human Health, Cancer, Total	Human Health, NonCancer, Total	Human Health, Criteria	Ecotoxicity, total
Life Cycle Stage Infrastructure	*kg CO2 eq*	*MJ*	*kg oil eq*	*kg H+ mole eq*	*kg N eq*	m3	*kg O3 eq*	*kg CFC11 eq*	*kg Fe eq*	*CTU*	*CTU*	*kg PM10 eq*	*CTU*
Wastewater Collection Pipe Network	0.0025	0.042	8.9E-04	9.4E-04	6.6E-07	5.8E-05	3.4E-04	4.8E-11	2.4E-04	3.5E-14	1.6E-14	2.6E-06	9.8E-07
Pumping, at WWT Plant	1.3E-04	0.0021	4.2E-05	3.2E-05	2.5E-08	1.2E-06	7.7E-06	6.8E-12	2.0E-04	2.0E-14	1.4E-13	5.0E-07	4.7E-07
Mobile Fuel Combustion at WWT Plant	0	0	0	0	0	0	0	0	0	0	0	0	0
Screening and Grit Removal	3.6E-04	0.0040	7.9E-05	6.1E-05	5.5E-08	4.4E-06	1.9E-05	1.7E-11	3.0E-04	2.9E-14	5.0E-14	7.2E-07	4.3E-07
Primary Sedimentation	0.0042	0.040	7.7E-04	6.1E-04	5.9E-07	5.5E-05	2.0E-04	2.0E-10	0.0027	2.9E-13	5.0E-13	6.7E-06	4.3E-06
Secondary Clarifiers	0.0013	0.012	2.4E-04	1.9E-04	1.8E-07	1.7E-05	6.2E-05	6.1E-11	8.5E-04	9.2E-14	1.5E-13	2.1E-06	1.4E-06
Sludge Thickening and Dewatering	3.7E-04	0.0055	1.1E-04	6.9E-05	5.9E-08	4.1E-06	2.0E-05	1.7E-11	3.9E-04	3.3E-14	1.3E-13	8.7E-07	6.2E-07
Aeration	0.0031	0.029	5.6E-04	4.6E-04	4.4E-07	3.9E-05	1.5E-04	1.5E-10	0.0021	2.2E-13	7.9E-13	5.1E-06	3.8E-06
Sludge Incineration	1.1E-04	0.0017	3.5E-05	2.3E-05	1.9E-08	1.1E-06	6.2E-06	5.6E-12	1.8E-04	1.3E-14	2.8E-14	3.8E-07	2.2E-07
Primary Disinfection, Sodium Hypochlorite	3.8E-06	1.7E-04	3.7E-06	6.0E-07	2.2E-10	5.7E-09	1.1E-07	2.4E-14	1.5E-09	5.0E-17	1.8E-17	2.2E-09	9.0E-10
Piping for Release of Wastewater Effluent	7.1E-05	0.0012	2.5E-05	2.7E-05	1.6E-08	3.1E-07	8.2E-06	1.3E-12	4.8E-06	1.0E-15	4.4E-16	8.5E-08	2.6E-08
Total	**0.012**	**0.14**	**0.0028**	**0.0024**	**2.0E-06**	**1.8E-04**	**8.1E-04**	**5.0E-10**	**0.0070**	**7.4E-13**	**1.8E-12**	**1.9E-05**	**1.2E-05**
% of Total Impact	***1.27%***	***1.77%***	***1.87%***	***1.57%***	***0.02%***	***5.27%***	***3.09%***	***5.66%***	***70.21%***	***7.33%***	***19.95%***	***4.26%***	***4.93%***

5.3 Base Case Normalized Results

Figure 5 displays the base case WWT normalized results. Larger sections of the chart indicate those impacts where WWT makes relatively larger contributions to national per capita impacts. Eutrophication impacts dominate the WWT normalized results. Eutrophication impacts are due to ammonia and phosphorus water emissions from release of the wastewater effluent.

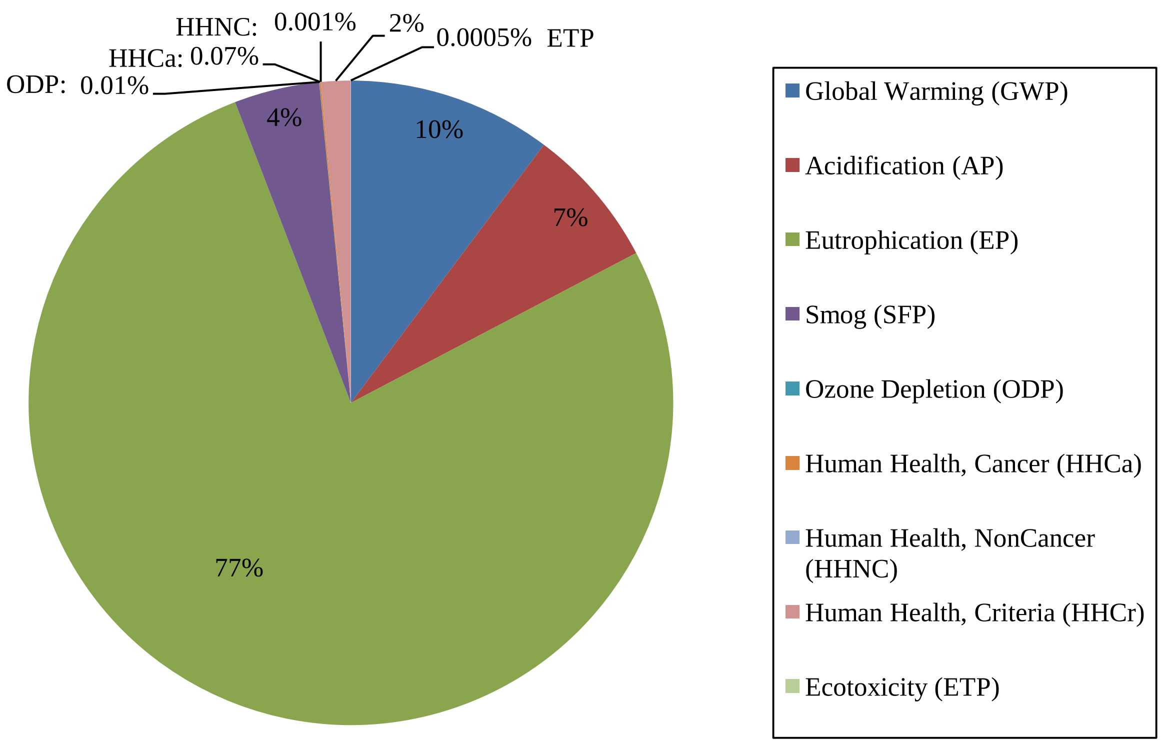


Figure 5. Base case WWT normalized results.

Figure 6 presents cost results alongside results normalized by life cycle stage and impact category and results normalized and weighted by life cycle stage and impact category. The following specific results are shown on this figure:

- Cost by stage: this category displays WWT cost by life cycle stage. Cost by stage are shown as a percentage of total costs.
- Normalized by stage: this category presents the normalized impact assessment results by life cycle stage. Life cycle stages have been normalized using TRACI v2.1 normalization factors.[24] Normalized life cycle stage results are shown as a percent of the total normalized result.

[24] Ryberg, M., Vieira, M.D.M., Zgola, M., Bare, J., and Rosenbaum, R.K., 2014. Updated US and Canadian normalization factors for TRACI 2.1. Clean Techn Environ Policy, 16: 329-339.

- Normalized and weighted by stage: this category presents the normalized and weighted impact assessment results by life cycle stage. Life cycle stages have been normalized using TRACI v2.1 normalization factors and have been weighted using NIST weighting factors.[24], [25] Normalized and weighted life cycle stage results are shown as a percent of the total normalized and weighted result.
- Normalized by impact: this category presents the normalized impact assessment results by impact category. Impact categories have been normalized using TRACI v2.1 normalization factors.[26] Normalized impact category results are shown as a percent of the total normalized result.
- Normalized and weighted by impact: this category presents the normalized and weighted impact assessment results by impact category. Impact categories have been normalized using TRACI v2.1 normalization factors and have been weighted using NIST weighting factors.[24], [27] Normalized and weighted impact category results are shown as a percent of the total normalized and weighted result.

Some findings of note from Figure 6:

- Weighting increases the relative importance of global warming potential.
- Results normalized (and normalized and weighted) by stage are dominated by release of the wastewater effluent. This corresponds to normalized (and normalized and weighted) results by impact category being driven by eutrophication potential. That is, release of the wastewater effluent leads to eutrophication through increased ammonia and phosphorus emissions to the Ohio River.

[25] Gloria, T.P., Lippiatt, B.C., and Cooper, J. 2007. Life cycle impact assessment weights to support environmentally preferable purchasing in the United States. Environ. Sci. Technol, 41, 7551-7557.

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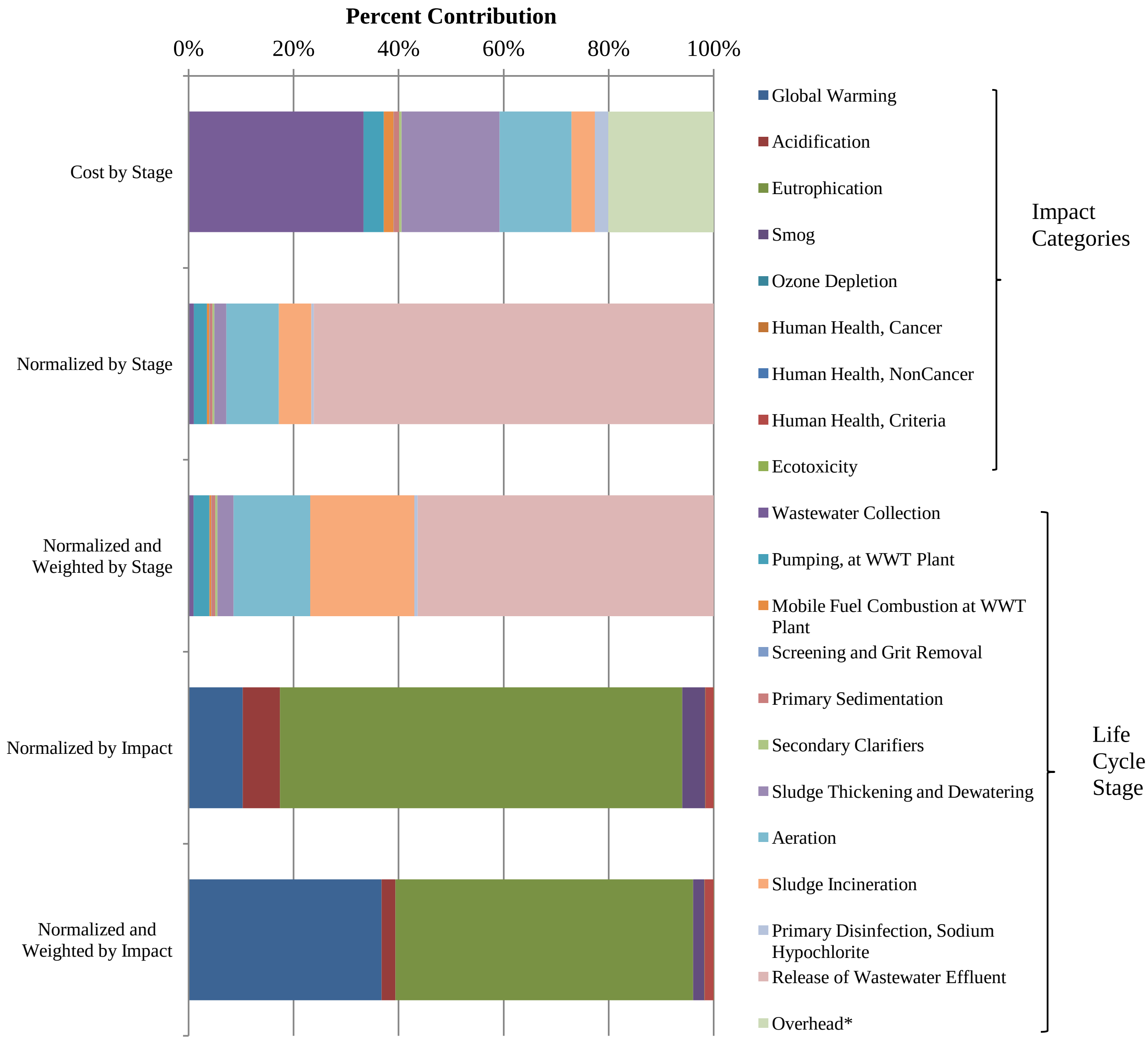

*Overhead is only included for the cost results' category

Figure 6. Normalized and weighted WWT results by stage and impact category

6. BASE CASE SENSITIVITY ANALYSES

LCAs inherently involve making assumptions. To see the influence of the assumptions made in an LCA model, it is important to conduct sensitivity analyses. To carry out such an analysis, the assumption of interest is changed and the entire LCA is recalculated. In this study, sensitivity analyses were conducted for key base case assumptions. Table 16 shows the sensitivity analyses for the base case WWT model, the values used, and whether LCA or cost results were generated for the sensitivity. Costs results were generated if changes to the LCA parameter could impact the costs. For example, changing the quantity of electricity used at the plant would change the costs. On the other hand, varying the electricity grid would not result in cost changes.

Table 16. Sensitivity analyses for base case WWT model runs.

Parameter	Values	LCA Results	Cost Results
Electricity usage at plant	±10% of value obtained from MSDGC	Yes	Yes
Electricity usage during wastewater collection	±10% of value obtained from MSDGC	Yes	Yes
Electricity grid	Average U.S. grid, ReliabilityFirst Corporation West (RFCW) North American Electrical Reliability Corporation (NERC) regional grid	Yes	No
Sodium hypochlorite consumption	±10% of value obtained from MSDGC	Yes	Yes
Carbon content of incinerated sludge	IPCC gives range of 40-50% carbon content of dry sludge.[17] Baseline modeled = 45%, minimum = 40%, maximum = 50%	Yes	No
Lifetime of collection system infrastructure components	±25 years weighted lifetime of infrastructure per life cycle stage. Baseline = 100 years at for buildings and tanks at plant, baseline for piping shown in Table 11, baseline for pumps and motors = 25 years	Yes	No
Lifetime of WWTP infrastructure components	±25 years weighted lifetime of infrastructure per life cycle stage. Baseline for piping shown in Table 11	Yes	No

6.1 LCA Sensitivity Results

Table 17 and Figure 7 cover the impact assessment results for the electricity sensitivity analyses. Changing the total electricity used at the plant changes the impacts at most +9.5 percent/-9 percent. The model is not sensitive to changing the electricity usage during collection, since the collection system is mostly gravity and requires minimal electricity for operation in comparison to electricity consumed at the WWTP. Eutrophication is not sensitive to the WWTP electricity usage, as it is driven by waterborne emissions associated with release of wastewater effluent. Similarly, global warming only changes +4.2 percent/-2.2 percent with a +/- 10 percent electricity usage change, since many of the GHG emissions are related to biogenic carbon dioxide releases during aeration and sludge incineration and nitrous oxide and methane emissions during sludge incineration. The use of the ReliabilityFirst Corporation West (RFCW) electricity grid, which is the North American Electrical Reliability Corporation (NERC) region the Mill Creek Plant is located, results in considerably higher global warming, smog, and acidification impacts compared to use of the U.S. average grid electricity mix, which is applied in the base case. This is largely due to the higher use of coal in the RFCW grid compared to the U.S. average grid. However, use of the RFCW grid electricity mix significantly reduced human health cancer and ecotoxicity impacts, which is due to the lower natural gas usage in the RFCW grid mix compared to the U.S. average grid mix.

The base case WWT carbon footprint results vary +/- 4.6 percent when modeling the range of potential carbon content in the dry sludge that is incinerated at the plant (Table 18). The model is sensitive to the quantity of biogenic carbon released during incineration (see discussion of biogenic carbon modeling in Section 5.1).

Results of the infrastructure sensitivity analyses are displayed in Figure 8 and Figure 9. Weighted average lifetimes of infrastructure components for each life cycle stage were determined by multiplying the relative mass contribution of different infrastructure components in each life cycle stage by their associated lifetime and summing these values. The minimum and maximum lifetimes modeled here vary +/- 25 years from these weighted average lifetimes. Overall life cycle impacts increase with a decrease in the infrastructure lifetime, since the infrastructure burdens are normalized over less total water treated. The infrastructure lifetime is only sensitive to the metal depletion category, since this is the primary impact category in which infrastructure is a significant component. Since the collection system is primary clay and concrete pipe, the metal depletion impact is not sensitive to varying the collection system lifetime. All other impact categories vary approximately less than 5 percent from the base case for the WWTP lifetime sensitivity analysis.

Impact results vary less than +/-5 percent when varying the sodium hypochlorite used during WWT primary disinfection +/- 10 percent (Figure 10). Human health, noncancer is the impact category most sensitive to the usage of sodium hypochlorite. Human health noncancer impacts are associated with air emissions from production of sodium hypochlorite and the upstream sodium hydroxide used in sodium hypochlorite production.

Table 17. LCA electricity sensitivity results for base case WWT model runs.

		per m3 wastewater treated										
Impact Category	**Unit**	**Base Case**	**Minimum Electricity Usage at WWTP**	**Maximum Electricity Usage at WWTP**	**Minimum Electricity Usage at Collection System**	**Maximum Electricity Usage at Collection System**	**RFC West Grid**	**Minimum Electricity Usage at WWTP % Change**	**Maximum Electricity Usage at WWTP % Change**	**Minimum Electricity Usage at Collection System % Change**	**Maximum Electricity Usage at Collection System % Change**	**RFC West Grid % Change**
Global Warming	kg CO2 eq	0.96	0.93	1.00	0.96	0.96	1.04	-2.2%	4.2%	-0.1%	0.04%	3.9%
Energy Demand	MJ	7.79	7.20	8.37	7.78	7.80	8.30	-7.5%	7.5%	-0.1%	0.1%	6.6%
Fossil Depletion	kg oil eq	0.15	0.14	0.16	0.15	0.15	0.17	-7.3%	7.2%	-0.1%	0.1%	3.0%
Acidification	kg H+ mole eq	0.15	0.14	0.17	0.15	0.15	0.19	-8.8%	8.8%	-0.1%	0.1%	9.0%
Eutrophication	kg N eq	0.010	0.010	0.010	0.010	0.010	0.010	-0.1%	0.0%	0.00%	0.04%	0.0%
Blue Water Use	m3	0.0034	0.0031	0.0037	0.0034	0.0034	N/A	N/A	N/A	N/A	N/A	N/A
Smog	kg O3 eq	0.026	0.024	0.028	0.026	0.026	0.034	-7.2%	7.1%	-0.2%	0.1%	14.6%
Ozone Depletion	kg CFC11 eq	8.9E-09	8.2E-09	9.5E-09	8.8E-09	8.9E-09	8.4E-09	-7.5%	7.5%	-0.1%	0.1%	24.7%
Metal Depletion	kg Fe eq	0.010	0.0099	0.010	0.010	0.010	0.010	-0.8%	0.8%	0.0%	0.0%	0.5%
Human Health, Cancer	CTU	1.0E-11	9.3E-12	1.1E-11	1.0E-11	1.0E-11	5.5E-12	-8.0%	8.0%	-0.1%	0.1%	-31.4%
Human Health, NonCancer	CTU	9.1E-12	8.9E-12	9.2E-12	9.1E-12	9.1E-12	9.2E-12	-1.6%	1.6%	-0.1%	0.0%	0.4%
Human Health, Criteria	kg PM10 eq	4.5E-04	4.1E-04	4.9E-04	4.5E-04	4.5E-04	5.3E-04	-8.4%	9.5%	0.0%	0.6%	7.3%
Ecotoxicity	CTU	2.5E-04	2.4E-04	2.6E-04	2.5E-04	2.5E-04	1.9E-04	-3.2%	4.9%	0.0%	0.8%	-19.3%

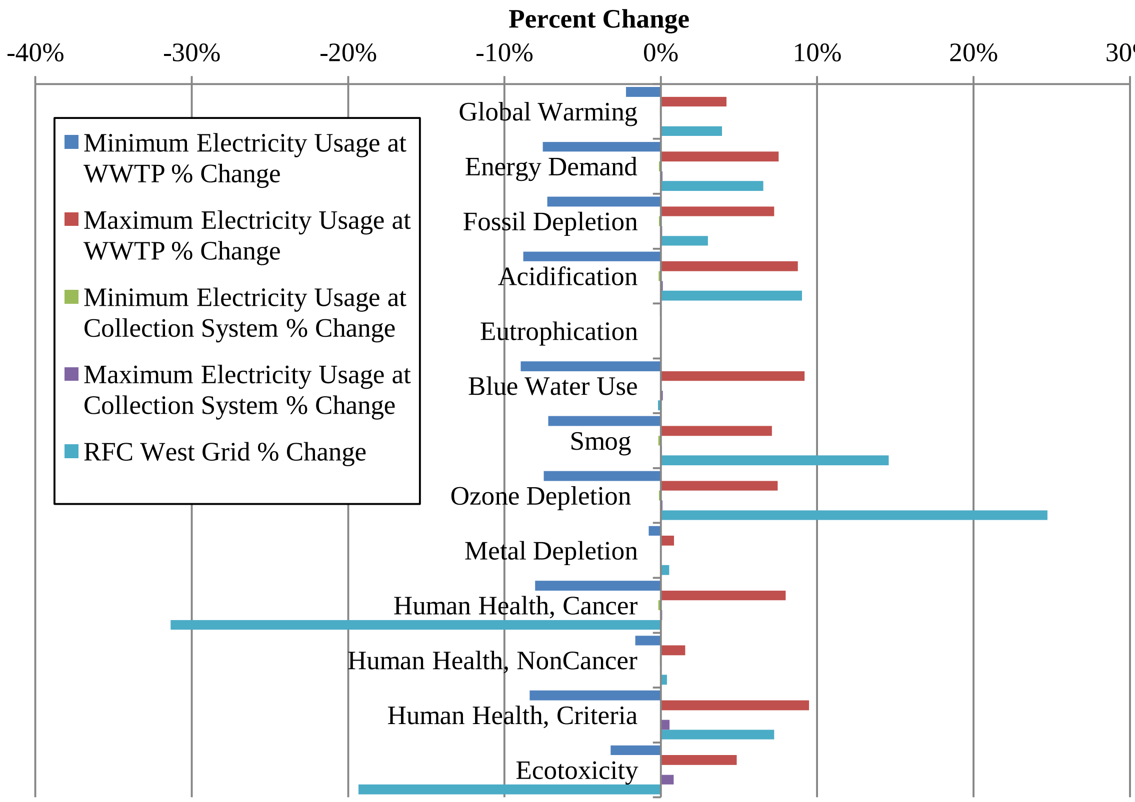

Figure 7. Electricity sensitivity analyses.

Table 18. Sludge carbon content sensitivity analysis.

	Sludge incineration kg CO_2 per m^3 water treated	Total WWT carbon footprint kg CO_2 eq per m^3 water treated	Total carbon footprint % change
Baseline sludge carbon content	0.40	0.96	-
Minimum sludge carbon content	0.35	0.91	-4.6%
Maximum sludge carbon content	0.44	1.00	4.6%

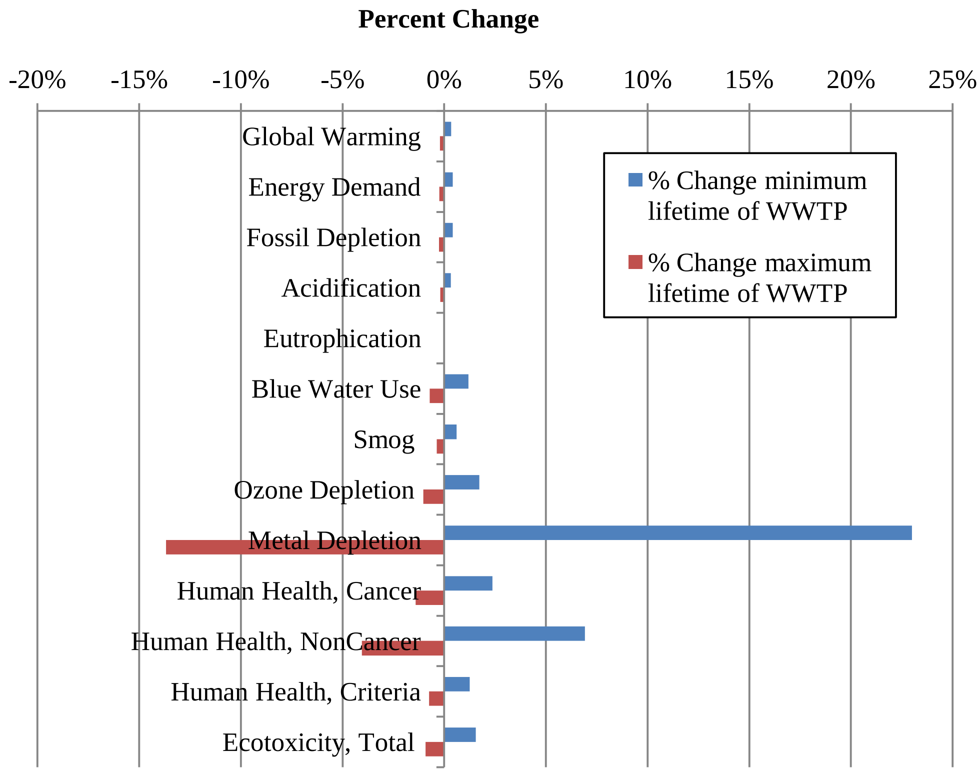

Figure 8. WWTP infrastructure lifetime sensitivity analysis.

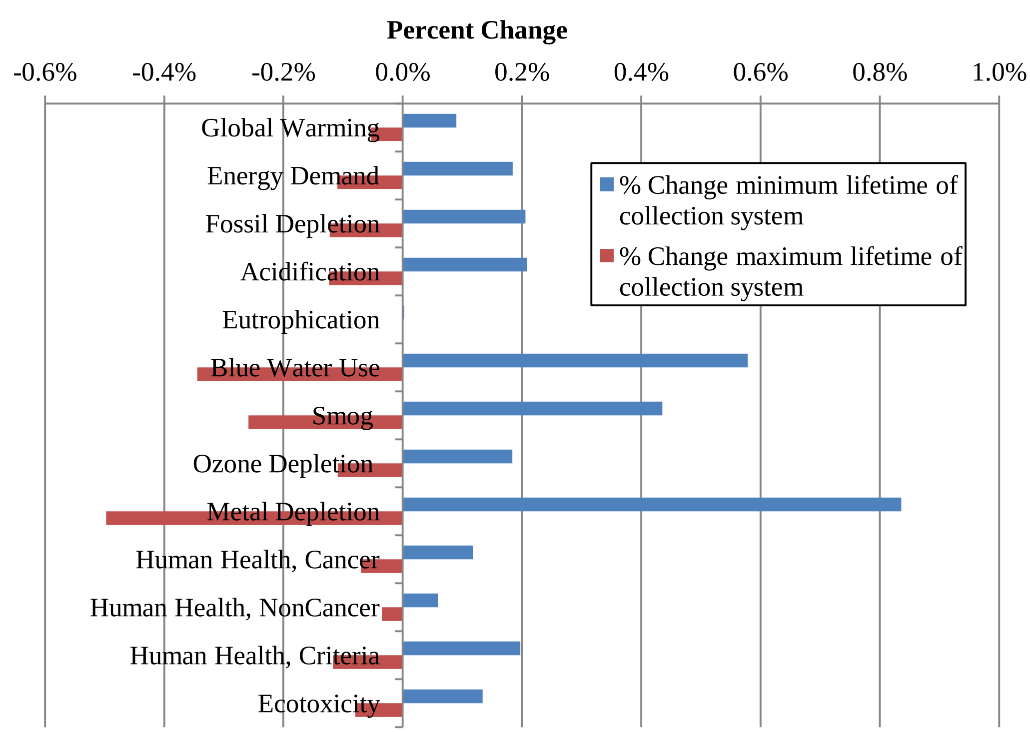

Figure 9. WWT collection system infrastructure lifetime sensitivity analysis.

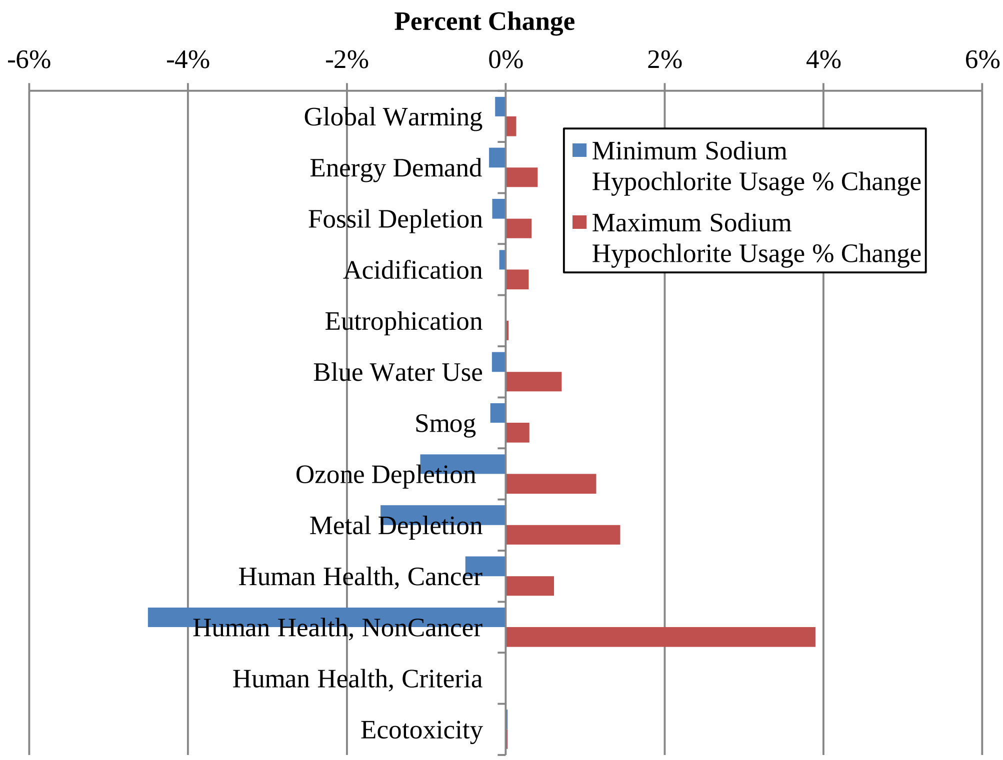

Figure 10. Sodium hypochlorite usage sensitivity analysis.

6.2 Cost Sensitivity Results

Table 19 summarizes the cost input values and cost results for each life cycle stage for the cost sensitivity results. Changing the total electricity used at the plant results in a change in the total annual cost of ±2 percent. Changing the electricity used at the plant does not impact the wastewater collection costs. If the electricity used for wastewater collection (apportioned for Mill Creek's portion of sewer pipes) is changed by ±10 percent, the wastewater collection cost changes by ±0.1% (electricity costs contribute only 1 percent of the wastewater collection costs; see Table 12).

Table 19. Cost sensitivity results for base case WWT model runs.

Life Cycle Stage	Base Case Value	Minimum Value	Maximum Value	Minimum Value % Change	Maximum Value % Change
Inputs					
Total Electricity at Plant (kWh/yr)	69,281,609	62,353,448	76,209,770	-10%	+10%
Results					
Wastewater Collection	$5,516,869	$5,511,392	$5,522,347	-0.1%[a]	0.1%[a]
Pumping, at WWT Plant	$638,870	$574,983	$702,757	-10%	10%
Mobile Combustion - at WWTP	$306,911	$306,911	$306,911	0%	0%
Screening and Grit Removal	$5,078	$4,571	$5,586	-10%	10%
Primary Sedimentation	$164,989	$157,940	$172,038	-4.27%	4.27%
Secondary Sedimentation	$80,036	$72,033	$88,040	-10%	10%
Sludge Thickening and Dewatering	$3,092,057	$3,042,817	$3,141,298	-1.59%	1.59%
Sludge Incineration	$732,741	$727,328	$738,155	-0.74%	0.74%
Aeration	$2,270,071	$2,043,063	$2,497,078	-10%	10%
Primary Disinfection, Sodium Hypochlorite	$436,021	$400,761	$466,733	-11%[b]	9%[b]
Facility-Wide Costs	$3,315,081	$3,315,081	$3,315,081	0%	0%
Total Costs ($/yr)	**$16,558,726**	**$16,197,617**	**$16,919,834**	**-2.2%**	**2.2%**

[a]Percent change is for electricity only. The total costs for collection include labor, natural gas, power, gasoline, O&M. Only the amount of electricity (power) was modified.
[b]Percent change is for quantity of sodium hypochlorite only. Calculated percent change using kg/m3 values used in the LCA (base case= 0.013718, min = 0.01226162, max = 0.01498642). Note the total costs for primary disinfection include sodium hypochlorite, materials, labor, and service. Only the amount of sodium hypochlorite was modified.

7. OVERALL FINDINGS AND NEXT STEPS

Results of the base case analysis show normalized WWT results are dominated by eutrophication. Eutrophication impacts are from release of ammonia and phosphorus emissions in wastewater effluent. Sludge incineration makes the largest contribution to global warming potential, much of which is related to biogenic CO_2 emissions from combustion of the sludge. Excluding biogenic carbon dioxide emissions more than halves the overall carbon footprint of treating wastewater in the base case. Aeration is the life cycle stage that consumes the most electricity, which is the reason it is the largest contributor for many impacts including energy demand, fossil depletion, acidification, blue water use, ozone depletion, human health cancer, and human health criteria. These impacts driven by electricity consumption were sensitive to the electricity usage and electricity grid sensitivity analyses conducted. Overall, primary disinfection with sodium hypochlorite only contributes zero to 6 percent for most impact categories, with the exception of blue water use, ozone depletion, metal depletion, and human health noncancer. Upstream processes associated with production of the sodium hypochlorite have relatively high impacts for these categories. Wastewater collection accounts for 33 percent of the total cost, followed by plant-wide overhead cost, which accounts for 20 percent of the cost, sludge thickening and dewatering, which accounts for 19 percent of the cost, and aeration, which accounts for 14 percent of the cost.

The base case WWT LCA and cost model developed here can serve as a framework for examining different disinfection technologies and treatment methods. EPA plans to evaluate alternatives to disinfection with sodium hypochlorite for the Mill Creek Wastewater Treatment Plant.

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