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Environmental Protection
Agency

2023 Revision* to:

Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants

* This 2023 revision entails errata regarding nitrous oxide emissions from wastewater biological treatment processes, as described on the next page.

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ERRATA

In 2023, EPA identified an error in Equation F-3, used to calculate nitrous oxide (N_2O) emissions from wastewater biological treatment processes. This equation, located on page F-2, included an incorrect molecular weight conversion factor of N to N_2O of 44/14. The correct conversation factor is 44/28. See the errata sheet located at the end of this document for more information.

EXECUTIVE SUMMARY

Human-caused nutrient enrichment of waterbodies from excessive nitrogen (N) and phosphorus (P) is one of the most pervasive environmental issues facing the United States (U.S. EPA, 2015a). In many watersheds, municipal and industrial wastewater treatment plants (WWTPs) can be major point sources of nutrients. Recent efforts to derive numeric nutrient criteria to protect the designated uses of waterbodies have resulted in limits that may be challenging to meet for most WWTPs in the United States with the treatment configurations currently in place. However, many stakeholders have expressed concern that there may be significant undesirable environmental and economic impacts associated with upgrading treatment configurations, as these configurations may require greater use of chemicals and energy, release more greenhouse gases, and generate greater volumes of treatment residuals for disposal.

The impacts can be assessed using holistic, systematic approaches using life cycle impact assessment (LCIA) and life cycle cost analysis (LCCA). These approaches provide a "cradle-to-grave" analysis of the environmental impacts and benefits as well as the economic costs and benefits associated with individual products, processes, or services throughout their life cycle. This study used LCIA and LCCA approaches to assess cost, human health, and ecosystem metrics associated with nine distinct wastewater treatment configurations designed to reduce the nutrient content of effluent from municipal WWTPs.

Table ES-1 depicts the five different total nitrogen and phosphorus treatment levels used to configure nine different wastewater treatment systems commonly used in the U.S. to achieve the specified nutrient concentrations. Level 1 represents a standard secondary treatment configuration with no additional processes for nutrient removal. For Levels 2-5, two configurations that could meet the performance target were selected per level, representing contrasts in factors such as biological processes, costs, and energy requirements. Each configuration was modeled with an average flow rate of 10 million gallons per day (MGD) and a maximum flow rate of 20 MGD.

Table ES-1. Target Effluent Nutrient Concentrations by Level

Level	Total Nitrogen, mg/L	Total Phosphorus, mg/L
1	no target specified	no target specified
2	8	1
3	4-8	0.1-0.3
4	3	0.1
5	<2	<0.02

For the life cycle impact assessment, this study considered 12 impact categories: eutrophication potential, cumulative energy demand, global warming potential, acidification potential, fossil depletion, smog formation potential, human health-particulate matter formation potential, ozone depletion potential, water depletion, human health-cancer potential, human health-noncancer potential, and ecotoxicity potential. The majority of impact categories address air and water environmental impacts, while three categories are human health impact indicators.

Eutrophication potential (i.e., potential for enrichment of waterbodies with nutrients) is the combined effect of direct nutrient discharges in the effluent, landfilled sludge leachate, and the water discharges and air emissions from upstream inputs such as electricity and chemical production. Eutrophication potential decreased dramatically between Level 1 and Level 2 and to a smaller degree between Level 2 to Levels 3 and 4, which were similar to each other. Level 5 had higher eutrophication potential than Level 4 due to the energy requirement of reverse osmosis and brine injection, which off-set the impact reduction associated with the lower effluent nutrient concentration. However, based on the uncertainty thresholds for impact results, the difference between Level 3, Level 4 and Level 5 is not considered significant.

Cumulative energy demand, acidification potential, fossil depletion, smog formation potential, particulate matter formation, and global warming potential all showed a roughly similar trend. The values for these categories all increased from Level 1 to Level 5 due to increasing electricity use and natural gas heating consumption required to achieve the lower nutrient values for the treatment systems selected.

Water depletion results were dominated by the high-water use of Level 5 treatment configurations, approximately 100 times the other configurations, primarily for deepwell injection of brine. The potential for reuse of wastewater following Level 5 treatment was not considered in this study.

Although not specifically designed for it, the treatment configurations may also remove trace pollutants (metals, toxic organics, and disinfection by-products [DBPs]) from effluent, providing a toxicity reduction co-benefit. For configuration Levels 1-3, metals in liquid effluent dominated toxicity impacts, whereas for Level 5, contributions from material and energy inputs dominated, with Level 4 configurations having significant contributions from both sources. For human health-cancer potential, Levels 1, 3, and 4 had lower impacts than Levels 2 and 5, whereas for human health-noncancer potential, toxicity impacts decreased as treatment became more advanced For ecotoxicity, Levels 3, 4, and 5 had lower toxicity than Levels 1 and 2. Overall, one of the Level 4 configurations and, to a lesser degree, one of the Level 3 configurations stood out in most effectively balancing effluent toxicity reductions against the increase in materials and energy required. Uncertainty for the toxicity impact assessment was greater than for other impacts due to trace pollutant data limitations and to uncertainty inherent in the impact estimation method (USEtox™).

The life cycle cost analysis provided results for capital costs, annual operation and maintenance costs, and net present value, which combines the capital and operation and maintenance costs into a single cumulative value (all in 2014$). In general, the net present value increased with increasing nutrient control levels. The Level 2 configurations were an exception to the trend due to the high annual costs associated with the three separate biological units.

Sensitivity analyses considered different interest rates, electricity grid composition, improved energy capture at the facility, and a retrofit scenario instead of building a new facility. Since electricity was a primary driver for many of the impact categories assessed, many of the trade-offs associated with greater nutrient reductions could be significantly reduced if the WWTP were to use an electrical grid with r with lower emissions and/or to use recovered resources (e.g., biogas) to generate on-site energy, reducing the need for purchased electricity.

Overall, two key findings emerged from this analysis. First, clear trade-offs in cost and potential environmental impact were demonstrated between treatment level configurations. This suggests that careful consideration should be given to the benefits from lower nutrient levels compared to the potential environmental and economic costs associated with treatment processes used to achieve those levels. Combining outcomes into metrics such as nutrients removed per dollar or per unit energy may help to identify configurations that strike an efficient balance between these objectives. For example, this analysis found that electricity per unit of total N and P equivalents removed remained consistent from Level 2 through Level 4 but was 2-3 times higher for Level 5 configurations. Second, this analysis demonstrated the value of a life cycle approach to assessing costs and benefits. For example, considering trace pollutants from a life cycle perspective illuminated that the benefits of increased trace pollutant removal from effluent could be outweighed by trace pollutant emissions from materials and energy usage for the Level 5 configuration, an insight that would not have been gained by analyzing on-site WWTP processes alone. In summary, considering multiple economic, social, and environmental costs and benefits from a life cycle perspective can provide critical insights for informed decision-making about wastewater treatment technologies.

FOREWORD

The objective of this study is to assess a series of wastewater treatment system configurations designed to reduce the nutrient content of effluent from municipal wastewater treatment facilities. The combination of life cycle assessment (LCA) and life cycle cost analyses (LCCA) provides a full picture of costs, both quantitative and qualitative, for the various wastewater treatment configurations evaluated. This technical report presents the results of the study. It does not discuss the policy implications of the analysis, nor does it discuss the EPA's policy on nutrient pollution, the development of nutrient criteria, approaches for addressing the problem, nor the full suite of benefits from the different treatment configurations that can be realized.

This report complements and supplements the EPA's May 2015 publication, *A Compilation of Cost Data Associated with the Impacts and Control of Nutrient Pollution* (https://www.epa.gov/nutrient-policy-data/compilation-cost-data-associated-impacts-and-control-nutrient-pollution), which provides the public with information to assist stakeholders and decision-makers in addressing cultural eutrophication.

ACRONYMS AND ABBREVIATIONS

A2O	Anaerobic/Anoxic/Oxic
AS	Activated sludge
BNR	Biological nutrient removal
BOD	Biochemical oxygen demand
CAPDETWorks™	Computer Assisted Procedure for the Design and Evaluation of Wastewater Treatment Systems
CBOD	Carbonaceous biochemical oxygen demand
CEC	Contaminants of emerging concern
CED	Cumulative Energy Demand
CHP	Combined heat and power
COD	Chemical oxygen demand
DBP	Disinfection byproduct
DBPFP	Disinfection byproduct formation potential
DQI	Data quality indicator
EDC	Endocrine disrupting chemicals
EF	Emission factor
eGRID	Emissions & Generation Resource Integrated Database
EPA	Environmental Protection Agency (U.S.)
ERG	Eastern Research Group, Inc.
FP	Formation potential
GHG	Greenhouse gas
GT	Gravity thickener
GWP	Global warming potential
HAA	Haloacetic acid
HAB	Harmful algal blooms
HAN	Haloacetonitrile
HHV	High heating value
ICE	Internal combustion engine
ISO	International Standardization Organization
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MBR	Membrane bioreactor
MCF	Methane conversion factor
N	Nitrogen
NNC	Numeric nutrient criteria
NOM	Natural organic matter
NPCC	NorthEast Power Coordinating Council
ORD	Office of Research and Development (U.S. EPA)
P	Phosphorus
PM	Particulate matter
PPCP	Pharmaceuticals and personal care products
PPI	Producer's price indices
RO	Reverse osmosis
THM	Trihalomethanes
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen

TP	Total phosphorus
TRACI	Tool for the Reduction and Assessment of Chemical and Environmental Impacts
UF	Ultrafiltration
UIC	Underground injection control
UNFCCC	United Nations Framework Convention on Climate Change
US LCI	United States Life Cycle Inventory Database
VFA	Volatile fatty acids
WWT	Wastewater treatment

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1. GOAL AND SCOPE DEFINITION

1.1 Introduction and Objective

Cultural eutrophication of waterbodies across the United States is one of the most pervasive environmental issues facing the country today. Whether in lakes or reservoirs, rivers or streams, estuaries or marine coastal waters, the human health, environmental, and economic impacts from excessive amounts of nitrogen (N) and phosphorus (P) continue to rise year after year. Communities struggle with harmful algal blooms (HABs) that produce toxins which can sicken people and pets, contaminate food and drinking water sources, destroy aquatic life, and disrupt the balance of natural ecosystems. HABs can raise the cost of drinking water treatment, depress property values, close beaches and fishing areas, and negatively affect the health and livelihood of many Americans (U.S. EPA, 2015a). Global climate change is only expected to exacerbate eutrophication even as Federal, state, and local governments struggle to address the sources of nutrient pollution (USGCRP, 2015).

In partnership with states, tribes, and other Federal agencies, the U.S. Environmental Protection Agency (EPA) has led the effort to address nutrient pollution by assisting states in prioritizing waters, providing scientific and technical assistance in the development of water quality standards for total nitrogen (TN) and total phosphorus (TP), and helping to guide implementation of nutrient criteria in waterbody assessments, including the development of total maximum daily loads for impaired waters and the inclusion of water-quality based effluent limits for point source dischargers.

In many watersheds, municipal and industrial wastewater treatment plants (WWTPs) can be major point sources of nutrients. Removal of TN and TP can vary significantly depending on the raw wastewater characteristics and the treatment technologies used at each WWTP. Recent efforts by states and the EPA to derive numeric nutrient criteria (NNC) that will protect the designated uses under the Clean Water Act reveal limits that clearly push the boundaries of treatment technologies currently in place for most facilities in the United States. Operators and other stakeholders have expressed concern that there may be potentially significant environmental and health implications and economic impacts associated with pushing those boundaries, given it can lead to greater use of chemicals, treatment residuals disposal, increased energy demands, and greater release of greenhouse gases. Studies in other countries also suggest a point of diminishing returns where the economic and environmental consequences may begin to outweigh the benefits of certain advanced treatment technologies (e.g., Foley et al., 2010). Such issues, which encompass economic, environmental, and social costs, are at the center of sustainability evaluations, and can be assessed using holistic, systematic approaches such as life cycle assessment (LCA) and life cycle cost analysis (LCCA).

LCA is a widely accepted technique to assess the environmental aspects and potential impacts associated with individual products, processes, or services. It provides a “cradle-to-grave” analysis of environmental impacts and benefits that can better assist in selecting the most environmentally preferable choice among the various options. The steps for conducting an LCA include (1) identifying goal and scope, (2) compiling a life cycle inventory (LCI) of relevant energy and material inputs and environmental releases, (3) evaluating the potential environmental impacts associated with identified inputs and releases, and (4) interpreting the results to help individuals make a more informed decision.

LCCA is a complementary process to LCA for evaluating the total economic costs of an asset by analyzing initial costs and discounted future expenditures over the life cycle of an asset (Varnier, 2004). It is used to evaluate differences in cost and timing of those costs between alternative projects. The LCCA conducted in this study is not "cradle-to-grave", but rather considers only costs incurred by the facility for establishing a new WWTP (i.e., greenfield project[1]). A retrofit case study was performed and described later in this report.

The objective of this study is to assess a series of wastewater treatment system configurations (hereafter referred to as "wastewater treatment configurations") designed to reduce the nutrient content of effluent from municipal WWTPs. The assessment considers treatment costs as well as human health and ecosystem impacts from a life cycle perspective. The combination of LCA and LCCA provides a full picture of costs, both quantitative and qualitative, for the various wastewater treatment configurations evaluated. This report uses the term wastewater treatment plant, or WWTP, while recognizing that an effort is underway to transition to a new term: "water resource recovery facility". The use of WWTP was selected only as a reflection of historical usage and is not intended to convey preference.

This study compares cost, human health, and ecosystem metrics associated with nine distinct wastewater treatment configurations to provide context for understanding the outcomes from an environmental, economic, and social/societal perspective. The nine wastewater treatment configurations fall into one of five different levels of nutrient reductions, as defined in Table 1-1. Level 1 is a baseline system consisting of a standard secondary treatment configuration with no specific nutrient removal target. The other four levels considered here specify nutrient removal targets with increasing stringency. The wastewater treatment configurations selected for assessment include two alternative configurations for each of the nutrient reduction levels 2 through 5. These configurations were selected because they generally represent configurations commonly used to achieve the specified nutrient performance levels. These configurations were also selected to provide contrast in factors such as the biological processes used, capital costs, operating costs, energy requirements, and sludge generation.

While effluent nutrient concentrations are the main driver of the treatment configuration upgrades analyzed by this study, there is also growing concern over the impacts associated with trace pollutants (Choubert et al., 2011a; Martin Ruel et al., 2012; Montes-Grajales et al., 2017). Trace pollutants are a broad class of compounds that are generally toxic to humans or the aquatic environment even at very low concentrations (U.S. EPA, 2015). Although the list of individual

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[1] Greenfield areas are normally undeveloped areas highly recommended for new construction. The benefits of greenfield construction relate to pristine pieces of land with little to no contamination that contain no structures in the premises. The most beneficial advantage is that there is no cost related to environmental remediation and is ready to start building right away. The most important drawback is that greenfield are usually located outside city centers that might require additional infrastructure upgrades but those are offset by more accessible land costs. Another advantage is that they offer larger pieces of real estate ideally for future expansion and their zoning classification is easier to be changed or adjusted as required. Keep in mind that greenfield usually require deforestation and could affect environmental sensitive areas including the habitat of endangered species.

compounds is continually evolving, the class generally includes pharmaceuticals and personal care products (PPCPs), toxic organics, disinfection byproducts (DBPs) and heavy metals. Importantly, as the prevalence of trace pollutants in modern waste streams is increasing (Ellis, 2008; U.S. EPA, 2015; Ebele et al., 2017), with varying levels of persistence in the environment, they are becoming an important component of modern waste stream management. Many of these pollutants already factor into standard LCA inventories, where emissions of upstream processes are accounted for and contribute to human and environmental health impact categories. However, very little work has been done to incorporate the effects of their direct management at WWTPs, especially in the context of LCA. Such an assessment would provide valuable information as to the full benefits afforded by advanced treatment technologies, as many of the same processes that are effective for nutrient removal are also effective at trace pollutant removal. Preliminary studies have been conducted on certain pollutant groups such as PPCPs and other toxic organics (Montes-Grajales et al., 2017; Rahman et al., 2018) though they have omitted important pollutant groups such as heavy metals and DBPs. This study, therefore, looked in greater detail at a more encompassing list of trace pollutants, including heavy metals, toxic organics and DBPs, to provide a more comprehensive description of the full costs and benefits afforded by advanced nutrient removal technologies.

The metrics used in this assessment are cost and a suite of LCA-related impacts. The LCA-related impacts include eutrophication, global warming, particulate matter formation, smog formation, acidification, and ozone depletion based on the Tool for Reduction and Assessment of Chemicals and other Environmental Impacts (TRACI) 2.1 life cycle impact assessment (LCIA) method; water use and fossil energy use based on the ReCiPe[2] method; human and ecosystem toxicity impacts based on the USEtox™ methodology version 2.02; and cumulative energy demand (Bare, 2012; Goedkoop et al., 2009; Huijbregts et al., 2010). These metrics are discussed in detail in Section 1.2.5 and Section 4.6. The trace pollutant removal analysis is integrated with the toxicity impact category results.

1.2 Scope

This study design follows the guidelines for LCA provided by ISO 14040/14044 (ISO, 2006a, b). The following subsections describe the scope of the study based on the wastewater treatment configurations selected and the functional unit used for comparison, as well as the system boundaries, LCIA methods, and datasets used in this study.

1.2.1 Wastewater Treatment Configurations

This study compares nine alternative wastewater treatment configurations that achieve varying levels of nutrient removal, including a baseline wastewater treatment configuration that is not specifically designed to remove nutrients and eight wastewater treatment configurations that are designed to achieve varying advanced levels of nitrogen and phosphorus removal. The target effluent concentrations for TN and TP for each of the performance levels are presented in Table 1-1, and are based on performance levels analyzed in a study by Falk and colleagues (2011). The wastewater treatment configurations selected for this study are presented in Table

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[2] The name of this method "ReCiPe" is derived from two factors. First, the method provides a recipe to calculate life cycle impact categories. Second, the acronym represents the initials of institutes that were the main contributors: RIVM and Radboud University, CML, and PRè (Goedkoop et al., 2008).

1-2 and described further in Section 1.2.4 and Appendix A. Table 1-2 also lists the abbreviated name used for each wastewater treatment configuration throughout this study. Selected configurations generally represent those most commonly used to achieve the desired performance levels for nutrient requirements and provide contrast in biological processes, capital and/or annual costs, or other factors such as energy requirements and sludge generation. The most common reasons wastewater treatment configurations were not selected include: 1) they are unique retrofits and otherwise not commonly used, 2) they are very similar to another selected technology, or 3) they exhibit a wide range of performance, which raises uncertainty as to the reliability with which the process can achieve a specific performance level. Ultimately, two wastewater treatment configurations were selected for each of Levels 2 through 5 to illustrate the range of costs and environmental impacts associated with varying levels of treatment performance. More detail on the system configuration selection process is included in Appendix A.

Table 1-1. Target Effluent Nutrient Concentrations by Level

Level	Total Nitrogen, mg/L	Total Phosphorus, mg/L
1	[a]	[a]
2	8	1
3	4-8	0.1-0.3
4	3	0.1
5	<2	<0.02

a – No target effluent concentration specified.

Table 1-2. Wastewater Treatment Configurations Selected for this Study

Full Name [a]	Performance Level	Abbreviated Name	Phosphorus Precipitation	Fermenter	Sand Filter	Denitrification Filter	Ultra-filtration	Reverse Osmosis
Conventional Plug Flow Activated Sludge	1	Level 1, AS						
Anaerobic/ Anoxic/Oxic	2	Level 2-1, A2O						
Activated Sludge, 3-Sludge System	2	Level 2-2, AS3	✓					
5-Stage Bardenpho	3	Level 3-1, B5	✓	✓	✓			
Modified University of Cape Town Process	3	Level 3-2, MUCT	✓	✓	✓			
5-Stage Bardenpho with Denitrification Filter	4	Level 4-1, B5/Denit	✓	✓	✓	✓		
4-Stage Bardenpho Membrane Bioreactor	4	Level 4-2, MBR	✓					
5-Stage Bardenpho with Sidestream Reverse Osmosis	5	Level 5-1, B5/RO	✓	✓	✓	10% [b]	90% [b]	90% [b]
5-Stage Bardenpho Membrane Bioreactor with Sidestream Reverse Osmosis	5	Level 5-2, MBR/RO	✓	✓				85% [b]

✓ Indicates technology is used in wastewater treatment configuration.

a – Refer to Section 1.2.4 for the system descriptions.

b – Percentages describe the relative flow of wastewater entering these processes at the WWTP.

1.2.2 Functional Unit

A functional unit provides the basis for comparing results in an LCA. The key consideration in selecting a functional unit is to ensure the wastewater treatment configurations are compared on the basis of equivalent performance. In other words, an appropriate functional unit allows for an apples-to-apples comparison. The functional unit for this study is the treatment of a cubic meter of municipal wastewater with the composition described in Table 1-3. The pH of the reference wastewater is 7.6 and the temperature averages are 23°C summer and 10°C winter.

The study evaluated theoretical wastewater treatment configurations with an average flow rate of 10 million gallons per day (MGD) and a maximum flow rate of 20 MGD[3]. The study results do not represent a specific, existing WWTP. As discussed in Section 3 the operational calculations are based on a year of treatment and standardized to a cubic meter basis using the total volume of water treated in the year. Infrastructure requirements are amortized over individual lifetimes associated with the equipment or buildings. Section 3 provides the lifetimes modeled for all infrastructure components captured in the study. While the WWTP infrastructure requirements are modeled, plant decommissioning is outside of the scope of the study.

It is important to note that the composition of effluent resulting from the wastewater treatment configurations is not part of the definition of the functional unit. Rather the level of treatment performance is a key differentiator of the configurations. Differences in effluent composition are captured in the estimation of impacts associated with the effluent discharges for each system. Effluent quality values for standard water quality parameters for the nine wastewater treatment configurations are depicted in Table 1-4. The effluent quality in Table 1-4 is based on the CAPDETWorks^{TM} output and may vary from actual WWTP effluent for the same wastewater treatment configuration. However, these wastewater treatment configurations were chosen based on actual effluent nutrient concentrations from literature as discussed in Appendix A. Effluent quality values for trace pollutants, which include toxic organics, DBPs and heavy metals, are discussed in further detail in Section 2.

Table 1-3. Composition of Influent Wastewater Considered in this Study

Characteristic	Value	Unit	Reference(s)
Suspended Solids	220	mg/L	1, 2, 3, 4
Volatile Solids	75	%	1, 2, 3, 4
Biological Oxygen Demand (BOD)	220	mg/L	1, 2, 3, 4
Soluble BOD	80	mg/L	2, 3, 4
Chemical Oxygen Demand (COD)	500	mg/L	1, 2, 3, 4
Soluble COD	300	mg/L	2, 3, 4
Total Nitrogen (TN) [a]	40	mg/L N	calculated

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[3] ERG used a 2.0 peaking factor for the study, assuming the WWTP served approximately 100,000 people (Health Research, Inc., 2014).

Table 1-3. Composition of Influent Wastewater Considered in this Study

Characteristic	Value	Unit	Reference(s)
Total Kjeldahl Nitrogen (TKN) [b]	40	mg/L N	1, 2, 3, 4
Soluble TKN	25	mg/L N	2, 3
Ammonia	22	mg/L N	1, 4
Nitrate	0	mg/L N	1, 2, 3, 4
Nitrite	0	mg/L N	1, 2, 3, 4
Total Phosphorus (TP)	5	mg/L P	2, 3
Cations	160	mg/L	3, 4
Anions	160	mg/L	3, 4
Settleable Solids	10	mg/L	1, 3, 4
Oil and Grease	100	mg/L	1, 3, 4
Nondegradable Fraction of Volatile Suspended Solids (VSS)	40	%	3, 4

[1] Tchobanoglous and Burton, 1991; [2] U.S. EPA OWM, 2008b; [3] ERG, 2009; [4] Hydromantis, 2014

a – TN is the sum of TKN, nitrate, and nitrite.

b – TKN is the sum of ammonia, organic nitrogen, and reduced nitrogen.

Table 1-4. Effluent Composition for the Nine Wastewater Treatment Configurations (mg/L)

Constituent	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Suspended Solids	20	20	20	8.0	8.0	8.0	9.0	1.3	1.9
BOD	7.7	4.7	3.1	2.3	2.3	7.0	3.1	1.2	0.62
Soluble BOD	3.9	2.3	1.5	2.3	2.3	7.0	2.1	1.2	0.45
COD	28	25	8.9	3.5	3.5	11	13	1.8	2.6
Soluble COD	5.8	3.5	2.3	3.5	3.5	11	3.21	1.8	0.70
Total Phosphorus	4.9	0.28	1.0	0.20	0.20	0.10	0.10	0.02	0.02
Total Nitrogen	30	8.0	7.8	6.0	6.0	3.0	3.0	0.73	2.0
TKN	30	1.9	2.1	0.52	0.52	0.52	1.0	0.15	0.20
Soluble TKN	29	0.52	1.6	0.52	0.52	0.52	0.42	0.09	0.08
Ammonia	15	0.52	0	0.52	0.52	0.52	0.42	0.09	0.08
Nitrate	0	6.1	5.7	5.5	5.5	2.4	2.0	0.63	1.8
Organic Nitrogen	15	1.4	2.1	0	0	0	0.58	0.06	0.12

1.2.3 System Definition and Boundaries

This section describes general aspects of each wastewater treatment configuration that are included in the LCA system boundary. The boundary for processes included in the assessment of each of the wastewater treatment configurations selected for evaluation includes all onsite wastewater and sludge treatment processes from the municipal WWTP headworks through final discharge of the treated effluent and disposal of sludge and other wastes. Off-site costs and environmental impacts associated with release of the effluent to the receiving stream, sludge transport and disposal, and for facilities with reverse osmosis (RO) units, brine disposal into onsite underground injection control (UIC) wells are also considered. The system boundary includes all relevant details of the wastewater treatment processes, environmental releases from each process, and the supply chains associated with the inputs to each process. Chemicals associated with periodic cleaning of equipment (e.g., membranes) are within the system boundary. Production of concrete, excavation activities, building materials, and a limited quantity of steel are included as infrastructure materials in the LCA. Pumps, in-unit mechanical systems, and electronics are excluded from the LCA study boundary due to lack of detailed information, although these types of equipment are included in the LCCA. The LCCA also includes costs for engineering and professional services that are not part of the LCA. A simplified system diagram is presented in Figure 1-1, which depicts the main materials and emission sources included in the model.

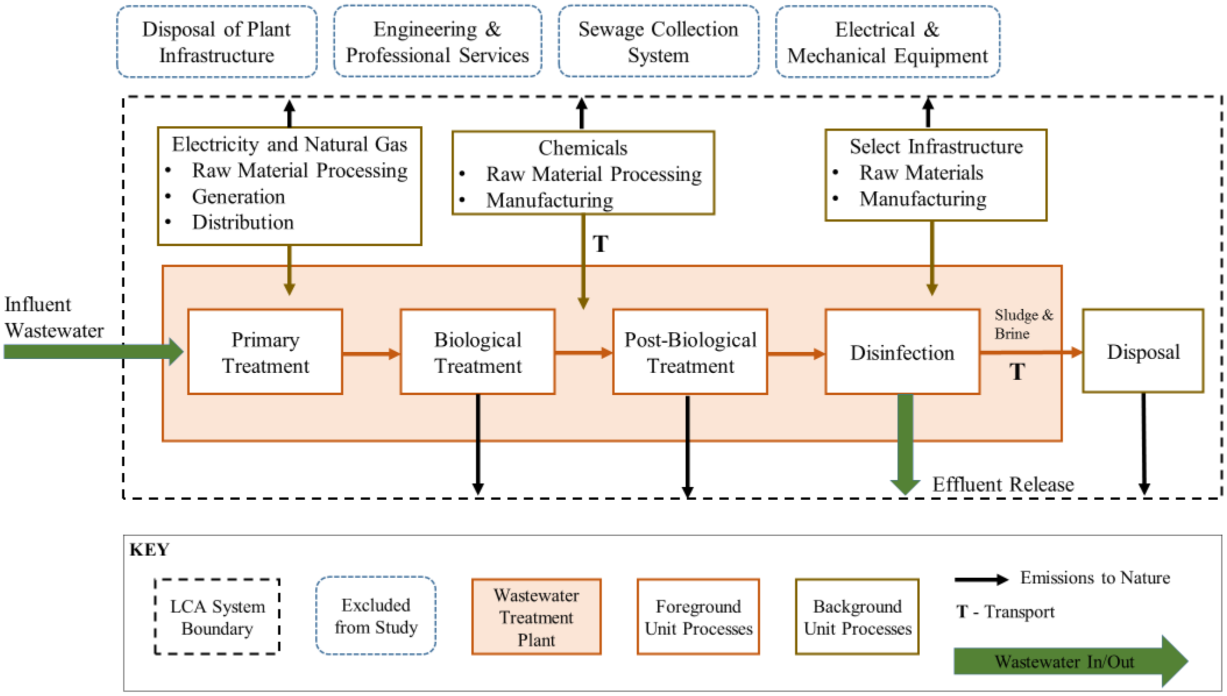

Figure 1-1. Generalized Study System Boundary

The four orange boxes in Figure 1-1 comprise the foreground unit processes that make up the wastewater treatment configuration at each WWTP. Electricity generation, chemical production, material extraction and manufacturing, and disposal processes are considered background unit processes. Disposal processes include landfilling of treated sludge and underground injection of brine solution. Background processes are still within the system boundary and are quantified within the analysis, although they exist beyond the physical boundaries of the wastewater treatment plant. The exterior dotted line in Figure 1-1 represents the system boundary considered in this LCA. The emissions to various compartments within nature (soil, air, water) are used in the estimation of environmental impacts. Details related to the calculation procedure and the environmental impacts included in this study are discussed in Section 4.

Excluded from the system boundaries are production of the components that make up the wastewater (e.g., drinking water treatment, residential organic waste, industrial wastewater pretreatment) and the collection system, including any raw sewage pump stations. It is assumed that these elements would be equivalent for all examined wastewater treatment configurations, and, therefore can be excluded from the scope of the analysis.

It is important to note that some potential benefits that may be realized from level 4 and level 5 wastewater treatment configuration are not captured in the system boundaries of this study. For instance, it may be possible to recycle the effluent from wastewater treatment for non-potable uses like toilet flushing or irrigation as the effluent quality may achieve non-potable requirements. Utilization of this recycled water would avoid production of potable water elsewhere. In an expanded system boundary, avoided production of potable water would result in an overall credit for these higher nutrient removal wastewater treatment configurations that is not included in this LCA study. Another potential benefit not included is the pathogen or other microbial contaminant removal.

1.2.4 System Descriptions of Wastewater Treatment Configurations

Flow diagrams of each wastewater treatment configuration are provided in Figure 1-2 through Figure 1-10. Each of these figures provides a visual representation of the detailed unit processes included in the relevant wastewater treatment configuration. The figures also show the source of process greenhouse gas (GHG) emissions and the type of chemical inputs.

In each wastewater treatment configuration, wastewater is first treated by screening, grit removal, and primary clarification. Screening removes large debris from the wastewater flow and grit removal extracts stone, grit, and other separable debris. Debris from this stage is transported to a landfill. In the next stage, primary clarification, solids are allowed to settle from the wastewater and grease to float to the top. Solids are pumped out from the bottom of the tank and scum and grease are skimmed off the top. These materials are either sent directly to a gravity thickener (configuration levels 1, 2-1, 2-2, 4-2) or first sent to a fermenter and then to the gravity thickener (configuration levels 3-1, 3-2, 4-1, 5-1, and 5-2) then to anaerobic digestion, and ultimately hauled away by truck for disposal in a landfill. The assumed distance from the wastewater treatment plant to the landfill is 25 miles one-way. In all cases, it is assumed the biogas from anaerobic digestion is flared. A detailed emission inventory associated with biogas flaring process is included in Appendix F. The sludge is assumed to be disposed in an average

U.S. municipal solid waste landfill in which methane is recovered for energy. The same biogas flaring and sludge landfilling assumptions were made for all wastewater treatment configurations as the study focuses on differentiating factors for nutrient removal technologies rather than options for sludge handling. Alternative treatment options for biogas is addressed later in the sensitivity analysis later in this report (Section 9.5).

After pretreatment and primary treatment, the processes involved in each wastewater treatment configuration varies. A description of each wastewater treatment configuration is provided in the subsequent sections, while a summary of their relevant attributes is given in Table 1-5.

1.2.4.1 Level 1: Conventional Plug Flow Activated Sludge (Level 1, AS)

The Level 1 configuration represents typical secondary treatment used by municipal WWTPs in the United States. This system focuses on reducing BOD and TSS concentrations to 30 mg/L and has no specific nutrient removal targets. In the conventional plug flow activated sludge wastewater treatment configuration, following pretreatment and primary treatment, wastewater is sent to a plug flow activated sludge reactor for carbonaceous biochemical oxygen demand (CBOD) removal. After plug flow activated sludge treatment, wastewater is sent to secondary clarification where solids are allowed to settle from the wastewater. Clarified effluent is disinfected using chlorine gas[4] followed by dechlorination using sodium bisulfite to remove residual chlorine prior to discharge. Effluent from the wastewater treatment process is discharged to surface water. Secondary clarifier sludge is pumped out from the bottom of the clarifier. Of this sludge, a portion is sent back to the plug flow activated sludge treatment process (return activated sludge) and the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

1.2.4.2 Level 2-1: Anaerobic/Anoxic/Oxic (Level 2-1, A2O)

In the Level 2-1 anaerobic/anoxic/oxic (A2O) wastewater treatment configuration, following pretreatment and primary treatment, wastewater is sent to the A2O process, which consists of an anaerobic zone, an anoxic zone, and an oxic zone for biological phosphorus removal, CBOD removal, nitrification (conversion of ammonia to nitrate), and denitrification (conversion of nitrate to nitrogen gas, which is released to the atmosphere). There is an internal recycle that returns nitrified mixed liquor from the oxic zone to the anoxic zone. A secondary clarifier follows the A2O process where solids are allowed to settle from the wastewater. Clarified effluent is disinfected using chlorine gas followed by dechlorination using sodium bisulfite to remove residual chlorine prior to discharge. Effluent from the wastewater treatment process is discharged to surface water. Secondary clarifier sludge is pumped out from the bottom

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[4] Chlorination using hypochlorite is more common than gaseous chlorine due to safety concerns and regulations on the handling and storage of pressurized liquid chlorine (Tchobanoglous et al., 2014). However, CAPDETWorks^{TM} only includes disinfection using chlorine gas (Hydromantis, 2014). As a result, ERG used chlorine gas for this study.

of the tank with a portion returned to the influent of the A2O process (return activated sludge) and the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

1.2.4.3 Level 2-2: Activated Sludge, 3-Sludge System (Level 2-2, AS3)

In the Level 2-2 activated sludge, 3-sludge wastewater treatment configuration, wastewater undergoes pretreatment and primary treatment before entering a plug flow activated sludge reactor for CBOD removal. Wastewater is then sent to the secondary clarifier where solids are allowed to settle from the wastewater. Sludge is pumped out from the bottom of the clarifier. Of this sludge, a portion is sent back to the plug flow activated sludge treatment process (return activated sludge) and the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Wastewater from the secondary clarifier is sent to a suspended growth nitrification reactor to convert ammonia nitrogen to nitrate, followed by a tertiary clarifier where solids are allowed to settle from the wastewater. A portion of the tertiary clarifier sludge is sent back to the nitrification reactor (return activated sludge) and the remainder (waste activated sludge) is sent to gravity thickening. Wastewater from the tertiary clarifier is sent to a suspended growth denitrification reactor to convert nitrate to nitrogen gas. Methanol is added immediately preceding the denitrification reactor as a supplemental carbon source. Prior to a final clarification step, the wastewater undergoes chemical phosphorus precipitation using aluminum salts, where solids are allowed to settle from the wastewater. A portion of the final clarifier sludge is sent back to the denitrification reactor (return activated sludge) and the remainder (waste activated sludge) is sent to gravity thickening. Clarified effluent is disinfected using chlorine gas followed by dechlorination using sodium bisulfite to remove residual chlorine prior to discharge. Effluent from the wastewater treatment process is discharged to surface water. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

1.2.4.4 Level 3-1: 5-Stage Bardenpho (Level 3-1, B5)

In the Level 3-1 5-Stage Bardenpho wastewater treatment configuration, wastewater undergoes pretreatment and primary treatment. Sludge from the primary clarifier enters a fermentation vessel to convert complex proteins and carbohydrates to volatile fatty acids (VFAs) that provide an internal carbon source for biological nutrient removal. Sludge from the fermenter is sent to gravity thickening. Primary clarifier effluent and fermenter supernatant enter a 5-stage Bardenpho nutrient removal reactor wherein the wastewater enters an anaerobic stage before alternating between anoxic and aerobic conditions in a total of five successive stages for biological phosphorus removal, CBOD removal, and enhanced nitrification and denitrification. There is an internal mixed liquor recycle that returns wastewater from the first aerobic zone to the first anoxic zone. Following the Bardenpho reactor, part of the remaining phosphorus in the wastewater is chemically precipitated, using aluminum salts, after which the effluent moves along to secondary clarification where solids are allowed to settle from the wastewater. Clarified effluent is passed through a sand filter for tertiary solids removal prior to disinfection using chlorine gas and dechlorination using sodium bisulfite to remove residual chlorine prior to discharge. Effluent from the wastewater treatment process is discharged to surface water. Sludge is removed from the bottom of the secondary clarifier. Of this sludge, a portion is sent back to the influent of the Bardenpho reactor (return activated sludge) while the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

1.2.4.5 Level 3-2: Modified University of Cape Town Process (Level 3-2, MUCT)

In the Level 3-2 modified University of Cape Town process wastewater treatment configuration, wastewater first undergoes pretreatment and primary treatment. Sludge from primary clarification enters a fermentation vessel to convert complex proteins and carbohydrates to VFAs that provide an internal carbon source for biological nutrient removal. Sludge from the fermenter is sent to gravity thickening. Primary clarifier effluent and fermenter supernatant enter a 4-stage biological nutrient removal (BNR) reactor, referred to as the modified University of Cape Town process. Within the reactor, wastewater enters an anaerobic phase and passes through two successive anoxic stages before a final aerobic stage for biological phosphorus removal, CBOD removal, and enhanced nitrification and denitrification. There is an internal mixed liquor recycle that returns wastewater from the end of the first anoxic stage to the head of the anaerobic stage, and an additional internal recycle that returns wastewater from the aerobic stage to the second anoxic stage. Following biological nutrient removal, phosphorus in the wastewater is chemically precipitated, using aluminum salts, after which the effluent moves along to secondary clarification where solids are allowed to settle from the wastewater. Clarified effluent is passed through a sand filter for tertiary solids removal prior to disinfection using chlorine gas and dechlorination using sodium bisulfite to remove residual chlorine prior to discharge. Effluent from the wastewater treatment process is discharged to surface water. Sludge is removed from the bottom of the secondary clarifier. Of this sludge, a portion is returned to the first anoxic stage in the BNR reactor (return activated sludge) while the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are also returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

1.2.4.6 Level 4-1: 5-Stage Bardenpho with Denitrification Filter (Level 4-1, B5/Denit)

In the Level 4-1 5-Stage Bardenpho with denitrification filter wastewater treatment configuration, wastewater first undergoes pretreatment and primary treatment. Sludge from primary clarification enters a fermentation vessel to convert complex proteins and carbohydrates to VFAs that provide an internal carbon source for biological nutrient removal. Sludge from the fermenter is sent to gravity thickening. Primary clarifier effluent and fermenter supernatant enter a 5-stage Bardenpho nutrient removal reactor wherein the wastewater enters an anaerobic stage before alternating between anoxic and aerobic conditions in a total of five successive steps for biological phosphorus removal, CBOD removal, and enhanced nitrification and denitrification. There is an internal mixed liquor recycle that returns wastewater from the first aerobic zone to the first anoxic zone. Following the Bardenpho reactor, phosphorus in the wastewater is chemically precipitated, using aluminum salts, after which the effluent moves along to secondary clarification where solids are allowed to settle from the wastewater. Clarified effluent then enters an upflow, attached growth denitrification filter for additional nitrogen removal. Methanol is added immediately preceding the denitrification filter as a supplemental carbon source. Wastewater is finally passed through a sand filter for tertiary solids removal prior to disinfection using chlorine gas and dechlorination using sodium bisulfite to remove residual chlorine prior to discharge. Effluent from the wastewater treatment process is discharged to surface water. Sludge is removed from the bottom of the secondary clarifier. Of this sludge, a portion is returned to the influent of the Bardenpho reactor (return activated sludge) while the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

1.2.4.7 Level 4-2: 4-Stage Bardenpho Membrane Bioreactor (Level 4-2, MBR)

In the Level 4-2 4-Stage Bardenpho membrane bioreactor wastewater treatment configuration, wastewater undergoes primary treatment before entering a 4-stage Bardenpho nutrient removal reactor. Within the reactor wastewater alternates twice between anoxic and aerobic stages for CBOD removal, and enhanced nitrification and denitrification. There is an internal mixed liquor recycle that returns wastewater from the first aerobic zone to the first anoxic zone. Methanol is added as a supplemental carbon source in the Bardenpho reactor in the second anoxic zone. Following the Bardenpho reactor, phosphorus in the wastewater is chemically precipitated, using aluminum salts, after which the effluent moves on for membrane filtration to remove solids from the wastewater, generating a permeate (effluent) and reject stream (sludge). Effluent is sent to disinfection using chlorine gas and dechlorination using sodium bisulfite to remove residual chlorine prior to discharge. Effluent from the wastewater treatment process is discharged to surface water. A portion of the sludge from the membrane filter is returned to the influent to the 4-stage Bardenpho (return activated sludge) while the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

1.2.4.8 Level 5-1: 5-Stage Bardenpho with Sidestream Reverse Osmosis Treatment (Level 5-1, B5/RO)

In the Level 5-1 5-Stage Bardenpho with sidestream reverse osmosis (RO) wastewater treatment configuration, wastewater first undergoes pretreatment and primary treatment. Sludge from primary clarification enters a fermentation vessel to convert complex proteins and carbohydrates to VFAs that provide an internal carbon source for biological nutrient removal. Sludge from the fermenter is sent to gravity thickening. Primary clarifier effluent and fermenter supernatant enters a 5-stage Bardenpho nutrient removal reactor wherein the wastewater goes through an anaerobic stage before alternating between anoxic and aerobic conditions in a total of five successive steps for biological phosphorus removal, CBOD removal, and enhanced nitrification and denitrification. There is an internal mixed liquor recycle that returns wastewater from the first aerobic zone to the first anoxic zone. Following the Bardenpho reactor, additional phosphorus in the wastewater is chemically precipitated, using aluminum salts, after which the effluent moves along to secondary clarification where solids are allowed to settle from the wastewater. Clarified effluent is split into two streams for further treatment. In order to meet the designed effluent quality, ten percent of the flow enters an upflow, attached growth denitrification filter for additional nitrogen removal, followed by a sand filter for tertiary solids removal. Methanol is added immediately preceding the denitrification reactor as a supplemental carbon source. The remaining 90 percent of the flow first undergoes a series of RO pre-treatment steps, including ultrafiltration for solids removal; chlorine gas addition for biofouling control (followed by dechlorination with sodium bisulfite due to low chlorine tolerance of the RO membranes); and antiscalant addition for scale control. Following pretreatment, the effluent underdoes RO treatment, generating a permeate (effluent) and reject stream (brine). Effluent from the 10 percent and 90 percent side stream steps are then recombined for final disinfection using chlorine gas and dechlorination using sodium bisulfite to remove residual chlorine prior to discharge to surface water. Brine from the RO unit is disposed of by injection into an onsite disposal well. A portion of the clarified sludge is returned to the influent of the Bardenpho reactor (return activated sludge) while the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

1.2.4.9 Level 5-2: 5-Stage Bardenpho Membrane Bioreactor with Sidestream Reverse Osmosis Treatment (Level 5-2, MBR/RO)

In the Level 5-2 5-Stage Bardenpho membrane bioreactor with sidestream RO wastewater treatment configuration, wastewater first undergoes pretreatment and primary treatment. Sludge from primary clarification enters a fermentation vessel to convert complex proteins and carbohydrates to VFAs that provide an internal carbon source for biological nutrient removal. Sludge from the fermenter is sent to gravity thickening. Primary clarifier effluent and fermenter supernatant enters a 5-stage Bardenpho nutrient removal reactor wherein the wastewater enters an anaerobic stage before alternating between anoxic and aerobic conditions in a total of five successive steps for biological phosphorus removal, CBOD removal, and enhanced nitrification and denitrification. There is an internal mixed liquor recycle that returns wastewater from the first aerobic zone to the first anoxic zone. Following the Bardenpho reactor, additional phosphorus in the wastewater is chemically precipitated, using aluminum salts, after which the effluent moves along to membrane filtration to remove solids from the wastewater, generating permeate (effluent) and a reject stream (sludge). In order to meet the designed effluent quality, effluent then splits into two streams with 15 percent of the flow receiving no sidestream treatment. The remaining 85 percent of flow undergoes a series of RO pre-treatment steps, including chlorine gas addition for biofouling control (followed by dechlorination with sodium bisulfite due to low chlorine tolerance of the RO membranes); and antiscalant addition for scale control. Following pretreatment, the effluent undergoes RO treatment, generating a permeate (effluent) and reject stream (brine). Effluent from the RO unit is recombined with the 15 percent stream for final disinfection using chlorine gas and dechlorinated using sodium bisulfite to remove residual chlorine prior to discharge to surface water. Brine from the RO unit is disposed of by injection into an onsite disposal well. A portion of sludge from the membrane filter is returned to the influent of the Bardenpho (return activated sludge) while the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

Table 1-5. Study Treatment Configuration Characteristics

Treatment Level ID		**L1**	**L2-1**	**L2-2**	**L3-1**	**L3-2**	**L4-1**	**L4-2**	**L5-1**	**L5-2**
Characteristic	***Description***	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3[a]**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR[c]**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO[c]**
SRT (days)	Primary Biological Process	10	15	10	15	15	15	19	15	21
	Secondary Biological Process	-	-	50	-	-	attached[b]	-	attached[b]	-
	Tertiary Biological Process	-	-	10	-	-	-	-	-	-
Quantify nitrification	Primary Biological Process	Minimal	Partial	Minimal	High	High	High	High	High	High
	Secondary Biological Process	-	-	High	-	-	N/A	Minimal	N/A	Minimal
	Tertiary Biological Process	-	-	N/A	-	-	-	-	-	-
HRT (hours)[d]	Aerobic	5.7	8.8	6.0	10	10	10	5.3	10	6.2
	Anoxic	-	6.0	6.2	7.4	8.2	10	2.6	9.2	3.7
	Anaerobic	-	2.5	4.3	2.5	1.6	0.77	0.94	1.7	0.69
	Total	*5.7*	*17*	*16*	*20*	*20*	*21*	*8.8*	*21*	*11*
Redox condition summary[d]		Aero	An-Anox-Aero	Aero-Aero-An	An-Anox-Aero-Anox-Aero	An-Anox-Anox-Aero	An-Anox-Aero-Anox-Aero-Anox	Anox-Aero-Anox-Aero	An-Anox-Aero-Anox-Aero-Anox	An-Anox-Aero-Anox-Aero
MLSS Concentration (mg/L)	Primary Biological Process	2500	3000	2500	3000	3000	3000	9000	3000	9000
	Secondary Biological Process	-	-	2500	-	-	N/A	9000	N/A	9000
	Tertiary Biological Process	-	-	2500	-	-	-	-	-	-

a - Secondary biological process is a nitrification reactor. Tertiary biological process is denitrification reactor.

b - Secondary biological process is an attached growth denitrification reactor with an HRT of 1 hour.

c - Secondary biological process is membrane filter with an HRT of 1.78 hours.

d - Aggregates information for primary, secondary and tertiary biological processes.

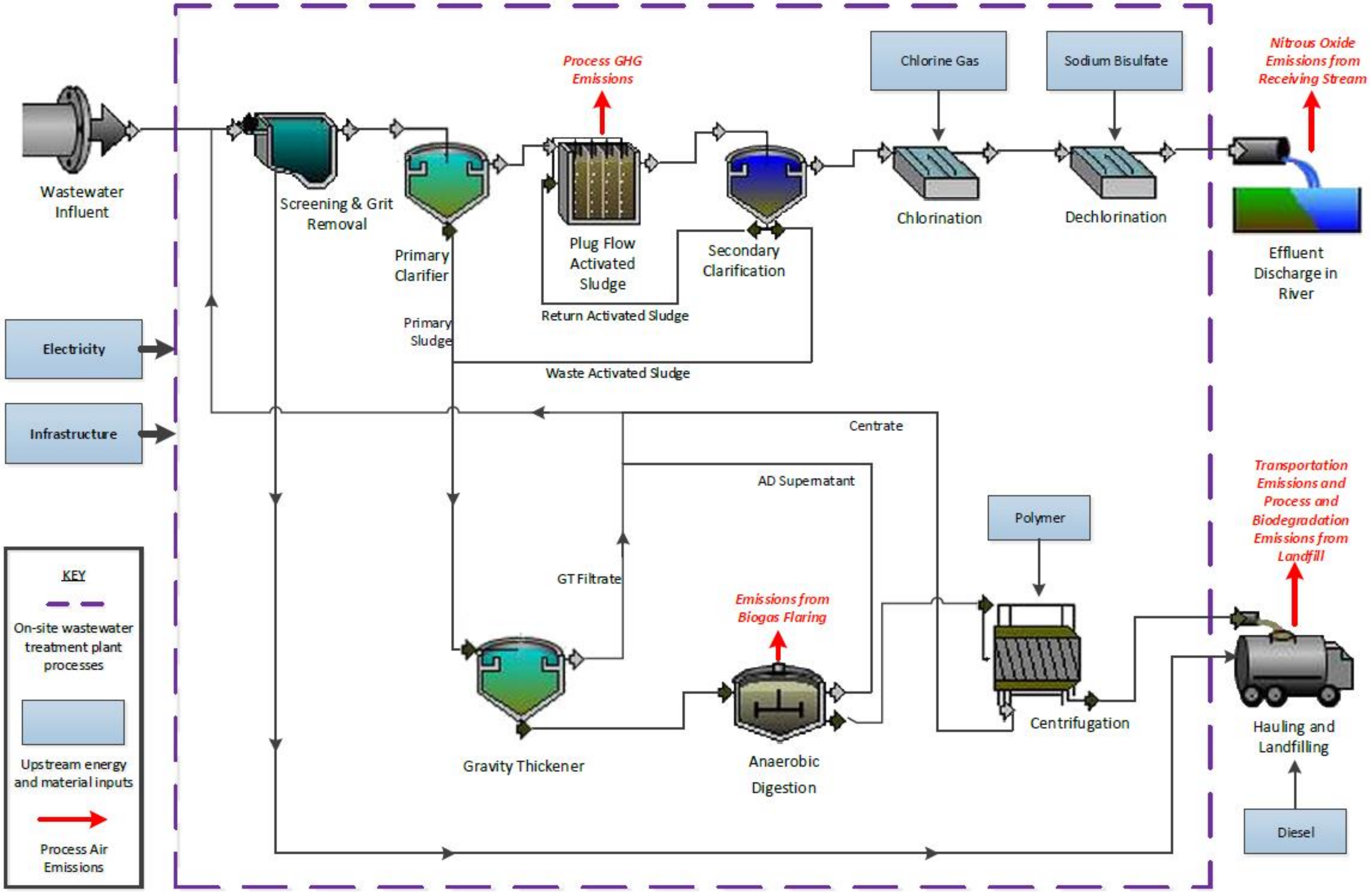


Figure 1-2. Level 1: Conventional Plug Flow Activated Sludge Wastewater Treatment Configuration

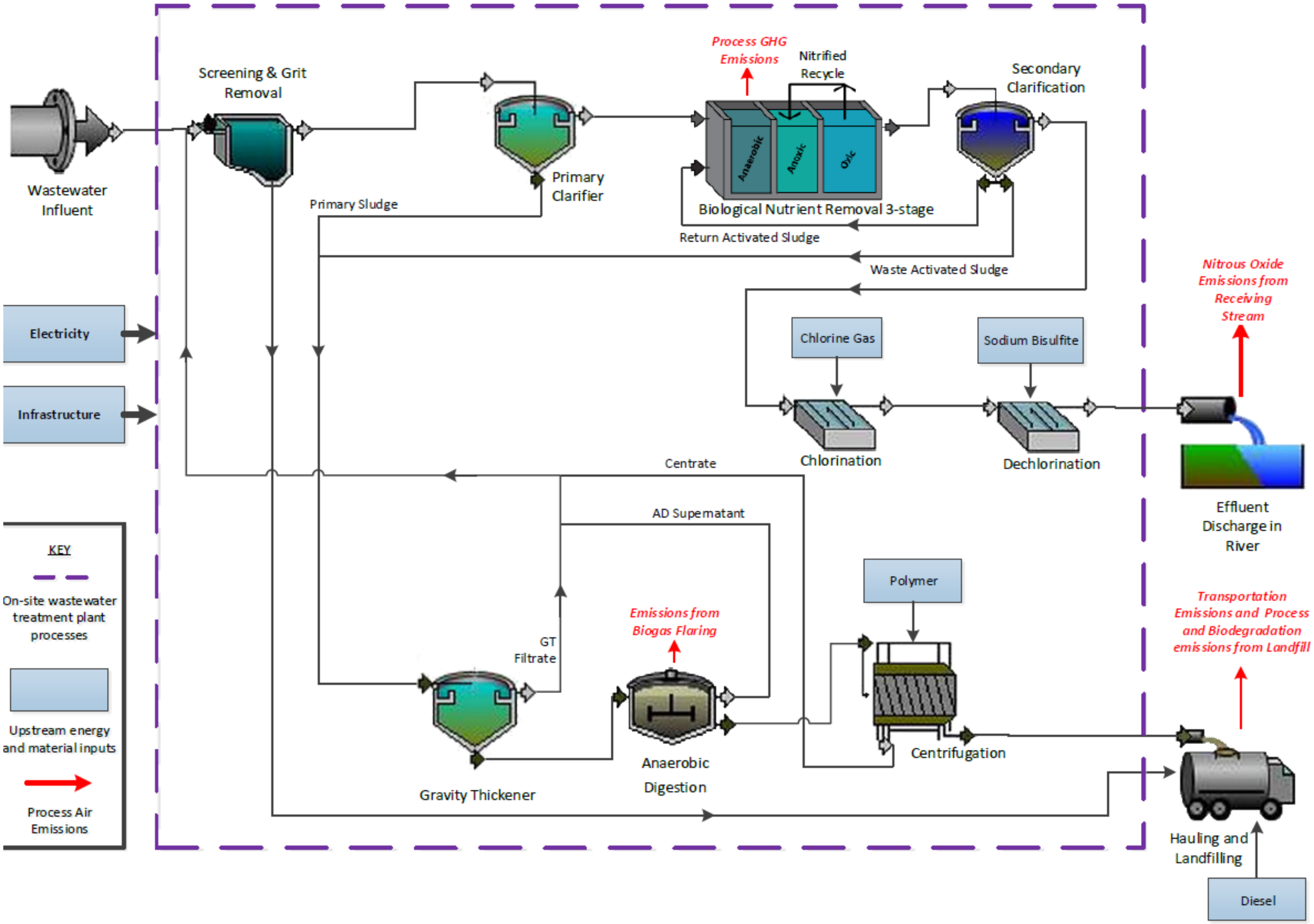


Figure 1-3. Level 2-1: Anaerobic/Anoxic/Oxic Wastewater Treatment Configuration

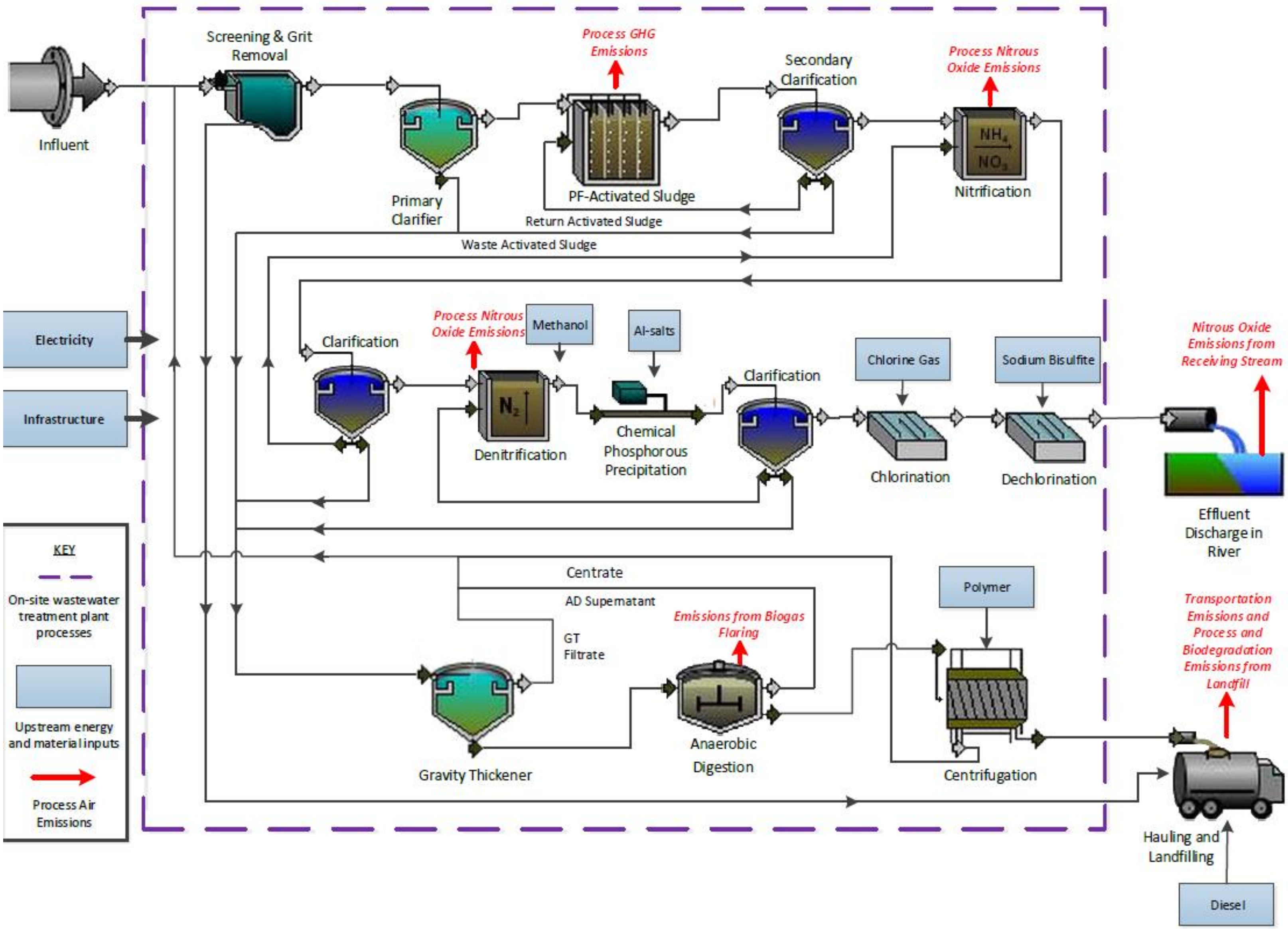


Figure 1-4. Level 2-2: Activated Sludge, 3-Sludge System Wastewater Treatment Configuration

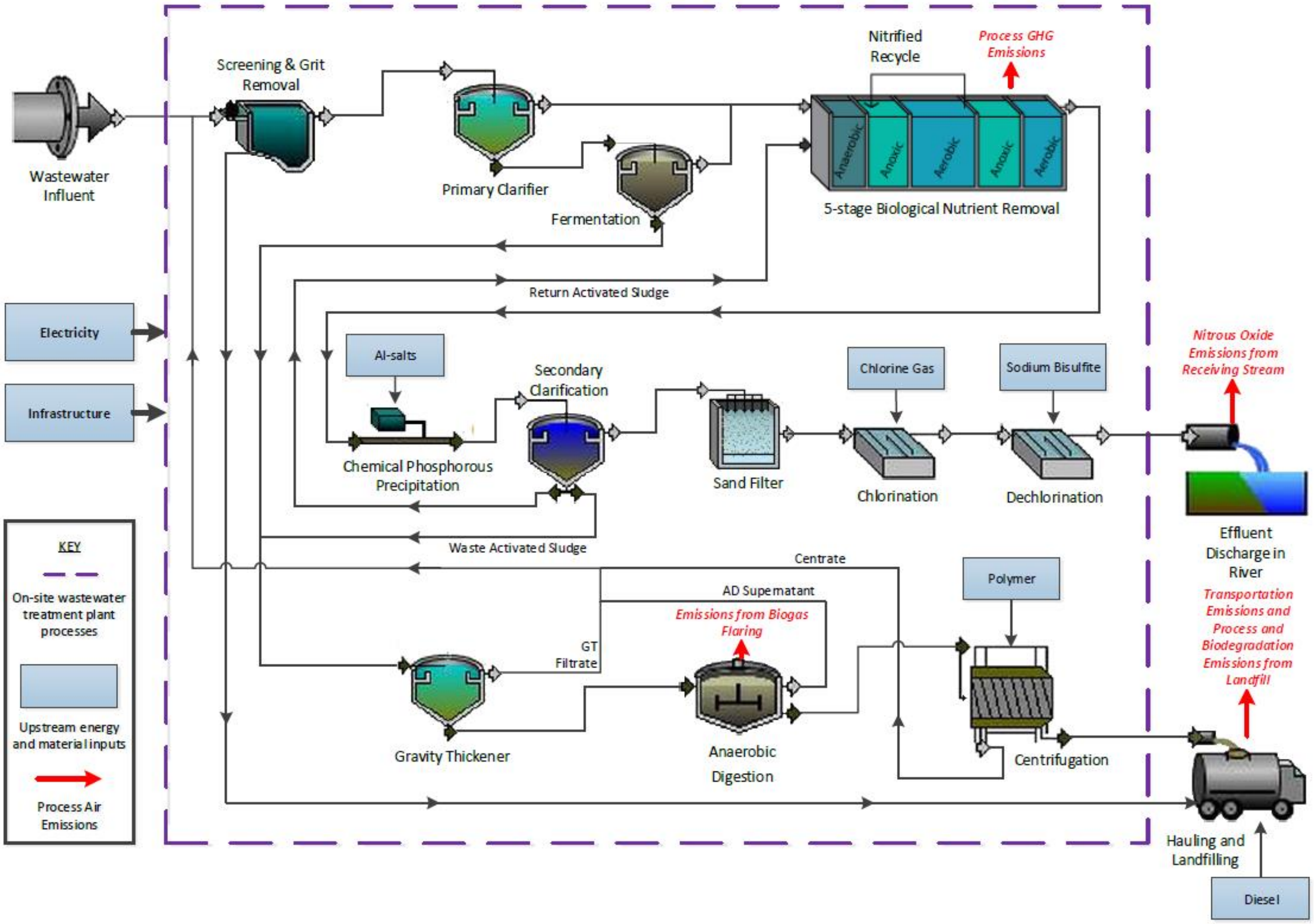


Figure 1-5. Level 3-1: 5-Stage Bardenpho System Wastewater Treatment Configuration

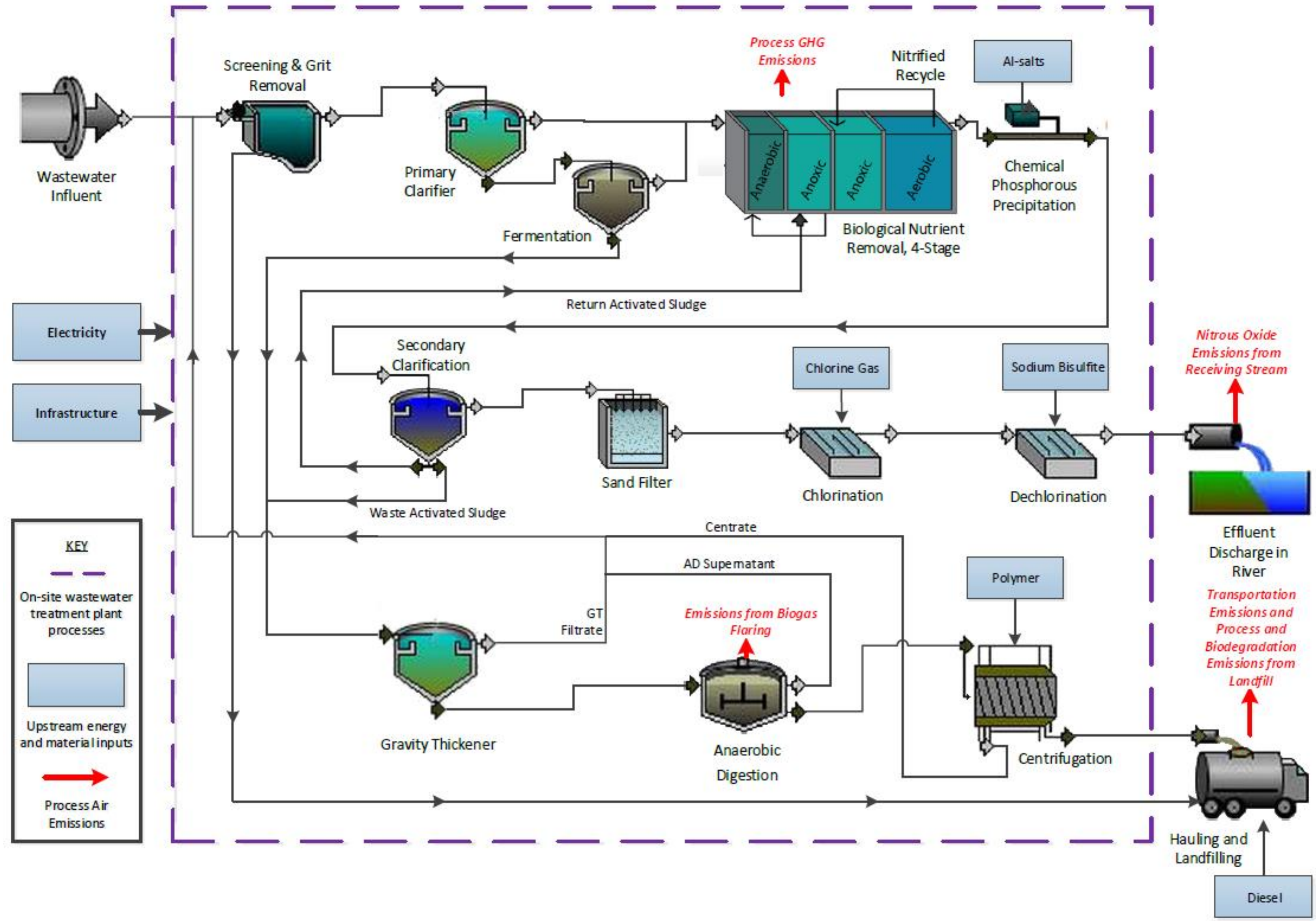


Figure 1-6. Level 3-2: Modified University of Cape Town Process Wastewater Treatment Configuration

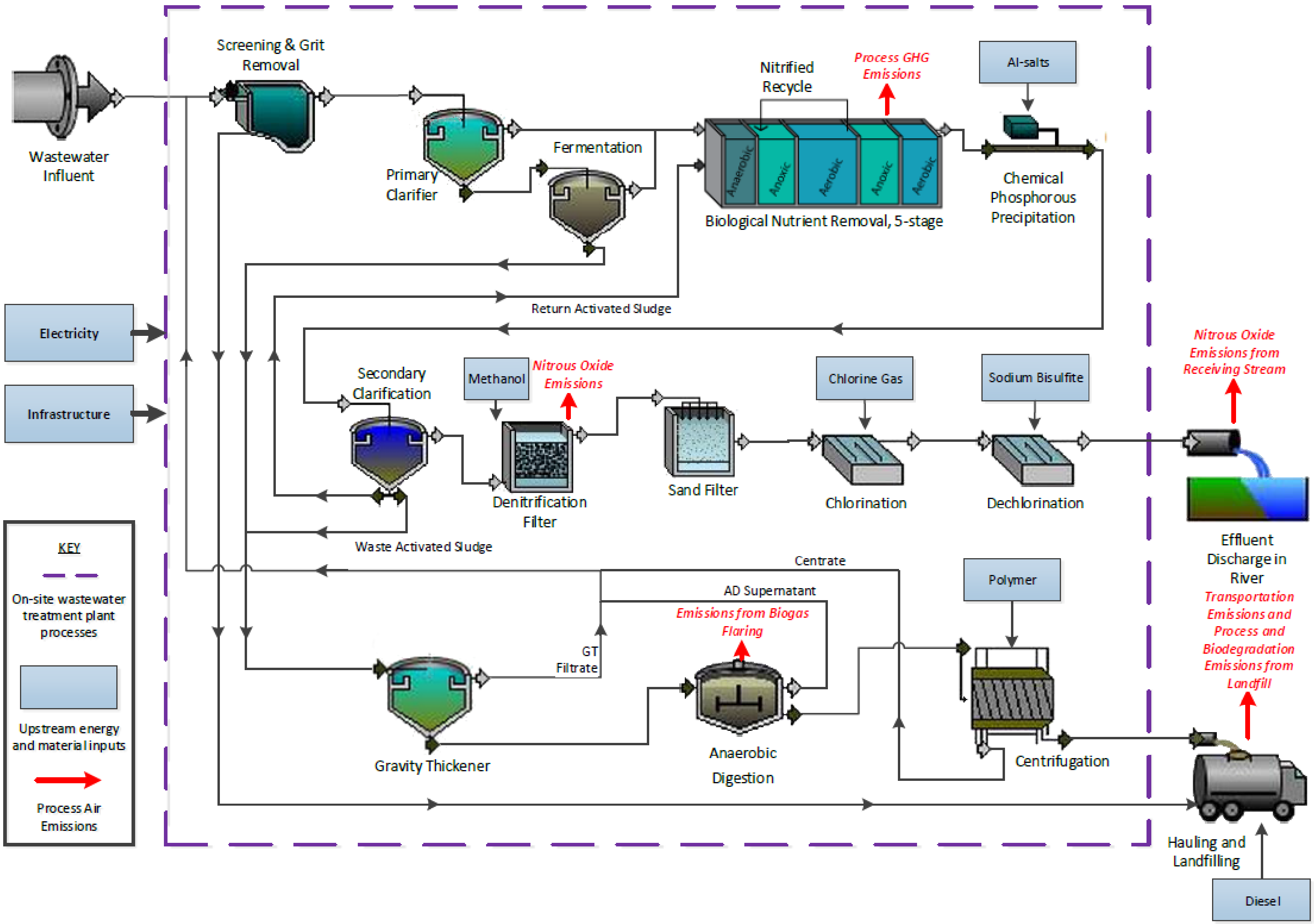


Figure 1-7. Level 4-1: 5-Stage Bardenpho System with Denitrification Filter Wastewater Treatment Configuration

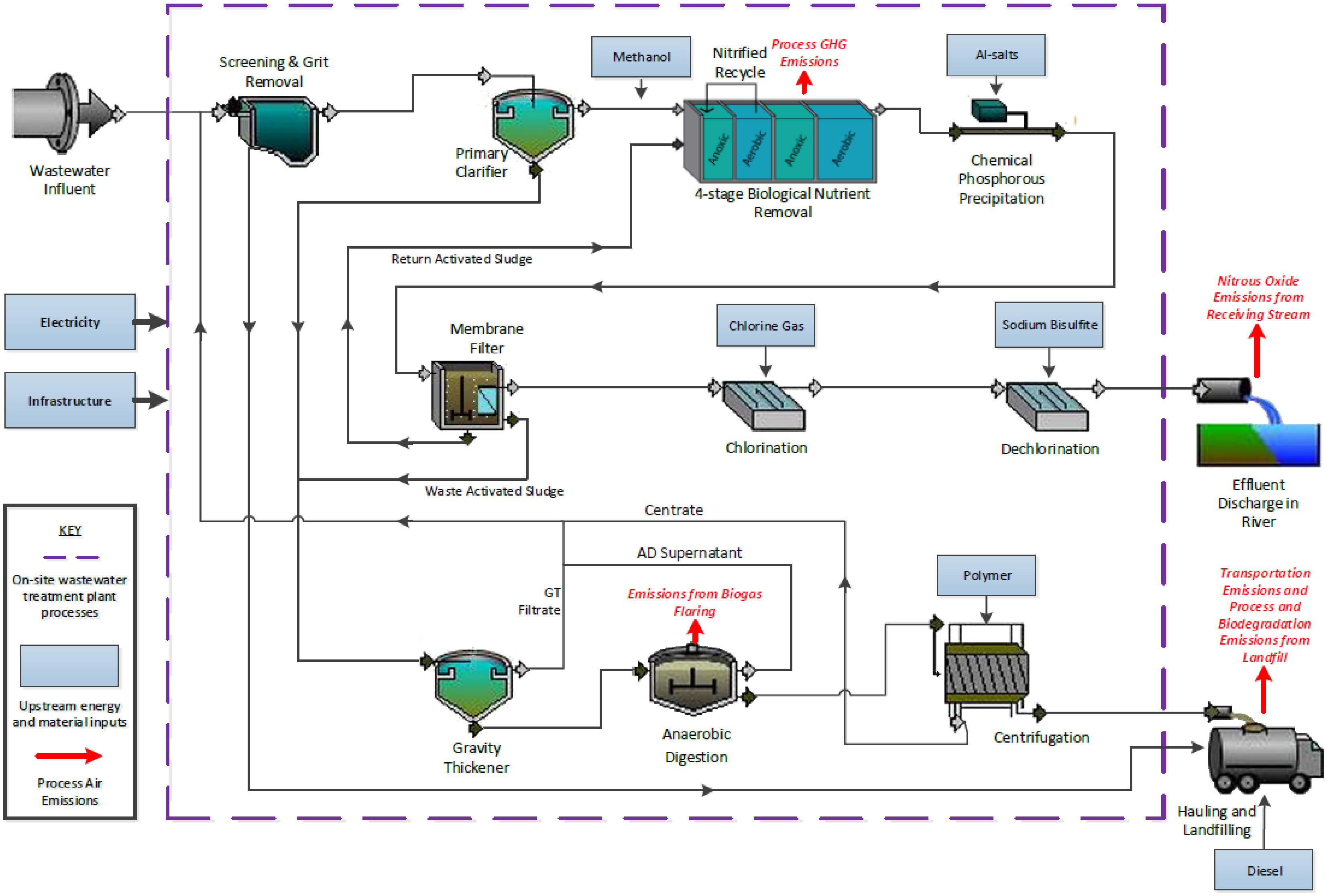


Figure 1-8. Level 4-2: 4-Stage Bardenpho Membrane Bioreactor System Wastewater Treatment Configuration

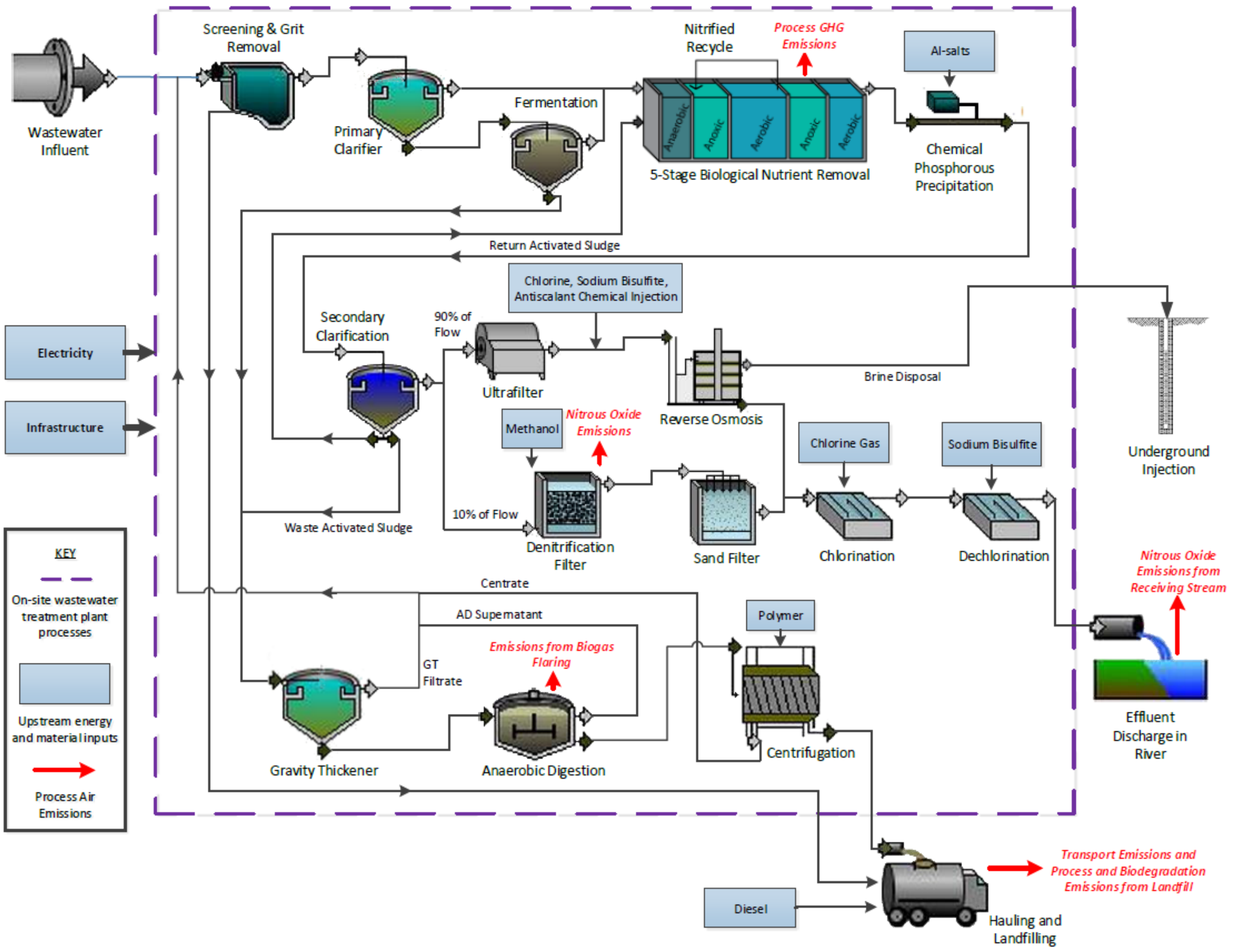


Figure 1-9. Level 5-1: 5-Stage Bardenpho with Sidestream Reverse Osmosis Wastewater Treatment Configuration

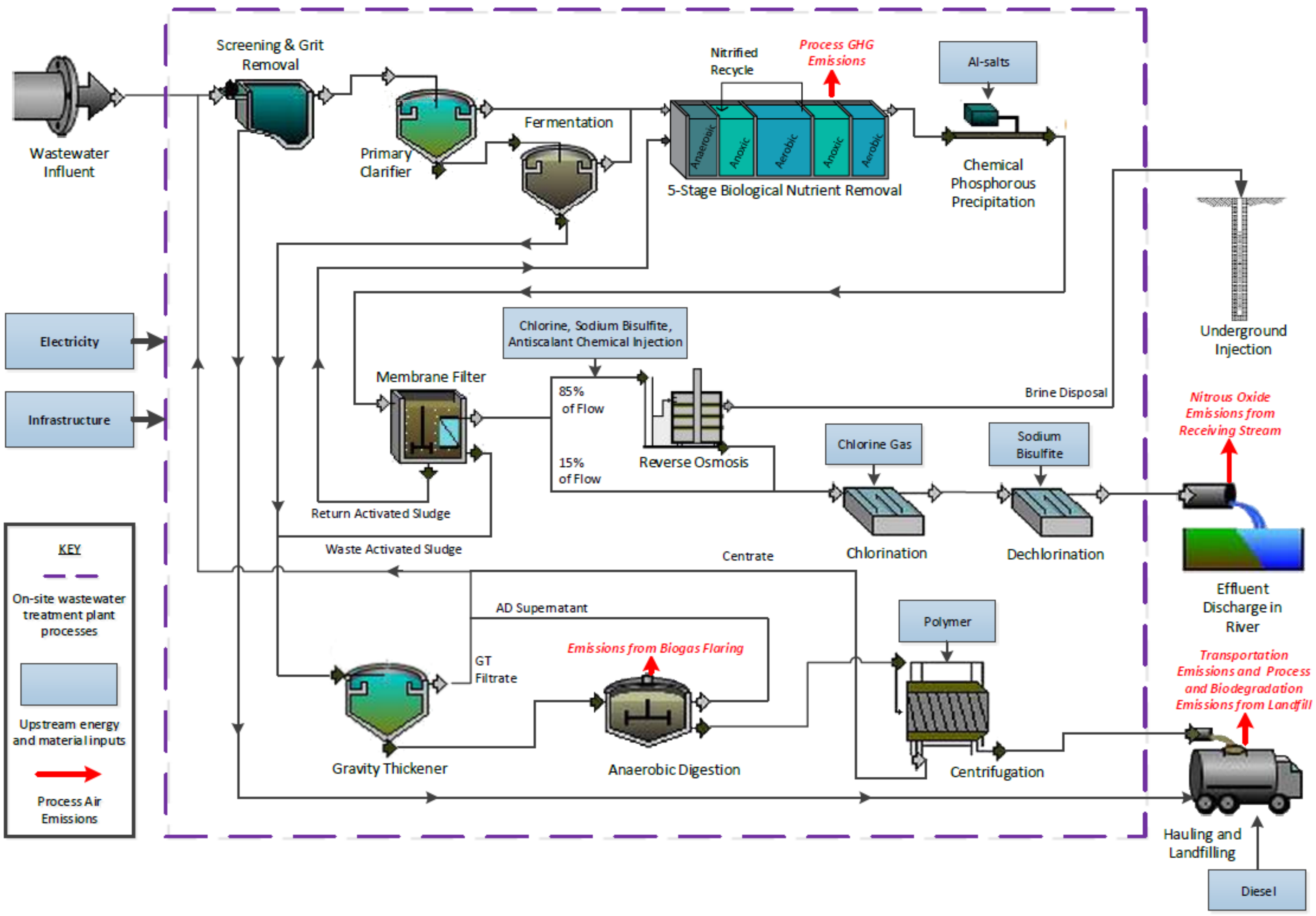


Figure 1-10. Level 5-2: 5-Stage Bardenpho Membrane Bioreactor with Sidestream Reverse Osmosis Wastewater Treatment Configuration

1.2.5 Metrics and Life Cycle Impact Assessment

Table 1-6 summarizes the metrics estimated in connection with each of the system configurations, together with the method and units used to characterize each.

The cost of each system configuration is estimated using standard approaches for life cycle costing, with more detail on the costing methodology provided in Section 2. Most of the LCIA metrics are estimated using the Tool for the Reduction and Assessment of Chemical and Environmental Impacts (TRACI), version 2.1 (Bare et al., 2003; Bare, 2011). TRACI is an LCIA method developed by the U.S. EPA. It includes a compilation of methods representing current best practice for estimating human health and ecosystem impacts based on U.S. conditions in conjunction with the information provided by life cycle inventory models. Toxicity impacts (e.g., human health toxicity – cancer, human health toxicity – non-cancer, and ecotoxicity) are based on the USEtox™ method (Rosenbaum et al., 2011) version 2.02. Global warming potential (GWP) is estimated in the baseline results using the 100-year characterization factors provided by the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report, which are the GWPs currently used for international reporting (Myhre et al., 2013). GWPs are also estimated in a sensitivity analysis using the more recent 100-year characterization factors provided by the IPCC 5th Assessment Report. In addition to TRACI, the ReCiPe LCIA method is used to characterize water consumption and fossil energy use (Goedkoop et al., 2008), impacts which are not included in the current version of TRACI. To provide another perspective on energy, cumulative energy demand including the energy content of all non-renewable and renewable energy resources extracted throughout the supply chains associated with each configuration is estimated using a method adapted from one provided by the Ecoinvent Centre (Ecoinvent Centre, 2010a). Detailed descriptions of each of the LCIA impact categories are also provided in Section 4.6.

The metrics included in this study range in geographic scale from global metrics such as GWP and fossil fuel depletion potential, to impact categories such as ecosystem toxicity potential, smog formation potential, and eutrophication potential that tend to be more local or regional in nature. In other words, some emissions/pollutants result in environmental impacts on a global level (e.g., emissions with long atmospheric lifetimes like greenhouse gases), while other pollutants primarily impact the regions or locations close to the point of release.

Table 1-6. Metrics Included in the LCA and LCCA Results

Metric	Method	Unit
Cost	LCCA	USD2014
Eutrophication Potential	TRACI 2.1	kg N eq.
Cumulative Energy Demand	ecoinvent	MJ-eq.
Global Warming Potential	TRACI 2.1	kg CO_2 eq.
Acidification Potential	TRACI 2.1	kg SO_2 eq.
Fossil Depletion	ReCiPe	kg oil eq.
Smog Formation Potential	TRACI 2.1	kg O_3 eq.
Human Health - Particulate Matter Formation	TRACI 2.1	$PM_{2.5}$ eq.

Table 1-6. Metrics Included in the LCA and LCCA Results

Metric	Method	Unit
Ozone Depletion Potential	TRACI 2.1	kg CFC-11 eq.
Water Depletion	ReCiPe	m^3
Human Health Toxicity – Cancer Potential	USEtox™ 2.02	CTUh
Human Health Toxicity – Noncancer Potential	USEtox™ 2.02	CTUh
Ecotoxicity Potential	USEtox™ 2.02	CTUe

2. TRACE POLLUTANT REMOVAL PERFORMANCE CHARACTERIZATION

Although the nine wastewater configurations evaluated in this study are designed to achieve various levels of nutrient removal targets, these treatment trains also remove other trace pollutants in the influents. It is important to capture these treatment performances in the holistic analysis in order to have a complete understanding of treatment strategies. This section summarizes the steps taken to characterize three major groups of trace pollutants with respect to their expected influent concentrations, fate within the study's nine wastewater treatment configurations, and final discharge into the environment. The groups include heavy metals, toxic organics and disinfection byproducts (DBPs). Depending on the pollutant, the final receiving environment (and thus the potential for impact) may include surface water discharge from the WWTP, partitioning to sludge with subsequent landfill disposal, or deep well injection in the case of RO brine. It was assumed that no toxicity-related impacts were associated with deep well injection. Volatilization was not found to be a major loss pathway for any of the included pollutants.

In the case of landfill disposal, environmental impact only occurs if the landfill liner fails and leachate is released. However, little data exists on actual failure rates. For this study, a failure rate of 5% was assumed based on a probabilistic modeling study that found, given typical landfill construction, failures generally occur within 10-30 years after landfill closure (Pivato, 2011).

For further reference, a full description of background, methods and results is provided in Appendix B, Appendix C and Appendix D, for heavy metals, toxic organics and DBPs, respectively.

2.1 Heavy Metals

The discharge of metals to the environment represents an ever-present concern, given their potential toxicity at even trace levels. WWTPs receive variable but sometimes high loads of metals depending on the mix of sources in their watershed, which can include industrial activities, domestic sources and stormwater (Yost et al., 1981; Ruel et al., 2011; Choubert et al., 2011b).

The direct management of metals has generally not been the focus of municipal WWTP design given the prioritization of organics and nutrient treatment. Heavy metals from industrial source are subject to other more targeted regulatory programs like the National Pretreatment Program (U.S. EPA, 2019a) which applies to industrial facilities. Nevertheless, trace heavy metals may still be present in municipal influents. Many common treatment processes allow for effective partitioning of metals to the sludge fraction, thus greatly reducing the quantity discharged in effluent.

Seven metals were included in this study that are commonly regulated and prevalent in the case study literature. Both criteria were assumed to be indirect indicators of the metal's demonstrated potential to cause environmental or human health impacts. The metals include Cadmium (Cd), Chromium (Cr), Copper (Cu), Mercury (Hg), Nickel (Ni), Lead (Pb), and Zinc (Zn). Table 2-1 summarizes ranges of influent concentrations established in several literature reviews, relevant effluent limits, and ranges of influent concentrations observed in the case studies used herein.

Table 2-1. Summary of Literature and Case Study Metal Influent Concentrations and Regulatory Effluent Concentrations.

Value		Concentrations in μg/L							Notes	Source
		Pb	**Cu**	**Zn**	**Ni**	**Cr**	**Cd**	**Hg**		
Influent Concentrations - Literature Reviews		5.7	63	181	11	10	0.21	0.36	19 Plants, France	1
		25	78	155	14	12.0	0.8	0.5	30 Plants, UK	2
		140-600	--	--	--	--	--	--	Combined WW	3
		232	489	968	455	378	19	--	12+ Cities, US	4
Case Study Ranges	High	68	118	493	77	290	10	7.0	This Study	5
	Medium	21	65	350	24	59	4.9	3.8	This Study	5
	Low	10.8	25	204	11	19	0.94	0.37	This Study	5
US CCC[a]		2.5	9	120	52	74/11[b]	0.25	0.77	Effluent Limits	6
US CMC[a]		65	13	120	470	570/16[b]	2	1.4	Effluent Limits	6

a - Criterion Continuous Concentration/Criteria Maximum Concentration, hardness dependent except for Cr (VI) and Hg. Values shown assume a hardness of 100 mg/L.

b - Chromium (III/VI)

1 - Choubert et al., 2011b; Ruel et al., 2012

2 - Rule et al., 2006

3 - Metcalf and Eddy, 2014

4 – Yost et al., 1981

5 - Linstedt et al., 1971; Brown et al., 1973; Chen et al., 1974; Oliver and Cosgrove, 1974; Aulenbach and Chan, 1988; Huang et al., 2000; Innocenti et al., 2002; Chipasa, 2003; Karvelas et al., 2003; Qdais and Moussa, 2004; Buzier et al., 2006; da Dilva Oliveira et al., 2007; Mohsen et al., 2007; Obarska-Pempkowiak and Gajewska, 2007; Carletti et al, 2008; Johnson et al., 2008; Dialynas and Diamadopoulos, 2009; Renman et al., 2009; Malamis et al., 2012; Arevalo et al., 2013; Garcia et al., 2013; Salihoglu, 2013; Inna et al., 2014; Reddy et al., 2014

6 - U.S. EPA, 2019b

Metal removal efficiencies for study system configurations were estimated based on a detailed literature review of performance results from similar systems. For system levels where no representative equivalent was identified but the important components were characterized, a composite removal efficiency was calculated based upon case study performance data of its major unit processes. For example, Level 3-1 includes a 5-stage Bardenpho process with subsequent sand filtration. However, results of the literature review only identified 5-stage Bardenpho WWTPs without sand filtration, and sand filtration as a standalone process. Therefore, a composite removal efficiency was calculated assuming a realistic stepwise removal, combining removal efficiencies for a 5-stage Bardenpho process with removal efficiencies for sand filtration. Table 2-2 summarizes the resulting minimum, average and maximum removal efficiencies for each treatment configuration. Supporting details for calculations and calculation assumptions are provided in Appendix B.

Table 2-2. Summary of Estimated Metal Removal Efficiencies[a]

Metal		Level 1 AS	Level 2-1 A2O	Level 2-2 AS3	Level 3-1 B5	Level 3-2 MUCT	Level 4-1 B5/Denit	Level 4-2 MBR	Level 5-1 B5/RO	Level 5-2 MBR/RO
Cu	Min	35%	35%	35%	75%	52%	75%	68%	93%	96%
	Mean	62%	62%	62%	80%	77%	80%	90%	97%	99%
	Max	84%	84%	84%	83%	96%	83%	99%	98%	100%
Pb	Min	40%	40%	40%	55%	39%	55%	68%	95%	97%
	Mean	65%	65%	65%	66%	70%	66%	88%	96%	99%
	Max	97%	97%	97%	75%	94%	75%	100%	97%	100%
Ni	Min	16%	16%	16%	42%	66%	42%	64%	82%	91%
	Mean	39%	39%	39%	45%	67%	45%	82%	90%	97%
	Max	91%	91%	91%	47%	68%	47%	100%	94%	100%
Zn	Min	12%	12%	12%	57%	83%	57%	75%	94%	97%
	Mean	42%	42%	42%	72%	89%	72%	85%	96%	99%
	Max	77%	77%	77%	83%	94%	83%	91%	98%	99%
Cd	Min	11%	11%	11%	40%	23%	40%	96%	93%	99%
	Mean	59%	59%	59%	47%	41%	47%	97%	94%	100%
	Max	83%	83%	83%	57%	59%	57%	98%	95%	100%
Cr	Min	16%	16%	16%	78%	88%	78%	83%	97%	99%
	Mean	64%	64%	64%	81%	88%	81%	91%	98%	100%
	Max	79%	79%	79%	84%	89%	84%	95%	98%	100%
Hg[b]	Min	17%	17%	17%	17%	17%	17%	93%	84%	98%
	Mean	53%	53%	53%	53%	53%	53%	97%	93%	100%
	Max	85%	85%	85%	85%	85%	85%	99%	98%	100%

a – "Removal Efficiency" used loosely; data more explicitly represents partitioning to sludge. Min and max represent minimum and maximum removal efficiencies reported in the literature. Where removal efficiencies are composites of multiple processes, minimum represents the composite of both contributing minimums, likewise for maximum.

b – No data for Hg removal found for 4-stage Bardenpho, 5-stage Bardenpho or MUCT. Therefore, conservatively assumed same removal for these biological treatment processes as documented for CAS (Level 1). Data for Levels 4-2, 5-1 and 5-2 represent the effect of tertiary polishing step alone, i.e. MBR and RO.

2.2 Toxic Organic Pollutants

Toxic organics are a diverse and growing category of chemical substances that includes commonly referred to pollutant groups such as contaminants of emerging concern (CECs), pharmaceuticals and personal care products (PPCPs), and endocrine disrupting chemicals (EDCs). The pollutant category includes medications, fragrances, insect repellents and other household items that can be harmful to environmental and human health at even trace levels (U.S. EPA, 2015; Montes-Grajales et al., 2017). Per- and polyfluoroalkyl substances (PFAS) are not included in this study.

Toxic organics are present in surface waters, groundwater, wastewater and WWTP effluent, both in the U.S. and globally (Ellis, 2008; Ebele et al., 2017; Montes-Grajales et al., 2017). No comprehensive list exists, though based on a diverse literature the number of contaminants is at least in the hundreds (if not thousands) and is continually being expanded upon as analytical techniques for measuring both presence and toxicity are continually refined. In order to provide a targeted analysis of their behavior in WWTPs, a restricted group of 43 pollutants (Table 2-3) has been included in this study. The list has been adapted and updated from two previous studies (Montes-Grajales et al., 2017; Rahman et al., 2018) where pollutants were selected based on frequency of detection in WWTPs and the availability of information regarding concentration, degradation, transformation and removal.

The concentration of trace pollutants can vary considerably on a daily and seasonal basis and between WWTPs (Martin Ruel et al., 2012). Based on a detailed review of the literature, influent concentration ranges were established for each pollutant (Table 2-3). For subsequent calculations, the medians of pollutant influent concentrations were used as means had a tendency to be biased by a small number of very high concentrations.

Table 2-3. Occurrence of the Selected Toxic Organic Compounds in WWTP Influent

Chemical Name	Chemical Type/Use	Influent Concentration (µg/L)				Sample Size
		Average	Median	Minimum	Maximum	
acetaminophen[a]	pain reliever, anti-inflammatory	97	19	0.02	400	12
androstenedione[a]	steroid hormone	0.29	0.10	0.02	1.3	7
atenolol	beta blocker	4.3	1.1	0.03	26	10
atorvastatin	lipid regulator	0.49	0.22	0.07	1.6	6
atrazine[b]	pesticide	0.02	0.02	1.0E-3	0.06	5
benzophenone	PCP, sunscreen	0.24	0.27	7.0E-3	0.42	4
bisphenol A	EDC, plasticizer	4.6	0.84	0.01	44	16
butylated hydroxyanisole[c]	beta blocker	1.3	0.16	0.13	3.5	3
butylated hydroxytoluene	beta blocker, cosmetic	0.93	0.41	0.05	3.5	5
butylbenzyl phthalate[d]	plasticizer	0.11	0.11	0.08	0.14	2
carbamazepine[a]	anti-convulsant	0.92	0.69	0.04	3.8	28
N,N-diethyl-meta-toluamide (DEET)	insect repellent	1.4	0.40	0.02	6.9	6
diclofenac	analgesics, anti-inflammatory	2.1	0.96	1.0E-3	17	20
dilantin	anti-seizure medication	0.16	0.17	0.05	0.24	4
dioctyl phthalate[b]	plasticizer, industry	23	1.4	1.1	67	3
estradiol[a,c]	EDC, steroid hormone	0.59	0.03	8.0E-3	5.0	11
estrone[a,c]	EDC, steroid hormone	0.17	0.05	0.01	1.0	9
galaxolide	beta blocker, PCP, fragrance	4.3	2.3	1.4E-3	25	16
gemfibrozil[a]	lipid regulator	3.1	1.6	0.02	22	15
hydrocodone	analgesic, opioid	0.08	0.11	0.02	0.12	5
ibuprofen[a]	analgesics, anti-inflammatory	7.8	2.4	1.0E-3	39	27
iopromide	contrast agent	7.4	0.05	0.01	38	6
meprobamate	tranquilizer, medication	0.40	0.35	0.01	0.97	5
naproxen[a]	analgesics, anti-inflammatory	8.5	2.5	2.0E-3	53	20
nonylphenol[b,c]	EDC, disinfectant, surfactant, solvent	3.4	2.3	0.02	9.7	14

Table 2-3. Occurrence of the Selected Toxic Organic Compounds in WWTP Influent

Chemical Name	Chemical Type/Use	Influent Concentration (µg/L)				Sample Size
		Average	Median	Minimum	Maximum	
octylphenol[b]	EDC, surfactant, solvent	1.9	0.41	0.12	8.7	12
o-hydroxy atorvastatin	lipid regulator	0.12	0.12	0.10	0.14	2
oxybenzone	PCP	1.2	0.39	0.03	3.8	4
p-hydroxy atorvastatin	lipid regulator	0.12	0.12	0.10	0.14	2
progesterone[a]	EDC	0.02	0.01	3.1E-3	0.06	4
sulfamethoxazole[a]	antibiotic	1.1	0.43	0.04	4.5	14
tris(2-chloroethyl) phosphate (TCEP)	flame retardant, plasticizer	0.35	0.24	0.17	0.65	3
tris(2-chloroisopropyl) phosphate (TCPP)	flame retardant	1.2	1.2	1.1	1.3	2
testosterone[a]	EDC	0.06	0.05	0.01	0.14	5
triclosan[a]	pesticide, disinfectant	2.7	0.80	2.3E-3	24	17
trimethoprim[a]	antibiotic	0.52	0.53	0.10	1.4	8
triclocarban[a]	disinfectant	0.42	0.42	0.29	0.54	2
tonalide	beta blocker, PCP, fragrance	1.5	0.80	5.0E-5	7.6	13
celestolide	PCP, fragrance	5.1	0.07	0.04	15	3
phantolide	fragrance	0.10	0.10	0.04	0.15	2
clofibric acid	lipid regulator	0.46	0.29	0.03	1.1	3
musk ketone	fragrance	0.12	0.12	0.10	0.15	3
diuron[b, c]	fragrance	0.14	0.11	0.05	0.25	3

a – Identifies substances with EPA developed analytical methods for detection of contaminants of emerging concern per (EPA, 2017).

b –Identifies substances with a European Quality Standard per (European Parliament, 2008).

c – Identifies substances identified in EPA's Candidate Contaminant List (CCL), version 4 (U.S. EPA, 2016c). The CCL identifies chemicals that are currently unregulated but may pose a risk to drinking water.

d - Identifies substances identified as human health criteria in Section 304(a) of the Clean Water Act (U.S. EPA, 2019c).

Table Acronyms: EDC – endocrine disrupting chemical, PCP – personal care product.

The behavior of toxic organics within study treatment configurations was estimated based on a review of the relevant literature for major unit processes, including:

- Biological Treatment
- Chemical Phosphorus Removal
- Membrane Filtration
- Anaerobic Digestion

Given the large list of pollutants and varying levels of available information, a combination of quantitative and qualitative information was used to arrive at final treatment performance ranges. The ranges take into account possible loss pathways that include transformation or degradation within biological unit processes, partitioning to solids and transformation or degradation during anaerobic digestion. Table 2-4 provides the resulting estimated range of cumulative removal efficiency for each of the nine WWTP configurations. Degradation and removal efficiency estimates were calculated as a weighted average of values for the 43 included pollutants. Relative influent concentration was used as the weighting factor. Additional background discussion and supporting calculations are provided in Appendix C.

Table 2-4. Summary of Cumulative Toxic Organics Degradation and Removal Efficiency in Study Treatment Configurations[a]

Treatment Level	Fraction Degraded			Fraction Removed (includes solids)		
	Minimum	Median	Maximum	Minimum	Median	Maximum
L1	52%	70%	85%	67%	81%	89%
L2-1	52%	73%	90%	67%	86%	95%
L2-2	52%	73%	90%	67%	86%	95%
L3-1	52%	75%	92%	67%	88%	97%
L3-2	52%	75%	92%	67%	88%	97%
L4-1	52%	75%	92%	67%	88%	97%
L4-2	52%	75%	91%	67%	88%	97%
L5-1	52%	75%	91%	94%	99%	100%
L5-2	52%	75%	91%	93%	98%	99%

a – Table values represent the cumulative effect of all the described treatment processes, calculated as a weighted average of the 43 toxic organics using influent concentration as the weighting factor.

2.3 Disinfection Byproducts

Disinfection of WWTP effluent is a necessary practice to minimize the acute risk associated with exposure to microbial pathogens, however it must be balanced with the chronic risk posed by the creation of disinfection byproducts (DBPs). DBPs are a class of chemical compounds that can be harmful to both aquatic and human health (Boorman, 1999; Nieuwenhuijsen et al., 2000; Mizgireuv et al., 2004; Villanueva et al., 2004; Muellner et al., 2007; Richardson et al., 2007; Watson et al., 2012).

DBPs are formed when DBP precursors, generally organic carbonaceous or nitrogenous compounds, are oxidized during chlorination or chloramination (Christman et al., 1983). By regulation, certain DBPs are managed at drinking water treatment plants, as their presence in water supplies poses a direct threat to human health (Sedlak and Gunten, 2011; US EPA, 2015c). Furthermore, as water recycling and reclamation programs expand (and as indirect potable reuse continues), management of DBPs and DBP precursors has become increasingly important at the WWTP as well (Krasner et al., 2008; Tang et al., 2012).

The importance of DBP and DBP precursor control at WWTPs has been growing in recent years for several reasons. First, the type of precursors formed through biological wastewater treatment are complex and, although overlapping with, are in many ways dissimilar from the natural organic matter (NOM)-derived precursors of drinking water-based DBPs. Therefore, lessons learned in drinking water DBP formation prediction and control are not directly translatable to WWTPs (Drewes and Croue, 2002; Tang et al., 2012). Additionally, there has been increasing concern over emerging and more toxic nitrogenous DBPs such as nitrosamines, halonitroalkanes, haloacetonitriles (HANs) and haloacetamides (Westerhoff and Mash, 2002; Joo and Mitch, 2007; Lee et al., 2007), which can be produced to varying degrees from dissolved organic nitrogen (DON) found in wastewater and WWTP effluent. Haloacetamides and HANs in particular are approximately two orders of magnitude more cytotoxic and genotoxic than the regulated trihalomethanes (THMs) and haloacetic acids (HAAs) (Muellner et al., 2007; Plewa and Wagner, 2009). The concentration of ammonia further complicates DBP formation kinetics, favoring the formation of certain groups at high concentrations and others at low (Krasner et al., 2008; Krasner et al., 2009b; Sedlak and Gunten, 2011). Similarly, chlorination practices, which can vary considerably between WWTPs, can have large effects on the overall formation of DBPs and, in combination with ammonia concentrations, can favor certain DBP groups over others. It is therefore important that comparisons of treatment configurations with differing nitrification and denitrification capabilities take into account multiple groups of DBPs that can capture these relative benefits and drawbacks.

For this study, models for DBP formation potential (FP) were used to compare the differences in DBP formation between study treatment configurations. FP is determined using a standardized procedure, eliminating variability from case study data that may arise owing to different disinfection practices. Ultimately, this allows for a clearer distinction between the effects of different treatment approaches on precursor control. To model disinfection byproduct formation potential (DBPFP), a comprehensive dataset linking effluent water quality of 23 different WWTPs to DBPFP was used (Krasner et al., 2008). The DBP and DBP groups included in the study include the regulated carbonaceous DBPs (THMs and HAAs) along with emerging and more toxic carbonaceous and nitrogenous DBPs (Table 2-5).

Table 2-5. Summary of Study Disinfection Byproducts

DBP (group/compound)	Characteristics	Precursors	Limit	Regulatory Authority
Trihalomethanes (THM)[a,b]				
Chloroform	carbonaceous, halogenated	influent refractory NOM, EfOM, nitrified effluent, humic compounds	80 µg/L (TTHM)	U.S. EPA, Stage 1/2 DBP Rule
Bromodichloromethane (BDCM)				
Chlorodibromomethane (DBCM)				
Bromoform				

Table 2-5. Summary of Study Disinfection Byproducts

DBP (group/compound)	Characteristics	Precursors	Limit	Regulatory Authority
Haloacetic Acids (HAA)[b,c]				
Monochloroacetic acid	carbonaceous, halogenated	influent refractory NOM, EfOM, nitrified effluent, humic compounds	60 µg/L (HAA5)	U.S. EPA, Stage 1/2 DBP Rule
Dichloroacetic acid (DXAA)				
Trichloroacetic acid (TXAA)				
Bromoacetic acid				
Dibromoacetic acid				
Nitrosamines[d]				
N-nitrosodimethylamine (NDMA)	nitrogenous, unhalogenated	DON, dimethylamine	10 ng/L	CA (action level)
Aldehydes				
Formaldehyde	carbonaceous, halogenated	DON, amino acids	N/A	N/A
Acetaldehyde				
Chloroacetaldehyde				
Dichloroacetaldehyde				
Trichloroacetaldehyde (chloral hydrate)				
Haloacetonitriles (HANs)				
Chloroacetonitrile	nitrogenous, halogenated	DON, amino acids	N/A	N/A
Bromoacetonitrile				
Iodoacetonitrile				
Trichloroacetonitrile				
Bromodichloroacetonitrile				
Dibromochloroacetonitrile				
Tribromoacetonitrile				

a - The four compounds together comprise the four primary trihalomethanes, sometimes referred to as TTHM or THM4

b - https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100C8XW.txt (U.S. EPA, 2015b)

c - These five compounds together comprise the five primary haloacetic acids, sometimes referred to as HAA5

d - California Department of Health Services, action level (CDHS, 2018)

Multiple linear regression models were constructed linking relevant water quality parameters with DBPFP. This was done by first performing a linear correlation analysis, which indicated COD and TKN to be the most influential predictors. Next, models were built for each DBP group (Table 2-5) using the adjusted coefficient of determination (R^2). Final models were significant at a >95% confidence level with the exception of NDMA, which was significant at a 93% confidence level. Table 2-6 gives model results for the nine study treatment configurations. Further discussion of methods, model construction and model results can be found in Appendix D.

Table 2-6. DBPFP Model Results for Study Treatment Configurations

Study Configuration	THMs	HANs	DXAAs	TXAAs	dihaloacet-aldehydes	trihaloacet-aldehydes	NDMA
	µg/L						ng/L
Level 1, AS	204	32	145	127	8.8	95	692
Level 2-1, A2O	274	14	129	113	4.9	54	680
Level 2-2, AS3	95	4.9	43	40	1.5	18	230
Level 3-1, B5	41	0.78	14	15	0.16	3.3	83
Level 3-2, MUCT	41	0.78	14	15	0.16	3.3	83
Level 4-1, B5/Denit	124	5.2	54	49	1.7	21	292
Level 4-2, MBR	144	6.6	65	59	2.2	26	347
Level 5-1, B5/RO	23	0.010	5.4	7.4	0.010	0.010	36
Level 5-2, MBR/RO	32	0.066	10	11	0.010	0.87	58

3. LIFE CYCLE COST ANALYSIS METHODOLOGY

This section presents ERG's methodology for developing life cycle costs for the nine greenfield wastewater treatment configurations included in this study. As such, the costs presented in the report are not applicable to operations that retrofit existing treatment systems to achieve further nutrient removal, and the difference from one treatment level to another may not represent the incremental retrofit costs due to existing infrastructure and site-specific conditions. In addition, the costs (as well as life cycle impacts discussed later in the report) are for the entire wastewater treatment configuration, not just those steps used to achieve nutrient removal.

The life cycle costs in the study are based primarily on the use of CAPDETWorks™, a model that performs planning-level design and cost estimation of WWTP construction projects. These planning-level costs do not include site-specific factors that may impact the costs (e.g., high groundwater table, shallow bedrock, deep excavation) as they are intended to represent the national average. These costs are supplemented with costs for additional unit processes that are not included in CAPDETWorks™ to provide costs for the entire wastewater treatment configuration. Section 3.1 describes CAPDETWorks™ and the data sources used for the additional unit processes. Section 3.2 describes the engineering cost estimation methodology. To the extent possible, purchased equipment and annual cost results are developed by unit process to allow for consistent presentation alongside results of the LCA model. Section 3.3 describes the life cycle cost analysis (LCCA) calculations that provide for a plant-level comparison of costs that occur throughout the life of the wastewater treatment configurations. The total plant costs are presented as: 1) total capital costs and total annual costs and 2) net present value that combines the one-time capital costs and annual costs into one value. The capital costs include the purchased equipment, direct costs (e.g., site preparation, site electrical, yard piping), and indirect costs (e.g., land, engineering design fee, interest during the 3-year construction period). The annual costs include the operating and maintenance labor, materials including replacement equipment, chemicals, and energy. In general, the purchased equipment costs were based on equipment sizing for the 20 MGD peak flow rate, while the annual costs were based on the 10 MGD annual average flow rate. For the net present value, the construction costs (in present value) are combined with the discounted annual costs during the WWTP planning period. Section 3.4 describes the quality of the data sources used in the LCCA.

3.1 Data Sources

ERG obtained cost data from the following sources or categories of sources:

- CAPDETWorks™ Version 3.0 (Hydromantis, 2014)
- EPA reports and fact sheets
- Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability (Falk et al, 2011)
- Wastewater treatment design textbooks
- Personal communication with technology vendors
- RSMeans Building Construction Cost Data (RSMeans, 2010)
- RSMeans Construction Cost Index (RSMeans, 2017)

The majority of the life cycle costs are based on CAPDETWorks™ Version 3.0 (Hydromantis, 2014) modeling output, supplemented with costs for unit processes that are not in CAPDETWorks™ (see Section 3.2.2 for details). EPA and the U.S. Army Corps of Engineers originally developed CAPDETWorks™ as a planning tool for WWTPs; Hydromantis Corporation now maintains and updates CAPDETWorks™. As described in Section 4.2.1 of *Municipal Nutrient Removal Technologies Reference Document* (U.S. EPA, 2008b), CAPDETWorks™ is used as follows:

> The user generates a process layout involving a number of unit operations. The user can also define input variables, including wastewater flow rate, wastewater influent quality, and desired effluent quality or other performance coefficients. Alternatively, the user can choose to use default values developed by Hydromantis. The software then calculates the required sizes of the unit operations and uses cost-curve models from the software's database to estimate the capital, labor, chemical, and energy costs that would be incurred. …The model uses several standard indices to update costs to current dollars: the Engineering News-Record (ENR) Construction Cost Index, the Marshall & Swift Index, and the Pipe Index. Values were obtained from a U.S. Department of Agriculture Web site (USDA, 2007) that transcribes historical values of these indices.

The cost functions included in CAPDETWorks™ Version 3.0 (the version used for this study) were updated in 2014. CAPDETWorks™ also allows users to input design values for each unit process (e.g., solids retention time, surface overflow rate) or use the default values developed by Hydromantis. CAPDETWorks^{TM} also allows users to input unit costs (e.g., concrete, construction labor rate, polymer).

ERG relied primarily on the following two EPA reports to evaluate and modify, as necessary, the default input design values in CAPDETWorks™ and support development of costs for the unit processes that are not in CAPDETWorks™:

- *Municipal Nutrient Removal Technologies Reference Document* (U.S. EPA, 2008b)
- *Nutrient Control Design Manual* (U.S. EPA, 2010)

The *Municipal Nutrient Removal Technologies Reference Document* (U.S. EPA, 2008b) is intended to provide information to assist local decision makers and regional and state regulators in planning cost-effective nutrient removal projects for WWTPs. This EPA report provides capital and operation and maintenance costs for case study WWTPs, as well as costs estimated using CAPDETWorks™. The purpose of the *Nutrient Control Design Manual* (U.S. EPA, 2010) is to provide guidance and design considerations for nitrogen and phosphorus control using biological nutrient removal and chemical phosphorus removal for WWTPs.

ERG also relied on *Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability* (Falk et al, 2011), a report published by Water Environment Research Foundation (WERF). This report is an LCA/LCCA evaluation of WWTPs with nitrogen and phosphorus treatment technologies to achieve five levels of effluent nutrient targets that match the five levels included in this study. While the WERF study used a different cost estimation tool, ERG used the WERF design input values to evaluate and modify, as necessary, the default input design values in CAPDETWorks™. ERG also used *Wastewater Engineering –*

Treatment and Resource Recovery (Tchobanoglous et al., 2014), a wastewater treatment design textbook, and the following documents to verify the default input design values and unit costs in CAPDETWorks™:

- *Wastewater Technology Fact Sheet – Screening and Grit Removal* (U.S. EPA, 2003b)
- Biosolids Technology Fact Sheet – Gravity Thickening (U.S. EPA, 2003a)
- *May 2016 National Industry-Specific Occupational Employment and Wage Estimates for NAICS 221300 – Water, Sewage and Other Systems* (U.S. DOL, 2017)

EPA's wastewater and biosolids technology fact sheets provide general design and cost information. ERG used these technology fact sheets to evaluate and modify, as necessary, the default input design values in CAPDETWorks™. ERG also compared the purchased equipment process costs from CAPDETWorks™ to the technology fact sheets and updated the purchased equipment costs where appropriate. The May 2016 National Industry-Specific Occupational Employment and Wage Estimates for NAICS 221300 – Water, Sewage and Other Systems (U.S. DOL, 2017) calculates average wages from data collected in a national survey of employers of every size, state, and industry for metropolitan and nonmetropolitan areas. ERG used this report to verify and update as necessary the labor rates in CAPDETWorks™ where appropriate.

The primary source of costs for the unit processes that are not in CAPDETWorks™ are from personal communication with technology vendors. ERG contacted companies that manufacture, distribute, or install dechlorination, ultrafiltration, reverse osmosis, and deep well injection systems. The vendors provided the following types of information for EPA's analysis:

- Operations and maintenance requirements (e.g., equipment replacement frequency)
- Ancillary equipment required for the system (e.g., antiscalant chemicals)
- Capital cost information
- Operations and maintenance cost information, including energy requirements

ERG used vendor contacts from previous studies for the dechlorination system costs (ERG, 2011a; ERG, 2011b; ERG, 2011c) and contacted vendors for information on ultrafiltration, reverse osmosis, and deep well injection as part of this study (ERG, 2015a; ERG, 2015b). The majority of the vendors provided supporting documentation, which were also used to develop the cost estimates for the unit processes not included in CAPDETWorks™.

ERG supplemented the information provided by vendors with unit costs for building components from the RSMeans Building Construction Cost Data (RSMeans, 2010) to calculate costs for general components of the unit processes not in CAPDETWorks™ (e.g., reinforced concrete basins). ERG used RSMeans Construction Cost Index (RSMeans, 2017) to convert costs obtained outside of CAPDETWorks™ to 2014 $ for consistency.

3.2 Engineering Cost Estimation

ERG developed engineering cost estimates that included the following components:

- Capital costs (one-time costs).

- Operation and maintenance costs that reoccur annually or on a set frequency (e.g., 5-year recurring costs for equipment replacement).

Capital costs include the purchased equipment, direct, and indirect costs to design and build the wastewater treatment configuration. Operating and maintenance costs include the operation and maintenance labor, materials, chemicals, and energy required to ensure long-term operation of the WWTP. In general, the capital costs are based on the 20 MGD maximum flow rate, while the operating and maintenance costs are based on the 10 MGD average flow rate.

Section 3.2.1 presents the calculations to convert all of the costs to a consistent dollar basis. Section 3.2.2 presents ERG's methodology for calculating the capital and operating and maintenance costs for the individual unit processes included in the wastewater treatment configurations. These unit process costs are presented alongside results from the LCA model and used in the LCCA. Discussion of the methodology for estimating the wastewater treatment configuration-wide direct and indirect costs is presented in Section 3.3.

3.2.1 Dollar Basis

The majority of the life cycle costs are based on CAPDETWorks™ modeling output, supplemented with costs for unit processes that are not in CAPDETWorks™. output is provided in 2014 dollars. As a result, ERG standardized and presented all costs in 2014 dollars using Equation 1 and the RS Means Historical Cost Index, presented in Figure 3-1.

$$\text{Cost (2014 \$)} = \text{Cost (20XX \$)} \times \frac{\text{2014 Cost Index}}{\text{20XX Cost Index}}$$

Equation 1

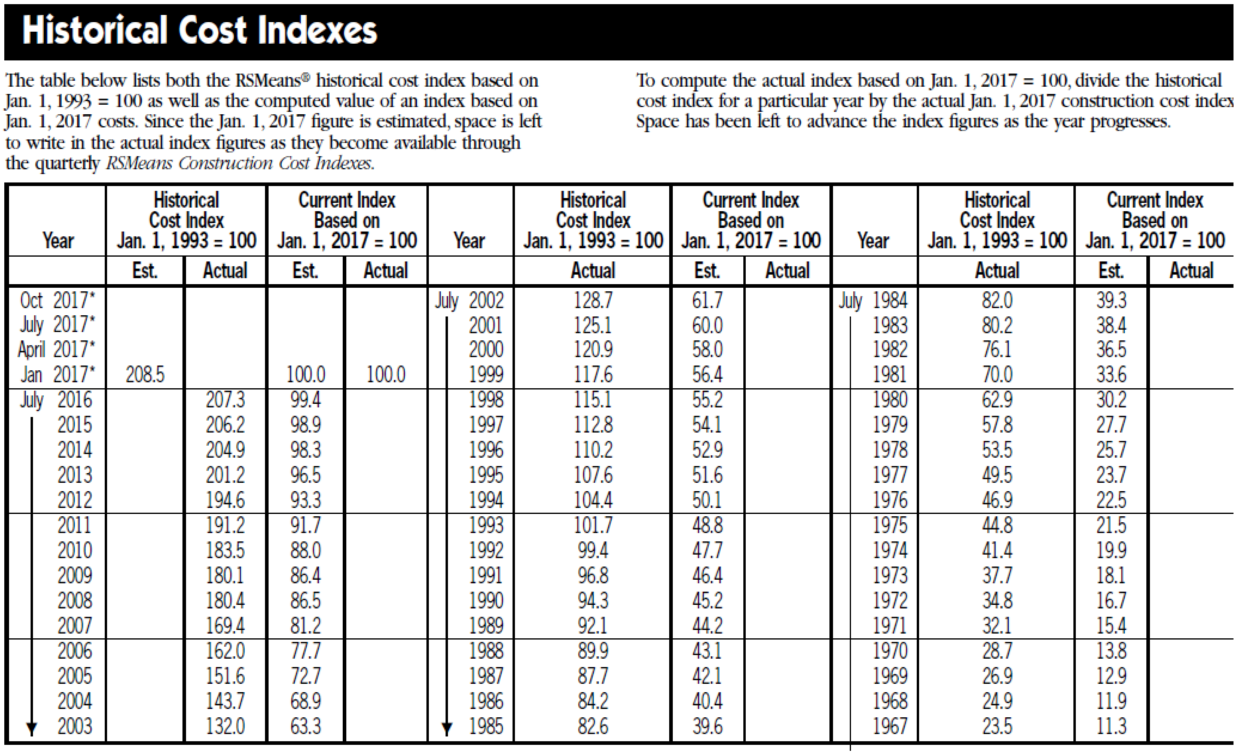
where:

Cost (2014 \$) = Cost in 2014 dollars

Cost (20XX \$) = Cost in pre- or post-2014 dollars, where XX represents the specific year

2014 Cost Index = 204.9

20XX Cost Index = See Figure 3-1, using the Historical Cost Index where January 1, 1993=100



Historical Cost Indexes

The table below lists both the RSMeans® historical cost index based on Jan. 1, 1993 = 100 as well as the computed value of an index based on Jan. 1, 2017 costs. Since the Jan. 1, 2017 figure is estimated, space is left to write in the actual index figures as they become available through the quarterly *RSMeans Construction Cost Indexes*.

To compute the actual index based on Jan. 1, 2017 = 100, divide the historical cost index for a particular year by the actual Jan. 1, 2017 construction cost index

Space has been left to advance the index figures as the year progresses.

Year	Historical Cost Index Jan. 1, 1993 = 100		Current Index Based on Jan. 1, 2017 = 100	
	Est.	Actual	Est.	Actual
Oct 2017*				
July 2017*				
April 2017*				
Jan 2017*	208.5		100.0	100.0
July 2016		207.3	99.4	
2015		206.2	98.9	
2014		204.9	98.3	
2013		201.2	96.5	
2012		194.6	93.3	
2011		191.2	91.7	
2010		183.5	88.0	
2009		180.1	86.4	
2008		180.4	86.5	
2007		169.4	81.2	
2006		162.0	77.7	
2005		151.6	72.7	
2004		143.7	68.9	
2003		132.0	63.3	

Year	Historical Cost Index Jan. 1, 1993 = 100	Current Index Based on Jan. 1, 2017 = 100	
	Actual	Est.	Actual
July 2002	128.7	61.7	
2001	125.1	60.0	
2000	120.9	58.0	
1999	117.6	56.4	
1998	115.1	55.2	
1997	112.8	54.1	
1996	110.2	52.9	
1995	107.6	51.6	
1994	104.4	50.1	
1993	101.7	48.8	
1992	99.4	47.7	
1991	96.8	46.4	
1990	94.3	45.2	
1989	92.1	44.2	
1988	89.9	43.1	
1987	87.7	42.1	
1986	84.2	40.4	
1985	82.6	39.6	

Year	Historical Cost Index Jan. 1, 1993 = 100	Current Index Based on Jan. 1, 2017 = 100	
	Actual	Est.	Actual
July 1984	82.0	39.3	
1983	80.2	38.4	
1982	76.1	36.5	
1981	70.0	33.6	
1980	62.9	30.2	
1979	57.8	27.7	
1978	53.5	25.7	
1977	49.5	23.7	
1976	46.9	22.5	
1975	44.8	21.5	
1974	41.4	19.9	
1973	37.7	18.1	
1972	34.8	16.7	
1971	32.1	15.4	
1970	28.7	13.8	
1969	26.9	12.9	
1968	24.9	11.9	
1967	23.5	11.3	

Source: (RSMeans, 2017).

Figure 3-1. RSMeans Historical Cost Indexes

3.2.2 Unit Construction and Labor Costs

As mentioned in Section 2, ERG developed the purchased equipment and annual cost results by unit process to allow for consistent presentation alongside results of the LCA model and use in the LCCA. ERG used CAPDETWorks™ Version 3.0 (Hydromantis, 2014), a software package designed for estimating the cost of wastewater treatment configurations, to calculate the unit process costs for each wastewater treatment configuration. Each of the wastewater treatment configurations used the same influent wastewater composition and flow rate discussed in Section 1.2.2 and presented in Table 1-3.

CAPDETWorks^{TM} includes default unit construction and labor costs that are used to calculate the purchased equipment and annual costs. ERG reviewed the CAPDETWorks^{TM} default unit construction and labor costs against those used in *Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability* (Falk et al, 2011). The most notable differences were for wall and slab concrete, and construction labor rate. For wall and slab concrete, ERG used the average of the costs from CAPDETWorks^{TM} and *Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability* (Falk et al, 2011), as presented in Table 3-1.

Table 3-1. Unit Construction and Labor Costs

Unit Construction Cost	CAPDETWorks™ Default Cost ($/cuyd)	Falk et al, 2011 Cost ($/cuyd)	Average Cost ($/cuyd)
Wall Concrete	350	750	550
Slab Concrete	650	1,250	950

For the construction labor rate, ERG used the average of seven labor rates for construction activities relevant to construction of a WWTP from the May 2016 National Industry-Specific Occupational Employment and Wage Estimates for NAICS 221300 – Water, Sewage and Other Systems (U.S. DOL, 2017). The seven labor categories that ERG used and their labor rates in 2016 $ were:

- First-Line Supervisor of Construction Trades: $34.38/hr
- Construction Laborers: $17.88/hr
- Construction Equipment Operators: $23.12/hr
- Electricians: $31.60/hr
- Pipelayers, Plumbers, Pipefitters, and Steamfitters: $22.16/hr
- Construction Trades Helpers: $15.91/hr
- Other Construction and Related Workers: $21.91/hr

The resulting average labor rate is $23.85/hr in 2016 $, which is $23.58/hr in 2014 $ using Equation 1 in Section 3.2.1. The U.S. DOL wages do not include overhead to account for employee benefits. ERG assumed that contractors would be used for the construction and applied a 2.1 private industry (i.e., contractors) multiplier (consultant multipliers typically range from 2-2.2), resulting in an average construction labor rate of $49.51/hr. ERG rounded the construction labor rate to $50/hr for use in this study.

3.2.3 Unit Process Costs

As mentioned in Section 2, ERG developed the purchased equipment and annual cost results by unit process to allow for consistent presentation alongside results of the LCA model and use in the LCCA. ERG used CAPDETWorks™ Version 3.0 (Hydromantis, 2014), a software package designed for estimating the cost of wastewater treatment configurations, to calculate the unit process costs for each wastewater treatment configuration. Each of the wastewater treatment configurations used the same influent wastewater composition and flow rate discussed in Section 1.2.2 and presented in Table 1-3.

CAPDETWorks™ includes all of the unit processes included in the nine wastewater treatment configurations for this study with the exception of:

- Dechlorination. Included in all nine wastewater treatment configurations.
- Fermentation. Included in:
  - Level 3-1 B5
  - Level 3-2 MUCT

    - Level 4-1 B5/Denit
    - Level 5-1 B5/RO
    - Level 5-2 MBR/RO
- 4-Stage Biological Nutrient Removal. Included in:
    - Level 3-2 MUCT
    - Level 4-2 MBR
- Methanol addition as a biological nutrient removal supplemental carbon source. Included in Level 4-2 MBR.[5]
- Ultrafiltration. Included in Level 5-1 B5/RO.
- Reverse Osmosis and Antiscalant Chemical Injection Pretreatment. Included in:
    - Level 5-1 B5/RO
    - Level 5-2 MBR/RO
- Deep Well Injection. Included in:
    - Level 5-B5/RO
    - Level 5-2 MBR/RO

Details on the approach developed for these unit processes are presented in the following subsections. The unit process costs for these unit processes were incorporated into the CAPDETWorks™ output for comparison to the LCA model results and development of the total plant costs.

Each of the nine wastewater treatment configurations was developed in CAPDETWorks™. As part of this study, ERG reviewed the *Municipal Nutrient Removal Technologies Reference Document* (U.S. EPA, 2008b), *Nutrient Control Design Manual* (U.S. EPA, 2010), *Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability* (Falk et al., 2011), *Wastewater Engineering: Treatment and Resource Recovery* (Tchobanoglous et al., 2014), and additional EPA wastewater treatment process fact sheets to confirm that the CAPDETWorks™ default design values were appropriate for use for this study. Based on our review, ERG used the CAPDETWorks™ default design values for the unit processes below that are included in one or more of the wastewater treatment configurations. Appendix E.1 includes the key parameters and default design values for the unit processes that were modeled using the CAPDETWorks™ default design values. For the remaining unit processes below, ERG revised the CAPDETWorks™ default design values. See Appendix E.1 for the details on the revised default design values. Note that ERG used these design values in the initial CAPDETWorks™ model for each wastewater treatment configuration. ERG then revised some of the design values to eliminate errors in CAPDETWorks™ (e.g., subsequent unit process designs were outside recommended design values) and achieve the effluent wastewater objectives for each of the treatment levels. The final design values used for each wastewater

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[5] Methanol addition is also required for Level 2-2 AS3 for the denitrification – suspended growth unit process and Level 4-1 B5/Denit and Level 5-1 B5/RO for the denitrification filters. However, CAPDETWorks™ includes the methanol addition for these unit processes.

treatment configuration are included in the final CAPDETWorks™ cost output discussed in Section 5.

- Default Design Values Used:
    - Membrane Bioreactor
    - Sand Filter
    - Centrifugation – Sludge
- Design Values Revised:
    - Preliminary Treatment – Screening
    - Preliminary Treatment – Grit Removal
    - Primary Clarifier
    - Plug Flow Activated Sludge
    - Biological Nutrient Removal 3/5 Stage
    - Denitrification – Suspended Growth
    - Denitrification – Attached Growth
    - Nitrification – Suspended Growth
    - Chemical Phosphorus Removal
    - Secondary Clarifier
    - Chlorination
    - Gravity Thickener
    - Anaerobic Digestion – Sludge
    - Haul and Landfill – Sludge

ERG updated the CAPDETWorks^{TM} default anaerobic digestion energy costs for all nine wastewater treatment configurations to rely on natural gas rather than using the produced gas for the reasons discussed in Section 3.2.3.8. ERG also determined that the CAPDETWorks™ default electricity cost of $0.10/kWh was appropriate for use for this study based on the national average electricity price as of May 2014 (U.S. EIA, 2015). The 2014 electricity costs match the 2014-dollar basis discussed in Section 3.2.1.

3.2.3.1 Dechlorination

Dechlorination is not a unit process available in CAPDETWorks^{TM}. Therefore, ERG developed a costing methodology for dechlorination based on the CAPDETWorks™ chlorination unit process and vendor costs, which was then incorporated into the CAPDETWorks™ outputs to calculate the total costs of all nine wastewater treatment configurations.

Capital cost elements for dechlorination include the dechlorination contact tank, dechlorination building, chemical storage building, sodium bisulfite liquid feed system, and miscellaneous items (e.g., grass seeding, site cleanup, piping). The dechlorination contact tank, dechlorination building, chemical storage building, and miscellaneous items are similar to the components included in the CAPDETWorks™ chlorination unit process. As a result, ERG estimated costs for these capital cost elements using the CAPDETWorks™ chlorination unit process with design values for contact time and chemical dose to simulate dechlorination. ERG estimated purchase costs for the sodium bisulfite liquid feed system based on cost information provided by a vendor.

Operating and maintenance cost elements for dechlorination include operating labor, maintenance labor, materials and supplies costs, sodium bisulfite chemicals, and energy. ERG estimated operating and maintenance labor, materials, and supplies costs using the CAPDETWorks™ chlorination unit process with design values for contact time and chemical dose to simulate dechlorination. Estimated energy costs for the sodium bisulfide feed system pump is based on energy usage provided by the vendor and the energy rate used for the CAPDETWorks™ costing ($0.10/kWh). Sodium bisulfite chemical costs are estimated using the following sodium bisulfite dosages with the chlorination effluent flow rate provided from the CAPDETWorks™ chlorination unit process:

- 1.5 mg/L for Levels 1, 2-1, 2-2, 3-1, 3-2, 4-1, and 4-2 wastewater treatment configurations.
- 3.0 mg/L for Levels 5-1 and 5-2 that includes 1.5 mg/L for the dechlorination requirement and 1.5 mg/L for the reverse osmosis pretreatment requirement.

ERG used a 40% sodium bisulfite solution cost of $344/ton in 2010 $ as provided by a vendor, converted to 2014 $ using the methodology presented in Section 3.2.1.

Detailed descriptions of the dechlorination costing approach are provided in Appendix E.2, including all cost bases, assumptions, and calculations.

3.2.3.2 Fermentation

Fermentation is not a unit process available in CAPDETWorks™. However, as detailed in *Municipal Nutrient Removal Technologies Reference Document* (EPA, 2008), a fermenter is an oversized gravity thickener with additional piping and mixers. In the *Municipal Nutrient Removal Technologies Reference Document*, the fermenter was modeled using the CAPDETWorks™ gravity thickener module and escalating the results by 50 percent (EPA, 2008). ERG used best professional judgement to confirm this approach and modeled the gravity thickener unit process in CAPDETWorks™ and multiplied the capital, operating, and maintenance costs by 1.5 to account for the larger size, additional equipment, and associated increased energy.

3.2.3.3 4-Stage Biological Nutrient Removal (Modified UCT and 4-Stage Bardenpho)

CAPDETWorks™ does not include a 4-stage biological nutrient removal (BNR) unit process, like those included in Level 3-2 as a 4-stage Modified University of Cape Town (UCT) and Level 4-2 as a 4-stage Bardenpho with membrane bioreactor. However, CAPDETWorks™ includes 3-stage and 5-stage BNR unit processes. For each of the wastewater treatment configurations with 4-stage BNR unit processes, ERG developed two separate CAPDETWorks™ models that included all of the same unit processes, except model 1 included the 3-stage BNR unit process and model 2 included the 5-stage BNR unit process. ERG combined the CAPDETWorks™ output from models 1 and 2 to estimate the capital, operating, and maintenance costs for the 4-stage BNR units, as described below.

Capital cost elements for BNRs include the BNR tank, blower system, internal recycle pumps, and sludge recycle pumps. Operating and maintenance cost elements for BNRs include operating labor, maintenance labor, materials costs, and energy.

For the 4-stage Modified UCT in Level 3-2, ERG modeled the 3-stage version using a 3-stage BNR with two internal recycle pumps to reflect the multiple recycles in the Modified UCT. ERG used the Level 3-1 wastewater treatment configuration for the 5-stage version. The capital costs for the BNR tanks, blower system, and BNR sludge recycle pumps were averaged for the 3- and 5-stage models, while the capital costs from the 3-stage model were used for the BNR internal recycle pumps. The capital costs for all other unit processes in these models had the same capital costs. The operating and maintenance costs for the BNR tank, BNR sludge recycle pumps, and blower system were averaged for the 3- and 5-stage models; the 3-stage model costs were used for the BNR internal recycle pumps; and the 5-stage model costs were used for the chemical phosphorus removal and alum feed system because the Modified UCT will achieve biological phosphorus removal closer to the 5-stage BNR model and, therefore, would require less alum to achieve the target effluent phosphorus concentration. The operating and maintenance costs for all other unit processes in these models had negligible differences between the 3- and 5-stage models.

For the 4-stage Bardenpho with membrane bioreactor, ERG modeled the 3-stage model using the 3-stage BNR with membrane bioreactor and 5-stage model using the 5-stage BNR with membrane bioreactor. The capital, operating, and maintenance costs for the BNR tank, BNR internal recycle pumps, and BNR sludge recycle pumps were averaged for the 3- and 5-stage models. The capital costs for all other unit processes in these models had negligible differences in the capital costs. The operating and maintenance costs for the chemical phosphorus removal and alum feed system from the 5-stage model were used because the 4-stage Bardenpho with membrane bioreactor will achieve biological phosphorus removal closer to the 5-stage BNR model and, therefore, would require less alum to achieve the target effluent phosphorus concentration. The operating and maintenance costs for all other unit processes in these models had negligible differences between the 3- and 5-stage models.

Details on how the 3- and 5-stage models were combined for the Level 3-2 and Level 4-2 wastewater treatment configurations are included in Section 5.

3.2.3.4 Methanol Addition for Biological Nutrient Removal Supplemental Carbon for Level 4-2 MBR

Biological nitrogen removal requires an adequate supply of carbon for denitrification. CAPDETWorks^{TM} includes an external carbon source (i.e., methanol addition) to:

- Level 2-2 AS3's denitrification – suspended growth
- Level 4-1 B5/Denit's denitrification filter
- Level 5-1 B5/RO's denitrification filter

ERG included fermenters to provide an internal carbon source for biological nitrogen removal occurring in the Bardenpho and Modified University of Cape Town reactors in:

- Level 3-1 B5
- Level 3-2 MUCT
- Level 4-1 B5/Denit
- Level 5-1 B5/RO
- Level 5-2 MBR/RO

However, there is no internal carbon source for denitrification in Level 4-2 MBR. As a result, the Level 4-2 wastewater treatment configuration required methanol addition from an external carbon source. CAPDETWorks^{TM} Version 3.0 does not include a stand-alone methanol addition unit process. Therefore, ERG developed a costing methodology for supplemental methanol addition based on the effluent nitrate target in CAPDETWorks^{TM} denitrification filter unit process, which was then incorporated into the CAPDETWorks^{TM} outputs to calculate the total costs for the Level 4-2 wastewater treatment configuration. CAPDETWorks^{TM} calculates the methanol addition in the denitrification filter unit process based on 3 mg methanol per mg nitrate removed (Hydromantis, 2014). ERG determined the CAPDETWorks^{TM} effluent nitrate target for the denitrification filter unit process as 1.95 mg/L nitrate based on the required denitrification to achieve the 3 mg/L total nitrogen for Level 4 (total Kjeldahl nitrogen effluent is 1.05 mg/L).

Capital cost elements for methanol addition include a methanol liquid feed system, chemical storage area, and miscellaneous items (e.g., grass seeding, site cleanup, piping). The methanol liquid feed system is the same as the methanol liquid feed system included in CAPDETWorks^{TM} denitrification filter unit process with design values for the effluent nitrate target to simulate the denitrification requirement. CAPDETWorks^{TM} does not include separate methanol storage area costs or miscellaneous items in the denitrification filter unit process. As such, ERG assumed that these costs are minimal and would be accounted for in the 4-stage Bardenpho costs.

Operating and maintenance cost elements for methanol addition include operating labor, maintenance labor, materials and supplies costs, methanol chemicals, and energy. ERG estimated methanol chemicals using the CAPDETWorks^{TM} denitrification filter unit process with design values for the effluent nitrate target to simulate the denitrification requirement. CAPDETWorks^{TM} does not include separate operating labor, maintenance labor, materials and supplies costs, and energy costs for the methanol system in the denitrification filter unit process. As a result, ERG assumed that these costs are minimal and would be accounted for in the 4-stage Bardenpho operating and maintenance costs. Methanol chemical costs are based on the CAPDETWorks^{TM} default cost of $0.60/lb methanol in 2014 $ (Hydromantis, 2014).

Detailed descriptions of the methanol addition for biological nutrient removal supplemental carbon are provided in Appendix E.4, including all cost bases, assumptions, and calculations.

3.2.3.5 Ultrafiltration

Ultrafiltration is not a unit process available in CAPDETWorks™ Version 3.0. Therefore, ERG developed a costing methodology for ultrafiltration outside of CAPDETWorks™ and then incorporated the cost elements into the CAPDETWorks™ outputs to calculate the total cost of each wastewater treatment configuration that includes ultrafiltration (Level 5-1 B5/RO).

Capital cost elements for ultrafiltration include the membrane filtration system (membrane equipment and all appurtenances such as feed pumps, backwash system, and clean-in-place system) and a building to house the membrane filtration system. ERG estimated purchased equipment costs for the membrane filtration system based on cost information provided by a vendor. ERG estimated capital costs for the building using a CAPDETWorks™ building unit total capital cost of $110/square foot and an estimated building footprint provided by the vendor.

Operating and maintenance cost elements for ultrafiltration include operating labor, maintenance labor, materials costs (assumed a 7-year membrane life), chemicals (membrane cleaning), and energy. Operating and maintenance labor costs were estimated using a combination of information provided by the vendor, best professional judgement, and labor rates from CAPDETWorks™. Membrane replacement and chemicals costs are based on cost information provided by the vendor. Estimated energy usage for the membrane filtration system is based on a combination of information provided by the vendor and literature sources. ERG then calculated estimated energy costs by multiplying the estimated energy usage by the energy rate used for the CAPDETWorks™ costing ($0.10/kWh).

Detailed descriptions of our ultrafiltration costing approach are provided in Appendix E.5, including all cost bases, assumptions, and calculations.

3.2.3.6 Reverse Osmosis (RO)

RO is not a unit process available in CAPDETWorks™ Version 3.0. Therefore, ERG developed a costing methodology for RO outside of CAPDETWorks™ and then incorporated the cost elements into the CAPDETWorks™ outputs to calculate the total cost of for each wastewater treatment configuration that includes RO (Level 5-1 B5/RO and Level 5-2 MBR/RO).

Capital cost elements for RO include the RO system (membrane equipment and all appurtenances such as feed pumps, backwash system, and clean-in-place system), a chlorine gas feed system, a dechlorination feed system, an antiscalant feed system, a brine surge sump, and a building to house the RO system. ERG estimated purchased equipment costs for the RO system based on cost information provided by a RO vendor. ERG estimated capital costs for the building using a CAPDETWorks™ building unit total capital cost of $110/square foot and an estimated building footprint provided by the RO vendor. Costs for the chlorination feed system are included within the CAPDETWorks™ chlorination module discussed previously in this section. Costs for the dechlorination and antiscalant feed systems were estimated based on cost information provided by a feed system vendor. For the brine surge sump, ERG first estimated the required sump volume, assuming a 60-minute hydraulic residence time, based on best professional judgement. ERG then estimated the brine sump total capital costs using online RS Means Building Construction Cost Data.

Operating and maintenance cost elements for RO include operating labor, maintenance labor, materials costs (assumed a 4-year membrane life), chemicals (membrane cleaning, antiscalant, chlorine gas, and sodium bisulfite dechlorination), and energy. Operating and maintenance labor costs were estimated using a combination of information provided by the RO vendor, best professional judgement, and labor rates from CAPDETWorks^{TM}. Membrane replacement and membrane cleaning chemical costs are based on cost information provided by the vendor. Antiscalant chemical costs were estimated using the dosage rate provided by the RO vendor and a chemical cost provided by a chemical vendor. Chlorine gas and sodium bisulfite chemical costs are included within the CAPDETWorks™ chlorination module and the supplemental dechlorination module developed by ERG discussed previously in this section. Estimated energy usage for the RO system is based on a combination of information provided by the RO vendor and literature sources; estimated energy usage for the dechlorination and antiscalant feed systems is based on information provided by the chemical feed system vendor. ERG then calculated estimated RO and feed system energy costs by multiplying the estimated energy usage by the energy rate used for the CAPDETWorks™ costing ($0.10/kWh).

Detailed descriptions of our RO system costing approach are provided in Appendix E.6, including all cost bases, assumptions, and calculations.

3.2.3.7 Deep Injection Well

Deep well injection is not a unit process available in CAPDETWorks™ Version 3.0. Therefore, ERG developed a costing methodology for deep well injection outside of CAPDETWorks™ and then incorporated the cost elements into the CAPDETWorks™ outputs to calculate the total cost of each wastewater treatment configuration that includes brine disposal (Level 5-1 B5/RO and Level 5-2 MBR/RO).

Capital cost elements for deep well injection include injection well pumps, a building to house the injection pumps and electrical control panel and drilling the underground injection well. Purchase costs for the injection well pumps were based on information provided by a pump vendor; pump freight costs were estimated based on information from an equipment supply vendor. ERG estimated capital costs for the building using a CAPDETWorks™ building unit total capital cost of $110/square foot and an estimated building footprint developed based on best professional judgement. ERG estimated costs for drilling a new underground injection well based on cost information provided by a waste disposal vendor.

Operating and maintenance cost elements for deep well injection include operating labor, maintenance labor, materials costs, and energy. Operating and maintenance labor costs were estimated using a combination of best professional judgement and labor rates from CAPDETWorks^{TM}. Materials costs were estimated as 2 percent of injection well pump purchase cost, based on CAPDETWorks™ methodology. ERG estimated energy usage for the injection well pumps using the pump HP rating and assuming continuous operation. ERG then calculated estimated injection well pump energy costs by multiplying the estimated energy usage by the energy rate used for the CAPDETWorks™ costing ($0.10/kWh).

Detailed descriptions of our deep well injection costing approach are provided in Appendix E.7, including all cost bases, assumptions, and calculations.

3.2.3.8 Anaerobic Digester Natural Gas Usage

CAPDETWorks™ assumes that the gas produced by the anaerobic digester is used to supply heat to the anaerobic digester. If the digester gas produced is insufficient, CAPDETWorks™ uses natural gas for the difference. Because most WWTPs flare the digester gas, ERG revised the energy calculations for the anaerobic digester to assume that all the heat required was provided by natural gas using Equation 2 and Equation 3, and that all digester gas produced was flared.

$$\text{Energy Costs} = \text{Electricity Cost} + \text{Total Natural Gas Required} \times \text{Natural Gas Cost}$$

Equation 2

where:

Energy Costs (2014 $/yr) = Energy cost to run the anaerobic digester for a year

Electricity Cost (2014 $/yr) = Electricity cost from CAPDETWorks™ to run the anaerobic digester for a year

Total Natural Gas Required (1,000 cuft/yr) = Natural gas required to heat the anaerobic digester (see Equation 3)

Natural Gas Cost (2014 $/1,000 cuft) = $15,500/1,000 cuft

$$\text{Total Natural Gas Required} = \frac{\text{Heat Required}}{\text{Boiler Efficiency} \times \text{Heat Exchanger Efficiency}} \times \frac{\text{Hours per Year Conversion}}{\text{Natural Gas Heating Value}} \times \text{Unit Conversion}$$

Equation 3

where:

Total Natural Gas Required (1,000 cuft/yr) = Natural gas required to heat the anaerobic digester

Heat Required (BTU/hr) = Heat required to heat the anaerobic digester

Boiler Efficiency (%) = 80%

Heat Exchanger Efficiency (%) = 90%

Hours per Year Conversion (hr/yr) = 8,760 hr/yr

Natural Gas Heating Value (BTU/cuft) = 1,000 BTU/cuft

Unit Conversion (1,000 cuft/cuft) = 1,000 cuft (with 1,000 cuft as the unit)/ 1,000 cuft (with cuft as the unit)

3.3 LCCA

LCCA enables a total cost comparison of the nine wastewater treatment configurations including all of the relevant costs that occur throughout the life of the treatment alternatives. The total plant costs are presented in two ways: 1) total capital costs along with total annual costs (see Section 3.3.1) and 2) net present value (see Section 3.3.2). The net present value is a method to combine one-time capital costs and periodic (annual) operating and maintenance costs into one value for direct comparison of costs for alternative wastewater treatment configurations.

3.3.1 Total Capital and Total Annual

The total capital costs include the purchased equipment, direct costs, and indirect costs. The purchased equipment includes the cost to purchase the equipment and freight to get the equipment to the WWTP site. The direct costs are costs incurred as a direct result of installing the WWTP. For this study, the direct costs include mobilization, site preparation, site electrical, yard piping, instrumentation and control, and lab and administration building. The indirect costs are non-direct costs incurred as a result of installing the WWTP. For this study, the indirect costs include land, miscellaneous items, legal costs, engineering design fee, inspection costs, contingency, technical, interest during construction, and profit. The total capital costs are calculated using Equation 4 for each wastewater treatment configuration.

$$\text{Total Capital Costs} = \text{Purchased Equipment Costs} + \text{Direct Costs} + \text{Indirect Costs}$$

Equation 4

where:

Total Capital Cost (2014 \$) = Total capital costs

Purchased Equipment Costs (2014 \$) = Costs to purchase the equipment for the WWTP, including ancillary equipment and freight costs (see the following subsection for details)

Direct Costs (2014 \$) = Costs incurred as a direct result of installing the WWTP (see the following subsection for details)

Indirect Costs (2014 \$) = Costs for all non-direct costs incurred as a result of installing the WWTP (see the following subsection for details)

The total annual costs (often referred to as O&M) include the operation and maintenance labor, materials, chemicals, and energy. CAPDETWorks™ includes the periodic replacement of equipment parts (e.g., membranes, filter media, pumps) in the materials' annual costs. ERG used the same methodology for the membrane replacement costs for ultrafiltration and RO, which are detailed in Sections 3.2.3.4 and 3.2.3.6. ERG calculated total annual costs using Equation 5.

$$\text{Total Annual Costs} = \text{Operation Costs} + \text{Maintenance Costs} + \text{Materials Costs} + \text{Chemical Costs} + \text{Energy Costs}$$

Equation 5

where:

Total Annual Costs (2014 \$/year) = Total annual operation and maintenance costs

Operation Costs (2014 \$/year) = Labor costs for manual labor required to operate the WWTP for a year, including operation, administrative, and laboratory labor

Maintenance Costs (2014 \$/year) = Labor costs for manual labor required to maintain the WWTP for a year

Materials Costs (2014 \$/year) = Materials costs for operation and maintenance of the WWTP for a year, including replacement equipment

Chemical Costs (2014 \$/year) = Chemical costs for chemicals required for WWTP operation (e.g., alum, polymer) for a year

Energy Costs (2014 \$/year) = Electricity costs to run the WWTP for a year

CAPDETWorks™ calculates the operation and maintenance costs based on labor required and average salary for each job description: administrative, operation, maintenance, and laboratory. The administrative and laboratory labor hours are based on the WWTP flow rate, while the operation and maintenance hours are calculated for each process based on factors like the flow rate, number of units in each process, wastewater characteristics (e.g., total dissolved solids), and process design factors (e.g., required air rate). CAPDETWorks™ calculates the materials costs for operation and maintenance for each unit process based on factors like flow rate, unit capacity, and total construction cost. CAPDETWorks™ calculates the chemical costs based on the specific unit processes and the dosage rate. CAPDETWorks™ calculates the energy costs using the energy consumption requirements for the unit processes and \$0.10/kWh. As of May 2014, the average price of electricity for all sectors was \$0.1023/kWh as published by the U.S. Energy Information Administration (US EIA, 2015). As a result, ERG used the CAPDETWorks™ default electricity price, which is reflective of 2014 to match the 2014-dollar basis discussed in Section 3.2.1.

ERG used the CAPDETWorks™ total annual costs for unit processes in CAPDETWorks™. For unit processes not in CAPDETWorks™, ERG calculated total annual costs including the same components as CAPDETWorks™, as applicable for the specific unit process.

Purchased Equipment Costs

ERG costed the purchased equipment primarily using CAPDETWorks™, as described in Section 3.2.2 above. However, certain unit processes comprising the system configurations are not available in CAPDETWorks™. For these unit processes, ERG developed costs outside of CAPDETWorks™ and then incorporated these cost elements into the CAPDETWorks™ outputs to calculate the total purchased equipment costs for each wastewater treatment configuration, as presented in Equation 6.

$$\text{Purchased Equipment Costs} = \sum \text{Unit Process Equipment Costs}$$

Equation 6

where:

Purchased Equipment Costs (2014 $) = Costs to purchase the equipment for the WWTP, including ancillary equipment and freight costs

Unit Process Equipment Costs (2014 $) = Costs to purchase the equipment for each unit process at the WWTP, including costs from CAPDETWorks™ and developed outside of CAPDETWorks™ (see Section 3.2.2 for details)

Direct Costs

CAPDETWorks™ includes direct costs for mobilization, site preparation, site electrical, yard piping, instrumentation and control, and lab and administration building. These direct costs account for the portions of the wastewater treatment configuration that are not directly associated with a unit process. CAPDETWorks™ calculates direct costs proportional to the WWTP flow based on cost curves generated from EPA's *Construction Costs for Municipal Wastewater Treatment Plants: 1973-1978* (U.S. EPA, 1980). Using this approach would not account for differences in the direct costs due to the increasing complexity of the nine wastewater treatment configurations. The CAPDETWorks™ approach is also inconsistent with standard engineering costing that calculates direct costs as a percentage of purchased equipment costs (Peters and Timmerhaus, 1991; Falk et al., 2011). As a result, ERG used the CAPDETWorks™ results from the Level 1 wastewater treatment configuration with the CAPDETWorks™ default unit process inputs to calculate direct cost factors for each direct cost element as a percentage of total purchased equipment cost as presented in Equation 7. Because CAPDETWorks™ calculates the same direct costs for all nine wastewater treatment configurations, calculating the direct cost factors using the lowest purchased equipment costs of the nine wastewater treatment configurations (i.e., Level 1), will result in the highest direct costs factors. ERG confirmed the calculated direct cost factors were reasonable based on other engineering sources (Falk et al., 2010).

$$\text{Direct Cost Factor} = \frac{\text{Level 1 Direct Cost}}{\text{Level 1 Purchased Equipment Cost}}$$

Equation 7

where:

Direct Cost Factor (%) = Direct cost factor for each direct cost element, see Table 1 below

Level 1 Purchased Equipment Cost (2014 $) = $19,600,000 (see Appendix E.8)

Level 1 Direct Cost (2014 $) = see Table 3-2 below

Table 3-2. Direct Cost Factors

Direct Cost Elements	Level 1 Direct Costs (2014 $)	Direct Cost Factor (%)
Mobilization	$818,000	4%
Site Preparation	$1,090,000	6%
Site Electrical	$2,360,000	12%

Table 3-2. Direct Cost Factors

Direct Cost Elements	Level 1 Direct Costs (2014 $)	Direct Cost Factor (%)
Yard Piping	$1,550,000	8%
Instrumentation and Control	$1,240,000	6%
Lab and Administration Building	$1,930,000	10%

Source: Appendix E.8.

ERG applied the direct cost factors from Table 3-2 to the total purchased equipment cost for each of the nine wastewater treatment configurations using Equation 8 to calculate the direct costs for each direct cost element.

$$\text{Direct Cost} = \text{Direct Cost Factor} \times \text{Purchased Equipment Cost}$$

Equation 8

where:

Direct Cost (2014 $) = Direct cost for each direct cost element

Direct Cost Factor (%) = Direct cost factor for each direct cost element, see Table 3-2

Purchased Equipment Cost (2014 $) = Total purchased equipment cost for each wastewater treatment configuration (see Equation 6)

Indirect Costs

CAPDETWorks™ includes indirect costs for land, miscellaneous items, legal costs, engineering design fee, inspection costs, contingency, technical, interest during construction, and profit. ERG used Equation 9 to calculate the total indirect costs.

$$\begin{gathered}\text{Indirect Costs} = \text{Land Cost} + \text{Remaining Indirect Costs} \\ + \text{Interest During Construction}\end{gathered}$$

Equation 9

where:

Indirect Costs (2014 $) = Costs for all non-direct costs incurred as a result of installing the WWTP

Land Cost (2014 $) = Total cost for the land required for the WWTP, see Equation 10 below

Remaining Indirect Costs (2014 $) = Indirect costs associated with miscellaneous costs, legal costs, engineering design fee, inspection costs, contingency, technical, and profit, see Equation 11 below

Interest During Construction (2014 $) = Interest paid during construction, see Equation 12 below

ERG used CAPDETWorks™ land costs, which are calculated using Equation 10.

$$\text{Land Cost} = \text{Treatment Area} \times \text{Land Unit Cost}$$

Equation 10

where:

Land Cost (2014 $) = Total cost for the land required for the WWTP

Treatment Area (acres) = Required treatment area for the WWTP based on the unit processes costed from CAPDETWorks™[6]

Land Unit Cost (2014 $/acre) = $20,000/acre, the CAPDETWorks™ default land unit cost, (Hydromantis, 2014)

For the remaining indirect costs ERG used contingency cost percentage based on cost estimate recommended practices (ACCEI, 2016) and CAPDETWorks™' indirect cost percentages (Table 3-3) to calculate indirect costs as a percentage of purchased equipment cost and direct construction costs for each wastewater treatment configuration as presented in Equation 11.

$$\text{Remaining Indirect Costs} = \text{Indirect Cost Factor} \times (\text{Purchased Equipment Cost} + \text{Direct Cost})$$

Equation 11

where:

Remaining Indirect Cost (2014 $) = Indirect costs associated with miscellaneous costs, legal costs, engineering design fee, inspection costs, contingency, technical, and profit

Indirect Cost Factor (%) = Indirect cost factor for each indirect cost element, see Table 3-3

Purchased Equipment Cost = Total purchased equipment cost (see Equation 6)

Direct Cost (2014 $) = Total direct costs (see Equation 8)

Table 3-3. Indirect Cost Factors

Indirect Cost Elements	Indirect Cost Factor (%)
Miscellaneous Costs	5%
Legal Costs	2%
Engineering Design Fee	15%

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[6] All unit processes in the wastewater treatment configurations for Levels 1 through 4 are included in CAPDETWorks™ land area calculations. For the Level 5 wastewater treatment configurations, ERG determined that the land requirements for the non-CAPDETWorks™ unit processes (i.e., Level 5-1: ultrafiltration, reverse osmosis, and deep injection well; Level 5-2: reverse osmosis and deep injection well) was minimal and would fit within the CAPDETWorks™ land area.

Table 3-3. Indirect Cost Factors

Indirect Cost Elements	Indirect Cost Factor (%)
Inspection Costs	2%
Contingency	20%
Technical	2%
Profit	15%

Source: Hydromantis, 2014; AACEI, 2016.

For the interest during construction, ERG used Equation 12.

$$\text{Interest During Construction} = (\text{Purchased Equipment Cost} + \text{Direct Costs} + \text{Select Indirect Costs}) \times \text{Construction Period} \times \frac{\text{Interest Rate During Construction}}{2}$$

Equation 12

where:

Interest During Construction (2014 $) = Interest paid during construction

Purchased Equipment Cost (2014 $) = Total purchased equipment cost for each wastewater treatment configuration (see Equation 6)

Direct Costs (2014 $) = Total direct costs (see Equation 8)

Select Indirect Costs (2014 $) = Indirect costs, including miscellaneous items, legal costs, engineering design fee, inspection costs, contingency, and technical

Construction Period (years) = 3 years based on CAPDETWorks™ default construction period (Hydromantis, 2014)

Interest Rate During Construction (%) = Interest rate during construction

ERG used 3% and 5% interest rates during construction, which are the same values ERG used for the discount rates discussed in Section 3.3.2. The 3% interest rate represents a conservative interest rate for a State Revolving Fund (SRF) loan as the SRF average loan rate was 1.7% in April 2016 (U.S. EPA, 2016a). The 5% interest rate represents a worse-case scenario reflective of rates that WWTPs in poor financial shape, but still able to borrow, would be able to obtain.

3.3.2 Net Present Value

ERG calculated the net present value using Equation 13. This equation assumes that the only value remaining in the WWTP at the end of the planning period is in the land, which increases in value by 3% over the planning period using CAPDETWorks$^{\text{TM}}$' approach.

$$\text{NPV} = \frac{\left(1+i\right)^{PP}-1)}{i \times (1+i)^{PP}} \times \left(\text{Amortized Construction Cost} + \text{Total O\&M Cost}\right)$$

$$+ \text{Land} \times \left(1 - (1.03^{PP}) \times \frac{1}{(1+i)^{PP}}\right)$$

Equation 13

where:

NPV (2014 $) = Net present value of all costs necessary to construct and operate the WWTP

Amortized Construction Cost (2014 $/yr) = Total construction costs amortized over the WWTP planning period, see Equation 14 below

Total O&M Costs (2014 $/yr) = Total annual operation and maintenance costs, see the previous subsection

Land (2014 $) = Land costs from CAPDETWorks™ models for each wastewater treatment configuration

i (%) = Real discount rate

PP (years) = WWTP planning period

1.03 = Factor to account for a 3% increase in land value over the WWTP planning period

ERG used 3% and 5% real discount rates, which are the same values ERG used to calculate the interest during construction. See the indirect costs subsection within Section 3.3.1 for a discussion on the basis for the selected interest rates. The real discount rate approximates the marginal pretax rate of return on an average investment in the private sector in recent years and has been adjusted to eliminate the effect of expected inflation. As a result, ERG did not adjust the construction or O&M costs for inflation. ERG used 20 years as the WWTP planning period.

ERG calculated amortized construction costs using Equation 14.

$$\text{Amortized Construction Cost} = -12 \times \text{PMT}\left(\frac{i}{12}, \text{PP, Total Capital Cost, 0, 0}\right)$$

Equation 14

where:

Amortized Construction Cost (2014 $) = Total construction costs amortized over the WWTP planning period

PMT = Excel® function that calculates the stream of equal periodic payments that has the same present value as the actual stream of unequal payments over the project life at a constant interest rate (for example, a mortgage converts the one-time cost of a house to a stream of constant monthly payments)

i (%) = 3% and 5% discount rates

PP (years) = WWTP planning period (20 years)

Total Capital Cost (2014 $) = Total capital costs, see Equation 4

3.4 Data Quality

In accordance with the project's Quality Assurance Project Plan (QAPP) entitled *Quality Assurance Project Plan for Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants* approved by EPA on March 25, 2015 (ERG, 2015c), ERG collected existing data[7] to develop cost estimates for the nine wastewater treatment configurations in this study. As discussed in Section 3.1, the cost estimate data sources include CAPDETWorks™ Version 3.0 (Hydromantis, 2014), EPA reports, peer-reviewed literature, publicly available equipment costs from and communication with technology vendors, and industry-accepted construction cost data and indices. ERG evaluated the collected information for completeness, accuracy, and reasonableness. In addition, ERG considered publication date, accuracy/reliability, and costs completeness when reviewing data quality. Finally, ERG performed conceptual, developmental, and final product internal technical reviews of the costing methodology and calculations for this study.

Table 3-4 presents the data quality criteria ERG used when evaluating collected cost data. ERG documented the data quality for each data source for each criterion in a spreadsheet for EPA's use in determining whether the cost data are acceptable for use. All of the references used to develop the costs met all of the data quality criteria with the exceptions of EPA's Wastewater Technology Fact Sheet – Dechlorination (U.S. EPA. 2000), EPA's Biosolids Technology Fact Sheet – Gravity Thickening (U.S. EPA, 2003a), and EPA's Wastewater Technology Fact Sheet – Screening and Grit Removal (U.S. EPA, 2003b). These references did not meet the criteria for currency (up to date). ERG used the Wastewater Technology Fact Sheet – Dechlorination to develop the contact time required to dechlorinate the residual chlorine. Although this EPA report is not current, the contact time for dechlorination has not changed since the fact sheet was published. ERG used the Biosolids Technology Fact Sheet – Gravity Thickening to revise the gravity thickener default CAPDETWorks^{TM} values for depth and standard cost for a 90 ft diameter thickener. ERG used the Wastewater Technology Fact Sheet – Screening and Grit Removal to revise the CAPDETWorks^{TM} purchased equipment cost for the preliminary treatment unit process (i.e., screening and grit removal). Although these EPA reports are not current, ERG revised the default values based on feedback from Falk et al. (2017) that the CAPDETWorks^{TM} default values, designed in the 1970s, were no longer appropriate.

Table 3-4. Cost Data Quality Criteria

Quality Criterion: Cost Data	Description/Definition
Current (up to date)	Report the time period of the data. Year of publication (or presentation, if a paper presented at a conference) is 2005 or after.
Complete	Identify if all units are reported. Identify the cost per year basis reported. [a]
Representative	Report if the costs are for unit processes used in the selected nutrient wastewater treatment configurations.

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[7] *Existing data* means information and measurements that were originally produced for one purpose that are recompiled or reassessed for a different purpose. Existing data are also called secondary data. Sources of existing data may include published reports, journal articles, LCI and government databases, and industry publications.

Table 3-4. Cost Data Quality Criteria

Quality Criterion: Cost Data	Description/Definition
Accurate/Reliable	Document the source of the data. Were the data (1) obtained from well-known technical references for engineering design and cost information, as well as for general cost factors (e.g., engineering, permitting, scheduling), or (2) from selected vendors that are the leaders within their areas of expertise determined based on the use of their technologies at municipal facilities that have well designed and operated wastewater treatment systems?

a – See Section 3.2.1 for the calculation ERG used to convert all costs to a standard year basis using RSMeans Construction Cost Index (RSMeans, 2017).

ERG developed the CAPDETWorks™ input files containing all the necessary information and data required for the tool to execute the wastewater treatment designs and engineering costing. All CAPDETWorks™ input files were reviewed by a team member knowledgeable of the project, but who did not develop the input files. The reviewer ensured the accuracy of the data transcribed into the input files, the technical soundness of methods and approaches used (i.e., included all of the cost components and LCA inputs) and the accuracy of the calculations (i.e., used the methodology in Section 3.3 to calculate the costs).

ERG developed the supplemental cost estimates for ultrafiltration, reverse osmosis, and deep well injection in an Excel® Workbook. A team member knowledgeable of the project, but who did not develop the Excel® workbook, reviewed the workbook to ensure the accuracy of the data transcribed into the workbook, the technical soundness of methods and approaches used, and the accuracy of calculations.

4. LCA METHODOLOGY

This chapter covers the data collection process, data sources, assumptions, methodology and parameters used to construct the LCI model for this study. Following the LCI discussion, details on the impact assessment are provided.

4.1 Life Cycle Inventory Structure

LCI data are the foundation of any LCA study. Every element included in the analysis is modeled as its own LCI unit process entry (see Appendix G for an example). It is the connection of LCI unit process data that constitutes the LCA model. A simplified depiction of a subset of this structure for this study is shown in Figure 4-1. The overall system boundaries were previously presented in Figure 1-1, and include all unit processes associated with plant operations and disposal of sludge, not just those processes associated with nutrient removal. It is not possible to display this type of figure for the entire LCA model, as each LCA model includes thousands of connected unit process inputs and outputs. Each box in the figure represents an LCI unit process. The full system is a set of nested LCIs where the primary process outputs, in red, of one process serve as inputs, in blue, to another process. Within each nested level, there can be flows both to and from the environment. Flows from the environment are written in black in Figure 4-1 and are represented by the thin black arrows crossing the system boundary from nature. Emissions to the environment are listed in green, and it is these flows that are tabulated in the calculation of environmental impacts. Intermediate inputs are shown in blue text. Intermediate inputs are those that originate from an extraction or manufacturing process within the supply-chain.

The distinction between the foreground and background systems is not a critical one. The foreground system tends to be defined as those LCIs that are the focus of the study. In this case, that is the WWTP itself. Foreground information was drawn directly from the CAPDETWorks™ Version 3.0 modeling software or calculated separately for input and output flows not captured by the software. Background LCI information is comprised of extractive and manufacturing processes that create material and energy inputs required by the wastewater treatment systems. Background data are drawn from a version of the U.S. LCI as well as ecoinvent databases that have been harmonized and modified by EPA's Office of Research and Development (ORD) (LCA Research Center, 2015). Details on the data sources for the background databases used is provided in Section 4.2 and detailed data sources and input and output flow values for the foreground unit processes are provided in Section 4.3.

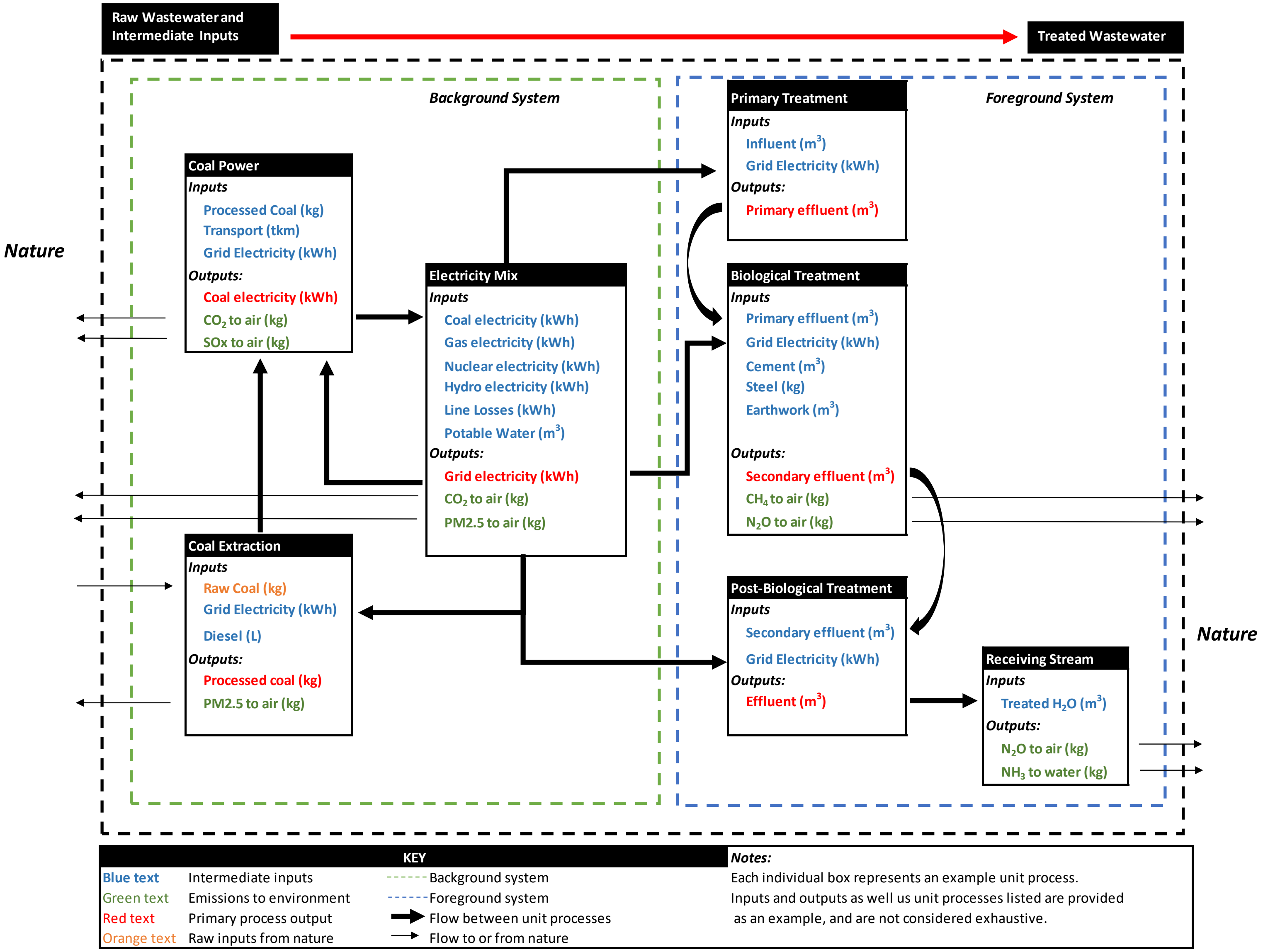

Figure 4-1. Subset of LCA Model Structure with Example Unit Process Inputs and Outputs

4.2 LCI Background Data Sources

The supply chains of inputs to the wastewater treatment processes are represented where possible using the EPA ORD LCA database (U.S. EPA, 2015f), which is a modified combination of the National Renewable Energy Laboratory's U.S. Life Cycle Inventory database (U.S. LCI) and ecoinvent Version 2.2 (NREL, 2015; Ecoinvent Centre, 2010b). The U.S. LCI is a publicly available life cycle inventory database widely used by LCA practitioners. Ecoinvent is also a widely used global LCI database available by paid subscription. Both allow the user access to inputs to and outputs from each unit process. Ecoinvent Version 3.2 is used to fill any gaps where data do not exist in the EPA ORD LCA database, U.S. LCI or ecoinvent Version 2.2 (Ecoinvent Centre, 2015). The list of background unit processes and their associated database source used in the LCA model is presented in Table 4-1.

Table 4-1. Background Unit Process Data Sources

Background Input	Original Unit Process Name	LCI Database
Electricity	Electricity, at industrial user	EPA ORD LCA Database
Natural Gas	Natural gas, combusted in industrial equipment	U.S. LCI
Chlorine Gas	chlorine, gaseous, diaphragm cell, at plant	ecoinvent v2.2
Polymer	polyacrylamide	ecoinvent v3.2
Sodium Bisulfite (40%)	Sodium hydrogen Sulfite, 40% in solution	ecoinvent v3.2
Sodium Bisulfite (12.5%)	Sodium hydrogen Sulfite, 12.5% in solution	ecoinvent v3.2
Truck Transport	Truck transport, class 8, heavy heavy-duty (HHD), diesel, short-haul, load factor 0.5	ecoinvent v2.2
Al Sulfate	Aluminium sulphate, powder, at plant	ecoinvent v2.2
Calcium Carbonate	Lime, from carbonation, at regional storehouse	ecoinvent v2.2
Methanol	Methanol, at plant	ecoinvent v2.2
Antiscalant	Polycarboxylates, 40% active substance | polycarboxylates production, 40% active substance	ecoinvent v3.2
Citric Acid	Citric acid | citric acid production	ecoinvent v3.2
Sodium Hypochlorite	Sodium hypochlorite, 15% in H2O, at plant	ecoinvent v2.2
Sulfuric Acid	Sulphuric acid, liquid, at plant_50% in solution	ecoinvent v2.2
Sodium Hydroxide	Sodium hydroxide, 50% in H2O, production mix, at plant	ecoinvent v2.2
Earthwork	Excavation, hydraulic digger	ecoinvent v2.2
Concrete	Ready mixed concrete, 20 MPa, at plant	EPA ORD LCA Database

Table 4-1. Background Unit Process Data Sources

Background Input	Original Unit Process Name	LCI Database
Building	Building, hall, steel construction	ecoinvent v2.2
Steel	Steel, low-alloyed, at plant	ecoinvent v2.2
Gravel	Gravel, crushed, at mine	ecoinvent v2.2
Anthracite	Anthracite, sand filter media	ecoinvent v2.2
Sand	Silica sand, at plant	ecoinvent v2.2

Electricity is a key background unit process for all the wastewater treatment configurations investigated. Table 4-2 displays the U.S. average electrical grid mix applied in the LCA model. This grid mix represents the weighted average of all U.S. grid regions, and as such is not representative of the grid mix in any specific location. For electricity at an industrial user, there is assumed to be a 21% increase in required electrical production attributable to losses during distribution and the energy industries own use. These data are based on the Emissions & Generation Resource Integrated Database (eGRID) information from 2009, which is currently applied in the EPA ORD LCA Database (LCA Research Center, 2015).

Table 4-2. U.S. Average Electrical Grid Mix

Fuel	%
Coal	44.8%
Natural Gas	24.0%
Nuclear	19.6%
Hydro	6.18%
Wind	2.29%
Woody Biomass	1.36%
Oil	1.02%
Geothermal	0.37%
Other Fossil	0.35%
Solar	0.03%

4.3 LCI Foreground Data Sources

As discussed earlier, for this study, the foreground system is defined as the WWTP itself. For each of the nine wastewater treatment configurations evaluated, foreground information was drawn directly from the CAPDETWorks™ Version 3.0 modeling software or calculated separately for input and output flows not captured by the software. This section describes the unit process LCI calculations, the methods used to estimate wastewater treatment process air emissions, and a summary of the LCI foreground data used. The foreground LCI unit process data developed for this study for all levels are summarized in Appendix H in Table H-1 through Table H-10. Table H-11 displays the sludge quantity produced and sent to landfill for each of the nine wastewater treatment configurations.

4.3.1 Foreground Unit Processes Calculations

Table 4-3 provides an overview of the foreground unit processes that make up each of the wastewater treatment configurations evaluated in this study. The quantity and quality of water inputs to and outputs from each unit process are tracked throughout the wastewater treatment configurations. Energy, chemical, and material inputs (e.g., background unit processes) to each of the unit processes are tracked in terms of energy, mass, or volume units. Also, rough estimates of the construction and maintenance requirements of the infrastructure for each unit process are tracked based on greenfield installations of the wastewater treatment configurations. In the case of infrastructure and capital equipment requirements, past analyses have shown the contribution of infrastructure to the overall results to be relatively insignificant (Emmerson et al., 1995). In general, these types of capital equipment are used to treat large volumes of wastewater over a useful life of many years. Thus, energy and emissions associated with the production of these facilities and equipment generally become negligible. Only major infrastructure elements such as concrete, earthwork, and buildings were, therefore, included in the study. Buildings were modeled using a general material inventory per square meter of floor area (Ecoinvent, 2010b).

Releases to air and water as well as waste outputs are also tracked for each unit process. Releases to air and water are tracked together with information about the environmental compartment to which they are released to allow for appropriate characterization of their impacts. Waste streams are connected to supply chains associated with providing waste management services such as landfilling.

Table 4-3. Foreground Unit Processes Included in Each Wastewater Treatment Configuration

	Wastewater Treatment Configuration								
Unit Process	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Preliminary Treatment – Screening	✓	✓	✓	✓	✓	✓	✓	✓	✓
Preliminary Treatment – Grit Removal	✓	✓	✓	✓	✓	✓	✓	✓	✓
Primary Clarification	✓	✓	✓	✓	✓	✓	✓	✓	✓
Plug Flow Activated Sludge	✓		✓						
Biological Nutrient Removal – 3-Stage		✓							
Fermenter				✓	✓	✓		✓	✓
Biological Nutrient Removal – 4-Stage					✓		✓		
Biological Nutrient Removal – 5-Stage				✓		✓		✓	✓
Chemical Phosphorus Removal			✓	✓	✓	✓	✓	✓	✓

Table 4-3. Foreground Unit Processes Included in Each Wastewater Treatment Configuration

	Wastewater Treatment Configuration								
Unit Process	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Nitrification – Suspended Growth			✓						
Denitrification – Suspended Growth			✓						
Secondary Clarifier	✓	✓	✓	✓	✓	✓		✓	
Membrane Filter [a, b]							✓		✓
Tertiary Clarification			✓ [c]						
Denitrification – Attached Growth						✓		✓	
Filtration – Sand Filter				✓	✓	✓		✓	
Chlorination	✓	✓	✓	✓	✓	✓	✓	✓	✓
Dechlorination	✓	✓	✓	✓	✓	✓	✓	✓	✓
Ultrafiltration [a]								✓	
Reverse Osmosis [a, d]								✓	✓
WWTP Effluent Discharge	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sludge – Gravity Thickening	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sludge – Anaerobic Digestion	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sludge – Centrifugation	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sludge – Haul and Landfill	✓	✓	✓	✓	✓	✓	✓	✓	✓
Brine – Underground Inject								✓	✓

✓ Indicates unit process is relevant for select wastewater treatment configuration.

a – Periodic chemical cleaning is included for all membranes.

b – Membrane bioreactor wastewater treatment configurations use a membrane filter for the solid-liquid separation process instead of a traditional secondary clarifier.

c – This configuration includes two instances of tertiary clarification.

d – Includes chlorination and dechlorination pretreatment.

Foreground information was drawn directly from the CAPDETWorks™ Version 3.0 modeling software or calculated separately for input and output flows not captured by the software. Although CAPDETWorks™ is designed for cost estimation, the underlying models include a number of parameters which can be accessed and used to describe the physical processes involved at each stage in the wastewater treatment configurations, such as sludge generation or treatment chemical usage. An example of converting CAPDETWorks™ output to

LCI is provided in Appendix G. Where CAPDETWorks™ parameters are not available for populating relevant items in the unit processes underlying the LCA model, values are estimated based on the best available information identified through literature review. Values for GHG emissions from the wastewater treatment processes are not provided by CAPDETWorks™ and, therefore, are estimated independently (See Section 4.3.2 and Appendix F). Calculation of inputs and outputs for unit processes not covered in CAPDETWorks™ are also described separately in Appendix E: Sections E.2 through E.7)

4.3.2 Process Air Emissions Estimation Methodologies

For this study it is necessary to separately estimate process-based greenhouse gas (GHG) emissions for the nine wastewater treatment configurations. Emissions are already captured in the background existing unit processes for fuel production and combustion as well as material and chemical production (e.g., unit processes listed in Table 4-1). Estimates of process-based air emissions are made for methane (CH_4) production from biological treatment, anaerobic digestion, landfill disposal of biosolids, and biogas flaring at the anaerobic digester. Estimates of nitrous oxide (N_2O) emissions from biological treatment and receiving waters are also included in the analysis (IPCC, 2006). Separate methodologies have been developed based on the available literature for each of these sources of GHGs. Carbon dioxide (CO_2) emissions from wastewater treatment processes are not included in the calculation of GHG emissions from wastewater treatment processes because they are of biogenic origin and are not included in national total emissions in accordance with IPCC Guidelines for national inventories (IPCC, 2006). The methodology for calculating GHG emissions associated with wastewater treatment is generally based on guidance provided in the IPCC Guidelines for national inventories; however, more specific emission factors for both CH_4 and N_2O are used based on site-specific emissions data from representative systems. A detailed discussion of the process GHG emission values incorporated in the model is provided in Appendix F. Appendix F also provides the GHG emissions methodology developed for biogas flaring at the anaerobic digester (Table F-3) as well as the GHG emissions methodology associated with avoided electricity from landfill CH_4 recovery (Table F-7).

4.4 LCI Limitations

Some of the main limitations that readers should understand when interpreting the LCI data and findings are as follows:

- **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, as energy requirements and related emissions are assumed to be quite small for support personnel activities.
- **Representativeness of Background Data:** Background processes are representative of either U.S. average data (in the case of data from U.S. EPA ORD or U.S. LCI) or European or Global average (in the case of ecoinvent) data. In some cases, European ecoinvent processes were used to represent U.S. inputs to the model (e.g., for chemical inputs) due to lack of available representative U.S. processes for these

inputs. The background data, however, met the criteria listed in the project QAPP for completeness, representativeness, accuracy, and reliability.

- **Process GHG Estimates:** There is uncertainty in estimating CH_4 and N_2O process emissions from biological treatment and in differentiating the various treatment levels due to the limited measurement data associated with the different wastewater treatment configurations evaluated. Based on current international guidance, many governments ignore CH_4 GHG emissions in their national inventories from centralized aerated treatment plants because they are considered negligible when compared to other sources. The source of emission can be highly variable from facility to facility and is not associated with the type of treatment configuration. Facility-level process GHGs are also highly dependent on the specific operational characteristics of a system used at one plant versus another, including pH, temperature, and level of aeration. Minimum thresholds for determining differences in GHG results between the waste treatment configurations are discussed in Section 4.6.15.
- **Full LCI Model 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 LCI models (and the underlying CAPDETWorks™ model) when interpreting the results. Comparative conclusions should not be drawn based on small differences in impact results. For this study, minimum threshold guidelines to determine differences in impact results are provided by category in Section 4.6.15.
- **Temporal Considerations:** The LCI model does not distinguish based on temporal correlations and treat short-term and long-term impacts similarly. ~~between emissions or discharges that occur immediately and those that are long-term~~. For instance, long-term emissions of COD in landfill leachate from sludge disposal is incorporated in the model. For the first 100 years, it is assumed the leachate is sent to a WWTP. However, after 100 years it is assumed the landfill ceases to operate and there are still some residual leachate emissions.
- **Transferability of Results:** The LCI data presented here relate to a theoretical average U.S. WWTP with a greenfield installation and the conditions specified in Section 1.2. LCI results may vary substantially for case-specific operating conditions and facilities, and for retrofits of existing systems.

4.5 LCA Modeling Procedure

Development of an LCA requires significant input data, an LCA modeling platform, and impact assessment methods. This section provides a brief summary of the LCA modeling procedure. 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, EPA reviewed assumptions based on their relevance to the process rather than their effect on the overall outcome of the study. In most cases, individual unit processes were parameterized to dynamically represent multiple treatment levels and configurations.

The model was constructed in OpenLCA Version 1.4.2, an open-source LCA software package provided by GreenDelta (GreenDelta, 2015). This open-source format allowed seamless sharing of the LCA model between project team members. For all novel foreground unit processes developed under this work, individual unit process templates were completed into the United States Department of Agriculture (USDA) and U.S. EPA's US Federal LCA Commons Life Cycle Inventory Unit Process Template (USDA and U.S. EPA, 2015). The OpenLCA model was reviewed to ensure that all inputs and outputs, quantities, units, and metadata correctly matched the unit process templates. Associated metadata for each unit process was recorded in the unit process templates along with the model values. This metadata includes detailed data quality indicators (DQI) for each flow within each unit process.

Once all necessary data were input into the OpenLCA software and reviewed, system models were created for each treatment level configuration. The models were reviewed to ensure that each elementary flow (e.g., environmental emissions, consumption of natural resources, and energy demand) was characterized under each impact category for which a characterization factor was available. The draft final system models were also reviewed prior to calculating results to make certain all connections to upstream processes and weight factors were valid. LCIA results were then calculated by generating a contribution analysis for the selected treatment configuration product system based on the defined functional unit of treatment of one cubic meter of wastewater. The subsequent section discusses the detailed LCIA methods used to translate the LCI model in OpenLCA into the impact categories assessed in this study.

4.6 Life Cycle Impact Assessment (LCIA)

LCIA is defined in ISO 14044 section 3.4 as the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (ISO, 2006b)." Within LCIA, the multitude of environmental LCI flows throughout the entire study boundaries (e.g., raw material extraction through chemical and energy production and through wastewater treatment and effluent release) are classified according to whether they contribute to each of the selected impact categories. Following classification, all of the relevant pollutants are normalized to a common reporting basis, using characterization factors that express the impact of each substance relative to a reference substance. One well known example is the reporting of all GHG emissions in CO_2-eq. The LCI and LCIA steps together compromise the main components of a full LCA.

ISO 14040 recommends that an LCA be as comprehensive as possible so that "potential trade-offs can be identified and assessed (ISO, 2006a)." Given this recommendation, this study applies a wide selection of impact categories that encompass both environmental and human health indicators. The selected LCIA categories address impacts at global, regional, and local scales.

This study considers 12 impact categories in assessing the environmental burdens of the nine wastewater treatment configurations. The majority of impact categories address air and water environmental impacts, while three of the selected impact categories are human health impact indicators. There are two main methods used to develop LCIA characterization factors: midpoint and endpoint. The impact categories selected for this study are all midpoint indicators.

Midpoint indicators are directly associated with a specific environmental or human health pathway. Specifically, midpoint indicators lie at the point along the impact pathway where the various environmental flows that contribute to these issues can be expressed in a common unit (e.g., CO_2-eq). Units such as CO_2 equivalents express a relevant environmental unit, in this case radiative forcing (W-yr/m^2/kg), in the context of a reference substance. This is mentioned to reinforce the fact that there are physical mechanisms underlying all of the impact assessment methods put forward. Endpoint indicators build off of these midpoint units and translate them into impacts more closely related to the final damage caused by the substance, which include: (1) human health, (2) man-made environment, (3) natural environment, and (4) natural resources (Udo de Haes et al., 1999). It is commonly believed that endpoint indicators are easier for many audiences to understand, but suffer due to the fact that they significantly increase the level of uncertainty associated with the results because the translation to final damage are typically less understood and lack data. To reduce uncertainty of the results, this work generally focuses on indicators at the midpoint level.

The LCIA method provided by the Tool for the Reduction and Assessment of Chemical and Environmental Impacts (TRACI), version 2.1, 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 study (Bare, 2012). Additionally, the ReCiPe LCIA method is recommended to characterize fossil fuel depletion and water use (Goedkoop et al., 2009). Energy is tracked based on point of extraction using the cumulative energy demand method developed by ecoinvent (Ecoinvent Centre, 2010a).

Summaries of each of the 12 impact categories evaluated as part of this study are provided in the subsequent sections. Each summary includes a table of the main substances considered in the impact category, associated substance characterization factor, and the compartment (e.g., air, water, soil) the substance is released to or extracted from (in the case of raw materials). These tables highlight key substances but should not be considered comprehensive.

4.6.1 Eutrophication Potential

Eutrophication occurs when excess nutrients (e.g., nitrogen or phosphorus) are introduced to surface and coastal water causing the rapid growth of aquatic plants. This growth (generally referred to as an “algal bloom”) reduces the amount of dissolved oxygen in the water, thus decreasing oxygen available for other aquatic species. Eutrophication midpoint indicators, applied in this study, can lead to a number of negative endpoint effects on human and ecosystem health. Oxygen depletion or changing nutrient availability can affect species composition and ecosystem function. Additionally, the proliferation of certain algal species can result in toxic releases that directly impact human health (Henderson, 2015).

Table 4-4 provides a list of common substances that contribute to eutrophication along with their associated characterization factors. As indicated in the table, air emissions can also contribute to eutrophication through the atmospheric deposition of nitrogen compounds. The TRACI 2.1 eutrophication method considers emissions to both fresh and coastal waters. TRACI 2.1 characterization factors for eutrophication are the product of a nutrient factor and a transport factor (Bare et al., 2003). The nutrient factor is based on the amount of algae growth caused by each pollutant. The relative eutrophying effect of a nitrogen or phosphorus species is determined by its stoichiometric relationship to the Redfield ratio (Norris, 2003). The Redfield ratio is the average C:N:P ratio of phytoplankton, and describes the necessary building blocks to facilitate algal growth and reproduction (Redfield, 1934). The transport factor accounts for the likelihood that the pollutant will reach a body of water based on the average hydrology considerations for the U.S. The transport factor is used to account for the fact that a nutrient reaching a body of water where it is not limiting will not contribute to eutrophication. Both air and water emissions have the potential to contribute to eutrophication; however, the fraction of air emissions which make their way into bodies of water is often lower, which is reflected in a smaller transport factor, and the correspondingly lower characterization factors of nitrogen oxide air emissions in Table 4-4.

Both BOD and COD are also shown in Table 4-4 as contributing to eutrophication impacts. Although the mechanism of oxygen consumption differs from that associated with nutrient emissions of nitrogen and phosphorus, the result remains the same. Only COD (and not BOD) values are characterized in this study to avoid double-counting (Norris, 2003).

In this study, U.S. average characterization factors are used, which are created as a composite of all water basins in the U.S. For a discussion of the procedure used to produce composite U.S. characterization factors, see Norris (2003). Using these factors, the results account for regional variation in nutrient and transport factors, although that regional variability is not presented in a disaggregated form. This is appropriate for the scope of this study as our aim is to estimate average U.S. impacts of wastewater treatment. However, it must be recognized that context specific features of an individual WWTP could serve to ameliorate or increase site-specific impacts. In addition, waterbody-specific nutrient limitations and local transport characteristics tend to be the most decisive factors in determining regional differences in eutrophication impacts (Henderson, 2015).

Table 4-4. Main Pollutants Contributing to Eutrophication Potential Impacts (kg N eq/ kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
BOD_5, Biological Oxygen Demand	N/A	Water	0.05
COD, Chemical Oxygen Demand	N/A	Water	0.05
Ammonia	NH_3	Water	0.78
Nitrate	NO_3-	Water	0.24
Nitrogen dioxide	NO_2	Air	0.04
Nitrogen monoxide	NO	Air	0.04
Nitrogen oxides	NO_x	Air	0.04
Nitrogen, organic bound	N/A	Water	0.99
Phosphate	PO_4^{3-}	Water	2.4
Phosphorus [a]	P	Water	7.3
Selected Method—			TRACI 2.1

a – Represents phosphorus content of unspecified phosphorus pollutants (e.g., “total phosphorus” in effluent composition).

4.6.2 *Cumulative Energy Demand*

The cumulative energy requirements for a system can be categorized by the fuels from which energy is derived. This method is not an impact assessment, but rather is a cumulative inventory of all energy extracted and utilized. Energy sources consist of non-renewable fuels (natural gas, petroleum, nuclear and coal) and renewable fuels. Renewable fuels include hydroelectric energy, wind energy, energy from biomass, and other non-fossil sources. Cumulative energy demand (CED) includes both renewable and non-renewable sources as well as the embodied energy in biomass and petroleum feedstocks. CED is measured in MJ/kg. Energy is tracked based on the higher heating value (HHV) of the fuel at the point of extraction. Table 4-5 includes a few examples of fuels that contribute to CED in this project and their associated characterization factors.

Table 4-5. Main Energy Resources Contributing to Cumulative Energy Demand

Energy Resource	Compartment	Units	Characterization Factor
Energy, gross calorific value, in biomass	Resource (biotic)	MJ/kg	1.0
Coal, hard, unspecified, in ground	Resource (in ground)	MJ/kg	19
Gas, natural, in ground	Resource (in ground)	MJ/kg	47
Oil, crude, in ground	Resource (in ground)	MJ/kg	46
Selected Method—		Ecoinvent	

4.6.3 *Global Warming Potential*

Global warming refers to an increase in the earth's temperature in relation to long-running averages. In accordance with IPCC recommendations, TRACI's GWP calculations are based on a 100-year time frame and represent the heat-trapping capacity of the gases relative to an equal weight of carbon dioxide. Relative heat-trapping capacity is a function of a molecule's radiative forcing value as well as its atmospheric lifetime. Table 4-6 provides a list of the most common GHGs along with their corresponding GWPs, or CO_2 equivalency factors, used in TRACI 2.1. Contributing elementary flows can be characterized using GWPs reported by the IPCC in either 2007 (Fourth Assessment Report) or in 2013 (Fifth Assessment Report) (IPCC, 2007; IPCC, 2013). While the 2013 GWPs are the most up-to-date, the 2007 GWPs have been officially adopted by the United Nations Framework Convention on Climate Change (UNFCCC) for international greenhouse gas reporting standards and are used by EPA in their annual greenhouse gas emissions report. The baseline results in this study apply the 2007 GWPs, but results with the 2013 GWPs are provided in a sensitivity analysis in Chapter 9.

Table 4-6. Main GHG Emissions Contributing to Global Warming Potential Impacts (kg CO_2 eq/kg GHG)

GHG	Chemical Formula	Compartment	GWP (IPCC 2007)	GWP (IPCC 2013)
Carbon dioxide	CO_2	Air	1.0	1.0
Nitrous oxide	N_2O	Air	3.0E+2	2.7E+2

Table 4-6. Main GHG Emissions Contributing to Global Warming Potential Impacts ($kg CO_2$ eq/kg GHG)

GHG	Chemical Formula	Compartment	GWP (IPCC 2007)	GWP (IPCC 2013)
Methane	CH_4	Air	25	28
Sulfur hexafluoride	SF_6	Air	2.3E+4	2.4E+4
Selected Method—			IPCC 2007 or 2013 100a	

4.6.4 Acidification Potential

The deposition of acidifying substances such as those listed in Table 4-7 have an effect on the pH of the terrestrial ecosystem. Each species within these ecosystems has a range of pH tolerance, and the acidification of the environment can lead to shifting species composition over time. Acidification can also cause damage to buildings and other human infrastructure (Bare, 2012). The variable buffering capacity of terrestrial environments yields a correspondingly varied response per equivalent unit of acidification. Due to a lack of data, the variable sensitivity of receiving regions is not captured in TRACI characterization factors (Norris, 2003). The acidification method in TRACI utilizes the results of an atmospheric chemistry and transport model, developed by the US National Acid Precipitation Assessment Program (NAPAP), to estimate total North American terrestrial deposition of expected SO_2 equivalents due to atmospheric emissions of NO_x and SO_2 and other acidic substances such as HCl and HF, as a function of the emissions location (Bare et al., 2003). Emissions location is modeled in this study as average U.S. using TRACI's composite annual North American emissions average of U.S. states.

Table 4-7. Main Pollutants Contributing to Acidification Potential Impacts ($kg SO_2$ eq/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Sulfur dioxide	SO_2	Air	1.0
Ammonia	NH_3	Air	1.9
Nitrogen dioxide	NO_2	Air	0.70
Nitrogen oxides	NO_x	Air	0.70
Hydrogen chloride	HCl	Air	0.88
Hydrogen fluoride	HF	Air	1.6
Hydrogen sulfide	H_2S	Air	1.9
Selected Method—		TRACI 2.1	

4.6.5 *Fossil Depletion*

Fossil depletion is a measure of the study systems demand for non-renewable energy resources. As non-renewable resources, the availability of fossil energy will not change (i.e., new fossil energy will not be produced) on relevant human timescales. When these resources are depleted and resource quality declines, the cost and environmental impact of accessing a given quantity of energy increases. Fossil depletion is measured in kg oil equivalent based on each fuel's heating value. Renewable energy systems and uranium are not included in the fossil depletion metric but are assessed within the CED methodology previously discussed. Table 4-8 presents common fossil fuel flows and their associated characterization factors for this impact category.

Table 4-8. Main Fossil Fuel Resource Contributing to Fossil Depletion (kg oil eq/kg Fossil Fuel Resource)

Fossil Fuel Resource	Compartment	Characterization Factor
Oil, crude, 42 MJ per kg	Resource (in ground)	1.0
Coal, 18 MJ per kg	Resource (in ground)	0.43
Coal, 29.3 MJ per kg	Resource (in ground)	0.70
Gas, natural, 30.3 MJ per kg	Resource (in ground)	0.72
Gas, natural, 35 MJ per m3	Resource (in ground)	0.83
Methane	Resource (in ground)	0.86
Selected Method—		ReCiPe

4.6.6 *Smog Formation Potential*

The smog formation impact category characterizes the potential of airborne emissions to cause photochemical smog. The creation of photochemical smog occurs when sunlight reacts with NO_x and volatile organic compounds (VOCs), resulting in tropospheric (ground-level) ozone (O_3) and particulate matter. Potential endpoints of such smog creation include increased human mortality, asthma, and deleterious effects on plant growth. Smog formation potential impacts are measured in kg of O_3 equivalents. Table 4-9 includes a list of smog forming chemicals expected to be associated with this project along with their characterization factors.

Table 4-9. Main Pollutants Contributing to Smog Formation Impacts (kg O_3 eq/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Sulfur monoxide	SO	Air	1.0
Carbon monoxide	CO	Air	0.06
Methane	CH_4	Air	0.01
Nitrogen dioxide	NO_2	Air	17
Nitrogen oxides	NO_x	Air	25
VOC, volatile organic compounds	N/A	Air	3.6

Table 4-9. Main Pollutants Contributing to Smog Formation Impacts (kg O_3 eq/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Selected Method—			TRACI 2.1

4.6.7 *Human Health—Particulate Matter Formation Potential*

Particulate matter (PM) emissions have the potential to negatively impact human health. Respiratory complications are particularly common among children, the elderly, and individuals with asthma (U.S. EPA, 2008a). Respiratory impacts can result from a number of types of emissions including PM10, PM2.5, and precursors to secondary particulates such as sulfur dioxide and nitrogen oxides. Respiratory impacts are a function of the fate of responsible pollutants as well as the exposure of human populations. Table 4-10 provides a list of common pollutants contributing to impacts in this category along with their associated characterization factors. Impacts are measured in relation to PM2.5 emissions.

Table 4-10. Main Pollutants Contributing to Human Health-Particulate Matter Formation Potential (kg PM2.5 eq/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Particulates, < 2.5 µm	N/A	Air	1.0
Particulates, > 2.5 µm, and < 10 µm	N/A	Air	0.23
Ammonia	NH_3	Air	0.07
Nitrogen oxides	NO_x	Air	7.2E-3
Sulfur oxides	SO_x	Air	0.06
Selected Method—			TRACI 2.1

4.6.8 *Ozone Depletion Potential*

Stratospheric ozone depletion is the reduction of the protective ozone within the stratosphere caused by emissions of ozone-depleting substance (e.g., CFCs and halons). The ozone depletion impact category characterizes the potential to destroy ozone based on a chemical’s reactivity and atmospheric lifetime. Potential impacts related to ozone depletion includes skin cancer, cataracts, immune system suppression, crop damage, other plant and animal effects. Ozone depletion potential is measured in kg CFC-11 equivalents. Table 4-11 lists common ozone depleting chemicals and their associated characterization factors in TRACI 2.1. Nitrous oxide is incorporated in the results based on the ReCiPe hierarchies midpoint method (Goedkoop et al., 2009).

Table 4-11. Main Pollutants Contributing to Ozone Depletion Potential Impacts (kg CFC11 eq/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	$C_2Cl_3F_3$	Air	1.0
Methane, bromochlorodifluoro-, Halon 1211	$CBrClF_2$	Air	7.1
Methane, bromotrifluoro-, Halon 1301	$CBrF_3$	Air	16
Methane, chlorodifluoro-, HCFC-22	$CHClF_2$	Air	0.05
Methane, trichlorofluoro-, CFC-11	CCl_3F	Air	1.0
Nitrous oxide	N_2O	Air	0.01
Selected Method—			TRACI 2.1, ReCiPe

4.6.9 Water Depletion

Water use results are displayed on a consumptive basis (i.e., depletion). When water is withdrawn from one water source and returned to another watershed this is considered consumption, as there is a net removal of water from the original water source. For instance, it is assumed that deepwell injection of the brine fluid from RO is consumptive water use, since water is being diverted from a watershed making it unavailable for subsequent environmental or human uses. Consumption also includes water that is withdrawn and evaporated or incorporated into the product. Cooling water that is closed-loop circulated, and does not evaporate, is not considered consumptive use. Water consumption is only included as an inventory category in this study, which is a simple summation of water inputs. The analysis does not attempt to assess water-related damage factors. For instance, there is no differentiation between water consumption that occurs in water-scarce or water-abundant regions of the world. Water consumption in this study includes values for upstream fuel and electricity processes. In addition to water consumption associated with thermal generation of electricity from fossil and nuclear fuels, the water consumption for power generation includes evaporative losses due to establishment of dams for hydropower. Table 4-12 shows some of the common flows associated with water use along with their characterization factors. Section 4.6.15 also discusses some of the uncertainty associated with calculating water depletion in LCA.

Table 4-12. Main Water Flows Contributing to Water Depletion

Water Flow	Compartment	Units	Characterization Factor
Water, lake	Resource (in water)	m^3 H_2O/m^3	1.0
Water, river	Resource (in water)	m^3 H_2O/m^3	1.0
Water, unspecified natural origin	Resource (in water)	m^3 H_2O/m^3	1.0
Water, well, in ground	Resource (in water)	m^3 H_2O/m^3	1.0
Water, unspecified natural origin/kg	Resource (in water)	m^3 H_2O/kg	1.0E-3
Selected Method—		ReCiPe	

4.6.10 Human Health—Cancer Potential

Carcinogenic human health results in this study are expressed on the basis of Comparative Toxic Units (CTU_h) based on the USEtox™ method (Huijbregts et al. 2010). Characterization factors within the USEtox™ model are based on fate, exposure, and effect factors. Each chemical included in the method travels multiple pathways through the environment based on its physical and chemical characteristics. The potential for human exposure (e.g., ingestion or inhalation) varies according to these pathways. The effect factor characterizes the probable increase in cancer-related morbidity for the total human population per unit mass of a chemical emitted (i.e., cases per kg) (Rosenbaum et al., 2008). The full USEtox™ model contains over 3,000 chemicals of global relevance and is the product of an international project to harmonize the approach to evaluation of toxicity effects. The USEtox™ model develops characterization factors at the continental and global scale. The exclusion of more localized parameters is justified in that it was found during the harmonization process that site-specific parameters have a far lower impact on results than do the substances themselves.

Global midpoint characterization factors are employed from the most recent version of USEtox™ available in OpenLCA, version 2.02. An updated version of USEtox™, version 2.11, was released in April 2019. Characterization factors for the heavy metals, toxic organics and DBPs were updated in the OpenLCA USEtox™ LCIA method to match version 2.11. All other characterization factors remain at the default value for OpenLCA's USEtox version 2 (recommended+interim) database. Not all heavy metals, toxic organics and DBPs have established characterization factors in the USEtox™ method. Several additional sources were used to identify appropriate characterization factors. When no appropriate characterization factor was identified, the pollutant was assigned a characterization factor equal to the median characterization factor for its trace pollutant group. Table B-5, Table C-8, and Table D-4 list values and sources of characterization factors for all heavy metals, toxic organics, and DBPs. For illustration purposes, Table 4-13 lists five of the primary chemicals contributing to cancer human health impacts in the US and Canada (Ryberg, 2014) along with their associated characterization factors.

The developers of the USEtox™ method are clear to point out that some of the characterization factors associated with human health effects should be considered interim, owing to uncertainty in their precise values ranging across one to three orders of magnitude. Sources of uncertainty are often attributable to the use of one exposure route as a proxy for another (route-to-route extrapolation). For a more detailed discussion of uncertainty present in these models, see the USEtox™ User's Manual (Huijbregts et al., 2010). Appropriate interpretation of results must consider the uncertainty associated with the use of interim characterization factors.

Table 4-13. Main Pollutants Contributing to Human Health - Cancer Potential Impacts (CTU_h/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Arsenic	As	Soil	1.8E-4[a]
Formaldehyde	CH_2O	Air	2.5E-5

Table 4-13. Main Pollutants Contributing to Human Health - Cancer Potential Impacts (CTU_h/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Chromium VI	Cr	Soil	5.0E-3[a]
Chromium VI	Cr	Air, urban	3.8E-3[a]
Chromium VI	Cr	Water	0.01[a]
Selected Method—			USEtox™ 2.11

a – Designates an interim characterization factor.

4.6.11 Human Health—Noncancer Potential

Non-carcinogenic human health results in this study are expressed on the basis of Comparative Toxic Units (CTU_h) based on the USEtox™ method, which is incorporated in TRACI 2.1. The impact method characterizes the probable increase in noncancer related morbidity for the total human population per unit mass of a chemical emitted (i.e., cases per kg) (Rosenbaum et al., 2008). These impacts are calculated using the same approach as that taken for human health - cancer (Section 4.6.10).

Global midpoint characterization factors are employed from the most recent version of USEtox™ available in OpenLCA, version 2.02. An updated version of USEtox™, version 2.11, was released in April 2019. Characterization factors for the heavy metals, toxic organics and DBPs were updated in the OpenLCA USEtox™ LCIA method to match version 2.11. All other characterization factors remain at the default value for OpenLCA's USEtox version 2 (recommended+interim) database. Not all heavy metals, toxic organics and DBPs have established characterization factors in the USEtox™ method. Several additional sources were used to identify appropriate characterization factors. When no appropriate characterization factor was identified, the pollutant was assigned a characterization factor equal to the median characterization factor for its trace pollutant group. Table B-5, Table C-8, and Table D-4 list values and sources of characterization factors for all heavy metals, toxic organics, and DBPs. For illustration purposes, Table 4-14 lists the main chemicals contributing to noncancer, human health impacts (Ryberg, 2014) along with their associated characterization factors.

As is discussed in Section 4.6.10, uncertainty in USEtox factors can range across one to three orders of magnitude for interim characterization factors, which are identified in Table 4-14. At the current time, all characterization factors for metal compounds are considered interim. Appropriate interpretation of results must consider the uncertainty associated with the use of interim characterization factors.

Table 4-14. Main Pollutants Contributing to Human Health—Noncancer Potential Impacts (CTU_h/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Acrolein	C_3H_4O	Soil	3.4E-5
Zinc, ion	Zn^{2+}	Soil	1.4E-4[a]

Table 4-14. Main Pollutants Contributing to Human Health—Noncancer Potential Impacts (CTU_h/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Arsenic, ion	As^{3+}	Soil	0.01[a]
Zinc, ion	Zn^{2+}	Air, urban	5.7E-3[a]
Mercury (+II)	Hg(II)	Air, urban	1.24[a]
Selected Method—			USEtox™ 2.11

a – Designates an interim characterization factor.

4.6.12 Ecotoxicity Potential

Ecotoxicity is a measure of the effect of toxic substances on ecosystems. The effects on freshwater ecosystems are used as a proxy for general ecological impact. Characterization factors within the ecotoxicity model are based on fate, exposure, and effect factors. Each chemical included in the method travels multiple pathways through the environment. As a result of these pathways, various compartments (e.g., freshwater, terrestrial) and the species they contain will have differing opportunities to interact with the chemical in question (exposure). The effect factor refers to the potential negative consequences on ecosystem health when exposure does occur (Huijbregts, 2010). The exclusion of more localized parameters is justified in that it was found during the harmonization process that these parameters have a far lower impact on results than do the substances themselves. Ecotoxicity impacts are measured in terms of the Potentially Affected Fraction of species due to a change in concentration of toxic chemicals (PAF m^3 ·day/kg). These units are also known as comparative toxicity units (CTUe).

Global midpoint characterization factors are employed from the most recent version of USEtox™ available in OpenLCA, version 2.02. An updated version of USEtox™, version 2.11, was released in April 2019. Characterization factors for the heavy metals, toxic organics and DBPs were updated in the OpenLCA USEtox™ LCIA method to match version 2.11. All other characterization factors remain at the default value for OpenLCA’s USEtox version 2 (recommended+interim) database. Not all heavy metals, toxic organics and DBPs have established characterization factors in the USEtox™ method. Several additional sources were used to identify appropriate characterization factors. When no appropriate characterization factor was identified, the pollutant was assigned a characterization factor equal to the median characterization factor for its trace pollutant group. Table B-5, Table C-8, and Table list values and sources of characterization factors for all heavy metals, toxic organics, and DBPs. For illustration purposes, Table 4-15 lists some of the main chemicals found to contribute to ecotoxicity impacts (Ryberg, 2013) and their USEtox™ global characterization factors.

As is discussed in Section 4.6.10, uncertainty in USEtox factors can range across one to three orders of magnitude for interim characterization factors, which are identified in Table 4-15. At the current time, all characterization factors for metal compounds are considered interim. Appropriate interpretation of results must consider the uncertainty associated with the use of interim characterization factors.

Table 4-15. Main Pollutants Contributing to Ecotoxicity Potential Impacts (CTUe [PAF m^3.day/kg Pollutant])

Pollutant	Chemical Formula	Compartment	Characterization Factor
Zinc, ion	Zn^{2+}	Ground water	1.3E+5[a]
Chromium VI	Cr(VI)	Ground water	1.0E+5[a]
Nickel, ion	Ni^{2+}	Ground water	3.0E+5[a]
Chromium VI	Cr(VI)	River	1.0E+5[a]
Arsenic, ion	As^{3+}	Ground water	1.5E+4[a]
Selected Method—			USEtox™ within TRACI 2.11

a – Designates an interim characterization factor.

4.6.13 Normalization

Normalization is an optional step in LCIA 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 in this study are normalized to reflect person equivalents in the U.S. using TRACI v2.1 normalization factors (Ryberg et al., 2013). Only impacts with TRACI normalization factors are shown. Some categories like water use and CED are excluded due to lack of available normalization factors.

4.6.14 LCIA Limitations

While limitations of the LCI model are specifically discussed in Section 4.4, some of the main limitations that readers should understand when interpreting the life cycle impact assessment findings are as follows:

- **Coverage of Emissions Leading to Toxicity:** ~~The scope for the results for the three USEtox™ categories (human health - cancer, human health - noncancer, and ecotoxicity) excludes toxicity from wastewater effluent and should be considered with low confidence. These category results are largely dependent on toxic pollutants from sludge in a landfill. However, these toxic pollutants may also be present in the effluent release at the WWTP.~~ The toxicity impacts associated with the sludge and the effluent are limited to pollutants selected in Chapter 2. Such toxic pollutants in the effluent were not assessed in the baseline LCA model; therefore, the toxicity impact categories are showing incomplete results.
- **Transferability of Results:** While this study is intended to inform decision-making for a wide range of stakeholders, the impacts presented here relate to a theoretical average U.S. WWTP. For instance, this study does not address geographic differences that could impact WWTP design, cost options, or local variation in environmental impacts. Further work is recommended to understand the variability of key parameters across specific regional and facility-level situations. Also, the study

looked at greenfield installations only so impacts or benefits would vary for retrofitted operations.

- **LCIA Method Uncertainty:** In addition to the uncertainty of the LCI data, there is uncertainty associated with the application of LCIA methodologies and normalization factors to aggregated LCI. For example, two systems may release the same total amount of the same substance, but one quantity may represent a single high-concentration release to a stressed environment while the other quantity may represent the aggregate of many small dilute releases to environments that are well below threshold limits for the released substance. The actual impacts would likely be very different for these two scenarios, but the LCI does not track the temporal and spatial resolution or concentrations of releases in sufficient detail for the LCIA methodology to model the aggregated emission quantities differently. Therefore, it is not possible to state with complete certainty that differences in potential impacts for two systems are significant differences. Although there is uncertainty associated with LCIA methodologies, all LCIA methodologies are applied to different wastewater treatment configurations uniformly. Therefore, comparative results can be determined with a greater confidence than absolute results for one system. Minimum threshold values for determining meaningful impact differences between wastewater treatment configurations by category are provided in the next section.

4.6.15 Interpreting LCIA Results Differences

Interpretation of LCIA results requires interpretation of the uncertainty associated with inventory data (lists of compounds and resources emitted or extracted by the system under study) and the impact models used to characterize inventory data, translating emissions into impacts. Note that there is also uncertainty associated with the definition of system boundaries, and determination of cutoff values for exclusion of data.

The current state of practice in life cycle assessment includes a quantitative analysis of the uncertainty in inventory data. In this study, much of the background process data, which is part of the ecoinvent database, includes such uncertainty analyses. Possible underestimations of uncertainty associated with ecoinvent are known (Weidema et al., 2011); however, ecoinvent and agricultural inventory uncertainties are expected to be lower overall than impact uncertainty.

At the impact level, uncertainty is not yet typically included in LCA studies; indeed, not all LCA software has this ability. A spatially explicit model of aquatic acidification (Roy et al., 2014) analyzed both parameter uncertainty (via a Monte Carlo approach) and spatial uncertainty. At the characterization factor level, parameter uncertainty contributed a factor of 100 uncertainty, whereas spatial variability ranged from 5 to 8 orders of magnitude for different acidifying compounds.

At the analysis level, it is important to consider that uncertainty in inventory or characterization is not purely multiplicative when considering differences between systems (Hong et al., 2010). For many LCA analyses, many background and some foreground processes will be shared between systems. For example, background electricity generation is often shared, while chemical additives or concrete could be shared foreground processes for wastewater treatment. Therefore, analyses of *differences* between systems must account for these shared processes. Within confidence bounds, systems may be different even if the difference between their impact scores is less than the absolute uncertainty on the corresponding characterization factor (e.g., factor 100 for acidification, from above).

In a case study, Humbert et al. (2009) provide guidelines for determining whether differences in LCA impact results are meaningful. In the energy and global warming category, this minimum significant difference is a 10 percent threshold (i.e., in comparing contributions to this category, a difference lower than 10 percent is not considered to be significant). For particulate matter formation, smog formation, acidification, ozone depletion, and eutrophication, the minimum significant difference is 30 percent. For the toxicity categories, an order of magnitude (factor 10) difference is typically required for a difference to be significant, especially if the dominant emissions are different between scenarios or are dominated by long-term emissions from landfills that can be highly uncertain. In the absence of a detailed uncertainty analysis, these threshold guidelines may serve to help interpretation. This study uses the percent difference thresholds defined by the Humbert et al. 2009 case study with the exception of GWP impact results. As discussed in Section 4.4, there are case-specific uncertainties for estimating GHG emissions from biological treatment. Therefore, this study uses a higher threshold of 30 percent to determine whether a notable GWP difference exists between wastewater treatment configurations. There are also specific considerations for uncertainty thresholds for water depletion results as discussed below.

There is currently a lack of water use data on a unit process level for LCIs. In addition, water use data that are available from different sources do not use a consistent method of distinguishing between consumptive use and non-consumptive use of water or clearly identifying the water sources used (freshwater versus saltwater, groundwater versus surface water). A recent article in the International Journal of Life Cycle Assessment summarized the status and deficiencies of water use data for LCA, including the statement, “To date, data availability on freshwater use proves to be a limiting factor for establishing meaningful water footprints of products” (Koehler, 2008). The article goes on to define the need for a standardized reporting format for water use, taking into account water type and quality as well as spatial and temporal level of detail.

Water consumption is modeled using values reported in literature. In some cases, consumptive use data may not be available. The ecoinvent database includes water in the life cycle inventory as an input and does not record water released to the environment (i.e., as an emission) or water consumed. However, ecoinvent is currently one of the most comprehensive LCI sources on water for upstream processes; many other available databases do not report water input/use as an inventory item. Therefore, when case-specific data were not available, ecoinvent data were utilized for the water calculations. When utilizing ecoinvent, the data are adapted to represent consumptive use to the extent possible: fresh water removed from the environment that is not internally recirculated.

Because water consumption values are uncertain, a minimum 30 percent difference is required to consider water consumption results significantly different. Comparative results can be determined with a greater confidence than absolute results for one system.

5. LIFE CYCLE COST BASELINE RESULTS

This section presents the LCCA results for the nine wastewater treatment configurations included in this study. Table 5-1 presents the total capital, total annual, and net present value for each of the wastewater treatment configurations. As discussed in Section 3.3.2, the net present value combines the one-time capital costs and periodic (annual) operating and maintenance costs into one value for direct comparison of costs. The following sections provide additional discussion differences with the results of the total capital and annual costs (Section 5.1) and net present value (Section 5.2). The results are discussed by unit process and aggregated treatment group, as shown in Table 5-2. For treatment groups, the unit processes are generally grouped sequentially; however, preliminary treatment stages are grouped with disinfection, even though these are not sequential unit processes because, in this study, these unit processes do not vary between wastewater treatment configurations. Complete cost results are presented in Appendix H.

Table 5-1. Total Costs by Wastewater Treatment Configuration

Wastewater Treatment Configuration	Total Capital Cost (2014 $)	Total Annual Cost [a] (2014 $/yr)	Net Present Value (2014 $)
Level 1, AS	$55,300,000	$5,140,000	$204,000,000
Level 2-1, A2O	$71,400,000	$5,470,000	$236,000,000
Level 2-2, AS3	$93,100,000	$10,150,000	$378,000,000
Level 3-1, B5	$86,400,000	$5,800,000	$267,000,000
Level 3-2, MUCT	$88,900,000	$5,960,000	$275,000,000
Level 4-1, B5/Denit	$92,800,000	$6,840,000	$301,000,000
Level 4-2, MBR	$90,100,000	$6,340,000	$285,000,000
Level 5-1, B5/RO	$160,000,000	$8,320,000	$439,000,000
Level 5-2, MBR/RO	$144,000,000	$8,070,000	$409,000,000

a – Total annual cost includes operational labor, maintenance labor, materials, chemicals, and energy (see Section 3.3 for details).

Table 5-2. Unit Processes by Treatment Group

Treatment Group	Unit Processes Included in the Stage	
Preliminary/Primary/Disinfection	Screening and Grit Removal	Chlorination
	Primary Clarifier	Dechlorination
Biological Treatment	Activated Sludge	Tertiary Clarification, Nitrification
	Secondary Clarifier	Denitrification, Suspended Growth
	Anaerobic/Anoxic/Oxic (A2O)	Nitrification, Suspended Growth
	4-Stage Bardenpho	Membrane Filter
	5-Stage Bardenpho	Fermentation
	Tertiary Clarification, Denitrification	Modified University of Cape Town
Post-Biological Treatment	Sand Filtration	Ultrafiltration
	Reverse Osmosis	Chemical Phosphorus Removal
	Denitrification, Attached Growth	

Table 5-2. Unit Processes by Treatment Group

Treatment Group	Unit Processes Included in the Stage	
Sludge Processing and Disposal	Centrifuge	Sludge Hauling and Landfill
	Anaerobic Digester	Gravity Thickener
Effluent Release	Effluent Release	
Brine Injection	Brine Injection	

5.1 Total Capital and Total Annual Cost Results

As described in Section 3.3, the total plant costs are presented as the total capital costs along with the total annual costs. This section presents the total capital and total annual costs and describes the differences in cost by process contribution and treatment group.

5.1.1 Total Capital Costs

Total capital costs generally increase from Level 1 to Level 5, as presented in Figure 5-1. For Level 2, the Level 2-1 A2O total capital costs are almost $22 million lower than the Level 2-2 AS3 total capital costs. The total capital costs for Level 2-2 AS3 are also over $4 million higher than both Level 3 wastewater treatment configurations. This is because the Level 2-2 AS3 wastewater treatment configuration includes three separate biological units (plug-flow activated sludge, nitrification, and denitrification) with dedicated clarifiers, while the Level 2-1 A2O, Level 3-1 B5, and Level 3-2 MUCT wastewater treatment configurations only include one biological unit that have three to five chambers with a secondary clarifier. The multiple clarifiers in Level 2-2 AS3 also results in more sludge generation and, as a result, has larger sludge processing and disposal units, which also contribute to the higher total capital cost for Level 2-2 AS3 compared to Level 2-1 A2O and both Level 3 wastewater treatment configurations. The total capital cost for Level 2-2 AS3 is more comparable to both Level 4 wastewater treatment configurations. Increasing effluent quality from Level 4 to Level 5 increases the total capital costs by over $50 million because of the added post-biological treatment units (i.e., ultrafiltration, reverse osmosis, and deep injection well for Level 5-1 B5/RO and reverse osmosis and deep injection well for Level 5-2 MBR/RO). Total capital costs for the preliminary/primary/disinfection treatment group are included but are comparable for all of the wastewater treatment configurations, as there are no significant design differences between these portions of the wastewater treatment configurations.

For this study, the total capital costs for the biological treatment group generally increases with increasing effluent quality because the biological treatment units are designed to achieve increased nitrogen and phosphorus removals; increased nitrogen and phosphorus removals require a larger sized and/or more complex biological treatment unit. Note that there are biological treatment units outside of the study that may not follow this trend. However, the Level 5-1 B5/RO biological treatment group total capital costs are similar to both Level 3 and Level 4-1 B5/Denit biological treatment group costs because they have the same biological unit processes (BNR plus secondary clarifier) and are designed to achieve the same nitrogen and phosphorus removals. The Level 4-2 MBR and Level 5-2 B5/RO have higher biological treatment group costs by more than $5 million. Although they are designed to achieve the same nitrogen and phosphorus removals as Level 3, Level 4-1 B5/Denit, and Level 5-1 B5/RO, the Level 4-2 MBR and Level 5-2 B5/RO have membrane bioreactors instead of secondary clarifiers, which increases cost. For all these wastewater treatment configurations, the nitrogen and phosphorus removed beyond the Level 3 targets is achieved through post-biological treatment units (e.g., denitrification filter, ultrafiltration, reverse osmosis).

The post-biological treatment group is a component of all levels except Level 1 AS and Level 2-1 A2O since these levels do not require chemical phosphorus removal or additional nutrient control unit processes. The lowest post-biological treatment capital costs are for Level 2-2 AS3 and Level 4-2 MBR, which only require chemical phosphorus removal. There is a large jump in post-biological treatment capital costs for the Level 5 wastewater treatment system configurations due to the addition of ultrafiltration and the reverse osmosis unit. The Level 5-1 B5/RO post-biological treatment capital cost is more than double the Level 5-2 MBR/RO because Level 5-1 B5/RO also includes the sand filter, ultrafiltration, and has a larger reverse osmosis unit.

The sludge processing and disposal treatment group capital costs are comparable for all the wastewater treatment configuration except for Level 2-2 AS3, which has a larger anaerobic digester, larger centrifuge, increased number of vehicles (hauling and land filling), and larger onsite sludge storage shed (hauling and land filling) capital costs. As discussed previously, the Level 2-2 AS3 system has three separate clarifiers and a very high alum dose that increases the quantity of sludge generated even beyond that of higher performing wastewater treatment configurations, which are able to achieve their level of phosphorus removal performance through a combination of chemical precipitation and other unit processes.

The Level 5 wastewater treatment configurations both have RO which requires brine disposal capital costs, while the other wastewater treatment configurations do not. The other capital costs include the direct and indirect costs that are calculated as a percentage of the purchased equipment cost component of the total capital cost (see Section 3.3.1 for details). As a result, the other capital costs increase as the other components of the total capital costs increase.

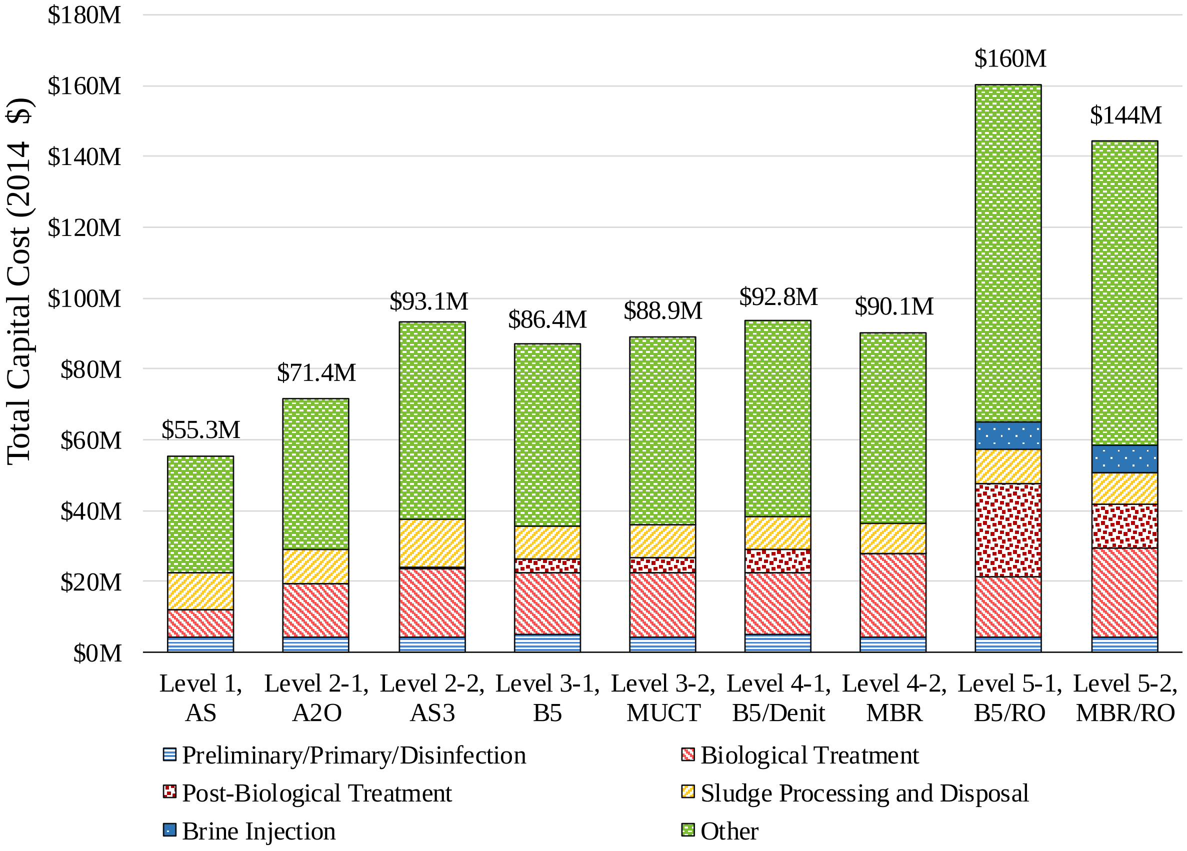

Figure 5-1. Total Capital Costs by Aggregated Treatment Group

5.1.2 Total Annual Costs

Figure 5-2 presents the total annual costs for all the wastewater treatment configurations broken into the annual cost components. The total annual costs are highest for Level 2-2 AS3, followed by Level 5-1 B5/RO and Level 5-2 MBR/RO. The annual costs for operation labor is highest for Level 2-2 AS3 because of the increased sludge processing and disposal from the 3-sludge system. The maintenance labor for Level 1, Level 2-1 A2O, and both Level 3 wastewater treatment configurations is generally comparable, while the maintenance labor for Level 2-2 AS3, both Level 4, and both Level 5 wastewater treatment configurations is generally comparable. The maintenance labor for Level 2-2 AS3, both Level 4, and both Level 5 wastewater treatment configurations is higher because these wastewater treatment configurations have more unit processes. The materials annual costs are highest for Level 2-2 AS3, again due to the increased sludge processing and disposal from the 3-sludge system. Level 2-2 AS3 annual chemical costs are between 3.3 times (Level 5-1 B5/RO) and almost 8.5 times (Level 2-1 A2O) higher than the other wastewater treatment configurations due to the large alum dose for chemical phosphorus removal in Level 2-2 AS3. This large dose is needed compared to other wastewater treatment configurations because Level 2-2 AS3 achieves phosphorus removal solely through chemical phosphorus precipitation while the other wastewater treatment configurations have some level of biological phosphorus removal. The annual costs for Levels 5-1 B5/RO and

5-2 MBR/RO are driven by the annual energy costs, which are between 2 times (Level 4-1 B5/MBR) and almost 4 times (Level 1 AS) higher than the annual energy costs for the other wastewater treatment configurations because both Level 5 configurations include an energy-intensive reverse osmosis unit.

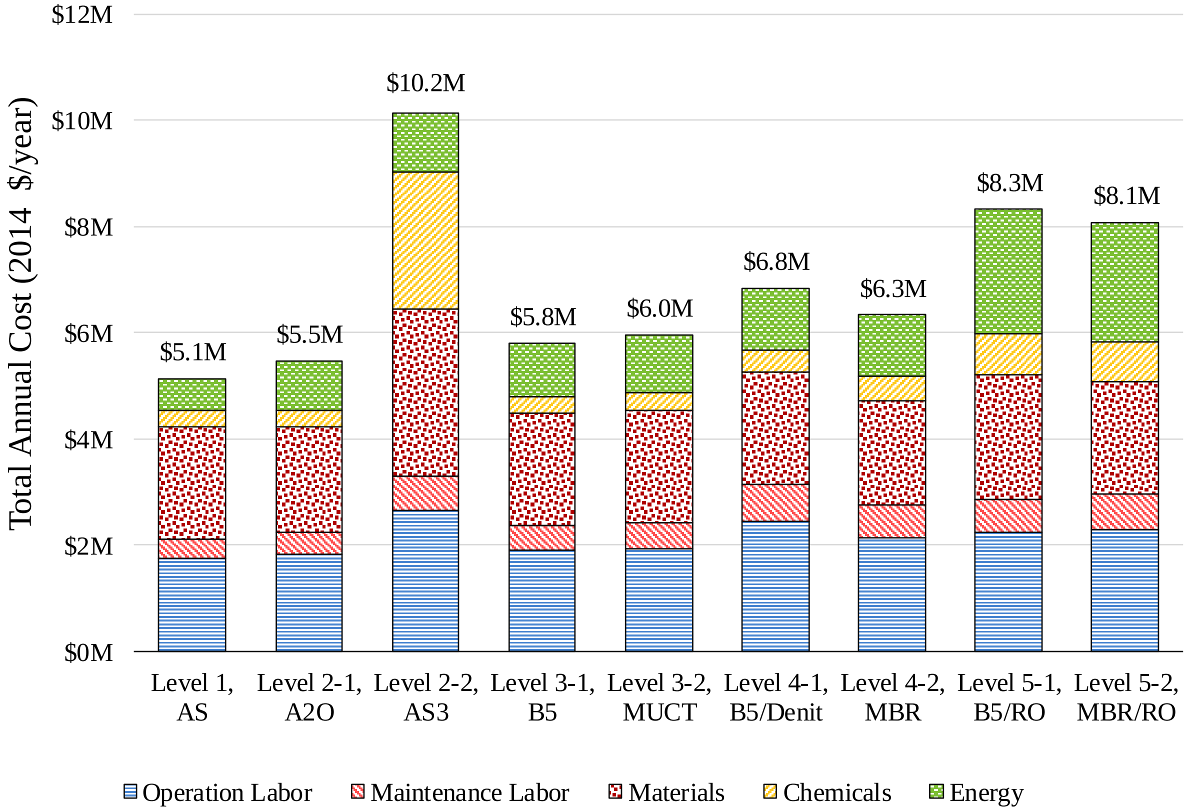

Figure 5-2. Annual Costs by Wastewater Treatment Configuration

Figure 5-3 presents the total annual costs for all the wastewater treatment configurations broken out according to treatment group. The total annual costs for the preliminary/primary/disinfection treatment group are comparable for all of the wastewater treatment configurations, as there are no significant operating differences between the various wastewater treatment configurations.

The biological treatment total annual costs are the highest for Level 2-2 AS3 due to the operational labor, maintenance labor, and chemical costs associated with the three separate biological units. The only chemical addition in the biological treatment portion of Level 2-2 AS3 is for methanol addition in the suspended growth denitrification process unit. The 4-stage and 5-stage Bardenpho and Modified University of Cape Town unit processes in Level 3-1 through Level 5-2 have comparable total annual costs, however the total annual costs for the membrane bioreactors are much higher than the total annual costs for the secondary clarifiers. As a result, the biological treatment total annual costs for the Level 4-2 MBR and Level 5-2 MBR/RO wastewater treatment configurations are high. These wastewater treatment configurations have higher annual operational labor due to the membrane bioreactor and membrane cleaning chemical costs. The Level 4-2 MBR also has supplemental methanol addition immediately preceding the 4-stage Bardenpho reactor, which accounts for the higher chemical costs than Levels 2-1 A2O and both Level 3 wastewater treatment configurations. The Level 4-1 B5/Denit wastewater treatment configuration also has supplemental methanol addition to the denitrification filter, but the methanol dose is lower than the Level 4-2 MBR.

The total annual costs for post-biological treatment are highest for Level 5-1 B5/RO, followed by Levels 2-2 AS3, Level 4-1 B5/Denit, and Level 5-2 MBR/RO, which are all comparable. The Level 5-1 B5/RO annual costs are the highest because of the high energy demand for the ultrafiltration, reverse osmosis unit, and brine injection well, along with having high material replacement costs for the ultrafiltration and reverse osmosis membranes. The Level 2-2 AS3 post-biological treatment annual costs are driven by the alum chemical costs for chemical phosphorus removal. Level 4-1 B5/Denit post-biological treatment annual costs are driven by operational and maintenance labor. The Level 5-1 MBR/RO post-biological treatment annual costs are driven by energy demand for the reverse osmosis and brine injection well, along with the materials replacement cost for the reverse osmosis membranes.

The sludge processing and disposal costs are comparable for all of the wastewater treatment configurations, except for Level 2-2 AS3, which is about $1 million/year more than the other configurations due to the additional sludge generated from the three clarifiers and high alum dose for chemical phosphorus removal.

The Level 5 wastewater treatment configurations both have brine disposal, while the other wastewater treatment configurations do not. The annual costs for the brine disposal are the same for both Level 5 configurations.

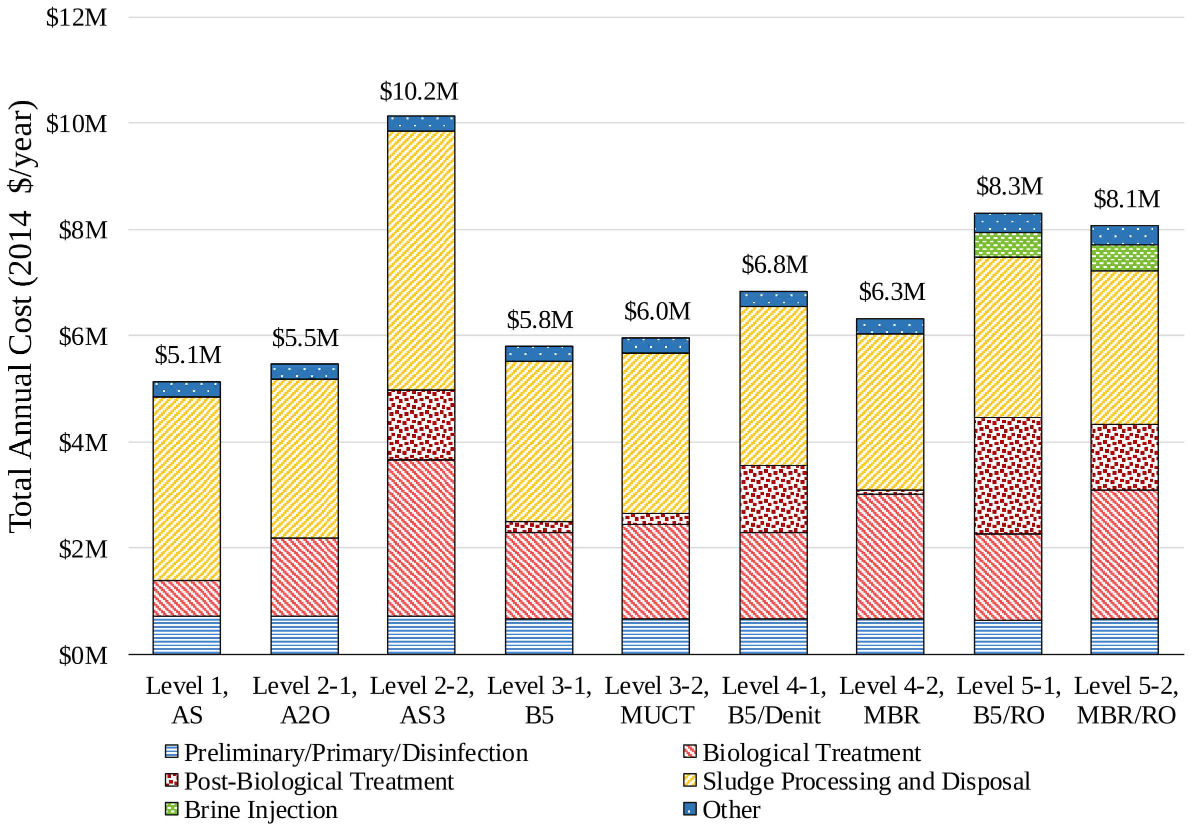

Figure 5-3. Annual Costs by Aggregated Treatment Group

5.2 Net Present Value Cost Results

The net present value, presented in Figure 5-4, trends similarly to the total annual costs discussed in Section 5.2. The net present value for Level 1 AS is the lowest, while the Level 5-1 B5/RO the highest. In general, the net present value increases with increasing nutrient control levels, except for Level 2-2 AS3, which has a net present value almost as high as the Level 5-2 MBR/RO wastewater treatment configuration due to the high annual costs associated with the three separate biological units as discussed in Section 5.1.2. The net present value for both Level 3 wastewater treatment configurations are similar, with only a $8 million difference. The net present value for both Level 4 wastewater treatment configurations are also similar, with only a $2 million difference.

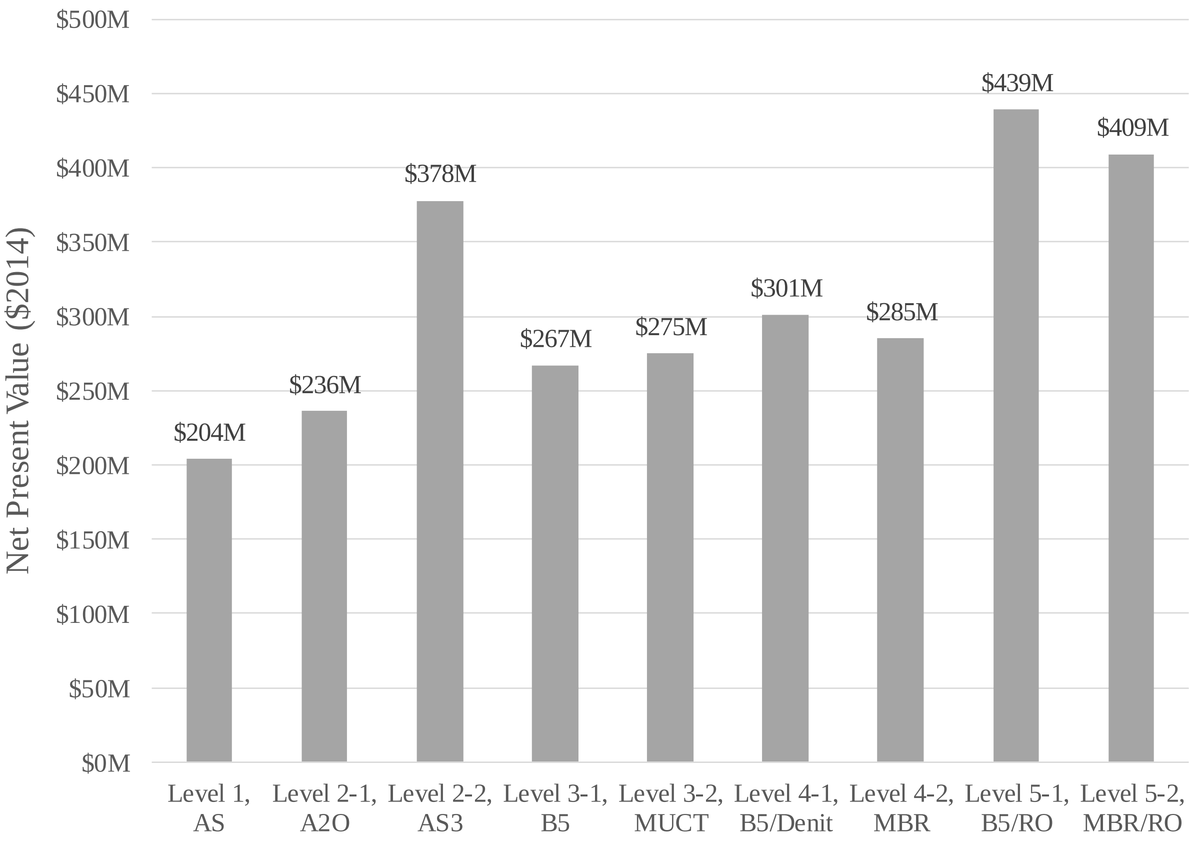

Figure 5-4. Net Present Value by Wastewater Treatment Configuration

5.3 Cost Results Quality Discussion

In accordance with the project’s Quality Assurance Project Plan (QAPP) entitled *Quality Assurance Project Plan for Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants* approved by EPA on March 25, 2015 (ERG, 2015c), ERG subjected the LCCA results to a multi-stage review, verification, and validation process.

The LCCA methodology and results received three levels of technical review, including conceptual review, developmental review, and final product review. ERG developed the planned LCCA approaches and methods; subjected them to internal review by ERG technical reviewers with knowledge relevant to engineering costing, but not directly involved in the approach development; and discussed them with GLEC and EPA during regular project meetings. During development of the LCCA methodologies and results, all CAPDETWorks™ output files and supplemental cost estimation spreadsheets underwent internal technical review to verify the estimates and calculations comported with the planned methods and approaches and confirm the accuracy of the calculations. Finally, ERG conducted an overall assessment of the reasonableness of the final LCCA results. For example, ERG confirmed that differences among the unit-process and configuration-level costs, and other factors such as chemical demand, energy use, and sludge generation, were reasonable based on engineering judgement of the relative size and complexity of the units and systems.

ERG validated the LCCA results by comparing them against available data that were not used in the project to develop the LCCA. For the CAPDETWorks™ costing, ERG compared the total capital and total annual costs and net present value costs for Level 1 AS, Level 2-1 A2O, Level 3-1 B5, Level 4-1 B5/Denit, and Level 5-1 B5/RO to similar treatment systems in Falk et al., 2011, which are presented in Table 5-3. ERG was unable to identify additional literature that included planning-level costs for greenfield wastewater treatment plants with similar wastewater treatment configurations. The other wastewater treatment configurations were not included in Falk et al., and are therefore not included in Table 5-3. In general, Falk et al. included limited detail for a direct comparison with the wastewater treatment configurations included in this study. As an example, Falk et al. did not provide the software used to develop the costs, only included select design parameters for select unit processes, and did not present the unit process-specific costs. The total capital costs in this study are 50-66% of the capital costs presented in Falk et al. Falk (2017) noted that Falk et al. included a raw sewage pump station, more conservative construction assumptions associated with site conditions (e.g., sheeting, shoring, dewatering), and higher concrete unit costs than for this study. The total annual costs for this study are between 1.5 and 5.0 times higher than the total annual costs in Falk et al. This difference is predominately due to the scope of the annual costs; this study included operational labor, maintenance labor, materials, chemicals, and energy, while Falk et al. only included chemicals and energy. For this study, the operational labor, maintenance labor, and materials accounted for 63 to 82% of the total annual costs. Although there are differences between the costs developed for this study and presented in Falk et al., literature sources indicate that CAPDETWorks™ construction estimates are within 20% of actual construction costs (U.S. EPA OWM, 2008b). The net present value for this study are $66 million to $104 million higher than the net present value from Falk et al. This is primarily due to the differences in total annual costs discussed above, but also because Falk et al. used 5% discount rate and 3.5% escalation rate for capital, energy, and non-energy components. This study calculated net present value using 3% discount rate and did not escalate any costs.

Table 5-3. Total Costs Compared to Falk et al., 2011

Wastewater Treatment Configuration	Total Capital Cost (2014 $)	Falk et al. Total Capital Costs (2014 $) [a]	Total Annual Cost (2014 $/yr)	Falk et al. Total Annual Costs (2014 $) [a]	Net Present Value (2014 $)	Falk et al. Net Present Value (2014 $) [a]
Level 1, AS	$55,300,000	$103,000,000	$5,140,000	$1,020,000	$204,000,000	$123,000,000
Level 2-1, A2O	$71,400,000	$142,000,000	$5,470,000	$1,410,000	$236,000,000	$167,000,000
Level 3-1, B5	$93,100,000	$161,000,000	$10,150,000	$2,620,000	$378,000,000	$201,000,000
Level 4-1, B5/Denit	$86,400,000	$171,000,000	$5,800,000	$3,570,000	$267,000,000	$234,000,000
Level 5-1, B5/RO	$88,900,000	$243,000,000	$5,960,000	$5,570,000	$275,000,000	$335,000,000

a – ERG converted Falk et al.'s costs from 2010 dollars to 2014 dollars using the calculations presented in Section 3.2.1.

b – Total annual cost includes operational labor, maintenance labor, materials, chemicals, and energy (see Section 3.3 for details).

Validation of the cost results for ultrafiltration, reverse osmosis, and brine disposal was difficult as these technologies represent the state-of-the-art in the municipal wastewater treatment industry with few or no applications in the U.S. and little or no published data. For ultrafiltration, ERG compared the cost results to Noble et al., 2003. Noble et al. describes a study of the performance of a pilot-scale microfiltration treatment system, and provides detailed capital and O&M cost estimates for a full-scale 5 MGD system. The vendor, US Filter, is a major membrane technology provider. The study regards surface-water treatment, rather than domestic wastewater treatment, and is somewhat dated. ERG found the capital costs for the two data sources differed by approximately 11%, which is well within the range of uncertainty for planning-level costs. ERG did not compare the operating and maintenance costs, as the Noble et al., 2003 costs are specific to treatment of surface water and are not applicable to domestic wastewater treatment.

For reverse osmosis, ERG compared the cost results to costs published by the Orange County Water District, 2010. The Orange County report described the estimated capital costs for a planned 30 MGD expansion of their Groundwater Replenishment System, which includes treatment of domestic wastewater using reverse osmosis and other technologies. We found the reverse osmosis capital costs for the two data sources differed by approximately 9%, which is well within the range of uncertainty for planning-level costs.

Energy usage is a significant component of total operating and maintenance costs for membrane technologies such as ultrafiltration and reverse osmosis. ERG validated the estimated energy usage provided by vendors to a literature source WateReuse Research Foundation, 2014. For ultrafiltration, estimated energy usage by the vendor (ERG, 2015a) and WateReuse Research Foundation, 2014 were 0.5 kWh/kgal and 0.75 to 1.1 kWh/kgal, respectively. Due to concerns regarding the validity of estimated energy usage, for the final ultrafiltration costs estimates, ERG used the average estimated energy usage reported by these two sources (see Appendix E.5). For reverse osmosis, estimated energy usage by the vendor (ERG, 2015b) and WateReuse Research Foundation, 2014 were 1.2 to 2.4 kWh/kgal and 1.9 to 2.3 kWh/kgal, respectively. These two estimates are similar and overlap for much of their range. For consistency with the ultrafiltration cost methodology, for the final reverse osmosis cost estimates, ERG used the average estimated energy usage reported by these two sources (see Appendix E.6).

ERG was unable to validate estimated brine disposal costs as published costs for deep well disposal of domestic wastewater are not available.

6. LIFE CYCLE IMPACT ASSESSMENT BASELINE RESULTS BY TREATMENT GROUP

This section presents the LCA results for the nine wastewater treatment configurations by impact category. Throughout this section, results calculated at the unit process level have been aggregated by treatment group, as shown in Table 5-2. For the treatment groups, the unit processes are generally grouped sequentially; however, preliminary treatment stages are grouped with disinfection, even though these are not sequential unit processes because, in this study, these unit processes do not vary by wastewater treatment configuration. In general, add-on technologies that occur in the treatment train after the main biological treatment unit process are classified as post-biological treatment, regardless of their treatment mechanism. The figures presented in this section include the abbreviated wastewater treatment configuration names. The associated full names with information on the differentiating unit processes were previously provided in Table 1-2. Full LCIA results by unit process are provided separately in Appendix I. For three high priority impact categories, eutrophication potential, CED, and GWP, results are also presented according to the underlying processes that contribute to results regardless of their treatment group. For example, all of the electricity use from each of the wastewater treatment unit processes are combined to show the cumulative contribution of electricity use to each impact category. It is important to note that uncertainties in life cycle data and LCIA are present in all modeled treatment configurations. As discussed in Section 4.6.15, any difference lower than 10 percent is not considered significant for CED. Differences lower than 30 percent are not considered significant for particulate matter formation, acidification, eutrophication, water depletion, smog formation, fossil depletion, and ozone depletion. For the toxicity categories, an order of magnitude (factor 10) difference is typically required to be meaningful. Because of this uncertainty magnitude, the toxicity results are presented and discussed separately in Section 7. Although there is uncertainty associated with LCIA methodologies, all LCIA methodologies are applied to different treatment configurations uniformly. Therefore, comparative results can be determined with a greater confidence than absolute results for one treatment configuration.

6.1 Eutrophication Potential

Given the focus of this project on wastewater treatment nutrient removal capacity, eutrophication is a critical metric for measuring the environmental performance of the nine studied treatment configurations. As discussed in Section 4.6.1, eutrophication occurs when excess nutrients are introduced to surface and coastal water causing the rapid growth of aquatic plants. Table 6-1 presents the nutrient concentrations and annual loads for the influent and effluent from the nine wastewater treatment configurations. Although the modeled concentrations and resulting loads are not identical between the two alternatives for some of the levels, the treatment objectives are the same and would generally result in the same effluent quality, with the possible exception of Level 2. The results associated with the Level 2 treatment configuration is provided in the next paragraph.

For this study, ERG designed the wastewater treatment configuration models in CAPDETWorks™ to achieve specific effluent nutrient concentrations. As such, there is a step-wise decreasing trend in total nitrogen and total phosphorus effluent concentrations and loads with increasing treatment levels. The only exception to this is the total phosphorus effluent concentration for Level 2-1 A2O, which is lower than the Level 2 total phosphorus effluent target of 1 mg/L. This is due to the way CAPDETWorks^{TM} calculates effluent total phosphorus from secondary clarifiers. To achieve total suspended solids of 20 mg/L for Level 2-1 A2O, the total phosphorus effluent concentration is about 0.3 mg/L; revising the clarifier design parameters to achieve total phosphorus effluent concentration of 1 mg/L results in total suspended solids around 70 mg/L, which is over the secondary treatment standards.

Table 6-1. Nutrient Discharges by Wastewater Treatment Configuration

Wastewater Treatment Configuration	Total Nitrogen		Total Phosphorus	
	Long-Term Average Concentration (mg/L)	Annual Load (lb/yr)	Long-Term Average Concentration (mg/L)	Annual Load (lb/yr)
Influent	40	1,220,000	5.0	152,000
Effluent Concentrations				
Level 1, AS	30	908,000	4.9	150,000
Level 2-1, A2O	8.0	244,000	0.29	8,570
Level 2-2, AS3	7.8	237,000	1.0	30,500
Level 3-1, B5	6.0	183,000	0.22	6,770
Level 3-2, MUCT	6.0	183,000	0.22	6,770
Level 4-1, B5/Denit	3.0	91,100	0.10	3,050
Level 4-2, MBR	3.0	91,500	0.10	3,020
Level 5-1, B5/RO	0.78	23,800	0.02	457
Level 5-2, MBR/RO	1.9	58,800	0.02	549

Figure 6-1 presents eutrophication potential results grouped according to treatment group. Eutrophication is the combined effect of direct nutrient discharges in the effluent, landfilled sludge leachate, and the water discharges and air emissions from upstream inputs to the treatment steps such as electricity and chemical production. The green bar represents the eutrophication potential related to effluent release and is directly related to the designed performance of each treatment level. As expected, the potential eutrophication impact from effluent release for the conventional activated sludge configuration (Level 1) are significantly greater compared to the other treatment configurations. The impact of effluent drops off markedly for Level 2 treatment configurations and remain consistently lower throughout the remaining treatment levels. Eutrophication impact potential is very similar for Levels 3 and 4; although the effluent nitrate values for Level 4 are lower than Level 3, they are offset by an increase in COD in the effluent (as shown in the effluent characteristics in Table 1-4).

The release of organic nitrogen, ammonia and phosphorus in the effluent drives the observed potential eutrophication impact for the majority of wastewater treatment configurations evaluated, whereas the contributions to eutrophication of the sludge and biological treatment groups are relatively consistent across Levels 2 through 5. The eutrophication potential impact from sludge disposal are primarily related to the long-term release of COD in landfill leachate described previously in Section 4.4. Sludge processing and disposal eutrophication impact generally does not vary substantially since the wastewater treatment configurations produce a similar quantity of sludge sent to landfill, with the exception of Level 2-2. Level 2-2 has higher eutrophication impact for the sludge processing and disposal treatment group because of the higher sludge generation in this level from the significant use of chemical phosphorus precipitation. The biological treatment step for conventional activated sludge has a noticeably lower impact than the other levels, which is due to the lower energy intensity of the more basic activated sludge treatment process. Overall, it is apparent that the potential cumulative eutrophication impact generally decreases between Level 1 and Level 2 and then again between Level 2 and Level 3 and Level 4. Level 5 results in an increase in eutrophication impact compared to Level 4 due to the high energy intensity of RO and brine injection, which off-set the reduction in impact associated with the effluent release. However, based on the uncertainty thresholds for impact results, the eutrophication potential difference between Level 3, Level 4 and Level 5 wastewater treatment configurations is not considered significant. As discussed in Section 4.6.1, both indirect and direct air and water emissions have the potential to contribute to eutrophication. Eutrophication from these energy intensive unit processes is largely due to the portion of the nitrogen oxide air emissions from upstream fuel combustion for electricity production that is modeled as deposited in water bodies. Nitrogen oxide emissions are largely associated with deposition from the combustion of coal in the average US electrical grid (coal is currently estimated to contribute approximately 45 percent to the average U.S. electrical grid as shown in Table 4-2, Section 4.2, which comes from 2009). For more detail, Table J-1 in Appendix J shows the contribution of each individual unit process to the overall eutrophication potential for each wastewater treatment configuration. To compare electricity consumption across the wastewater treatment configurations refer to Table H-1 through Table H-10 in Appendix H.

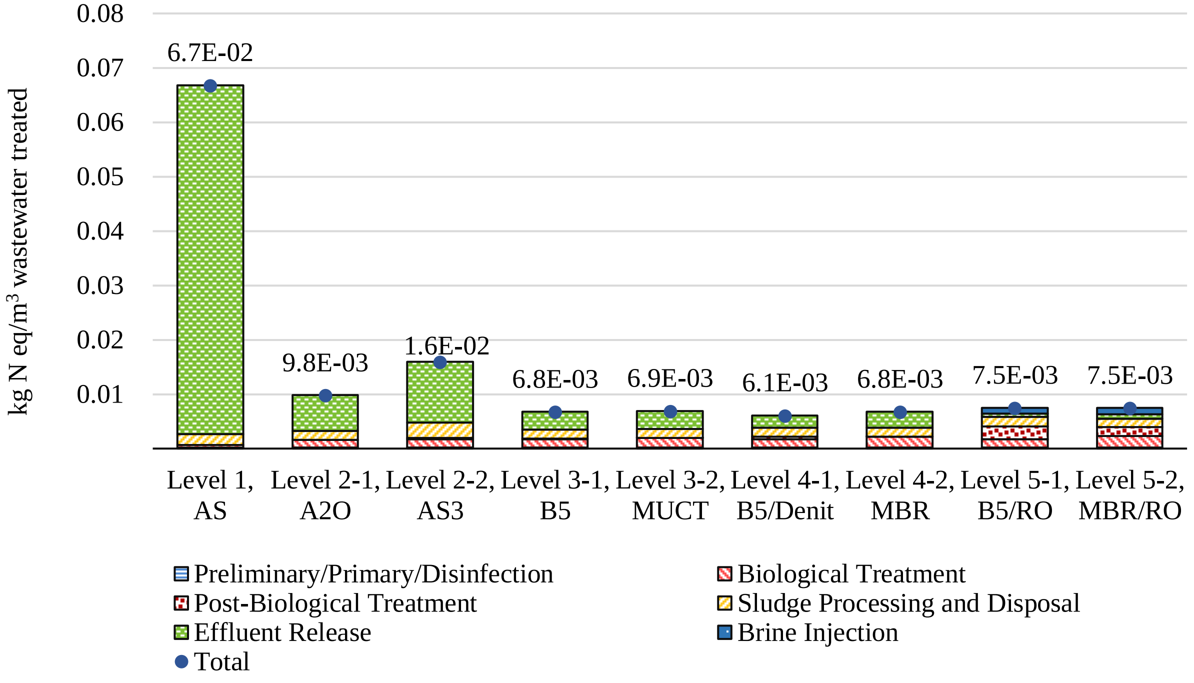

Figure 6-1. Eutrophication Potential Results by Treatment Group

The impact of increased energy use, particularly in Level 5, is visible in Figure 6-2. As previously discussed, disposal of sludge in a municipal solid waste landfill also contributes to eutrophication impact, primarily related to the long-term release of COD in landfill leachate.

Natural gas, infrastructure, chemicals, process emissions, and sludge transport cumulatively contribute between 0.3 and 4 percent of eutrophication impact depending on treatment level.

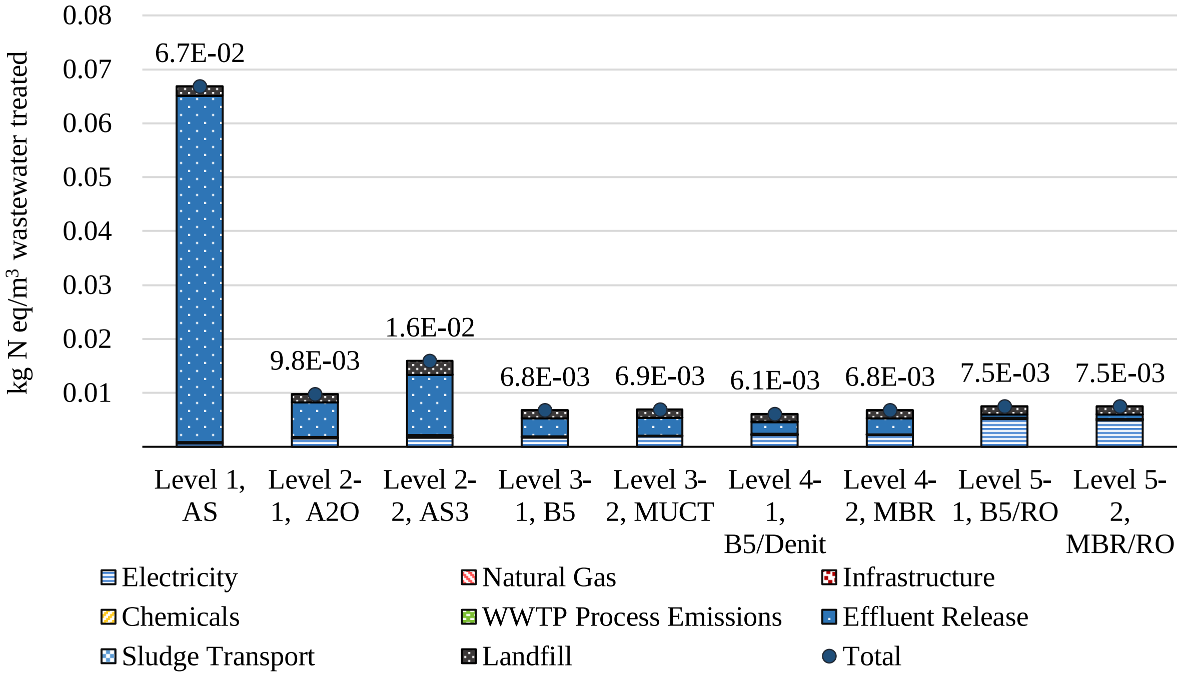

Figure 6-2. Eutrophication Potential Results by Process Contribution

6.2 Cumulative Energy Demand

Figure 6-3 and Figure 6-4 present CED results grouped according to treatment group and by process contribution. The CED results are driven by direct energy use in the form of electricity and natural gas at the WWTP as well as energy consumption associated with upstream chemical and infrastructure production. Fuel inputs for transportation and landfill management are also incorporated in the CED results.

The separation processes selected for use in this study to remove nutrients from wastewater require energy, and this energy requirement generally increases with the level of separation. Between 43 and 88 percent of CED is attributable to electricity use associated with each wastewater treatment configuration, including supply-chain electricity use. Natural gas consumption, primarily to provide heat for anaerobic digestion, is the second largest contributor to CED, accounting for between five and 30 percent of CED.

The biological treatment units and sludge processing and disposal from Level 2 through Level 5 all produce a relatively consistent energy demand. More significant differences in energy demand between treatment systems are associated with the post-biological treatment units, such as denitrification, membrane bioreactors, ultrafiltration, and RO. For Levels 5-1 and 5-2, RO filtration and brine injection cumulatively contribute 48 and 49 percent of CED impact, respectively. For more detail, Table J-2 shows the contribution of each individual unit process to the overall CED for each wastewater treatment configuration. The upstream energy demand of chemical production is visible in Figure 6-4, particularly for Level 2-2. Level 2-2 CED from chemical production is largely associated with the methanol requirement for denitrification and aluminum sulfate used for chemical phosphorus precipitation.

As discussed in Section 1.2.3, it may be possible, depending on the demand, to recycle the effluent from Levels 1 through 5 for a variety of reuse applications ranging from landscape irrigation to indirect potable reuse (U.S. EPA 2012b). While recycled water was not considered in the system boundaries of this study, recycling the water would likely offset some of the increased CED of the higher nutrient removal wastewater treatment configurations by displacing production of potable water elsewhere. The magnitude of the offset would depend upon the current source of water for that reuse application.

The effect of biogas energy recovery on CED is discussed in Section 9.5.

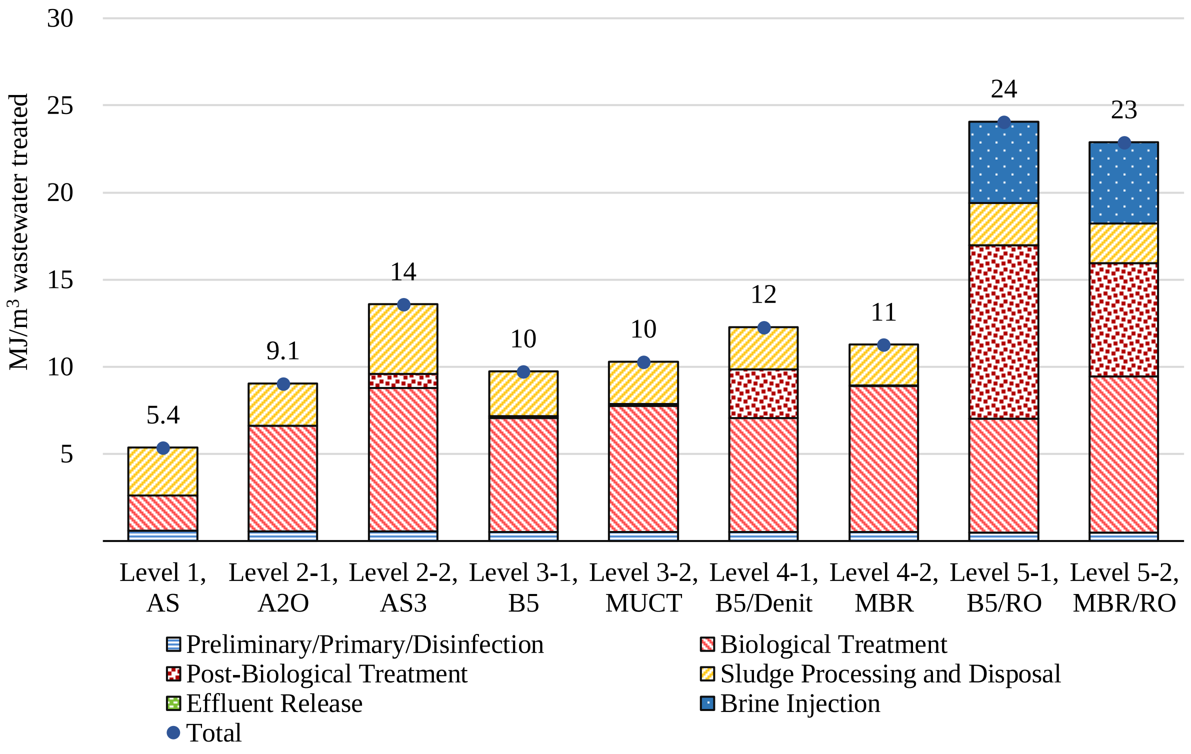

Figure 6-3. Cumulative Energy Demand Results by Treatment Group

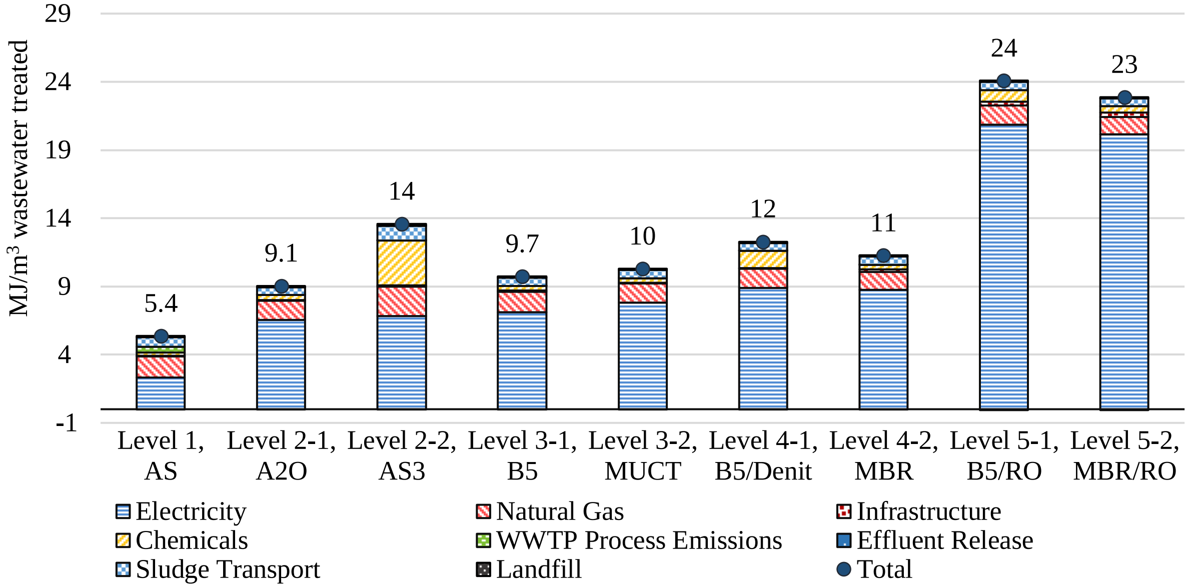

Figure 6-4. Cumulative Energy Demand Results by Process Contribution

6.3 Global Warming Potential

Figure 6-5 presents the GWP results grouped according to treatment group. Overall, the GWP of the treatment configurations increases with the stringency of effluent quality criteria, as additional unit processes are required. The total GWP of Level 5 is over three times greater than that for Level 1. The GWP of the biological treatment subcategory increases by approximately 415 percent as we progress from Level 1 to Level 3. GWP impact associated specifically with biological treatment then remains relatively constant between Levels 3 and 5. The increase between Level 1 and Level 3, is due both to the increasing energy demand of the biological treatment configurations as well as the increased production of process GHG emissions. The advanced biological treatment units contain a combination of aerobic, anoxic, and anaerobic stages, in which both CH_4 and N_2O emissions may be generated and ultimately emitted from the treatment system. Based on available data to characterize these types of treatment configurations, as described in Appendix F, CH_4 emissions from biological treatment are the most impactful process GHGs; however, there is uncertainty associated with estimating these process GHGs and in differentiating the various treatment levels due to the limited measurement data associated with the different treatment configurations evaluated.

RO and brine injection together increase the GWP of Levels 5-1 and 5-2 by approximately 35 percent. The attached growth denitrification filter contributes just over 10 percent of GWP impact to Level 4-1. Sludge processing and disposal, shown in yellow, contributes between 0.22 and 0.27 kg of CO_2 eq. per cubic meter of wastewater for each treatment system. Over half of the sludge processing and disposal impact is attributable to operation of anaerobic digesters. Although the absolute contribution demonstrates consistency between treatment levels, the relative contribution to total impact scores decreases from a high of 53 percent for Level 1 to only 12 percent for Level 5-1. Fugitive release of CH_4 from landfilled biosolids at end-of-life (EOL) is responsible for approximately one-quarter of total sludge processing and disposal GWP emissions. While indirect N_2O emissions from wastewater after discharge of effluent into receiving waters contribute less than three percent of GWP impact for Levels 2 through 5, this source of GHG emissions constitutes nearly 13 percent of Level 1 GWP. These emissions decrease across the treatment levels corresponding to increased removal of nitrogen from the final effluent. Nitrous oxide emissions from wastewater effluent are the result of denitrification processes that occur in the receiving water after wastewater is discharged from the treatment facility. Documentation of the N_2O GHG calculations for receiving waters is provided in Appendix F.

For more detail, please refer to Table J-3 and Table J-4, which shows the contribution of individual unit processes to the overall GWP.

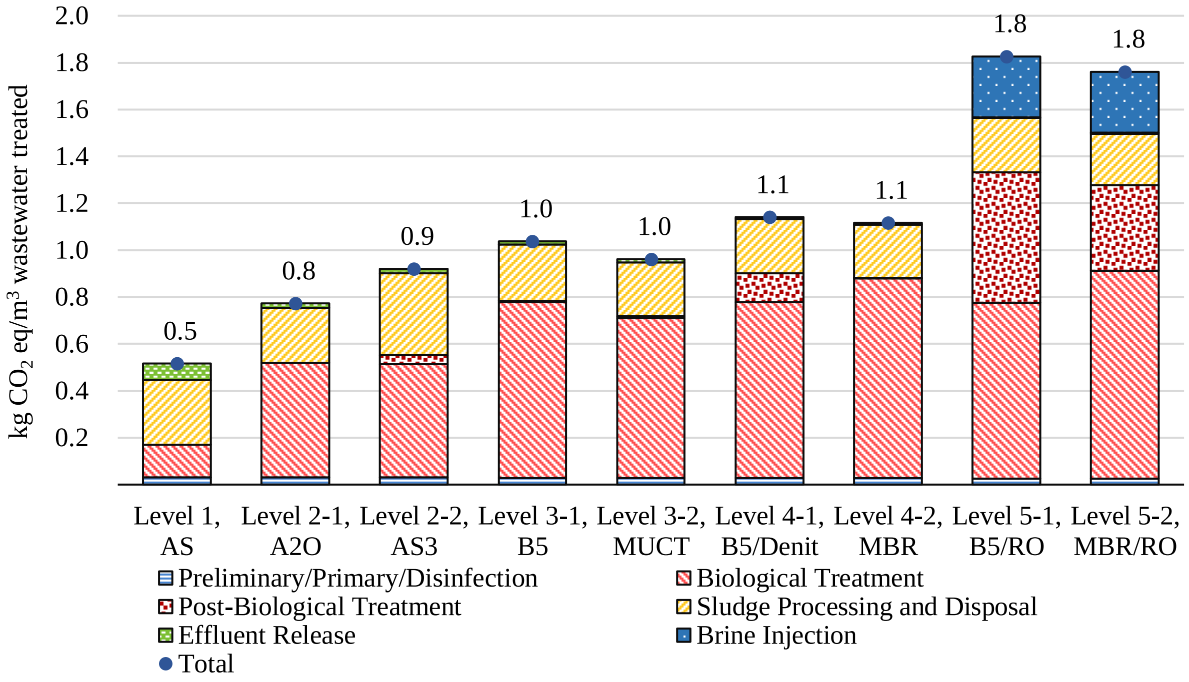

Figure 6-5. Global Warming Potential Results by Treatment Group

Figure 6-6 aggregates GWP impact according to process contribution, highlighting the dominant contribution of electricity use to GWP impact. The relative percentage of GWP impact provided by electricity use increases from a low of 28 percent for Level 1 to a high of 64 percent for Level 5-2. Process GHG emissions from biological treatment units and anaerobic digestion are the second largest source of GWP impact and are similar in magnitude to electricity contributions for several treatment levels. The relative contribution of GHG process emissions is greatest for Levels 3 and 4 due to the unit processes used to attain the high degree of nutrient removal combined with a relatively lower energy footprint as compared to Level 5 configurations. For Level 1, the release of N_2O emissions is shifted to receiving streams.

Natural gas use and landfill disposal of biosolids are both noticeable contributors to GWP impact, remaining consistent across treatment configurations. Natural gas contributes between four and 18 percent of GWP impact. Fugitive landfill methane emissions contribute a further three to 13 percent, depending upon the configuration. It is important to remember that fugitive landfill emissions occur over long periods of time as the anaerobic degradation of sludge proceeds in the landfill environment. Although the fugitive landfill methane releases occur gradually over many years, the approach used here models the impacts of the aggregated emissions using 100-year GWPs. This is consistent with the use of 100-year GWPs used for all other life cycle GHG emissions, as discussed in Section 4.6.3. Future refinements to landfill LCA modeling may include time-scale modeling of landfill methane emissions; however, this is not part of the current study. Such future refinements of time scale modeling of long-term GHGs may lead to exclusion of methane emissions released after 100 years. As discussed in Appendix F Section F.1.5, this study has assumed landfill gas capture and energy recovery is based on average municipal landfill statistics in the U.S. There are a few instances where relative impact associated with these unit process categories can rise above ten percent for a specific treatment level. Effluent release, landfill emissions, and natural gas use contribute 14, 13, and 18 percent of Level 1 impact, respectively. Chemical use in Level 2-2, which relies heavily on chemical phosphorus precipitation, contributes 11 percent of GWP impact.

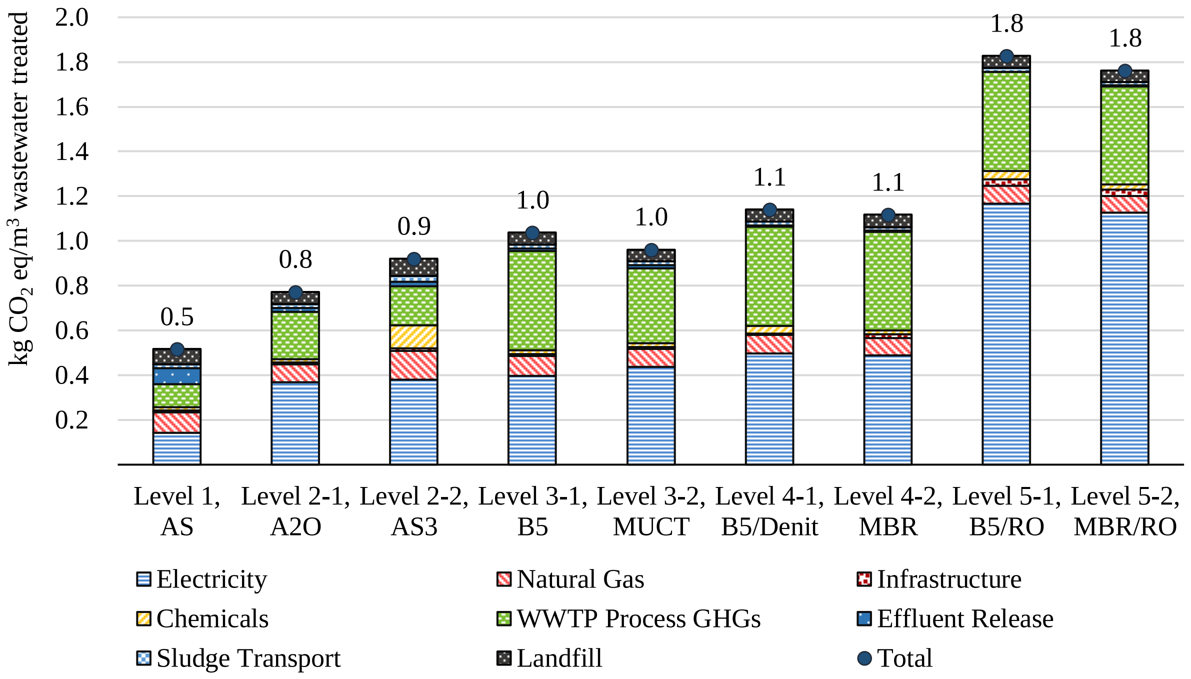

Figure 6-6. Global Warming Potential Results by Process Contribution

6.4 Acidification Potential

Figure 6-7 presents results for acidification potential grouped according to treatment group. Acidification impact associated with biological treatment, post-biological treatment, and brine disposal are the dominant treatment groups contributing to acidification impact. Electricity use attributable to these treatment processes is the primary source of acidifying emissions. Eighty-eight percent of Level 1 impact in this category is associated with electricity use, and the relative contribution rises to over 95 percent for Level 5. Approximately 70 to 80 percent of acidification impact is associated with sulfur dioxide and nitrogen oxide emissions from coal combustion. The contribution of biogas flaring to acidification impact, again from sulfur oxides and nitrogen oxide emissions, varies between 0.1 and 9 percent depending on the treatment level with lower levels having higher relative contributions from biogas flaring. The effect of biogas energy recovery on acidification potential impact is discussed in Section 9.5. For more detail, Table J-4. presents the contribution of individual unit processes to acidification potential impact.

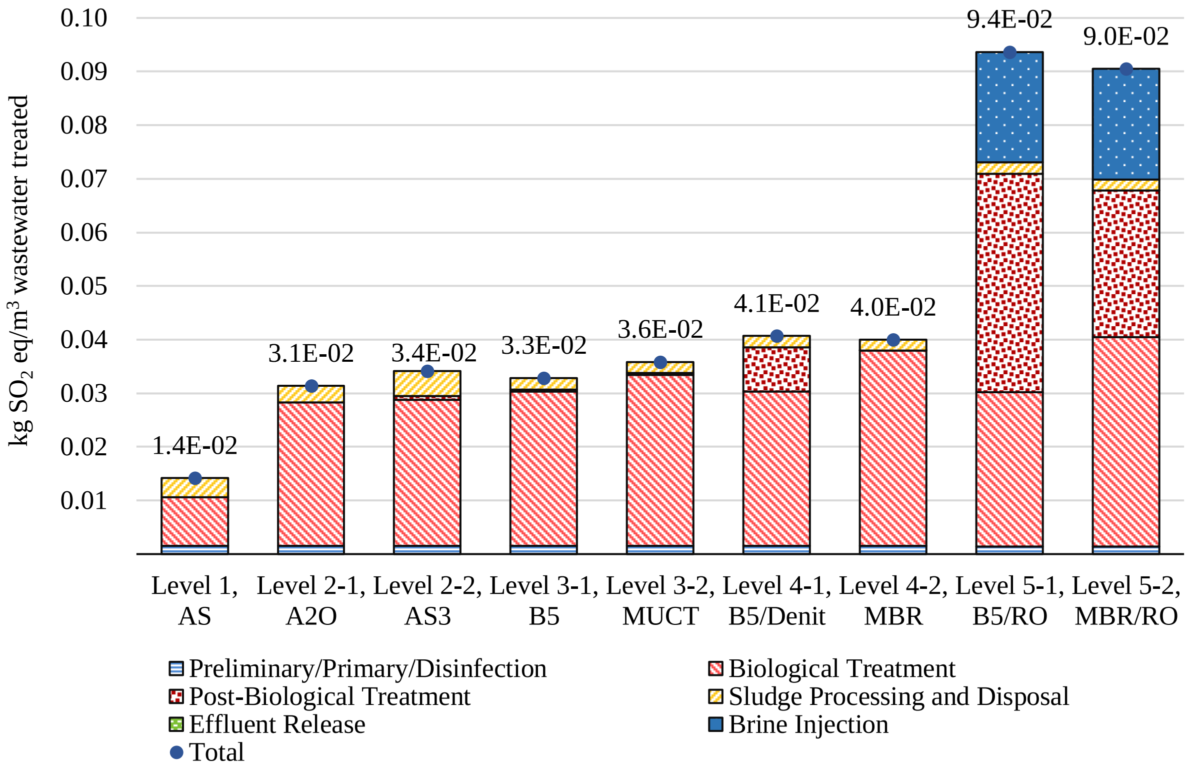

Figure 6-7. Acidification Potential Results by Treatment Group

6.5 <u>Fossil Depletion</u>

Figure 6-8 presents the fossil depletion results according to treatment group. Approximately 50 percent of fossil depletion impact for the Level 1 treatment system are attributable to electricity consumption. Electricity contributes over 90 percent of total fossil depletion impact for Level 5 configurations. Within electricity consumption, the contribution to fossil depletion is associated with coal, natural gas, and crude oil in a static ratio of approximately 2:1:1. An electricity credit, derived from the combustion of landfill gas, is reflected in the figure and serves to reduce relative fossil depletion impact by between one and six percent depending upon the treatment level, with greater relative decreases being associated with lower levels of nutrient removal.

Natural gas combustion used to provide process heat for anaerobic digestion contributes 31 percent of the relative impact for Level 1. The relative contribution of natural gas combustion decreases for higher treatment levels. Truck transport of processed biosolids to the landfill also figures prominently in the results, contributing approximately 13 percent of the impact associated with Level 1. The absolute contribution of sludge hauling to fossil depletion is greatest for Level 2-2 due to the increase in sludge volume associated with chemical precipitation. The contribution of chemical use to fossil depletion amounts to over five percent of impact for Level 1 and over nine percent for Level 4-1. The increase associated with Level 4-1 is due to the use of methanol for denitrification. For more detail, Table J-5 shows the contribution of individual unit processes to fossil depletion potential.

The high energy use in the biological treatment group is due to the biological treatment units (e.g., 3-stage Bardenpho, Modified University of Cape Town) and membrane filtration solids separation in Levels 4-2 and 5-2. For the biological treatment units, energy use is due to aeration, mixing, internal recycle and return activated sludge pumping. Membrane filtration use energy for aeration, permeate pumping, and internal recycle. Energy use for the post-biological treatment group is high for Levels 4-1, 5-1, and 5-2. For Level 4-1, over 95 percent of post-biological energy use is associated with the denitrification filter. For Level 5-1, post-biological energy use is approximately 70 percent for the RO and 25 percent for ultrafiltration. For Level 5-2, close to 100 percent post-biological energy use is for RO.

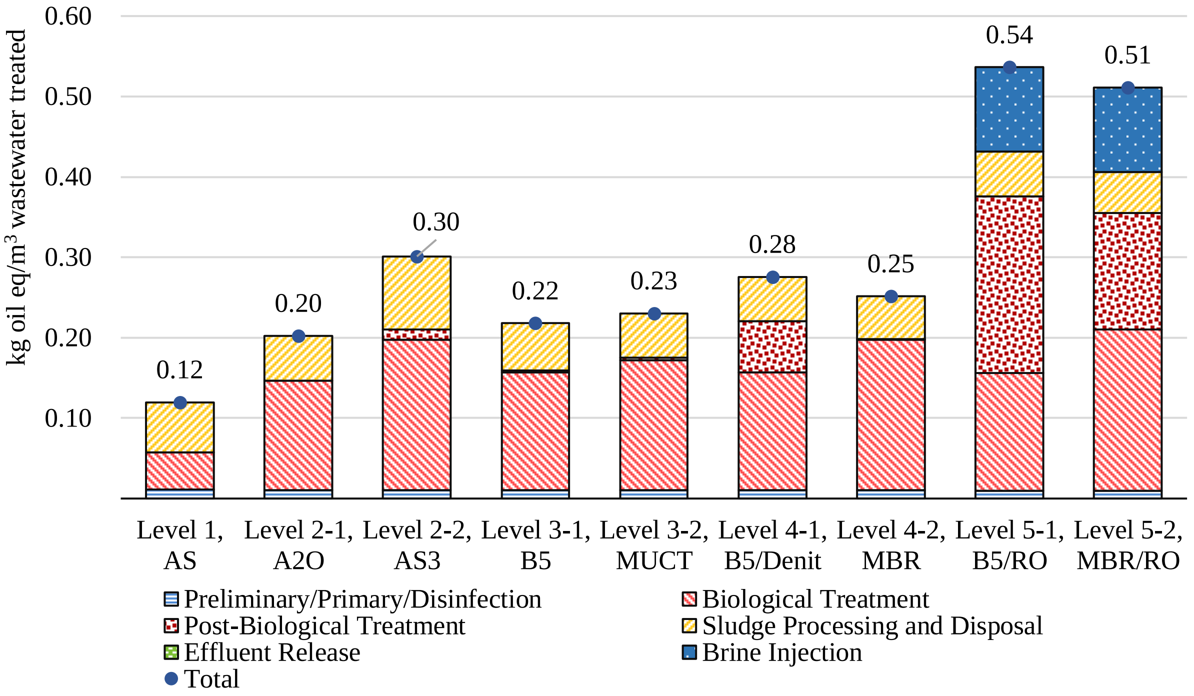

Figure 6-8. Fossil Depletion Results by Treatment Group

6.6 Smog Formation Potential

Figure 6-9 presents the smog formation potential results by treatment group. Greater than 95 percent of smog formation potential is linked to air emissions of nitrogen oxides from fuel combustion processes. Coal combustion, which is primarily associated with electricity generation, produces high nitrogen oxide emissions. For the Level 5 wastewater treatment configurations, coal combustion contributes most of the impact. However, only about half of the smog formation potential is due to coal combustion for the conventional activated sludge system configuration. For Level 1, the relative smog formation impact of biogas flaring is 27 percent, with the absolute impact of biogas flaring consistent across wastewater treatment configuration. Other typical combustion processes such as transport and industrial manufacturing contribute less than one percent of cumulative impact in this category. For more detail, Table J-6 shows the contribution of individual unit processes to smog formation potential.

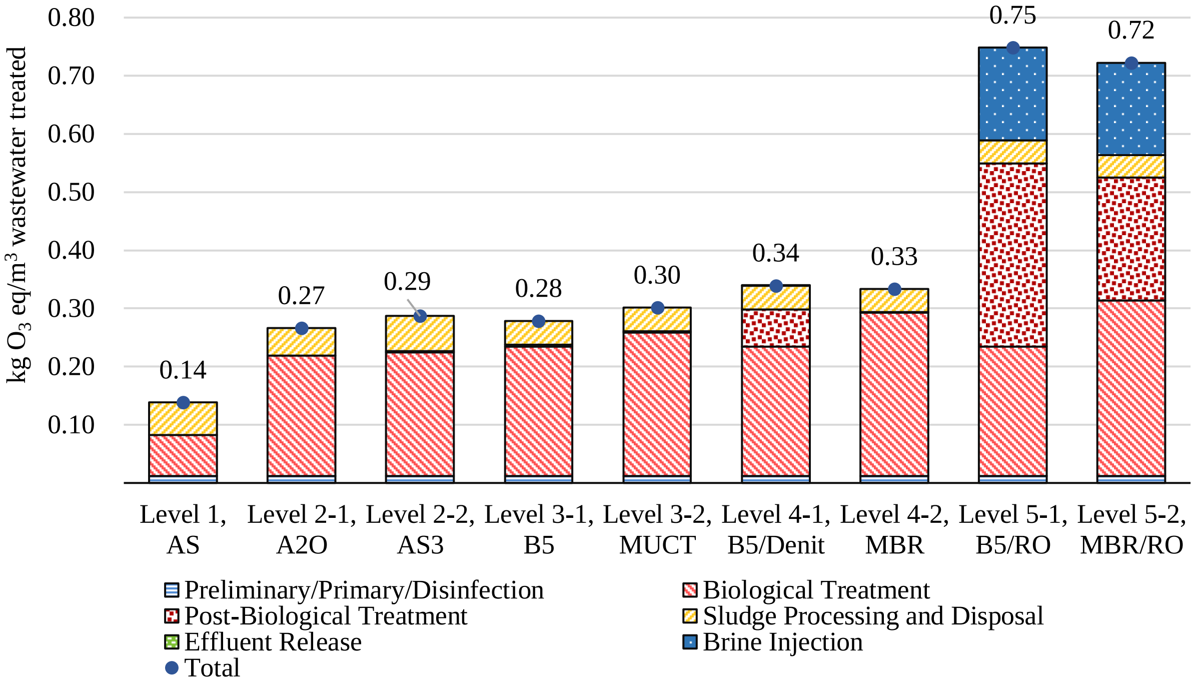

Figure 6-9. Smog Formation Potential Results by Treatment Group

6.7 Human Health-Particulate Matter Formation Potential

Figure 6-10 presents the PM formation potential results by treatment group. PM formation is considered a human health impact category due to its close association with respiratory conditions, leading to increased morbidity (Bare, 2012). Over 92 percent of the impact in this category is attributable to the combustion of fossil fuels for electricity production. Biogas flaring produces a relatively low level of PM-related emissions and does not contribute greater than three percent of total PM impact for any treatment level assessed. Approximately 45 to 50 percent of PM impact is attributable to PM2.5 for all treatment levels. Sulfur dioxide, a precursor to secondary particulates (Bare, 2012), contributes a further 30 to 40 percent of total impact in this category. Recovery of methane energy at the landfill, and the corresponding electricity off-set, provides a credit that reduces impact in this category by just under 12 percent for the Level 1 treatment system. The relative contribution of electricity off-sets to reductions in particulate matter formation potential impact decreases with increasing energy intensity as the level of nutrient removal increase. For more detail, Table J-7 shows the contribution of individual unit processes to particulate matter formation potential.

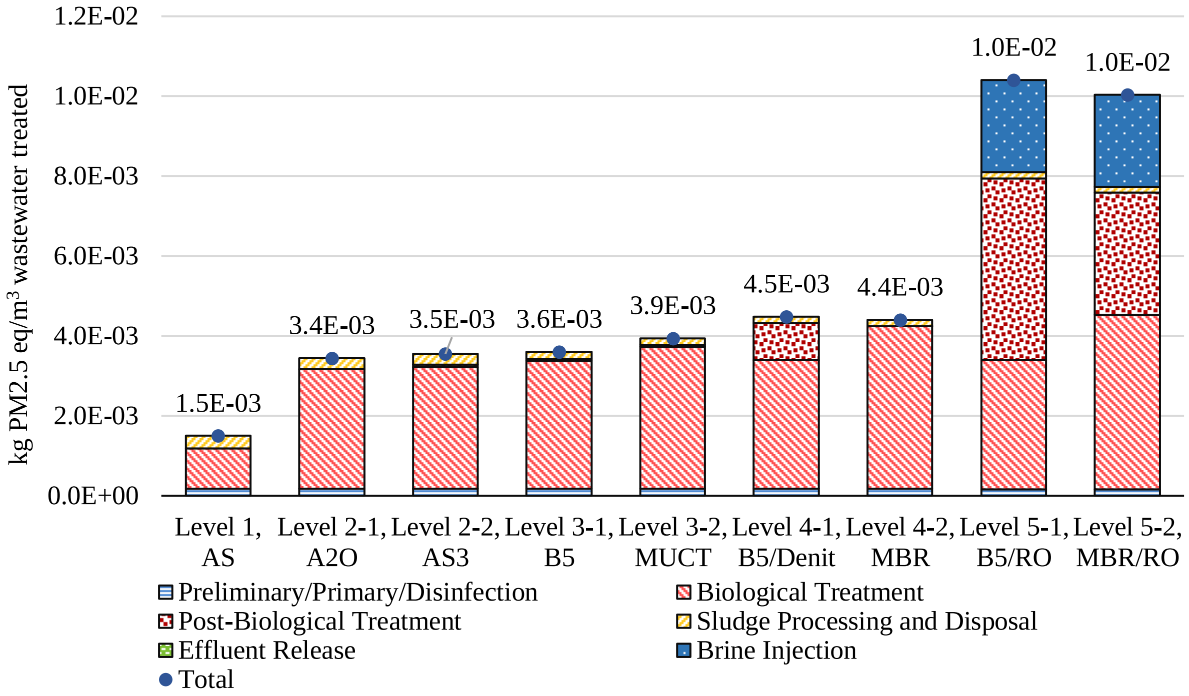

Figure 6-10. Human Health Particulate Matter Formation Potential Results by Treatment Group

6.8 Ozone Depletion Potential

Figure 6-11 presents ozone depletion potential results by treatment group. Results are driven by process and effluent related N_2O emissions. Combustion processes, such as biogas flaring, are also sources of N_2O. Electricity use accounts for most of the remaining ozone depletion potential. Electricity related impact is driven by the assumed use of three refrigerant substances[8] in power generation facilities. These substances were widely used refrigerants, but their incidence is currently decreasing following the implementation of the Montreal Protocol, which legislates the global phase out of the most powerful ozone depleting substances. Overall, the normalized impact from ozone depletion tends to be lower compared to other impacts assessed in this study due to the benefits realized from the Montreal Protocol, see Table 8-3. For more detail, Table J-8 shows the contribution of individual unit processes to ozone depletion potential.

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[8] R-40 = monochloromethane, R-10 = tetrachloromethane, and HCFC-140 = 1,1,1 trichloroethane

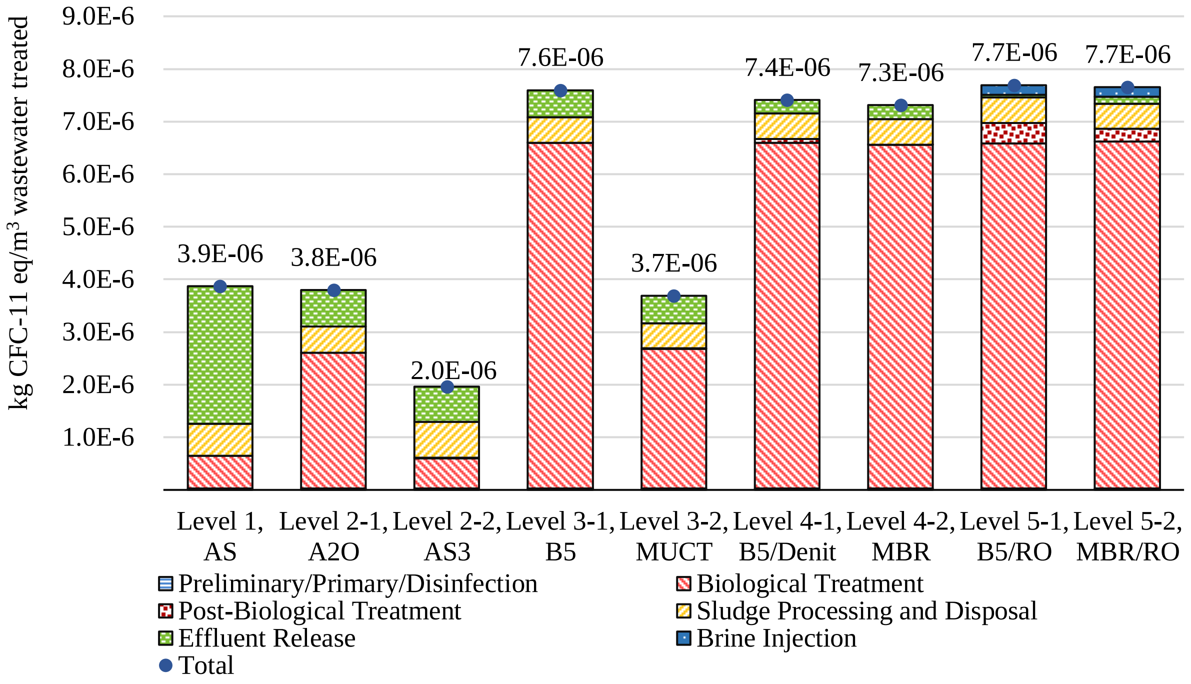


Figure 6-11. Ozone Depletion Potential Results by Treatment Group

6.9 Water Depletion

For Levels 1 through 4 between 55 and 75 percent of water depletion is due to consumptive water use in fuel and electricity production. Chemical manufacturing also contributes strongly to water use. Chlorine production is responsible for 16 percent of the impact for Level 1 treatment. Alum, methanol, and chlorine production contribute 15 percent of impact for Level 4-1, despite the rise in energy intensity. For Level 2-2, the use of alum for chemical phosphorus removal accounts for approximately 55 percent of water depletion impact associated with this wastewater treatment configuration. Level 2-2 relies on chemical precipitation for phosphorus removal, whereas other treatment systems also utilize biological nutrient removal, which lowers their alum requirement. Water use at the landfill facility is responsible for between 4 and 11 percent of impact Level 1 through Level 4 systems. For foreground unit processes, there was no direct water use (e.g., for washing) modeled; however, the loss of water from deepwell injection for Level 5 wastewater treatment configurations was considered in the analysis. As seen in Figure 6-12, the water depletion results are dominated by deepwell injection of brine resulting from Level 5 RO filtration. Approximately 17 percent of influent wastewater is diverted to deepwell injection in these wastewater treatment configurations. This water was originally drawn from surface or groundwater, and diversion to deepwell injection makes it unavailable for subsequent environmental or human uses. Reuse of treated wastewater was not considered in the system boundaries of this study, which is a possibility for all treatment levels, and would serve to reduce water depletion impact. Table J-9 shows the contribution of individual unit processes to water depletion.

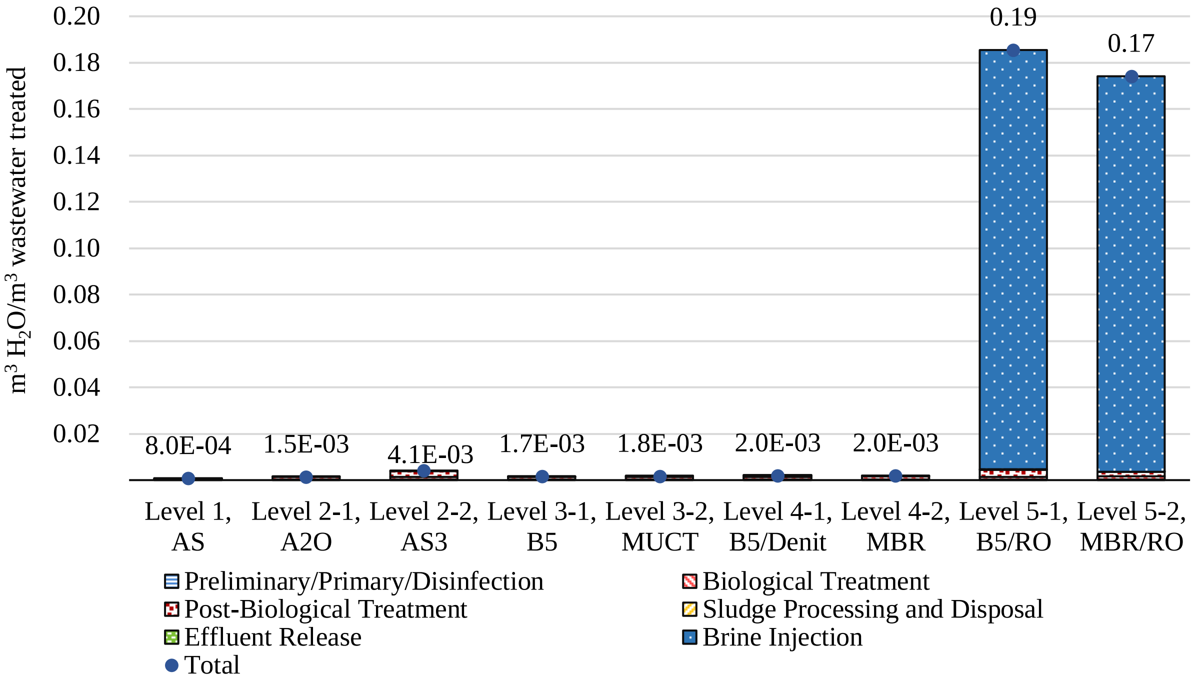


Figure 6-12. Water Depletion Results by Treatment Group

7. TOXICITY LCIA RESULTS

Toxicity results are presented for the three USEtox™ impact categories. Presented results include impacts associated with metals, toxic organics and DBPs in effluent and sludge for each wastewater treatment configuration as well as upstream impacts associated with energy, chemical and material production.

Figure 7-1 presents summary contribution results for all nine treatments systems in the three toxicity impact categories. The figure is intended to highlight the most important aspects of each treatment configuration that contributes to toxicity impacts. All results in Figure 7-1 are standardized such that the total impact of each treatment configuration equals 100%. Contributions to impact are aggregated in the following groups: material and energy inputs, effluent metals, effluent toxic organics, effluent DBPs, metals in sludge, and toxic organics in sludge. Metals in liquid effluent are the dominant contributor among the three trace pollutant categories. For treatment Levels 1 thorough 4-1, metals in liquid effluent are the single largest contributor to ecotoxicity and non-cancer human health impacts. For Levels 4-2 through 5-2, contributions from plant material and energy inputs dominate toxicity impacts. As treatment becomes more rigorous from Level 1 to Level 5, the contributions of trace pollutants to toxicity impact decrease. There is a slight increase in toxicity impacts associated with sludge landfilling along the same continuum, however total toxicity contributions from sludge disposal never exceed 10%. Contributions from toxic organic chemicals, either in sludge or liquid effluent, are only visible for the non-cancer human health impact category amounting to four percent or less of total impact for all treatment configurations. DBPs contribute greater than 10% of total impact for the cancer human health impact category in Levels 1, 2-1, and 4-2.

It is important to consider the uncertainty inherent in the calculation of toxicity related impacts using the USEtox™ method (Huijbregts et al., 2010). Many of the characterization factors used to quantify impacts in these categories are considered interim by USEtox™ developers. All toxicity related characterization factors associated with metals and metal ions, which dominate the results of this study, are considered interim at this time. Moreover, the characterization factors assume impacts result from a specific ionic form of each metal species that is not necessarily the same form in which the metal is emitted from treatment systems. This is a common limitation of the USEtox™ method, and it implies the assumption that once emitted, transformations to a more toxic form may occur within the receiving environment. Overall, the uncertainty associated with interim characterization factors is between one and three orders of magnitude (Huijbregts et al., 2010).

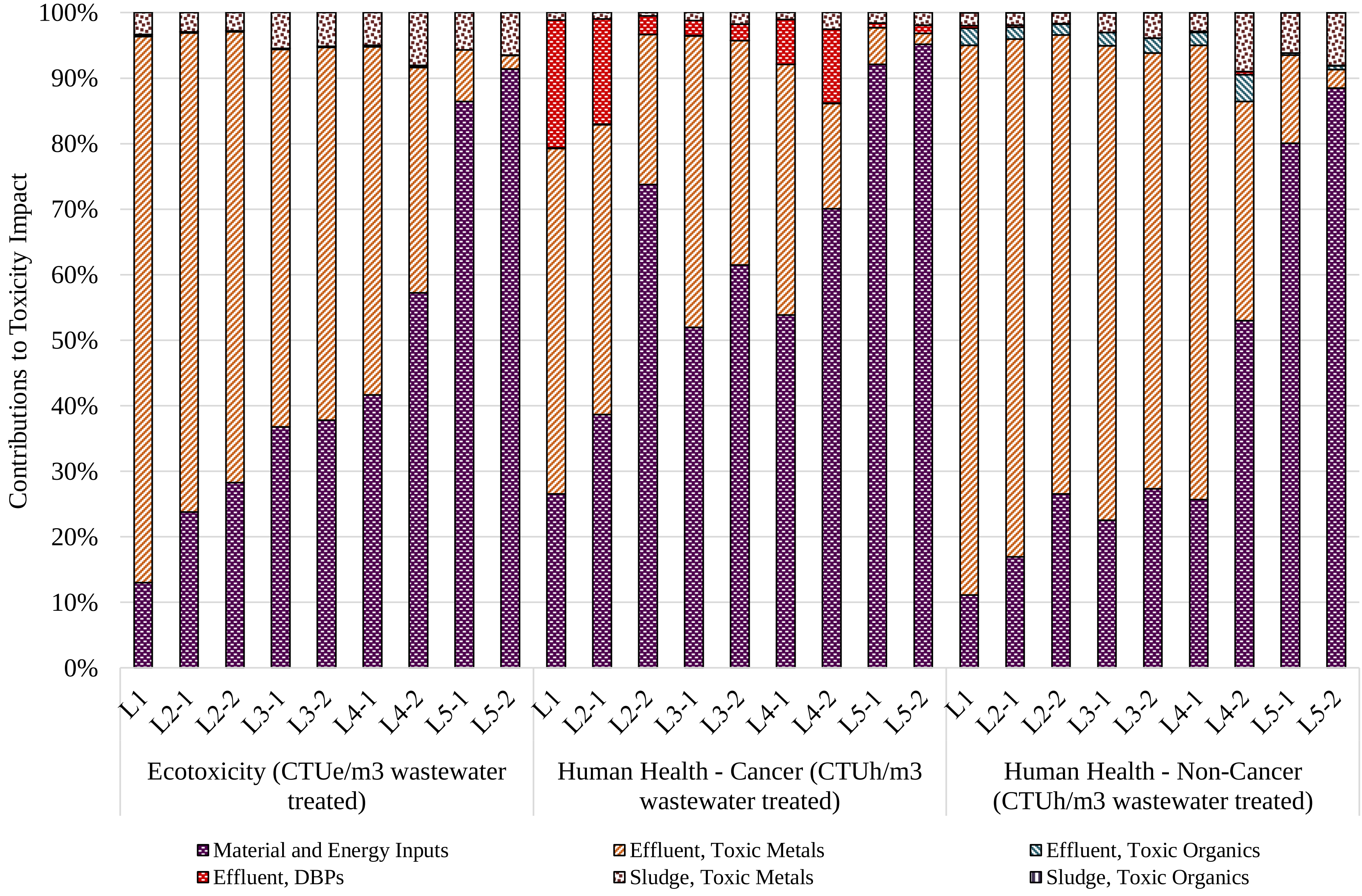


Figure 7-1. Contribution Analysis of Cumulative Toxicity Impacts

7.1 Human Health-Cancer Potential

Figure 7-2 presents the human health-cancer results by treatment group. Error bars in the figure represent the range of results generated by applying minimum and maximum removal efficiency scenario assumptions outlined in Sections 2.1 and 2.2 for metals and toxic organic pollutants, respectively. Contributions to toxicity impact from metals, toxic organics and DBPs summarized in Figure 7-1 are included in this figure within the effluent release and sludge processing and disposal treatment groups.

This figure reinforces the important contribution of metals in treatment plant effluent to cumulative human health-cancer impacts for the lower treatment Levels. The figure also demonstrates that for Level 5 treatment configurations, the increasing contribution of plant material and energy inputs outweighs the benefits of effluent improvements. Electricity consumption of the RO filter and brine injection system is primarily responsible for this increase. The Level 2-2 treatment system is associated with the highest cancer potential impacts attributable largely to aluminum sulphate production for chemical phosphorus precipitation.

When considering the average removal efficiency scenario, Levels 3-2 and 4-2 most effectively balance improvements in effluent quality against the increase in material and energy inputs required to achieve this goal. This is in large part due to the effectiveness of the MUCT unit process (Level 3-2) and the MBR unit process (Level 4-2) in removing metals from the liquid effluent. The MBR unit process, in particular, showed metal removal performance almost on par with RO, though without the detrimentally high energy requirements.

The range of impacts found for Level 1 and 2-1 are also worth noting, as although average metal removal efficiencies of these levels are lower than other configurations (around 40-60% depending on the metal), there is evidence to suggest that removals can be greater than 80% in some cases. Combined with lower process-based impacts, a high efficiency Level 1 or Level 2-1 system may perform best with respect to human health-cancer potential impacts.

Table J-10 documents the contribution of individual unit processes to the human health – cancer potential.

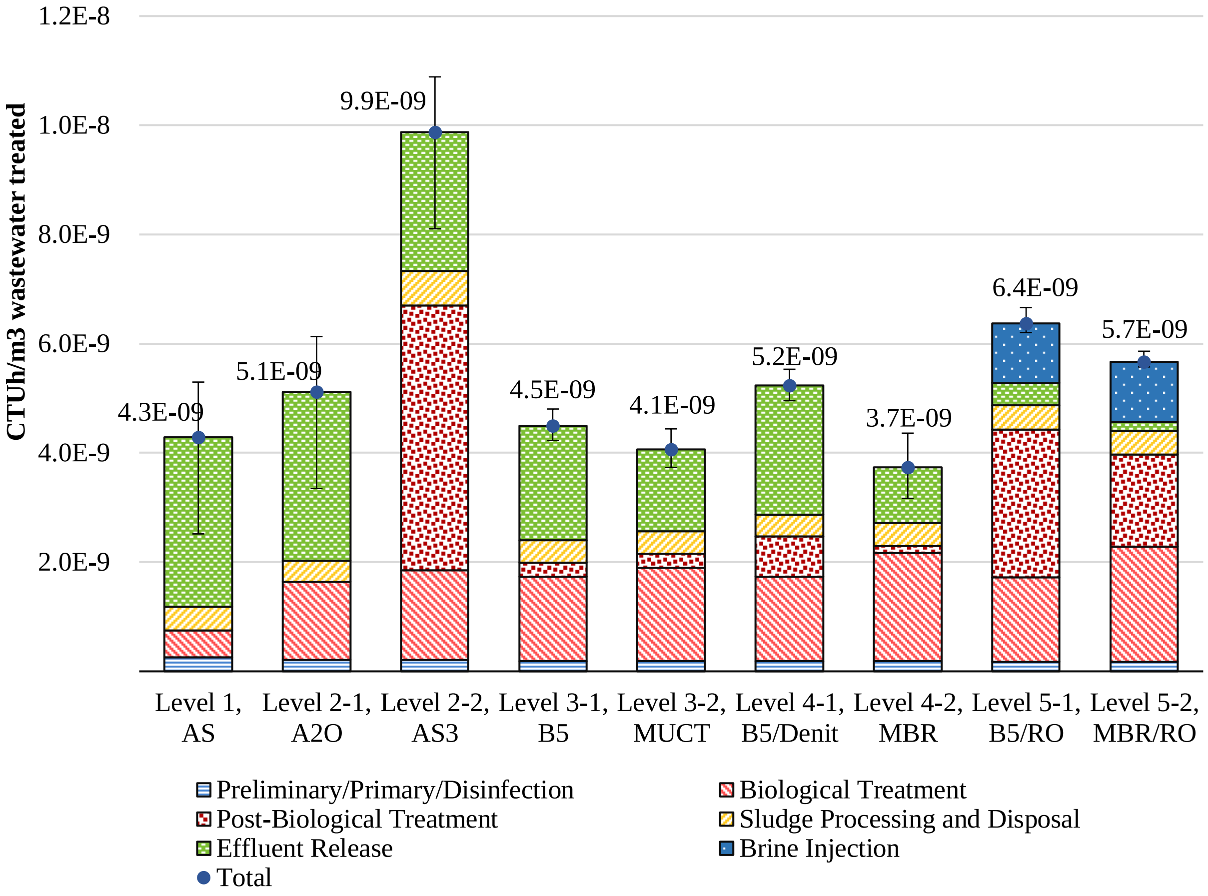


Figure 7-2. Human Health – Cancer Potential Results by Treatment Group (CTUh/m3 wastewater treated)

7.2 Human Health-Noncancer Potential

Figure 7-3 presents the human health-noncancer results by treatment group. Error bars in the figure represent the range of results generated by applying minimum and maximum removal efficiency scenario assumptions outlined in Sections 2.1 and 2.2 for metals and toxic organic pollutants, respectively. Contributions to toxicity impact from metals, toxic organics and DBPs summarized in Figure 7-1 are included in this figure within the effluent release and sludge processing and disposal treatment groups.

The toxicity impact of metals in treatment plant effluent is even more pronounced for the non-cancer human health impact category where it dominates contributions for Level 1 through Level 4-1 treatment configurations. Figure 7-1 shows that DBPs also contribute to non-cancer human health potential especially for Levels 1 and 2-1. When considering the average removal efficiency scenario, total toxicity impacts generally decrease as you move from lower treatment levels to the Level 4-2 treatment system before again increasing for Level 5. The low impacts associated with Level 4-2 are again associated with the high metals removal performance of the MBR unit process without the high energy inputs required of the RO membrane separation process. Also, the removal efficiency range is narrower for the membrane separation processes than for the lower treatment levels that rely more heavily on less precise biological processes for partitioning of metals to sludge. Even considering the high removal efficiency scenario for the lower three treatment levels, total non-cancer potential impacts are greater than or equal to the toxicity impact of Levels 4-2 and 5.

Table J-11 shows the contribution of individual unit processes to human health–noncancer potential.

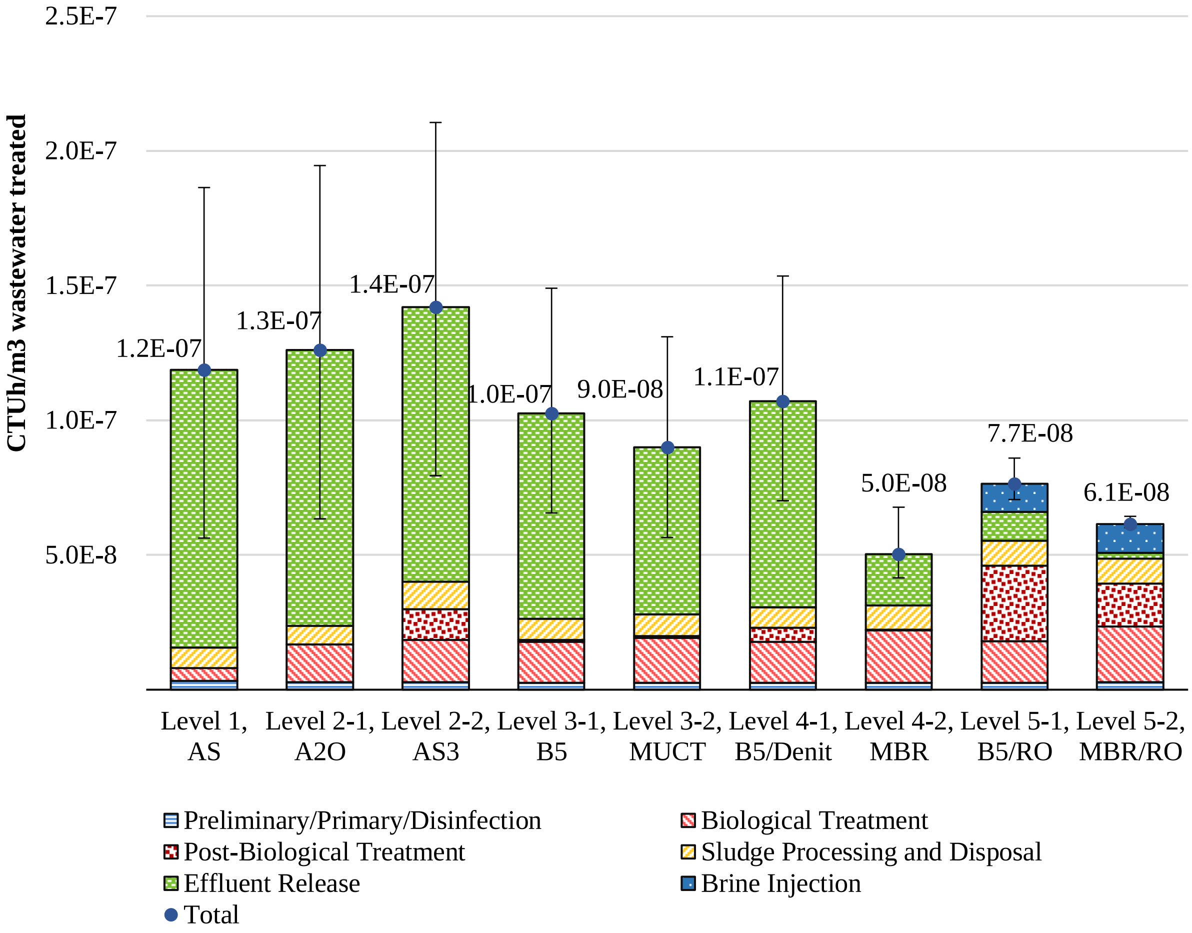


Figure 7-3. Human Health – Noncancer Potential Results by Treatment Group (CTUh/m^3 wastewater treated)

7.3 Ecotoxicity Potential

Figure 7-4 presents ecotoxicity results by treatment group. Error bars in the figure represent the range of results generated by applying minimum and maximum removal efficiency scenario assumptions outlined in Sections 2.1 and 2.2 for metals and toxic organic pollutants, respectively. Contributions to toxicity impact from metals, toxic organics and DBPs summarized in Figure 7-1 are included in this figure within the effluent release and sludge processing and disposal treatment groups.

Ecotoxicity impacts are also strongly linked to metals released with the liquid effluent, especially for Levels 1 and 2. Similar to the previous toxicity impact categories, the average removal efficiency results demonstrate a minimum toxicity impact associated with the Level 4-2 treatment system. However, taking into account the range of potential removal efficiencies, there is considerable overlap in results between Level 4-2 and other configurations. For example, the Level 5 treatment systems perform well compared to the lower treatment levels and provide greater assurances of reaching the average removal efficiency performance due to the greater reliability of their membrane processes. However, when compared against high removal efficiency scenarios for lower treatment levels, Level 5 systems may result in greater potential impact. Likewise, considerable overlap in the estimated removal efficiency performance of Levels 1 through 4-1 make it challenging to draw reliable conclusions regarding their relative performance.

Table J-12 shows the contribution of individual unit processes to ecotoxicity potential.

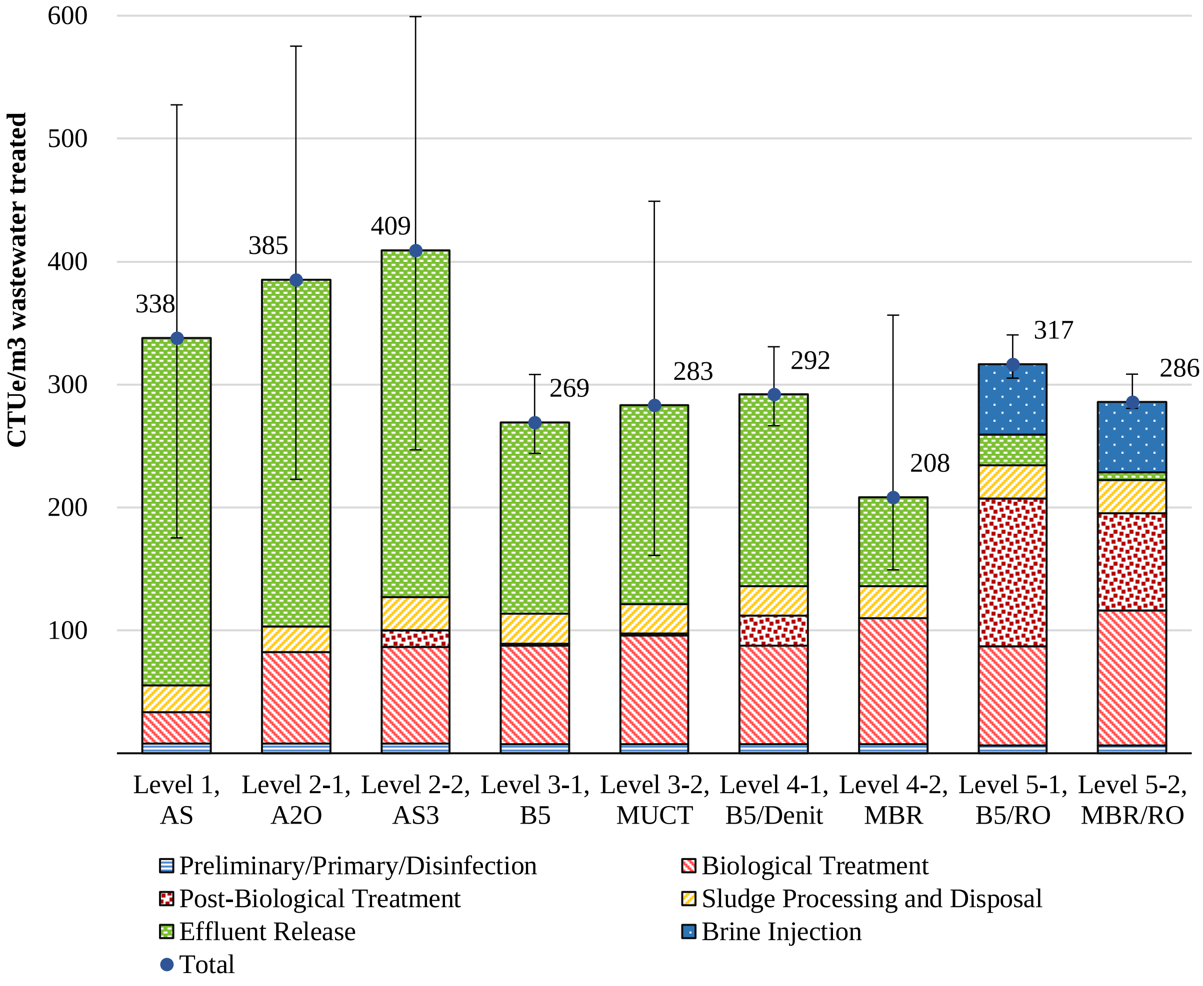


Figure 7-4. Ecotoxicity Potential Results by Treatment Group (CTUe/m^3 wastewater treated)

8. SUMMARY BASELINE RESULTS

This section presents the baseline summary LCIA and cost (as net present value) results to understand the trade-offs in impacts between operation of the different wastewater treatment configurations. Following a presentation of the baseline summary results, a normalization step is applied to the LCIA results to interpret the relative magnitude of the different impact categories assessed.

8.1 Baseline Results Summary

presents a summary of the relative results for the main impact categories. Results have been normalized to the maximum impact within each category. The side-by-side presentation of the results serves to highlight the trade-offs that exist between the various treatment configurations for traditional LCIA categories. Summary results are also displayed in a table format in Table 8-1. **Figure 8-2** presents the results in Table 8-1 for three representative treatment configurations in a graphical format to help visualize the relative impacts and trade-offs. In this graph, seven of the LCIA endpoints and costs are displayed on their own axis in spiral format, with the greatest impact furthest from the center. The shaded areas reflect a "footprint" of impact. Graphical displays of the results in this manner can aid in interpreting results and facilitating associated decision-making when comparing options. The specific information presented in Figure 8-2 is intended to be purely illustrative and is not intended to imply the relative importance of any endpoint or any winnowing of treatment configurations.

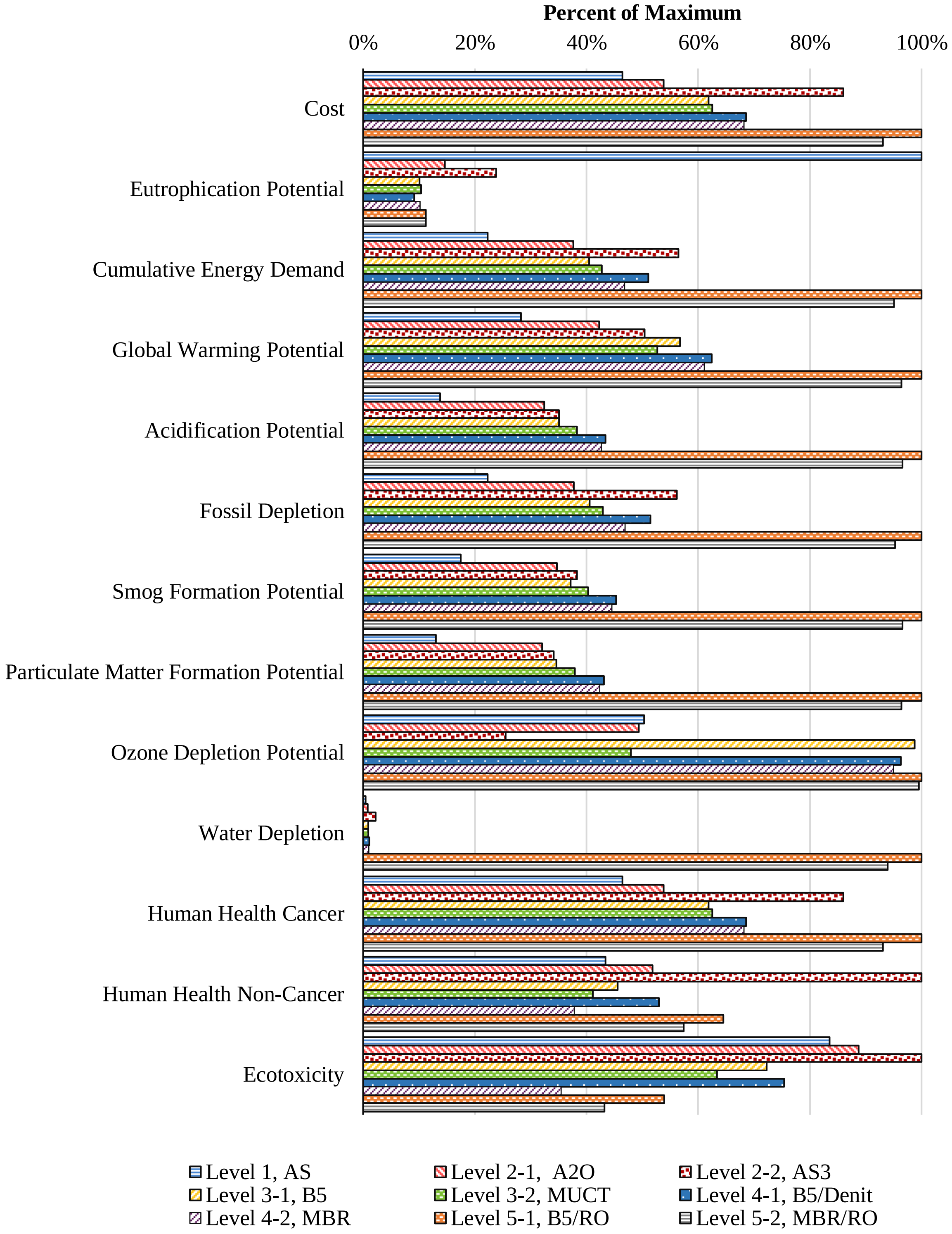


Figure 8-1. Relative LCIA and Cost Results for Nine Wastewater Treatment Configurations

Table 8-1. Summary LCIA and Cost Results for Nine Wastewater Treatment Configurations (per m^3 wastewater treated)

Impact Name	Unit	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Cost	*$ USD*	0.64	0.74	1.2	0.84	0.86	0.94	0.89	1.4	1.3
Eutrophication Potential	*kg N eq*	0.07	9.8E-3	0.02	6.8E-3	6.9E-3	6.1E-3	6.8E-3	7.5E-3	7.5E-3
Cumulative Energy Demand	*MJ*	5.4	9.1	14	9.7	10	12	11	24	23
Global Warming Potential	*kg CO2 eq*	0.52	0.77	0.92	1.0	0.96	1.1	1.1	1.8	1.8
Acidification Potential	*kg SO2 eq*	0.01	0.03	0.03	0.03	0.04	0.04	0.04	0.09	0.09
Fossil Depletion	*kg oil eq*	0.12	0.20	0.30	0.22	0.23	0.28	0.25	0.54	0.51
Smog Formation Potential	*kg O3 eq*	0.13	0.26	0.29	0.28	0.30	0.34	0.33	0.75	0.72
Particulate Matter Formation	*PM2.5 eq*	1.4E-3	3.3E-3	3.5E-3	3.6E-3	3.9E-3	4.5E-3	4.4E-3	0.01	0.01
Ozone Depletion Potential	*kg CFC-11 eq*	3.9E-6	3.8E-6	2.0E-6	7.6E-6	3.7E-6	7.4E-6	7.3E-6	7.7E-6	7.7E-6
Water Depletion	*m3 H2O*	8.0E-4	1.5E-3	4.1E-3	1.7E-3	1.8E-3	2.0E-3	2.0E-3	0.19	0.17
Human Health Cancer Potential	*CTUh*	4.3E-9	5.1E-9	9.9E-9	4.5E-9	4.1E-9	5.2E-9	3.7E-9	6.4E-9	5.7E-9
Human Health Non-Cancer Potential	*CTUh*	1.2E-7	1.3E-7	1.4E-7	1.0E-7	9.0E-8	1.1E-7	5.0E-8	7.7E-8	6.1E-8
Ecotoxicity Potential	*CTUe*	338	385	409	269	283	292	208	317	286

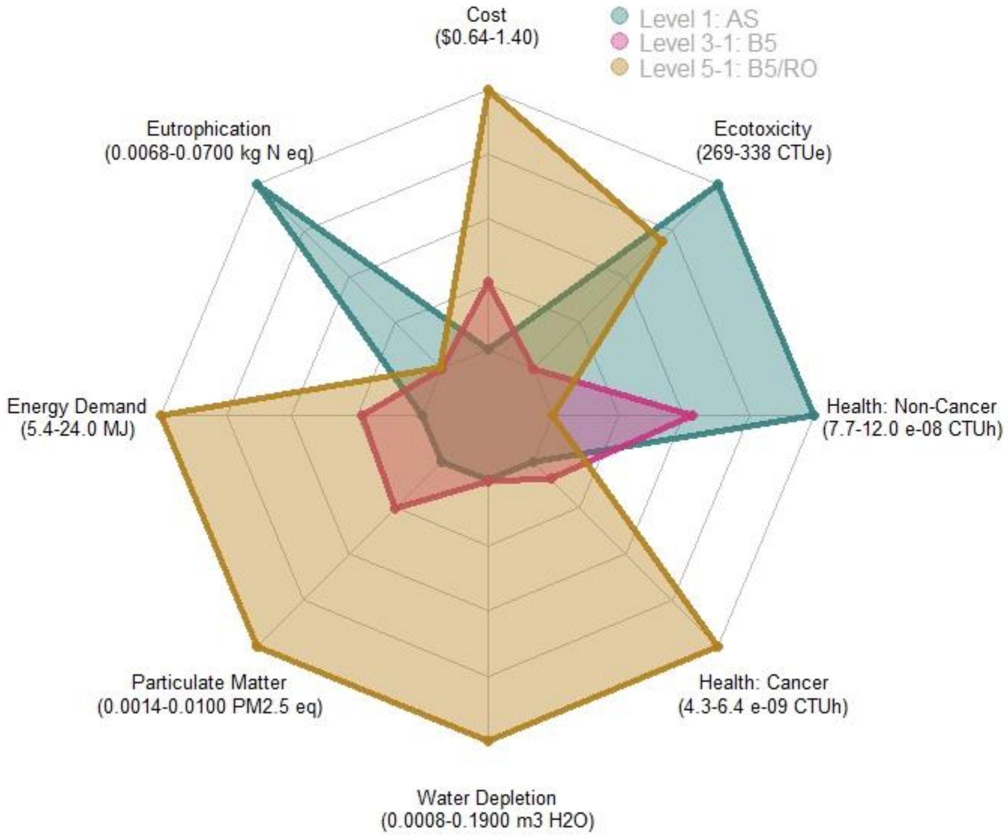


Figure 8-2. Illustrative Comparison of LCIA and Cost Results for Three Wastewater Treatment Configurations

8.2 Normalized Baseline Results

Normalization is a process of standardizing impact results in all categories such that the contribution of impact results associated with the functional unit can be judged relative to total national or global impact for a given category. Table 8-2 shows normalization factors and U.S. national per capita impacts in the year 2008. This is the most recent year normalization factors for LCA are available (Ryberg et al., 2014; Lippiatt et al., 2013). Normalization factors are not available for the impact categories fossil depletion and CED; therefore, these categories are excluded from the normalization step. Toxicity results are also excluded due to the higher magnitude of uncertainty associated with normalization factors for these categories. The normalization factor is the total U.S. impact for the specified category in 2008. Impact per person is estimated by dividing the normalization factor by the U.S. population. The U.S. population in 2008 is estimated as 304,100,000 people (World Bank, 2016). So, for example, the second row of Table 8-2 indicates that average per capita GHG emissions from all U.S. sources was just over 24 metric tons of CO_2 eq in 2008.

Table 8-2. 2008 U.S. Normalization Factors and Per Capita Annual Impacts

Impact Category [a]	Unit	Normalization Factor (US-2008)	Impact per Person [b]	Source
Eutrophication	kg N eq/yr	6.6E+9	22	Ryberg et al., 2014
Global Warming	kg CO2 eq/yr	7.4E+12	2.4E+4	Ryberg et al., 2014
Acidification	kg SO2 eq/yr	2.8E+10	92	Ryberg et al., 2014
Smog	kg O3 eq/yr	4.2E+11	1.4E+3	Ryberg et al., 2014
Particulate Matter Formation	kg PM2.5 eq/yr	7.4E+9	24	Ryberg et al., 2014
Ozone Depletion	kg CFC-11 eq/yr	4.9E+7	0.16	Ryberg et al., 2014
Water Depletion	liter H2O eq/yr	1.7E+14	5.6E+2	Lippiatt et al., 2013

a – Normalization factor not available for cumulative energy demand and fossil depletion, so these categories are excluded from normalization step.

b – Impact per person calculated using 2008 population of 304,100,000.

The process of normalization allows us to better assess the significance of impacts by providing absolute benchmarks at the national level. The functional unit for this study is a cubic meter of wastewater treated. In order to provide a gross, general context to these numbers, this presentation of normalized results calculates values based on the range of per capita municipal wastewater that is generated each year. The average generation of domestic municipal wastewater in the U.S. is estimated to be between 50 and 89 gallons per person per day (Tchobanoglous et al., 2014). This is a large range, reflecting the wide variation in use patterns as determined by factors such as climate, household size, and home and community conservation measures. This level of daily use translates to an annual domestic wastewater generation between 70 and 123 cubic meters per year per person. By multiplying impact results calculated in this study by the annual cubic meters of domestic wastewater treated each year at municipal wastewater facilities and dividing by per capita normalization factors, it is possible to calculate the approximate annual contribution of domestic wastewater treatment to total per capita impact in each of the included impact categories. This calculation excludes wastewater generated by commercial, public, and industrial sources, and therefore overestimates the impact from individuals and does not reflect the full national burden of wastewater treatment. The results of this calculation for the nine treatment systems and environmental impact in seven categories are presented in Table 8-3.

The overall trend in results is the same as that for unnormalized results, with impact in most categories increasing with the level of treatment. However, we can now more easily see the dramatic reduction in normalized contribution to eutrophication between conventional activated sludge treatment and all of the advanced treatment options. Overall per capita eutrophication impact may decrease 12 to 36 percent when shifting from the Level 1 wastewater treatment configuration to the higher nutrient removal wastewater configurations. The results highlight the fact that emissions resulting from wastewater treatment do not contribute equally to all impact categories. Wastewater treatment contributions to GWP and ozone depletion are less than one percent of the average national per capita emissions that contribute to these impact categories across all treatment levels. This implies that more emphasis should be put on eutrophication results compared to GWP or ozone depletion results for the wastewater treatment sector. Emissions associated with impact categories linked strongly with energy consumption such as acidification, smog formation, particulate matter formation, and human health-cancer start out at levels between zero and four percent per capita impacts, but rise to between three and 19 percent per capita impacts by the time Level 5 treatment is reached. These results also demonstrate the significance of impacts associated with a broad range of impact categories not typically thought of in relation to wastewater treatment, particularly at the more advanced levels of nutrient removal, and indicate a possibility for shifting burdens from eutrophication to other categories of environmental impact.

Table 8-3. Estimated Annual Contribution of Municipal Wastewater Treatment Per Capita Impact in Seven Impact Categories

Impact Category [a]	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Eutrophication Potential	21 - 38%	3 - 6%	5 - 9%	2 - 4%	2 - 4%	2 - 3%	2 - 4%	2 - 4%	2 - 4%
Global Warming Potential	0.1 - 0.3%	0.2 - 0.4%	0.3 - 0.5%	0.3 - 0.5%	0.3 - 0.5%	0.3 - 0.6%	0.3 - 0.6%	0.5 - 0.9%	0.5 - 0.9%
Acidification Potential	1 - 2%	2 - 4%	2 - 4%	2 - 4%	3 - 5%	3 - 5%	3 - 5%	7 - 13%	7 - 12%
Smog Formation Potential	1%	1 - 2%	1 - 3%	1 - 2%	2 - 3%	2 - 3%	2 - 3%	4 - 7%	4 - 6%
Particulate Matter Formation Potential	0 - 1%	1 - 2%	1 - 2%	1 - 2%	1 - 2%	1 - 2%	1 - 2%	3 - 5%	3 - 5%
Ozone Depletion Potential	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%
Water Depletion	<1%	<1%	<1%	<1%	<1%	<1%	<1%	2 - 4%	2 - 4%

a – Normalization factor not available for cumulative energy demand and fossil depletion, so these categories are excluded from normalization step.

b – Toxicity results are interim.

9. SENSITIVITY ANALYSIS

9.1 Overview

Sensitivity analysis is an important component in the production of robust LCA and LCCA study results. As with any modeling process, the construction and analysis of an LCA and LCCA model and results requires making and documenting many assumptions. Many individual assumptions are known to have only an insignificant effect on the final impact results calculated for a given functional unit, but the effect of other assumptions is uncertain or is known to be significant. In the latter two cases, sensitivity analysis is employed to quantify the effect of modeling choices on LCA results. In this study, a sensitivity analysis was performed on the interest rate used in the LCCA analysis, the choice of GWP factors, the modeled electrical grid fuel mix, and the treatment of anaerobic digestion biogas. A case study is also presented illustrating cost results for a WWTP incorporating nutrient control technology as a retrofit rather than as a greenfield plant. The details of what elements were changed in each of the models and the subsequent effect on results categories are documented in the following subsections.

9.2 Interest and Discount Rates

As discussed in Section 3.3, ERG used the same value for the interest and discount rates. While there are slight differences in the interest and discount rates, it is appropriate to use the same value for the interest and discount rates when developing planning level costs. In this sensitivity analysis, ERG changed the interest rate during construction (see Equation 12), which is part of the total capital costs, and the real discount rate used to calculate the net present value (see Equation 13) from 3% to 5%. The interest and discount rates are not used to calculate the annual costs; as a result, this section focuses on changes to the total construction costs and net present value. The 3% interest rate represents a conservative interest rate for a State Revolving Fund (SRF) loan as the SRF average loan rate was 1.7% in April 2016 (U.S. EPA, 2016a). The 5% interest rate represents a worse-case scenario reflective of rates that WWTPs in poor financial shape, but still able to borrow, would be able to obtain.

Figure 9-1 presents the total construction costs using the 3% and 5% interest and discount rates. On average, the total construction costs increased by approximately 2.6% using the 5% interest rate, due to an increase in the interest paid during construction. **Figure** 9-2 presents the net present value using the 3% and 5% interest and discount rates. The net present value decreased using the 5% interest and discount rates by an average of 18%. The difference in the net present value is primarily because the majority of the costs for the wastewater treatment configurations are annual costs that occur in the future, which become smaller when using the 5% discount rate versus the 3% discount rate.

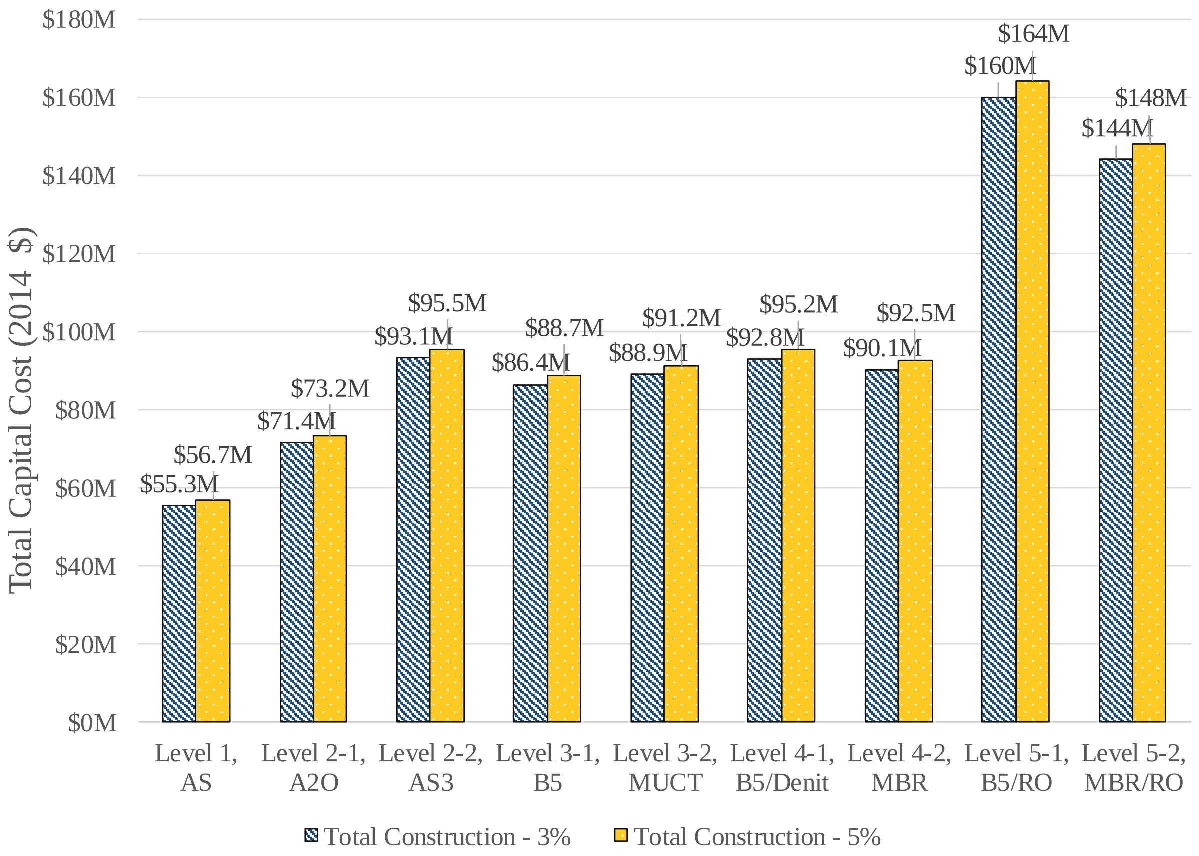


Figure 9-1. 3% versus 5% Interest Rate Total Construction Sensitivity Analysis Results

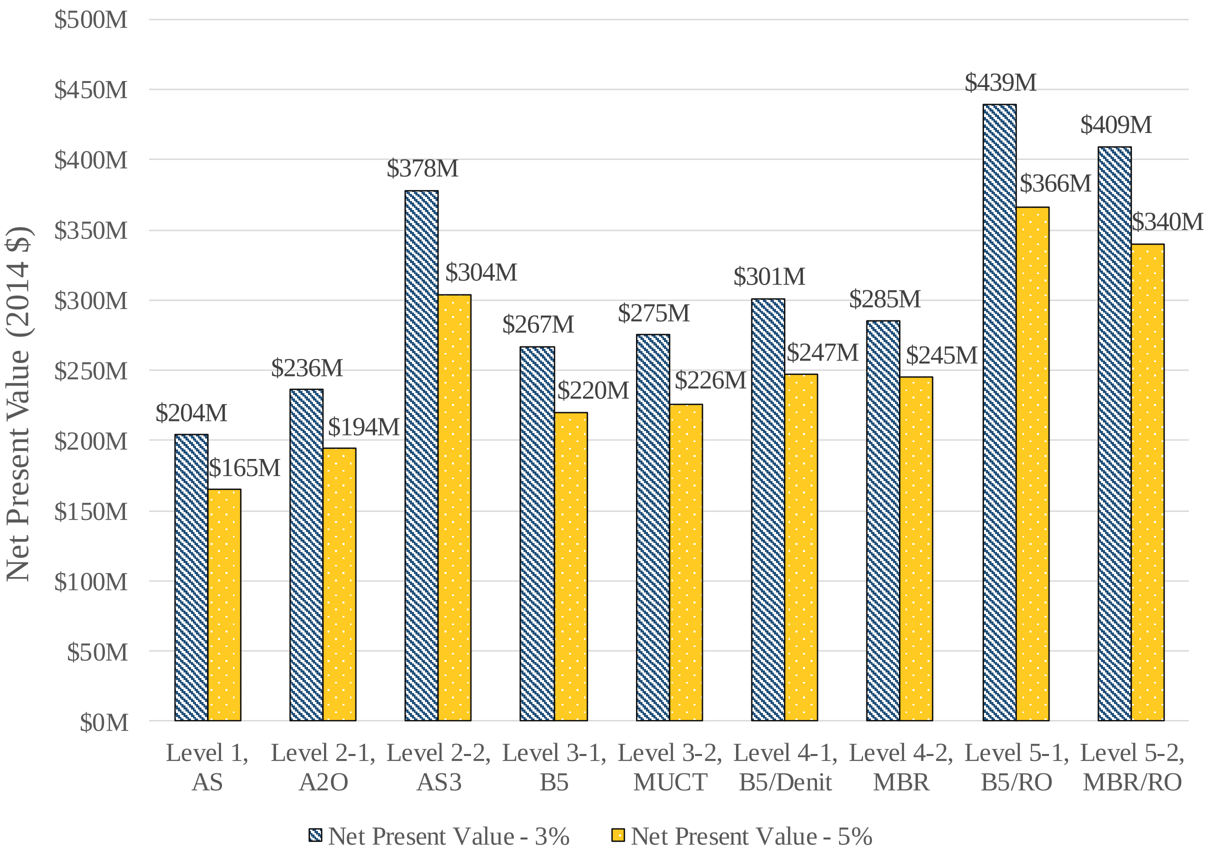


Figure 9-2. 3% versus 5% Interest and Discount Rate Net Present Value Sensitivity Analysis Results

9.3 Global Warming Potential

In this sensitivity analysis, the effect of using IPCC's most recent 2013 GWPs from the Fifth Assessment Report was assessed (IPCC, 2013). The baseline study used 2007 GWP factors from the IPCC Fourth Assessment Report, which have been officially adopted by the UNFCCC for international GHG reporting standards and are used by EPA in their annual greenhouse gas emissions report (IPCC, 2007). GWPs are the values used to transform the emission of all molecules that have heat trapping potential into a standardized unit. The standardization process takes CO_2 as its reference value setting its value to one, with all other factors being set relative to that standard (i.e., kilograms CO_2 eq.). There are many parameters that feed into determination of CO_2 eq. values, and the scientific basis for these values continues to evolve, with the IPCC reviewing and updating factors as the evidence improves. Table 9-1 shows both the 2007 and the updated 2013 IPCC GWP factors for the primary GHGs resulting from the life cycle of wastewater treatment. The last column in the table show the percent change associated with the 2013 update relative to the 2007 values.

Table 9-1. 2007 versus 2013 IPCC GWPs

GHG	GWP IPCC 2007	GWP IPCC 2013	Percent Change
Carbon dioxide	1.0	1.0	0%
Nitrous oxide	3.0E+2	2.7E+2	-12%
Methane	25	28	+11%

The effect of the GWP update on cumulative results depends upon the relative contribution of each GHG to the total GWP impact for each of the wastewater treatment configurations. Across all nine wastewater treatment configurations, the effect of selecting the 2007 versus 2013 GWP factors was shown to alter the GWP impact scores by between 1.8 and 3.8 percent. Figure 9-3 shows the magnitude of these effects per cubic meter of treated wastewater for each of the nine wastewater treatment configurations. The stacked bars correspond to the three main GHGs, which are responsible for the majority of GWP impact. The fact that methane and nitrous oxide are both prevalent GHGs for these systems, and the similarly equal and opposite change in GWP results for these two gases served to mitigate the impact of the update on cumulative results for this study. Table 9-2 lists the percent change in GWP impact that results from the choice between 2007 and 2013 GWP factors. At an aggregate level, the results of this study were not notably affected by GWP factor selection.

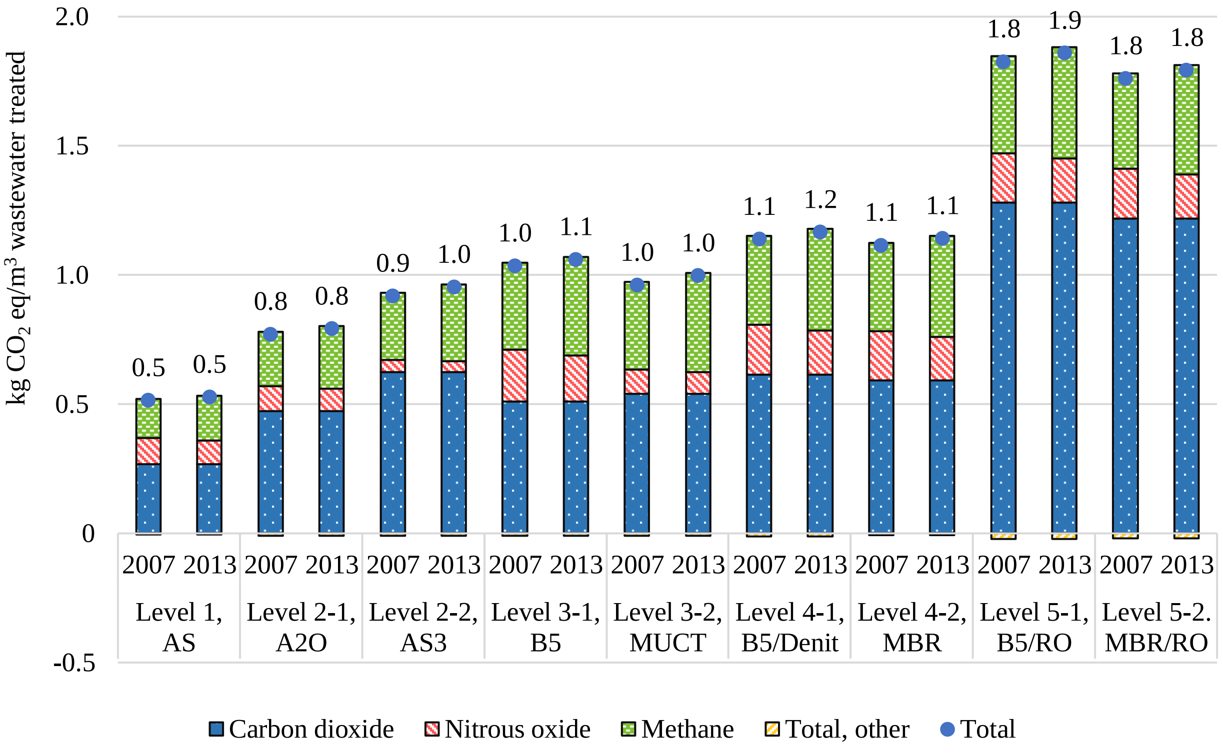


Figure 9-3. 2007 versus 2013 IPCC GWP Sensitivity Analysis Results

Table 9-2. Percent Change in GWP Impact due to GWP Factor Selection

	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2. MBR/RO
Percent Change[a]	2.5%	2.7%	3.7%	2.3%	3.8%	2.3%	2.4%	1.8%	1.8%

a – Percent Change = $(GWP_{2013}-GWP_{2007})/GWP_{2007}$

9.4 Electrical Grid Mix

In this sensitivity analysis, an alternative electrical mix with a “cleaner” grid (e.g., shift away from coal) was applied. Table 9-3 displays the electrical grid mix for the NorthEast Power Coordinating Council (NPCC), in addition to the baseline average mix of fuels used as the basis for this study. This information is based on eGRID data from 2012. NPCC covers states such as New York, Connecticut, Rhode Island, Massachusetts, Vermont, New Hampshire, and Maine. This electrical grid is included in a sensitivity analysis, as it contains a higher portion of electricity from natural gas, nuclear, and hydro and a lower portion of electricity from coal as compared to the U.S. average electrical grid. The last column of Table 9-3 presents the percent change within individual fuel types when shifting from the baseline U.S. average electrical grid mix to the NPCC electrical grid mix.

Table 9-3. NPCC eGRID Regional versus U.S. Average Electrical Grid Mix

Fuel	Baseline U.S. Average Percent of Mix	NPCC Sensitivity Analysis Percent of Mix	Percent Change
Coal	45%	3.1%	-93%
Natural Gas	24%	49%	+100%
Nuclear	20%	30%	+51%
Hydro	6.2%	12%	+94%
Wind	2.3%	1.6%	-28%
Biomass	1.4%	3.6%	+170%
Oil	1.0%	0.38%	-63%
Geothermal	0.37%	0%	-100%
Other Fossil	0.35%	1.1%	+220%
Solar	0.03%	0.03%	0%

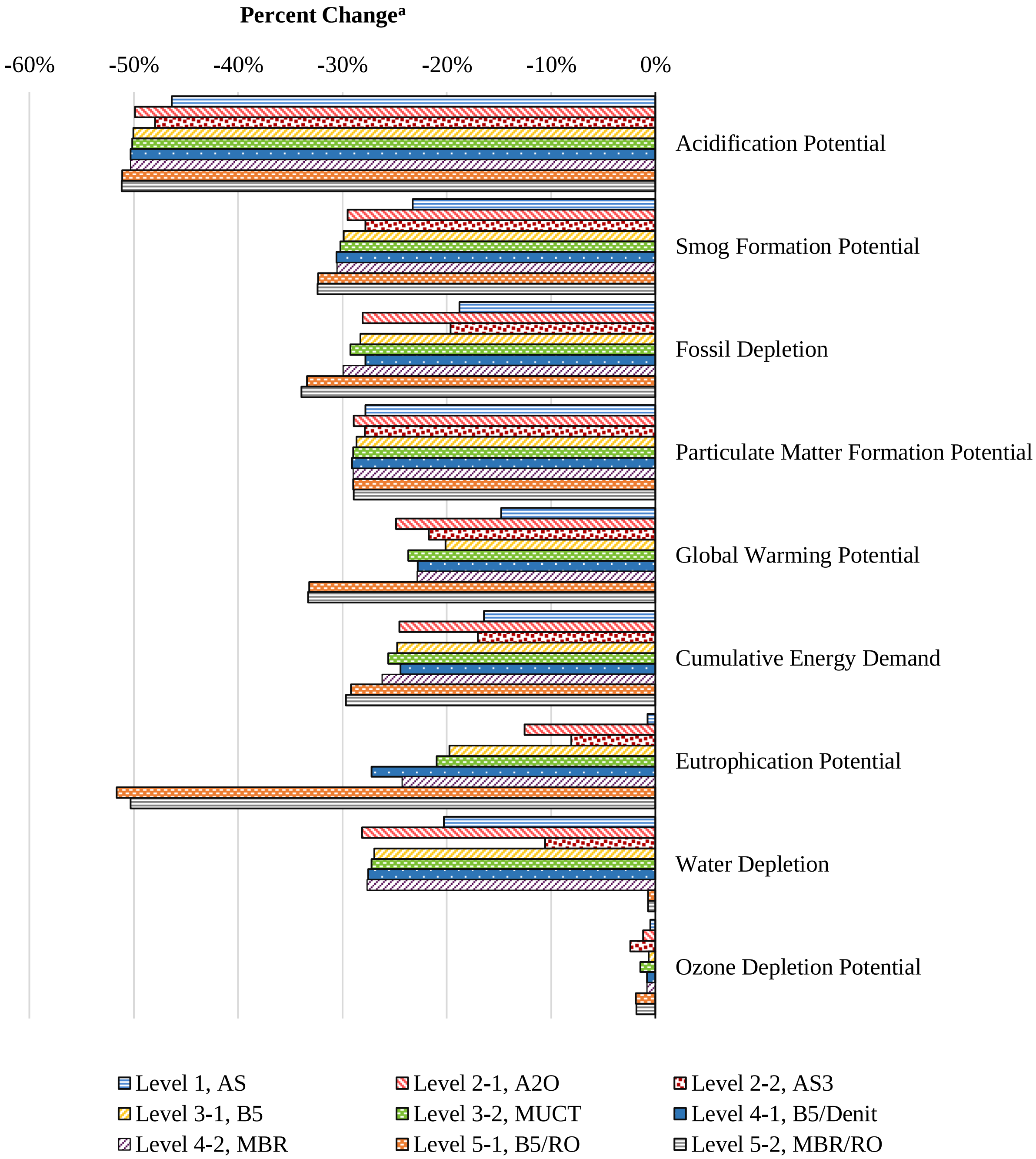
When conducting the sensitivity analysis, the electrical grid mix that serves the wastewater treatment plant is varied for each of the nine wastewater treatment configurations, while the electrical grid mixes associated with background processes remain constant. This is reasonable since it is likely background chemicals and fuels are not produced in the same region of the U.S. that they are utilized. Results for all of the impact categories were rerun and compared to the baseline values. As displayed in Figure 9-4, the relative impact of this substitution depends both upon the wastewater treatment configuration and on the impact category. The impacts in this figure are sorted, with the greatest average reduction across all treatment levels shown at the top and the smallest average reduction across all treatment levels shown at the bottom. The effect of this substitution of electrical grid mix on cumulative impact scores is significant across the majority of impact categories and treatment levels with a few notable exceptions. Ozone depletion potential impact is not shown to be sensitive to the choice of electrical grid with the percent change for all wastewater treatment configurations being less than one percent. The impact on eutrophication potential for Levels 1 and 2 are overshadowed by the predominance of eutrophying emissions associated with effluent release. Similarly, the effect on water depletion impact for Level 5 is reduced due to the predominant impact of brine injection to results in this category.

In general, those wastewater treatment configurations with a higher energy demand per cubic meter of wastewater treated show a greater sensitivity to the source of electricity. A number of interesting patterns are visible in Figure 9-4. The relative effect of this sensitivity analysis between wastewater treatment configurations is most pronounced for eutrophication potential. The percent change associated with eutrophication impacts in Level 1 and Level 5– are approximately -1 and -50 percent, respectively. The large variation in these values can be explained by large differences in the aspects of the LCA model that contribute to impact in each category. As mentioned above, eutrophication impact for Level 1 is predominated by effluent release, so the change in grid energy has little influence on impact. Alternatively, by the time water is cleaned to Level 5 standards, there is so little nutrient content in the effluent itself that electricity impact predominates. Similarly, for other impact categories that show an increasing sensitivity to electricity choice as we move from Level 1 to Level 5, we can attribute this to the increased contribution of electricity to impact results as effluent standards increase.

The consistently high effect on acidification and particulate matter impacts across the treatment systems is demonstrative of the dependence of these impact categories on emissions resulting from electricity production. Toxicity results are excluded from Figure 9-3.

The deviation in general trends associated with Level 2-2 are due to the exceptional reliance of this wastewater treatment configuration on chemical flocculent for phosphorus removal, and the impact associated with these chemical additions. In this way, this wastewater treatment configuration is less sensitive to overall changes in the electrical grid fuel mix.

The findings of this sensitivity analysis indicate that electricity is a primary driver for many of the impact categories assessed in this study. Utilization of “cleaner” fuels for electricity or recovery of resources at the WWTP to produce energy on-site could serve to offset some of the burdens realized when including additional energy intensive unit processes to achieve increased nutrient removal.



[a] Percent Change = [(NPCC$_{\text{impact}}$-AvgGrid$_{\text{impact}}$)/AvgGrid$_{\text{impact}}$]

Figure 9-4. Electrical Grid Mix Sensitivity Analysis Results

Table 9-4. Electrical Grid Sensitivity Analysis, U.S. Average versus NPCC Electrical Grid (per m^3 wastewater treated)

		Level 1, AS		Level 2-1, A2O		Level 2-2, AS3		Level 3-1, B5		Level 3-2, MUCT		Level 4-1, B5/Denit		Level 4-2, MBR		Level 5-1, B5/RO		Level 5-2, MBR/RO	
Impact Name	**Unit**	**U.S. Avg.**	**NPCC**	**U.S. Avg.**	**NPCC**	**U.S. Avg.**	**NPCC**	**U.S. Avg.**	**NPCC**	**U.S. Avg.**	**NPCC**	**U.S. Avg.**	**NPCC**	**U.S. Avg.**	**NPCC**	**U.S. Avg.**	**NPCC**	**U.S. Avg.**	**NPCC**
Global Warming Potential	**kg CO2 eq**	0.52	0.44	0.77	0.58	0.92	0.72	1.0	0.83	0.96	0.73	1.1	0.88	1.1	0.86	1.8	1.2	1.8	1.2
Eutrophication Potential	**kg N eq**	0.07	0.07	9.8E-3	8.6E-3	0.02	0.01	6.8E-3	5.4E-3	6.9E-3	5.5E-3	6.1E-3	4.5E-3	6.8E-3	5.1E-3	7.5E-3	3.6E-3	7.5E-3	3.7E-3
Acidification Potential	**kg SO2 eq**	0.01	6.9E-3	0.03	0.02	0.03	0.02	0.03	0.02	0.04	0.02	0.04	0.02	0.04	0.02	0.09	0.05	0.09	0.04
Fossil Depletion	**kg oil eq**	0.12	0.10	0.20	0.15	0.30	0.24	0.22	0.16	0.23	0.16	0.28	0.20	0.25	0.18	0.54	0.36	0.51	0.34
Smog Formation Potential	**kg O3 eq**	0.13	0.10	0.26	0.18	0.29	0.21	0.28	0.20	0.30	0.21	0.34	0.24	0.33	0.23	0.75	0.51	0.72	0.49
Particulate Matter Formation	**PM2.5 eq**	1.4E-3	9.8E-4	3.3E-3	2.4E-3	3.5E-3	2.6E-3	3.6E-3	2.6E-3	3.9E-3	2.8E-3	4.5E-3	3.2E-3	4.4E-3	3.1E-3	0.01	7.4E-3	0.01	7.1E-3
Ozone Depletion Potential	**kg CFC-11 eq**	3.9E-6	3.9E-6	3.8E-6	3.8E-6	2.0E-6	1.9E-6	7.6E-6	7.5E-6	3.7E-6	3.6E-6	7.4E-6	7.3E-6	7.3E-6	7.2E-6	7.7E-6	7.6E-6	7.7E-6	7.5E-6
Cumulative Energy Demand	**MJ**	5.4	4.5	9.1	6.8	14	11	9.7	7.3	10	7.7	12	9.3	11	8.3	24	17	23	16
Water Depletion	**m3 H2O**	8.0E-4	6.4E-4	1.5E-3	1.1E-3	4.1E-3	3.7E-3	1.7E-3	1.2E-3	1.8E-3	1.3E-3	2.0E-3	1.5E-3	2.0E-3	1.4E-3	0.19	0.18	0.17	0.17

9.5 <u>Biogas Energy Recovery</u>

The baseline model assumes flaring of biogas produced during anaerobic digestion. This sensitivity analysis investigates the effect on plant level environmental impact and life cycle cost from shifting to energy recovery using a combined heat and power (CHP) engine.

9.5.1 System Description

Biogas system components include the prime mover, which drives the electrical generator, a heat exchanger, gas processing/cleaning equipment, electrical controls and enclosure. An Internal Combustion Engine (ICE) is modeled as the CHP prime mover. ICEs are a common and industry tested technology (Wiser et al. 2010). Biogas exiting the anaerobic digesters is at ambient pressure and is saturated with moisture. Compression, drying and removal of impurities is required before gas can be combusted in a CHP engine. The biogas processing and CHP system boundary is depicted in Figure 9-5. Biogas and CHP system specifications are listed in Table 9-5.

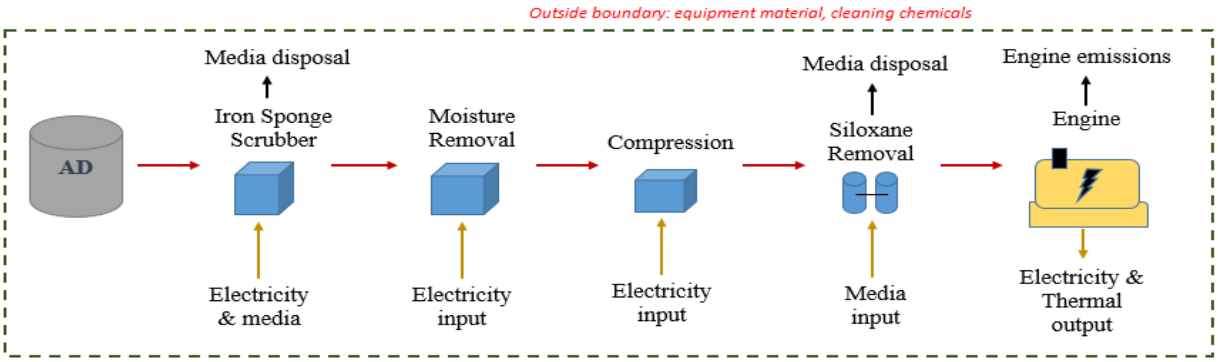


Figure 9-5. System Diagram of Biogas Processing and CHP System

Iron sponge scrubbers are assumed for hydrogen sulfide (H_2S) removal, being a widely used and commercially proven technology. H_2S is corrosive of metallic system components in the presence of water, and can lead to elevated sulfur oxide (SO_x) emissions from the prime mover. H_2S is a common constituent of biogas generated at municipal WWTPs often comprising 200-3500 ppmv of biogas (Wiser et al. 2010). A representative H_2S concentration of 500 ppmv is used to estimate iron sponge requirements (Wiser et al. 2010). The desired temperature range for adsorption via iron sponge is between 25 and 60 °C, which corresponds to the temperature of biogas as it exits the anaerobic digesters. Hydrated iron oxide is usually sold embedded onto wood chips. Iron sponge adsorption requires the presence of moisture in the biogas, so process placement before moisture removal is common. Approximately 20 kg of H_2S can be adsorbed per 100 kg of sorbent material (Ong et al. 2017). The oxide impregnated wood chips can be regenerated by flushing the bed with atmospheric oxygen, which releases H_2S as elemental sulfur. The regeneration process can be repeated approximately 1-2 times before the adsorbent media requires replacement (Abatzoglou and Boivin 2009). This analysis assumes 1 regeneration cycle, achieving 85 percent of original sorbent capacity. The necessary equipment has a modest footprint and is usually located outdoors to mitigate safety concerns.

Table 9-5. Biogas Processing and CHP System Specifications for Nine Treatment System Configurations

System Parameter	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Annual Biogas Production (m^3)	1.6E+6	1.3E+6	1.8E+6	1.3E+6	1.3E+6	1.3E+6	1.3E+6	1.3E+6	1.2E+6
Biogas Production (scfm)	1.1E+2	88	1.2E+2	85	85	85	87	85	82
Available Biogas Energy (MJ)[a]	2.7E+7	2.4E+7	3.2E+7	2.3E+7	2.3E+7	2.3E+7	2.3E+7	2.3E+7	2.2E+7
ICE Availability	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
ICE Power (kw)	3.2E+2	2.8E+2	3.8E+2	2.7E+2	2.7E+2	2.7E+2	2.8E+2	2.7E+2	2.6E+2
Electricity Production (kWh/yr)	2.5E+6	2.2E+6	3.0E+6	2.2E+6	2.2E+6	2.2E+6	2.2E+6	2.2E+6	2.1E+6
Thermal Energy (MJ/yr)	1.2E+7	1.1E+7	1.4E+7	1.0E+7	1.0E+7	1.0E+7	1.0E+7	1.0E+7	9.9E+6
AD Heat Requirement (MJ/yr)[b,c]	1.7E+7	1.6E+7	2.4E+7	1.5E+7	1.5E+7	1.5E+7	1.5E+7	1.5E+7	1.4E+7
WWTP Electricity Requirement (kWh/yr)	2.8E+6	6.7E+6	6.8E+6	8.1E+6	8.6E+6	9.8E+6	8.2E+6	2.2E+7	2.0E+7
Percent of AD Heat Demand Satisfied (%)	70%	68%	59%	67%	67%	67%	70%	67%	71%
Percent of Facility Electricity Demand Satisfied (%)	90%	33%	43%	30%	27%	24%	25%	10%	10%
H_2S removed (kg/day)	1.9	1.6	2.2	1.6	1.6	1.6	1.6	1.6	1.5
Iron Oxide requirement (kg/yr)	1.8E+3	1.6E+3	2.2E+3	1.6E+3	1.6E+3	1.6E+3	1.6E+3	1.6E+3	1.5E+3
Siloxane removed (kg/day)	0.44	0.36	0.48	0.35	0.35	0.35	0.36	0.35	0.33
Activated Carbon requirement (kg/yr)	1.6E+3	1.3E+3	1.8E+3	1.3E+3	1.3E+3	1.3E+3	1.3E+3	1.3E+3	1.2E+3

[a] Accounts for 5 percent fugitive biogas loss and 20 percent flaring rate.

[b] Expressed as CHP thermal energy, accounts for 90 percent efficiency of heat exchanger.

[c] AD – anaerobic digester/digestion

Moisture removal is the next step in biogas processing as it enhances performance of the subsequent siloxane removal step (Wiser et al. 2010). Moisture removal via chilling and condensation is proposed to ensure sufficiently dry biogas. Refrigeration energy demands typically account for less than two percent of the energy content of the processed biogas. A conservative value of two percent is used to estimate electricity demands of the refrigeration process (Ong et al. 2017).

Compression of biogas is necessary prior to combustion in the prime mover. Fuel pressurization to between 3 and 5 psi is sufficient for use in ICEs. Use of a blower is recommended for moderate compression requirements up to 15 psig (Wiser et al. 2010). Compression follows H_2S and moisture removal to ensure longevity of compressor components. Blowers have the benefit of being low cost, require no oil, lack VOC emissions and have minimal maintenance requirements (Wiser et al. 2010). Energy requirements for compression are estimated based on the use of heavy duty rotary blowers that operate at brake horsepowers of between 2.4 and 3.3 depending upon the biogas flowrate in standard cubic feet per minute (scfm), which ranges between 82 and 118 scfm depending upon the system configuration (see Table 9-5).

The final biogas cleaning and processing step involves removal of siloxanes, which are another common contaminant of biogas generated via anaerobic digestion of wastewater sludge. Siloxanes can be removed using refrigeration or sorbents such as activated carbon, alumina, synthetic resins, or liquid sorbents. Siloxane removal via activated carbon adsorption is modeled given its prevalent use, low cost and maintenance requirements. Coal is modeled as the activated carbon feedstock, based on LCI information presented in Bayer et al. (2005).

The ICE is sized based upon the available energy content of biogas produced by each system assuming a 90 percent availability factor (i.e. 10 percent system downtime). The quantity of biogas available for energy consumption equals total biogas production less fugitive emissions (5 percent) and flared biogas (UNFCCC 2012). The analysis assumes that 20 percent of biogas is flared due to system downtime, upsets and lack of available storage capacity required to handle inconsistency in biogas production. ICE power requirements range from approximately 260 to 380 kW depending upon the system configuration, placing it in line with other WWTP CHP installations based on installed kW/MGD (U.S. DOE 2016). Electrical and thermal efficiency values of 34 percent and 45 percent are selected, respectively, representing the average of the reported ICE efficiency range in Wiser et al. (2010). ICE emissions are representative of an ICE engine utilizing selective catalytic reduction for NO_x control, and an oxidation catalyst system for carbon monoxide and VOC emission control.

9.5.2 Biogas Sensitivity LCIA Results

LCIA results by treatment group are presented for GWP in Figure 9-6. The addition of energy recovery yields a decrease in GWP impact for all system configurations due to the avoided environmental burdens of natural gas and grid electricity consumption associated with the electrical and thermal products of the CHP system. The absolute decrease in GWP impact varies between 0.21 and 0.31 kg CO_2-eq. per m^3 wastewater treated according to the quantity of biogas available for energy recovery. The relative effect on system level GWP impact is greatest for treatment Level 1, and decreases as total GWP impact increases for the higher levels of nutrient removal. The addition of energy recovery reduces Level 1 GWP impact by approximately 50 percent, while the reduction in GWP impact for Level 5 treatment configurations is less than 15 percent of base GWP impact. Base and CHP sensitivity LCIA results and corresponding percent reduction values are presented for all impact categories in Table 9-6. Figure 9-6 shows that the benefits of energy recovery are sufficient to offset the GWP impact of the sludge processing and disposal treatment group.

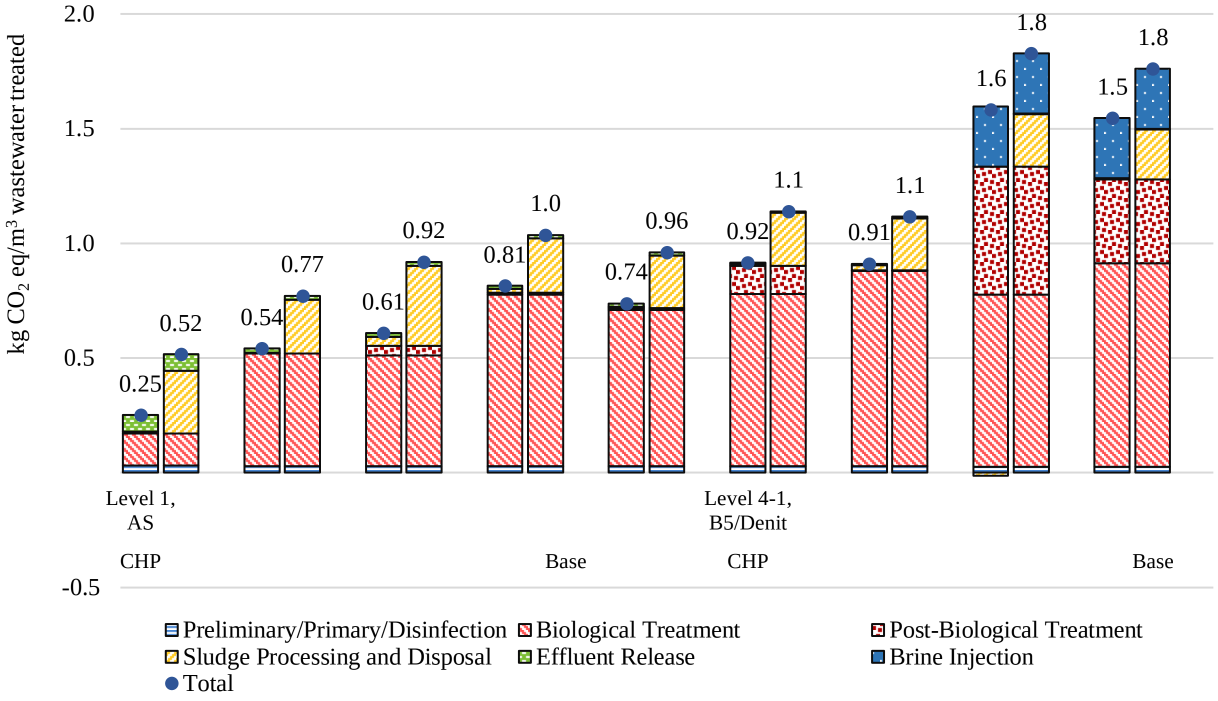


Figure 9-6. Global Warming Potential by Treatment Group for Base Results and the CHP Energy Recovery Sensitivity

Figure 9-7 presents results by treatment group for the CED inventory indicator, and demonstrates reductions in system level energy demand for all treatment configurations. Absolute reduction in CED range from 3.5 to 5.4 MJ/m^3 wastewater treated, according to biogas production associated with each configuration. The relative reduction in CED is greater than that observed for GWP, and varies between 16 and 86 percent for Levels 5-2 and 1, respectively. Figure 9-7 shows that the sludge processing and disposal treatment group now contributes an energy credit to the system, reducing the net CED of each treatment configuration.

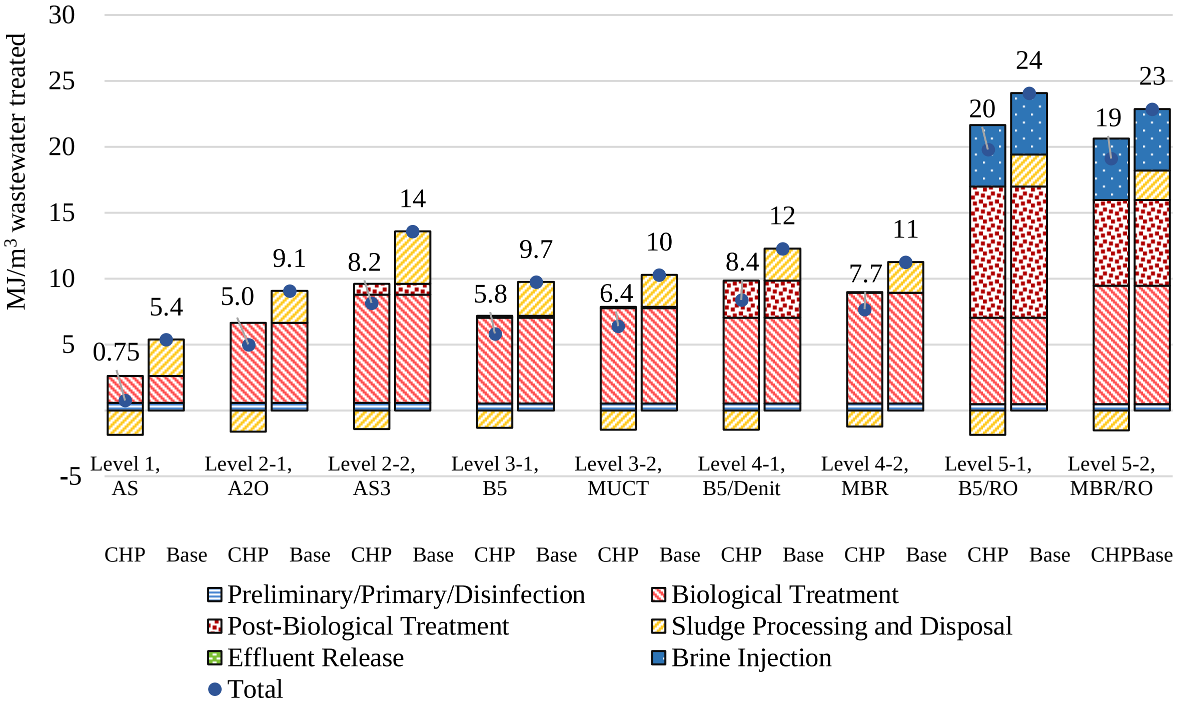


Figure 9-7. Cumulative Energy Demand by Treatment Group for Base Results and the CHP Energy Recovery Sensitivity

Table 9-6 shows that acidification, PM formation, smog formation, and fossil depletion potential all show significant reductions in system level impact in response to biogas energy recovery. Relative reductions in impact for these four impact categories are all greater for the lower treatment levels where absolute impact results are lower owing to lower relative energy and material consumption. Biogas production is also greatest for Level 1 and Level 2-2, leading to greater quantities of recovered energy. Energy recovery has a less dramatic effect on ozone depletion and eutrophication potential impact, with relative reductions in impact potential of between 1 and 26 percent. Eutrophication potential demonstrates a pattern unlike the other impact categories, where percent reductions in eutrophication impact are greatest for the higher treatment levels, which are associated with the lowest absolute eutrophication impact.

Table 9-6. Summary of Comparative Impact Assessment Results for the Base Case and CHP Energy Recovery Sensitivity

Impact Category	**Description**	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Global Warming Potential	Base Results	0.52	0.77	0.92	1.0	0.96	1.1	1.1	1.8	1.8
	CHP Sensitivity	0.25	0.54	0.61	0.81	0.74	0.92	0.91	1.6	1.5
	Percent Reduction[a]	*51%*	*30%*	*34%*	*21%*	*23%*	*20%*	*18%*	*13%*	*12%*
Cumulative Energy Demand	Base Results	5.4	9.1	14	9.7	10	12	11	24	23
	CHP Sensitivity	0.75	5.0	8.2	5.8	6.4	8.4	7.7	20	19
	Percent Reduction[a]	*86%*	*45%*	*40%*	*40%*	*38%*	*32%*	*32%*	*18%*	*16%*
Eutrophication Potential	Base Results	0.07	9.8E-3	0.02	6.8E-3	6.9E-3	6.1E-3	6.8E-3	7.5E-3	7.5E-3
	CHP Sensitivity	0.07	9.2E-3	0.02	6.2E-3	6.4E-3	5.6E-3	6.3E-3	6.9E-3	7.0E-3
	Percent Reduction[a]	*1%*	*6%*	*5%*	*8%*	*8%*	*9%*	*7%*	*8%*	*7%*
Water Depletion	Base Results	8.0E-4	1.5E-3	4.1E-3	1.7E-3	1.8E-3	2.0E-3	2.0E-3	0.19	0.17
	CHP Sensitivity	3.9E-4	1.1E-3	3.6E-3	1.3E-3	1.4E-3	1.7E-3	1.7E-3	0.19	0.17
	Percent Reduction[a]	*51%*	*25%*	*12%*	*21%*	*20%*	*18%*	*14%*	*0%*	*0%*
Acidification Potential	Base Results	0.01	0.03	0.03	0.03	0.04	0.04	0.04	0.09	0.09
	CHP Sensitivity	1.1E-3	0.02	0.02	0.02	0.03	0.03	0.03	0.08	0.08
	Percent Reduction[a]	*92%*	*36%*	*44%*	*30%*	*28%*	*25%*	*21%*	*12%*	*11%*
Particulate Matter Formation	Base Results	1.5E-3	3.4E-3	3.5E-3	3.6E-3	3.9E-3	4.5E-3	4.4E-3	0.01	1.0E-2
	CHP Sensitivity	1.1E-4	2.2E-3	2.1E-3	2.6E-3	2.9E-3	3.4E-3	3.5E-3	9.2E-3	9.0E-3
	Percent Reduction[a]	*93%*	*35%*	*41%*	*29%*	*27%*	*24%*	*20%*	*12%*	*10%*
Smog Formation Potential	Base Results	0.14	0.27	0.29	0.28	0.30	0.34	0.33	0.75	0.72
	CHP Sensitivity	0.02	0.16	0.15	0.18	0.21	0.24	0.25	0.64	0.63
	Percent Reduction[a]	*88%*	*39%*	*46%*	*34%*	*31%*	*28%*	*25%*	*14%*	*13%*
Ozone Depletion Potential	Base Results	3.9E-6	3.8E-6	2.0E-6	7.6E-6	3.7E-6	7.4E-6	7.3E-6	7.7E-6	7.7E-6
	CHP Sensitivity	3.4E-6	3.4E-6	1.5E-6	7.2E-6	3.3E-6	7.0E-6	7.0E-6	7.3E-6	7.3E-6
	Percent Reduction[a]	*12%*	*10%*	*26%*	*5%*	*10%*	*5%*	*5%*	*5%*	*5%*
Fossil Depletion	Base Results	0.12	0.20	0.30	0.22	0.23	0.28	0.25	0.54	0.51
	CHP Sensitivity	0.01	0.11	0.18	0.13	0.14	0.19	0.17	0.44	0.42
	Percent Reduction[a]	*89%*	*46%*	*42%*	*41%*	*39%*	*33%*	*33%*	*18%*	*17%*

a – Percent Reduction = $(\text{Base}_{\text{GWPimpact}}-\text{CHP}_{\text{GWPimpact}})/\text{Base}_{\text{GWPimpact}}$

9.5.3 Biogas Sensitivity LCCA

The base case LCCA results were updated to reflect the increased capital and O&M costs associated with the installation and ongoing maintenance of a CHP system. The cost sensitivity includes the avoided cost of reduced natural gas consumption, as well as revenue from the sale of electricity. Equipment costs for ICE CHP generally fall in the range of \$465 to \$1600 per kW of installed generation capacity (Wiser et al. 2010). The average of this range, \$1033/kW, is used in this analysis. Gas processing costs typically add \$600/kW of generation capacity (Darrow et al. 2017). The same direct and indirect cost factors are applied to the CHP system as are described in Section 2. Inclusive operation and maintenance costs are estimated per kWh of electricity production. Gas cleaning and processing O&M costs typically range from 0.015 to 0.025 \$/kWh, while prime mover maintenance costs typically fall in the range of 0.01 to 0.025 \$/kWh (Wiser et al. 2010). The average of these reported ranges is used in this analysis, 0.02 and 0.0175 \$/kWh, respectively.

Electricity revenue is estimated using the same cost factor, \$0.10/kWh, that is used to estimate system energy cost in the main LCCA analysis. Avoided natural gas costs are based on a natural gas purchase price of \$15.50 per 1000 ft^3.

Figure 9-8 summarizes the effect of including CHP and energy recovery on total system cost. The effect on system net present value over a 30-year time horizon is relatively modest, yielding a reduction in system net present value of between six and nine million dollars depending upon the configuration. The relative reduction in system net present value is greatest for level 1, yielding a 3.5 percent reduction in system net present value relative to the base scenario that assumes flaring of biogas. Table 9-7 summarizes base case and biogas case study life cycle costs.

Table 9-7. Summary of Biogas LCCA Costs (million 2014 \$s)

Treatment System Configuration	Net Present Value		Annual Labor, Material and Chemical Cost		Annual Energy Cost		Annual Amortization Cost	
	with CHP	Base	with CHP	Base	with CHP	Base	with CHP	Base
Level 1, AS	\$197	\$204	\$4.6	\$4.5	\$0.11	\$0.59	\$3.8	\$3.7
Level 2-1, A2O	\$230	\$236	\$4.6	\$4.5	\$0.5	\$0.9	\$4.8	\$4.8
Level 2-2, AS3	\$369	\$378	\$9.1	\$9.0	\$0.6	\$1.1	\$6.3	\$6.2
Level 3-1, B5	\$261	\$267	\$4.9	\$4.8	\$0.6	\$1.0	\$5.8	\$5.8
Level 3-2, MUCT	\$269	\$275	\$4.9	\$4.9	\$0.7	\$1.1	\$6.0	\$5.9
Level 4-1, B5/Denit	\$295	\$301	\$5.8	\$5.7	\$0.8	\$1.2	\$6.3	\$6.2
Level 4-2, MBR	\$294	\$285	\$5.9	\$5.2	\$0.7	\$1.1	\$6.1	\$6.0
Level 5-1, B5/RO	\$433	\$439	\$6.1	\$6.0	\$1.9	\$2.3	\$11	\$11
Level 5-2, MBR/RO	\$403	\$409	\$5.9	\$5.8	\$1.9	\$2.2	\$10	\$10

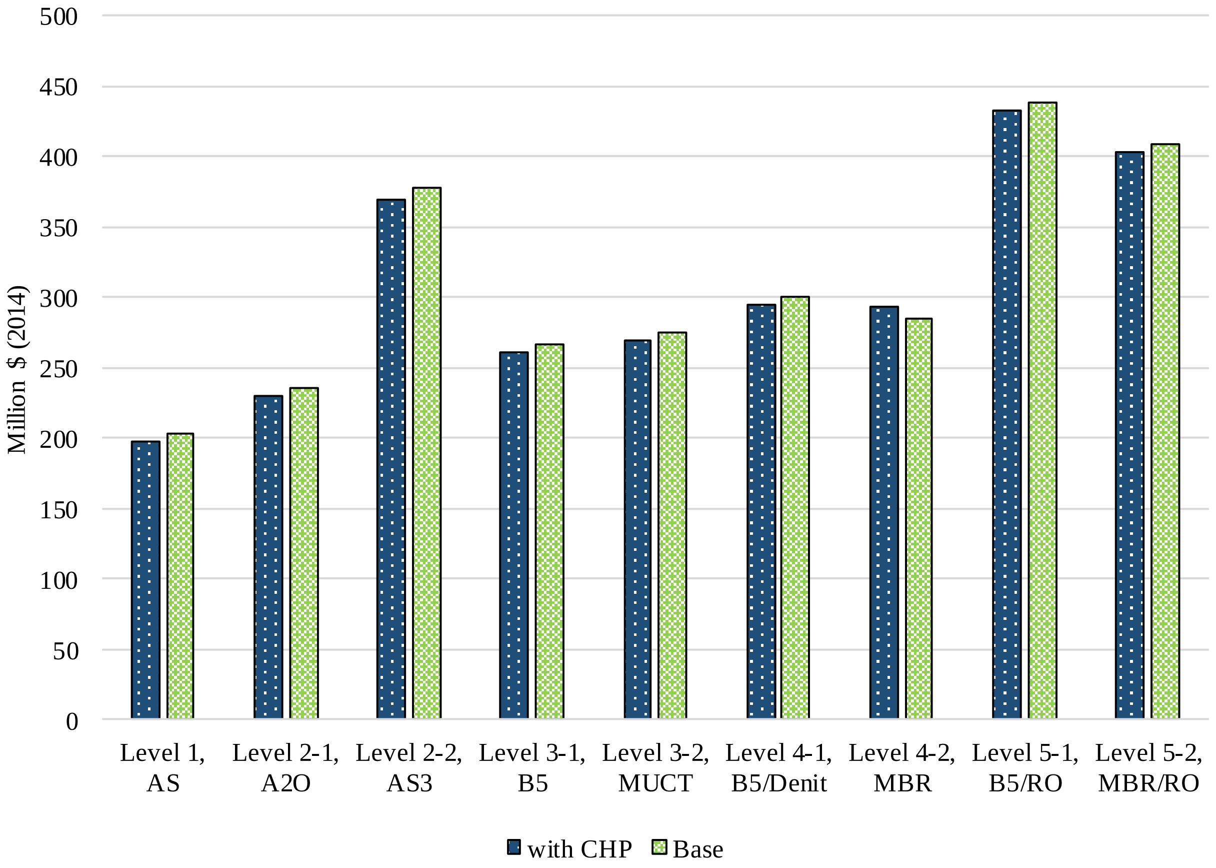


Figure 9-8. Biogas Case Study Net Present Value Comparison

9.6 Retrofit Case Study

While this report displays cost results for greenfield installations, existing plants may incorporate nutrient control technology in a retrofit. In this section, ERG conducted a case study to investigate the potential cost implications of such a retrofit. This case study considers a retrofit of the Level 2-1 A2O wastewater treatment configuration as the baseline (see Figure 9-9) with the addition of chemical phosphorus removal and a denitrification filter to achieve the Level 4 target effluent nutrient concentrations of 3 mg/L total nitrogen and 0.1 mg/L total phosphorus (see Figure 9-10).

Table 9-8 presents the total capital, total annual, and net present value for the nine greenfield wastewater treatment configurations and the Level 2-1 greenfield wastewater treatment configuration plus the cost for the retrofit chemical phosphorus removal and denitrification filter (Level 2-1 to 4 Retrofit) (presented in bold). While the Level 2-1 to 4 Retrofit wastewater treatment configuration achieves the Level 4 effluent nutrient targets, the total capital cost, total annual cost, and net present value are between the greenfield Level 2-1 A2O and both greenfield Level 3 wastewater treatment configurations. As shown in Figure 9-11, the capital cost for the Level 2-1 to 4 Retrofit wastewater treatment configuration is $12M to $15M lower than the greenfield Level 4 wastewater treatment configurations, but is designed to achieve the same effluent nutrient concentrations, due to lower biological treatment and post-biological treatment capital costs. The chemical phosphorus removal and denitrification filter portion of the Level 2-1 to 4 Retrofit capital costs are $6.9M. As shown in Figure 9-12, the total annual costs for Level 2-1 to 4 Retrofit are about $0.6M/yr to $0.8M/yr higher than the greenfield Level 3 wastewater treatment configurations, but $0.3M/yr to $0.4M/yr lower than the greenfield Level 4 wastewater treatment configurations. The annual costs for just the chemical phosphorus removal and denitrification filter portion of the Level 2-1 to 4 Retrofit is $1.11M/yr.

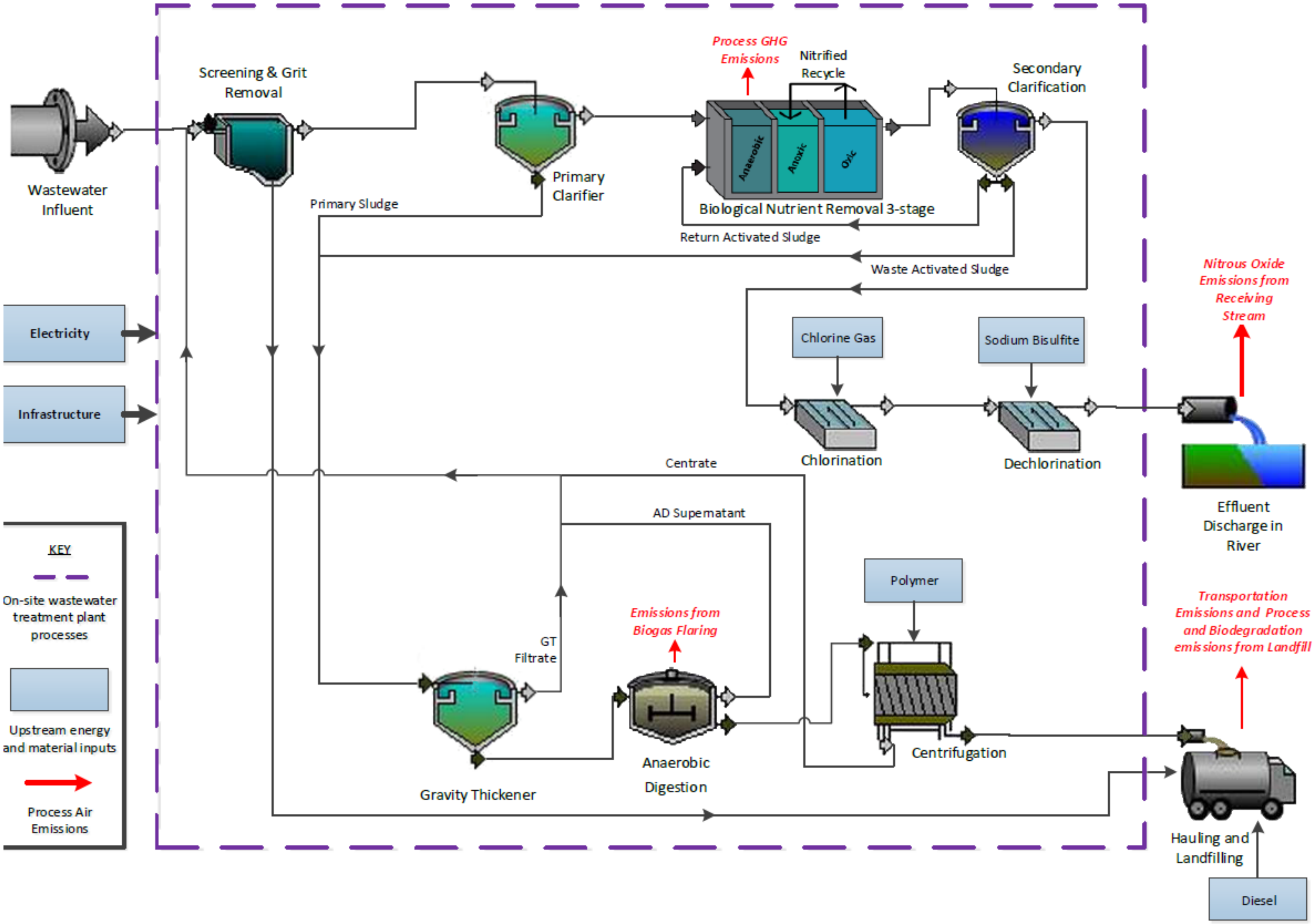


Figure 9-9. Level 2-1: Anaerobic/Anoxic/Oxic Wastewater Treatment Configuration (Baseline for Retrofit)

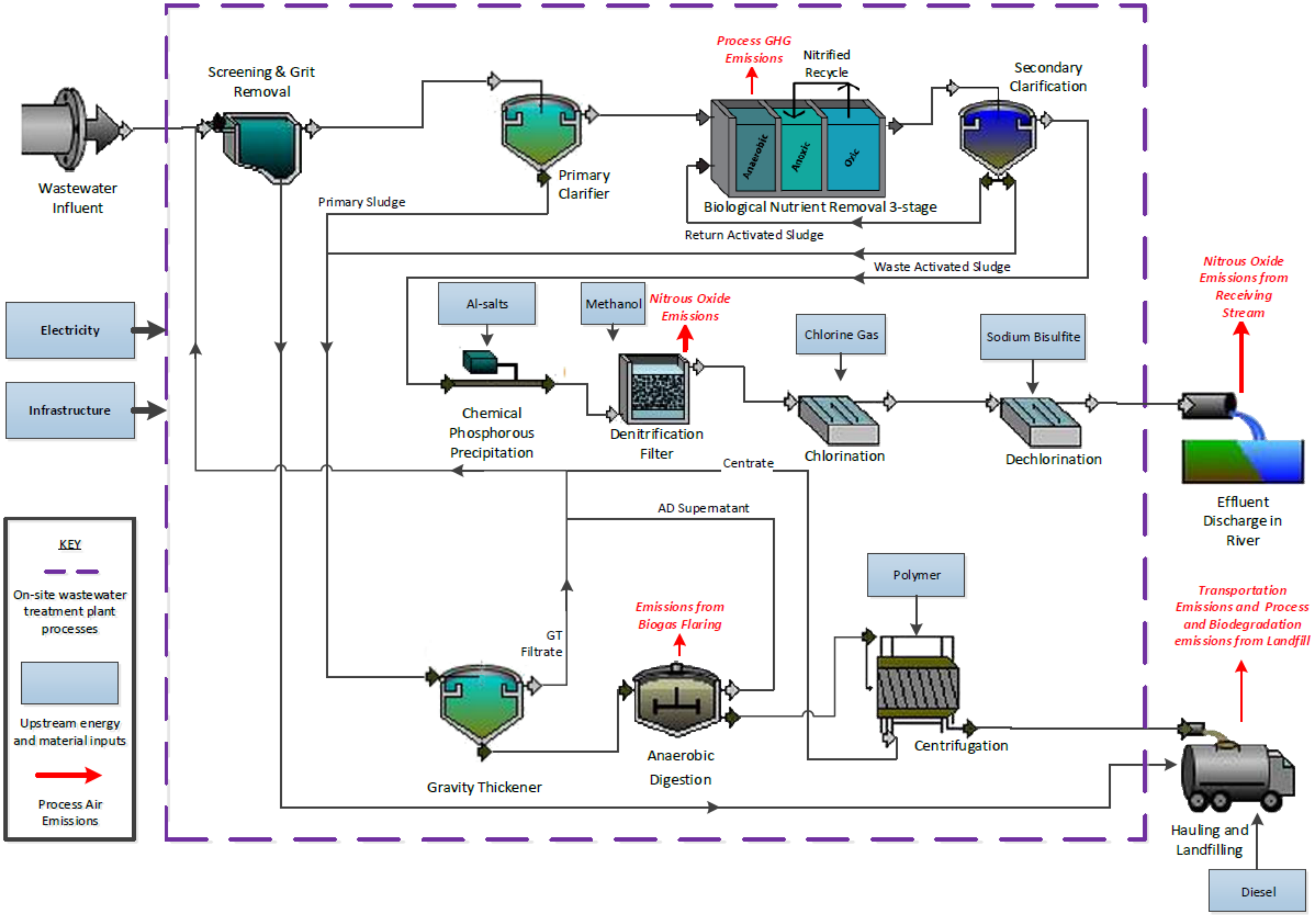


Figure 9-10. Level 2-1 to 4 Retrofit: Anaerobic/Anoxic/Oxic with Chemical Phosphorus Removal and Denitrification Filter Wastewater Treatment Retrofit Configuration

Table 9-8. Greenfield and Level 2-1 to 4 Retrofit Total Costs

Wastewater Treatment Configuration	Total Capital Cost (2014 $)	Total Annual Cost [a] (2014 $/yr)	Net Present Value (2014 $)
Level 1, AS	$55,300,000	$5,140,000	$204,000,000
Level 2-1, A2O	$71,400,000	$5,470,000	$236,000,000
Level 2-2, AS3	$93,100,000	$10,150,000	$378,000,000
Level 3-1, B5	$86,400,000	$5,800,000	$267,000,000
Level 3-2, MUCT	$88,900,000	$5,960,000	$275,000,000
Level 4-1, B5/Denit	$92,800,000	$6,840,000	$301,000,000
Level 4-2, MBR	$90,100,000	$6,330,000	$285,000,000
Level 2-1 to 4, Retrofit [b]	**$78,300,000**	**$6,580,000**	**$273,000,000**
Level 5-1, B5/RO	$160,000,000	$8,320,000	$439,000,000
Level 5-2, MBR/RO	$144,000,000	$8,080,000	$409,000,000

a – Total annual cost includes operational labor, maintenance labor, materials, chemicals, and energy (see Section 3.3 for details).

b – Costs are presented for the greenfield Level 2-1 plus the retrofit chemical phosphorus removal and denitrification filter. The capital cost, annual cost, and net present value for the chemical phosphorus removal and denitrification filter retrofit are $6.9M, $1.11M, and $37M, respectively.

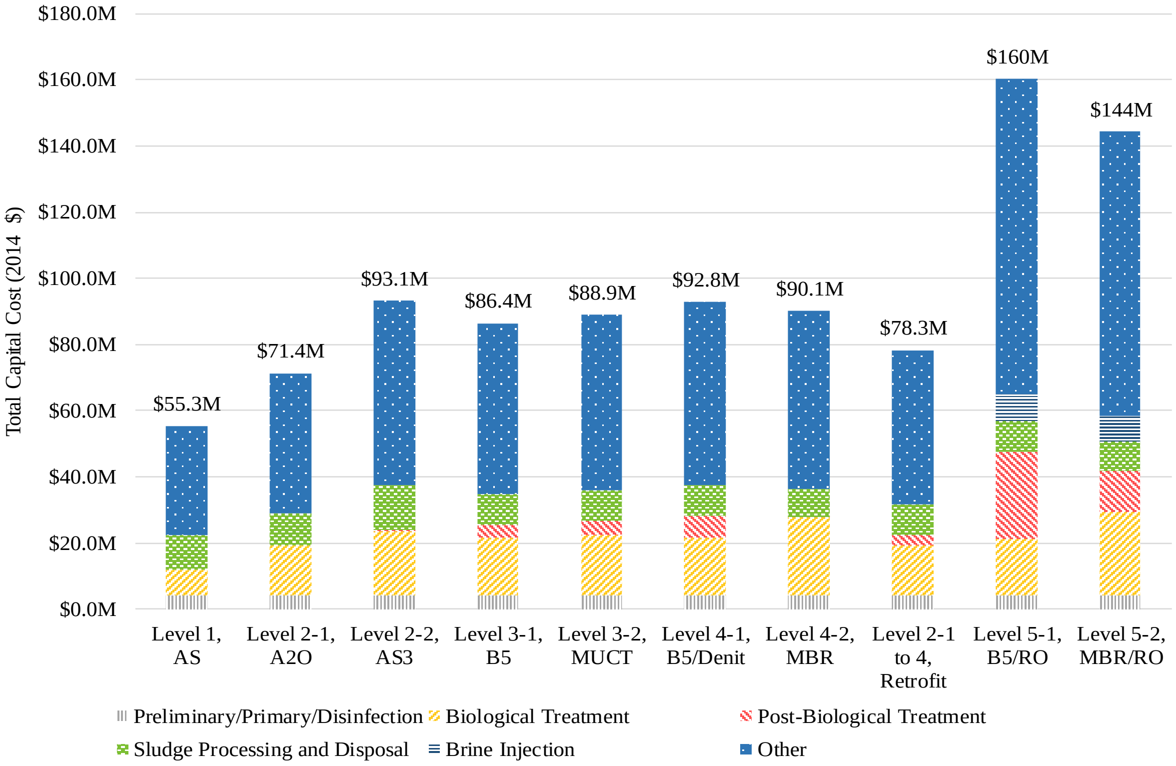


Figure 9-11. Level 2-1 A2O Baseline and Retrofit Total Capital Costs by Aggregated Treatment Group

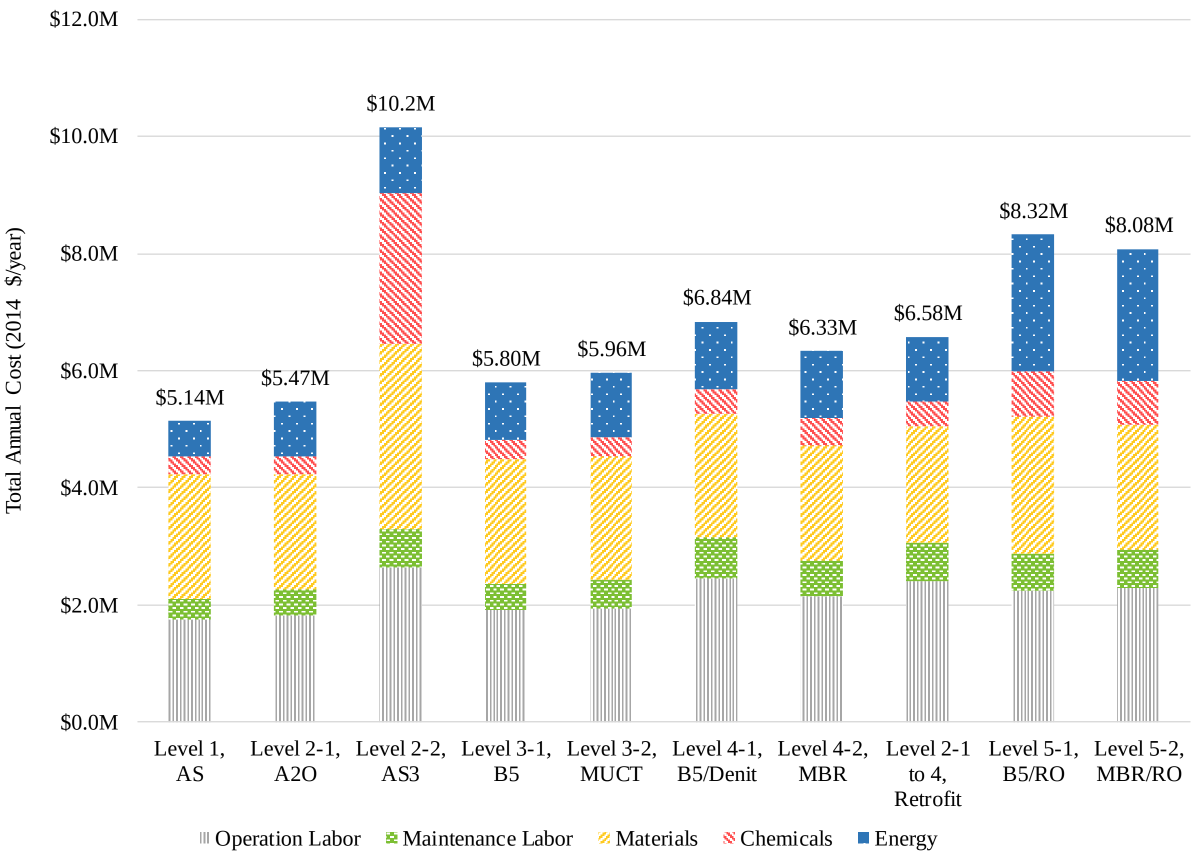


Figure 9-12. Level 2-1 A2O Baseline and Retrofit Total Annual Costs by Annual Cost Category

Figure 9-13 presents relative impact results for all greenfield treatment configurations plus the Level 2 retrofit case study. Retrofit LCIA results are generally in line with those associated with other Level 4 treatment configurations. GWP and ozone depletion potential lower for the retrofit case study, relative to other Level 4 treatment configurations, due to lower estimated N2O emissions. Eutrophication impacts are slightly elevated, compared to Level 4-1 and 4-2. Table 9-9 lists summary LCIA results for all treatment levels plus the Level 2 retrofit case study system. Retrofit results are in bold in Table 9-9.

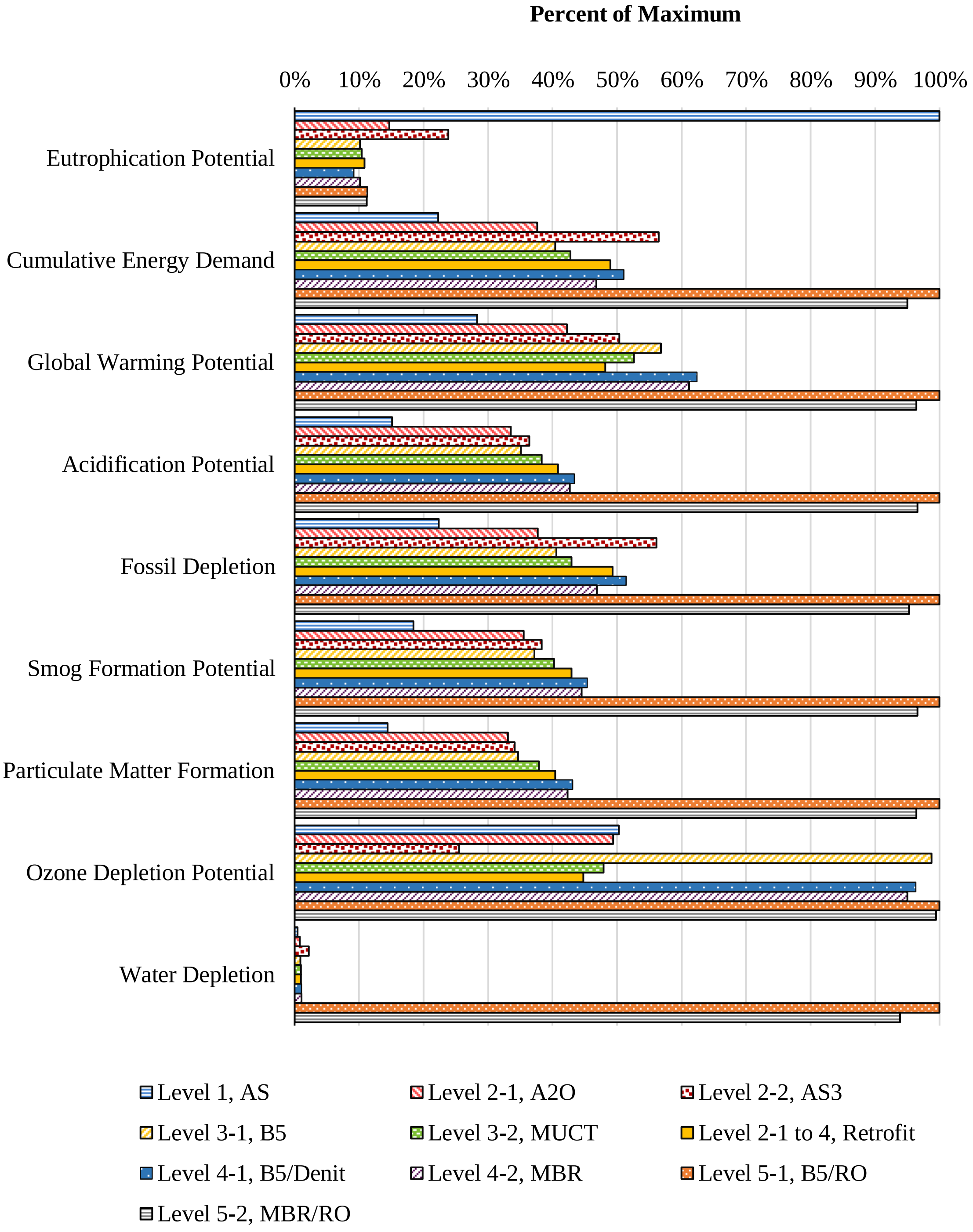


Figure 9-13. Relative LCIA Results for Nine Greenfield Wastewater Treatment Configurations and the Level 2 Retrofit Case Study

Table 9-9. Summary LCIA and Cost Results for Nine Greenfield Wastewater Treatment Configurations and the Level 2 Retrofit Case Study (per m^3 wastewater treated)

Impact Category	**Unit**	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 2-1 to 4, Retrofit**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Cost	$ USD	$0.64	$0.74	$1.18	$0.84	$0.86	**$0.85**	$0.94	$0.89	$1.37	$1.28
Global Warming Potential	kg CO2 eq	0.52	0.77	0.92	1.0	0.96	**0.88**	1.1	1.1	1.8	1.8
Cumulative Energy Demand	MJ	5.4	9.1	14	9.7	10	**12**	12	11	24	23
Eutrophication Potential	kg N eq	0.07	9.8E-3	0.02	6.8E-3	6.9E-3	**7.3E-3**	6.1E-3	6.8E-3	7.5E-3	7.5E-3
Water Depletion	m3 H2O	8.0E-4	1.5E-3	4.1E-3	1.7E-3	1.8E-3	**1.9E-3**	2.0E-3	2.0E-3	0.19	0.17
Acidification Potential	kg SO2 eq	0.01	0.03	0.03	0.03	0.04	**0.04**	0.04	0.04	0.09	0.09
Particulate Matter Formation	PM2.5 eq	1.5E-3	3.4E-3	3.5E-3	3.6E-3	3.9E-3	**4.2E-3**	4.5E-3	4.4E-3	0.01	0.01
Smog Formation Potential	kg O3 eq	0.14	0.27	0.29	0.28	0.30	**0.32**	0.34	0.33	0.75	0.72
Ozone Depletion Potential	kg CFC-11 eq	3.9E-6	3.8E-6	2.0E-6	7.6E-6	3.7E-6	**3.4E-6**	7.4E-6	7.3E-6	7.7E-6	7.7E-6
Fossil Depletion	kg oil eq	0.12	0.20	0.30	0.22	0.23	**0.26**	0.28	0.25	0.54	0.51

10. CONCLUSIONS

This study met its goal to assess a series of wastewater treatment configurations that reduce the nutrient content of effluent from municipal WWTPs considering treatment costs as well as human health and ecosystem impacts from a life cycle perspective.

The LCA results highlight the trade-offs that exist between the various treatment configurations for cost and traditional LCIA impact categories. The largest normalized impact observed across all combinations of treatment configurations and impact categories was the eutrophication impact for the Level 1 treatment configuration. It is clear that use of a traditional Level 1 treatment configuration results in the lowest costs, but also significantly higher normalized eutrophication impacts compared to all other study treatment system configurations. When considering the impaired state of many of this nation's water bodies related to nutrients, the use of nutrient removal technologies explored in this study are tools that could be used to improve water quality. This study aims to help communities and businesses consider the environmental and economic costs and benefits of advanced nutrient removal options.

Given the predominant contribution of electricity and energy consumption to impact results in many of the impact categories, it is necessary to think critically about the energy efficiency of treatment processes, particularly in relation to their level of nutrient removal. A series of ratios are presented in Table 10-1 to help in this process. The aggregate level of nutrient removal increases rapidly as nutrient removal standards progress from Level 1 to Level 5. The total electricity demand that coincides with increasing levels of nutrient removal, increases substantially across the treatment configurations, from 0.20 to 1.5 kWh/m^3 wastewater treated. However, when considering the electricity consumption compared to each unit of nutrient removed reveals that the electricity demand does not increase across the majority of the treatment configurations on the basis of nutrient equivalents removed. Electricity per unit of total nitrogen and phosphorus equivalents removed remains consistent from Level 2 through Level 4. However, due to the large electrical demand of the reverse osmosis process, total electricity per nutrient removal is generally two to three times higher for the Level 5 treatment configurations compared to Levels 2 through 4.

Table 10-1. Nutrient Removal Electricity Performance Metrics

Treatment Level	**1**	**2-1**	**2-2**	**3-1**	**3-2**	**4-1**	**4-2**	**5-1**	**5-2**
Total P removed (g/m^3)	0.06	4.7	4.0	4.8	4.8	4.9	4.9	5.0	5.0
Total N removed (g/m^3)	9.7	32	32	34	34	37	37	39	38
Total Electricity Demand (kWh/m^3)	0.20	0.48	0.51	0.52	0.57	0.65	0.64	1.5	1.4
Total Electrical Demand/Total P removed (kWh/g)	N/A[a]	0.10	0.13	0.11	0.12	0.13	0.13	0.30	0.29
Total Electrical Demand/Total N removed (kWh/g)	N/A[a]	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.04

a – Values not shown for Level 1 since this treatment configuration not designed for nutrient removal.

While this work was primarily focused on nutrients, the effect of study treatment configurations on the removal of trace pollutants was also reviewed to determine if additional benefits, not part of the original treatment design, may be realized from the implementation of more advanced treatment processes. This part of the project focused on potential toxicity impacts associated with heavy metals, toxic organics and disinfection byproducts. Results showed that metals were by far the most influential pollutant group in terms of life cycle toxicity impacts. Similar to nutrients, tradeoffs were identified between high effluent-based impacts at low levels of treatment and high process-based impacts at high levels of treatment. Generally, Levels 3 and 4 (and specifically Levels 3-2 and 4-2) resulted in the lowest overall toxicity impacts, owing to their high metal removal efficiencies and moderate material and energy requirements. Relative to Level 4-2 in particular, the higher and more consistent degree of metal removal provided by Level 5 was outweighed by greater process-based impacts, resulting in greater total impacts in all toxicity categories. Results of the analysis reveal that heavy metals contribute more strongly to human health and ecotoxicity impacts than do the toxic organics and DBPs with sufficient data to be evaluated.

The electrical grid sensitivity analysis showed that the importance of electricity and energy use and the trade-offs associated with achieving the key eutrophication reductions could largely be offset if the WWTP were to utilize an electrical grid with reliance on energy sources such as natural gas, hydro, and nuclear or use of recovered resources to generate on-site energy in order to reduce the need for purchased electricity. While an effort to achieve reductions in the environmental burdens associated with electricity production is certainly warranted given the information presented in the results section, Table 10-1 provides an indication of which treatment options may serve communities and businesses attempting to reduce environmental impacts while simultaneously controlling energy costs. The realization of benefits associated with these insights is not dependent on improvements in the electrical grid, which lie outside of the control of many WWTPs. Other strategies within the facilities boundaries, such as energy recovery from biogas, may help to offset environmental impacts from increased nutrient removal.

Generally, the results show the benefits to eutrophication impact associated with more stringent levels of nutrient removal. This benefit is generally increasingly offset by increases in other environmental impacts as the standard of removal progresses from Level 2 to Level 5, with Level 5 showing the most dramatic increase in cost and other impacts due to the exacting standard of treatment required. However, given local and regional environmental and economic considerations, the selection of the most appropriate treatment configuration will vary by location. This work cannot answer the question of how much nutrient removal can be considered sufficient for any specific WWTP or body of water. The question is inherently local or regional in nature, and an individual or institution must consider a number of factors when trying to determine what is appropriate for their situation. This study does indicate that careful consideration should be given to the benefits that are expected to be gained by pursuing the more advanced levels of nutrient removal, and that these benefits should be weighed against the environmental and economic costs discussed in Sections 5, 6 and 7. As discussed earlier, this study focused on the implementation of greenfield treatment configurations, and the economic impacts may vary significantly for retrofitted operations.

Overall, this study built a comprehensive framework to assess the environmental, human health, and cost implications of shifting to higher nutrient removal wastewater treatment configurations. The LCCA and LCA models constructed here can be continually built upon to improve the baseline analysis or investigate additional wastewater treatment configurations or variability with regional conditions. The system boundaries could also be expanded to understand the influence and potential benefit of recycling water from the effluent of the higher nutrient removal wastewater configurations to displace production of potable water elsewhere.

11. REFERENCES

Abatzoglou, N.; Boivin, S. 2009. A review of biogas purification processes. *Biofuels Bioproducts & Biorefining*. 3: 42–71.

ACCEI (American Association of Cost Engineers International). 2016. Cost Estimate Classification System – As Applied in Engineering, Procurement, and Construction for the Process Industries. Recommended Practice No. 18R-97. TCM Framework: 7.3 – Cost Estimating and Budgeting.

Ahmed, M. B., J. L. Zhou, H. H. Ngo, W. Guo, N. S. Thomaidis, and J. Xu. 2017. Progress in the biological and chemical treatment technologies for emerging contaminant removal from wastewater: A critical review. *Journal of Hazardous Materials* 323: 274–298. doi:10.1016/j.jhazmat.2016.04.045.

Ahn, J.H., S. Kim, H. Park, B. Rahm, K. Pagilla, and K. Chandran. 2010. N_2O Emissions from Activated Sludge Processes, 2008-2009: Results of a National Monitoring Survey in the United States. *Environmental Science and Technology*. 44: 4505-4511.

Alberta Environment. 2007. Quantification Protocol for the Anaerobic Decomposition of Agricultural Materials Project: Excel Biogas Calculator. http://environment.gov.ab.ca/info/library/7917.pdf Accessed 5 April, 2016

Alexander, J. T., F. I. Hai, and T. M. Al-aboud. 2012. Chemical coagulation-based processes for trace organic contaminant removal: Current state and future potential. *Journal of Environmental Management* 111: 195–207.

Alfonsín, C., A. Hospido, F. Omil, M. Moreira, and G. Feijoo. 2014. PPCPs in wastewater — Update and calculation of characterization factors for their inclusion in LCA studies. Journal of Cleaner Production 83: 245–255.

Alvarino, T., S. Suarez, J. Lema, and F. Omil. 2018. Understanding the sorption and biotransformation of organic micropollutants in innovative biological wastewater treatment technologies. *Science of The Total Environment* 615: 297–306. doi:10.1016/j.scitotenv.2017.09.278.

Arévalo, J., L. M. Ruiz, J. Pérez, B. Moreno, and M. Á. Gómez. 2013. Removal performance of heavy metals in MBR systems and their influence in water reuse. *Water Science and Technology* 67: 894–900.

Arican, B., C. F. Gokcay, and U. Yetis. 2002. Mechanistics of nickel sorption by activated sludge. *Process Biochemistry* 37: 1307–1315. doi:10.1016/S0032-9592(02)00015-8.

Aulenbach, D., B., and Y.-Y. Chan. 1988. Heavy Metals Removal in a Rapid Infiltration Sand Column. *Particulate Science and Technology* 6: 467–481. doi:10.1080/02726358808906517.

Aulenbach, D. B., N. L. Clesceri, M. A. Meyer, C. Vasundevan, E. Beckwith, and S. Joshi. 1984. Removal of heavy metals in potw using alum or sodium aluminate for phosphorus removal. In , 318–330.

Ayres, D. M., A. P. Davis, and P. M. Gietka. 1994. Removing heavy metals from wastewater. *Engineering Research Centre Report* 90.

Bare, J., G. Norris, D. Pennington, and T. McKone. 2003. TRACI: The tool for the reduction and assessment of chemical and other environmental impacts. *Journal of Industrial Ecology*. 6(3-4): 49-78.

Bare, J. 2011. TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0. *Clean Technology and Environmental Policy*. 13(5): 687-696.

Bare, J. C. 2012. Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Version 2.1 - User’s Manual; EPA/600/R-12/554.

Barker, D. J., and D. C. Stuckey. 1999. A review of soluble microbial products (SMP) in wastewater treatment systems. *Water Research* 33: 3063–3082. doi:10.1016/S0043-1354(99)00022-6.

Bayer, P.; Heuer, E.; Karl, U.; Finkel, M. 2005. Economical and ecological comparison of granular activated carbon (GAC) adsorber refill strategies. *Water Research*. 39: 1719–1728.

Boorman G A. 1999. Drinking water disinfection byproducts: review and approach to toxicity evaluation. *Environmental Health Perspectives* 107: 207–217. doi:10.1289/ehp.99107s1207.

Bott, C. and D. Parker. 2011. Nutrient Management Volume II: Removal Technology Performance & Reliability. Water Environment Research Federation Report NUTR1R06k. IWA Publishing, London, U.K.

Brown, H. G., C. P. Hensley, G. L. McKinney, and J. L. Robinson. 1973. Efficiency of heavy metals removal in municipal sewage treatment plants. *Environmental letters*, *5*(2), 103-114.

Brown, M. J., and J. N. Lester. 1979. Metal removal in activated sludge: the role of bacterial extracellular polymers. *Water Research* 13: 817–837. doi:10.1016/0043-1354(79)90217-3.

Buzier, R., M.-H. Tusseau-Vuillemin, C. M. dit Meriadec, O. Rousselot, and J.-M. Mouchel. 2006. Trace metal speciation and fluxes within a major French wastewater treatment plant: Impact of the successive treatments stages. *Chemosphere* 65. Environmental Chemistry: 2419–2426. doi:10.1016/j.chemosphere.2006.04.059.

CDHS, 2018. NDMA and Other Nitrosamines – Drinking Water Issues. California Department of Health Services. https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/NDMA.html. Accessed September 1, 2019.

Cantinho, P., M. Matos, M. A. Trancoso, and M. M. C. dos Santos. 2016. Behaviour and fate of metals in urban wastewater treatment plants: a review. *International Journal of Environmental Science and Technology* 13: 359–386. doi:10.1007/s13762-015-0887-x.

Carletti, G., F. Fatone, D. Bolzonella, and F. Cecchi. 2008. Occurrence and fate of heavy metals in large wastewater treatment plants treating municipal and industrial wastewaters. *Water Science and Technology* 57: 1329–1336.

Chandran, K. 2012. Greenhouse Nitrogen Emissions from Wastewater Treatment Operation: Phase I, Final Report. Water Environment Research Foundation. U4R07.

Chang, W.-C., C.-H. Hsu, S.-M. Chiang, and M.-C. Su. 2007. Equilibrium and kinetics of metal biosorption by sludge from a biological nutrient removal system. *Environmental technology* 28: 453–462.

Chao, A. C., and T. M. Keinath. 1979. Influence of process loading intensity on sludge clarification and thickening characteristics. *Water Research* 13: 1213–1223. doi:10.1016/0043-1354(79)90165-9.

Chen, K. Y., C. S. Young, T. K. Jan, and N. Rohatgi. 1974. Trace metals in wastewater effluents. *Journal (Water Pollution Control Federation)*, 2663-2675.

Cheng, M., J. Patterson, and R. Minear. 1975. Heavy-Metals Uptake by Activated-Sludge. *Journal Water Pollution Control Federation* 47: 362–376.

Chipasa, K. B. 2003. Accumulation and fate of selected heavy metals in a biological wastewater treatment system. *Waste Management* 23: 135–143. doi:10.1016/S0956-053X(02)00065-X.

Choubert, J. M., S. Martin Ruel, M. Esperanza, H. Budzinski, C. Miège, C. Lagarrigue, and M. Coquery. 2011a. Limiting the emissions of micro-pollutants: what efficiency can we expect from wastewater treatment plants? *Water Science and Technology* 63: 57–65. doi:10.2166/wst.2011.009.

Choubert, J.-M., M. Pomiès, S. Martin Ruel, and M. Coquery. 2011b. Influent concentrations and removal performances of metals through municipal wastewater treatment processes. *Water Science and Technology* 63: 1967–1973. doi:10.2166/wst.2011.126.

Christman, R. F., D. L. Norwood, D. S. Millington, J. D. Johnson, and A. A. Stevens. 1983. Identity and yields of major halogenated products of aquatic fulvic acid chlorination. *Environmental Science & Technology* 17: 625–628. doi:10.1021/es00116a012.

Czepiel, P., P. Crill, and R. Harriss. 1995. Nitrous Oxide Emissions from Municipal Wastewater Treatment. *Environmental Science and Technology*. 29: 2352-2356.

da Silva Oliveira, A., Bocio, A., Trevilato, T. M. B., Takayanagui, A. M. M., Domingo, J. L., & Segura-Muñoz, S. I. (2007). Heavy metals in untreated/treated urban effluent and sludge from a biological wastewater treatment plant. Environmental Science and Pollution Research-International, 14(7), 483.

Daelman, M.R.J., E.M. Voorthuizen, L.G.J.M. van Dongen, E.I.P. Volcke, and M.C.M van Loosdrecht. 2013. Methane and nitrous oxide emissions from municipal wastewater treatment–results from a long-term study. *Water Science and Technology*. 67(10): 2350-2355.

Darrow, K.; Tidball, R.; Wang, J.; Hampson, A. 2017. Catalog of CHP Technologies. U.S. Environmental Protection Agency.

Dialynas, E., and E. Diamadopoulos. 2009. Integration of a membrane bioreactor coupled with reverse osmosis for advanced treatment of municipal wastewater. *Desalination* 238. Issues 1 and 2: First International Workshop between the Center for the Seawater Desalination Plant and the European Desalination Society: 302–311. doi:10.1016/j.desal.2008.01.046.

Doederer, K., W. Gernjak, H. S. Weinberg, and M. J. Farré. 2014. Factors affecting the formation of disinfection by-products during chlorination and chloramination of secondary effluent for the production of high quality recycled water. *Water Research* 48: 218–228. doi:10.1016/j.watres.2013.09.034.

Drewes, J. E., and J.-P. Croue. 2002. New approaches for structural characterization of organic matter in drinking water and wastewater effluents. *Water Supply* 2: 1–10. doi:10.2166/ws.2002.0039.

Dukes, S. and A. von Gottberg. 2006. Koch Membrane Systems. Membrane Bioreactors for RO Pretreatment. Water Environment Foundation. WEFTEC®.

Ebele, A. J., M. A. Abdallah, and S. Harrad. 2017. Pharmaceuticals and personal care products (PPCPs) in the freshwater aquatic environment. *Emerging Contaminants* 3: 1–16. doi:10.1016/j.emcon.2016.12.004.

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

Ecoinvent Centre. 2010b. Ecoinvent Version 2.2. Swiss Centre for Life Cycle Inventories, Dübendorf, CH.

Ecoinvent Centre. 2015. Ecoinvent Version 3.2. Swiss Centre for Life Cycle Inventories, Dübendorf, CH.

Ellis, J. B. 2008. Assessing sources and impacts of priority PPCP compounds in urban receiving waters. In *11th International Conference on Urban Drainage*. Edinburgh, Scotland, UK.

Emara, M. M., F. A. Ahmed, F. M. A. El-Aziz, and A. M. A. El–Razek. 2014. Biological Nutrient Removal in Bardenpho process. *Journal of American Science* 10.

Emmerson, R.H.C., G.K. Morse, J.N. Lester, and D.R. Edge. 1995. The Life-Cycle Analysis of Small Scale Sewage-Treatment Processes. *Water and Environment Journal.* 9(3): 317-325.

Environment Canada. 2005. Biogas Flare. https://www.ec.gc.ca/inrp-npri/14618D02-387B-469D-B1CD-42BC61E51652/biogas_flare_e_04_02_2009.xls Accessed 5 April, 2016

ERG (Eastern Research Group). 2009. Draft Technical Support Document: Analysis of Secondary Treatment and Nutrient Control at POTWs.

ERG. 2011a. Personal communication between Kavya Kasturi of ERG and Robert Clark of FreightCenter.com.

ERG. 2011b. Personal communication between Kavya Kasturi of ERG and Troy Litherland of EnPro Technologies.

ERG. 2011c. Personal communication between Kavya Kasturi of ERG and Miguel Gutierrez of Siemens Industry, Inc.

ERG. 2013. Supplemental Costs and Loadings Documentation – O&M Costs for Off-Site Disposal. Memoranda to the Steam Electric Effluent Guideline Rulemaking Record. EPA-HQ-OW-2009-0819-2888 DCN SE01825.A66.

ERG. 2014. Personal communication between Kavya Kasturi of ERG and Scott Fisher of Brenntag Mid-South.

ERG. 2015a. Personal communication between Amber Allen of ERG and Donald Moore of Evoqua Water Technologies LLC.

ERG. 2015b. Personal communication between Amber Allen, Debra Falatko, and Mark Briggs of ERG and Stacey Bickler of Wigen Water Technologies.

ERG. 2015c. Quality Assurance Project Plan for Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants.

EP. 2008. Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy, amending and subsequently repealing Council Directives 82/176/EEC, 83/513/EEC, 84/156/EEC, 84/491/EEC, 86/280/EEC and amending Directive 2000/60/EC of the European Parliament and of the Council. *Official Journal of the European Union* OJ L 348: 84–97.

EU. 2013. *39/EU of the European Parliament and of the Council amending Directives 2000/60/EC and 2008/105/EC as regards priority substances in the field of water policy*. 2013.

Foley, J., D. de Haas, K. Hartley, and P. Lant. 2010. Comprehensive life cycle inventories of alternative wastewater treatment. *Water Research*. 44(5): 1654-1666.

Falk, M.W., J.B. Neethling, and D.J. Reardon. 2011. Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability. NUTR1R06n. Water Environment Research Federation. IWA Publishing, London, U.K.

Falk. 2017. Personal communication with M. Falk, Expert Review Follow-up, 10 November 2017.

Garcia, N., J. Moreno, E. Cartmell, I. Rodriguez-Roda, and S. Judd. 2013. The cost and performance of an MF-RO/NF plant for trace metal removal. *Desalination* 309: 181–186. doi:10.1016/j.desal.2012.10.017.

Ghosh, S., and S. Bupp. 1992. Stimulation of Biological Uptake of Heavy Metals. *Water Science and Technology* 26: 227–236. doi:10.2166/wst.1992.0403.

Goedkoop, M., R. Heijungs, M. Huijbregts, A.D. Schryver, J. Struijs, and R. van Zelm. 2009. ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and endpoint level; First Edition Report I: Characterization.

Goldstone, M. E., P. W. W. Kirk, and J. N. Lester. 1990a. The behaviour of heavy metals during wastewater treatment I. Cadmium, chromium and copper. *Science of The Total Environment* 95: 233–252. doi:10.1016/0048-9697(90)90068-6.

Goldstone, M. E., P. W. W. Kirk, and J. N. Lester. 1990b. The behaviour of heavy metals during wastewater treatment II. Lead, nickel and zinc. *Science of The Total Environment* 95: 253–270. doi:10.1016/0048-9697(90)90069-7.

Goldstone, M. E., C. Atkinson, P. W. W. Kirk, and J. N. Lester. 1990c. The behaviour of heavy metals during wastewater treatment III. Mercury and arsenic. *Science of The Total Environment* 95: 271–294. doi:10.1016/0048-9697(90)90070-B.

GreenDelta. 2015. OpenLCA, 1.4.2; GreenDelta: Berlin, Germany.

Hartman, P. and J. Cleland. 2007. Wastewater Treatment Performance and Cost Data to Support an Affordability Analysis for Water Quality Standards. Montana Department of Environmental Quality.

Health Research, Inc. 2014. Recommended Standards for Wastewater Facilities. Policies for the Design, Review, and Approval of Plans and Specifications for Wastewater Collection and Treatment Facilities – 2014 Edition. A Report of the Wastewater Committee of the Great

Lakes – Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers. Albany, New York.

Henderson, A.D. 2015. Eutrophication. In Life Cycle Impact Assessment, edited by M.Z. Hauschild and M.A.J. Huijbregts, Springer, New York.

Hong, J., S. Shaked, R.K. Rosenbaum, and O. Jolliet. 2010. Analytical uncertainty propagation in life cycle inventory and impact assessment: application to an automobile front panel. *The International Journal of Life Cycle Assessment* 15(5): 499–510.

Huang, C.-P., H. Aleen, J. Wang, L. Takiyama, H. Poesponegro, D. Pirestani, S. Myoda, and D. Crumety. 2000. Chemical characteristics and solids uptake of heavy metals in wastewater treatment. In *Chemical characteristics and solids uptake of heavy metals in wastewater treatment*. Water Environment Federation.

Huang, H., Q.-Y. Wu, X. Tang, R. Jiang, and H.-Y. Hu. 2016. Formation of haloacetonitriles and haloacetamides and their precursors during chlorination of secondary effluents. *Chemosphere* 144: 297–303. doi:10.1016/j.chemosphere.2015.08.082.

Huijbregts, M., M. Hauschild, O. Jolliet, M. Margni, T. McKone, R.K. Rosenbaum, and D. van de Meent. 2010. USEtox™ User Manual. http://www.usetox.org/sites/default/files/support-tutorials/user_manual_usetox.pdf. Accessed 12 December 2015.

Humbert, S., V. Rossi, M. Margni, O. Jolliet, and Y. Loerincik. 2009. Life cycle assessment of two baby food packaging alternatives: glass jars vs. plastic pots. *The International Journal of Life Cycle Assessment* 14(2): 95–106.

Hunter, M. T., J. C. Painter, and W. W. E. Jr. 1983. The effects of sludge age and metal concentration on copper equilibrium in the activated sludge process. *Environmental Technology Letters* 4: 475–484. doi:10.1080/09593338309384235.

Huo, S., B. Xi, H. Yu, Y. Qin, F. Zan, and J. Zhang. 2013. Characteristics and transformations of dissolved organic nitrogen in municipal biological nitrogen removal wastewater treatment plants. *Environmental Research Letters* 8: 044005. doi:10.1088/1748-9326/8/4/044005.

Hydromantis. 2014. CAPDETWorks™ Version 3.0 Software: Rapid Design and Costing Solution for Wastewater Treatment Plants.

Inna, D., J. N. Lester, M. D. Scrimshaw, and E. Cartmell. 2014. Speciation and fate of copper in sewage treatment works with and without tertiary treatment: the effect of return flows. *Environmental Technology* 35: 1–9. doi:10.1080/09593330.2013.800565.

Innocenti, L., D. Bolzonella, P. Pavan, and F. Cecchi. 2002. Effect of sludge age on the performance of a membrane bioreactor: influence on nutrient and metals removal. *Desalination* 146: 467–474. doi:10.1016/S0011-9164(02)00551-9.

IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, edited by H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and Tanabe K. National Greenhouse Gas Inventories Programme, IGES, Japan.

IPCC. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller. Cambridge University Press, Cambridge, U.K. and New York, NY.

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley. Cambridge University Press, Cambridge, U.K. and New York, NY.

ISO. 2006a. Environmental management -- Life cycle assessment -- Principles and framework. ISO No. 14040. International Organization for Standardization, CH.

ISO. 2006b. Environmental management -- Life cycle assessment -- Requirements and guidelines. ISO No. 14044. International Organization for Standardization, CH.

Jan, T.-K., and D. R. Young. 1978. Chromium Speciation in Municipal Wastewaters and Seawater. *Journal (Water Pollution Control Federation)* 50: 2327–2336. JSTOR.

Jelic, A., M. Gros, A. Ginebreda, R. Cespedes-Sánchez, F. Ventura, M. Petrovic, and D. Barcelo. 2011. Occurrence, partition and removal of pharmaceuticals in sewage water and sludge during wastewater treatment. *Water Research* 45: 1165–1176. doi:10.1016/j.watres.2010.11.010.

Johnson, P. D., P. Girinathannair, K. N. Ohlinger, S. Ritchie, L. Teuber, and J. Kirby. 2008. Enhanced removal of heavy metals in primary treatment using coagulation and flocculation. *Water environment research*, *80*(5), 472-479.

Jones, L., T. Sullivan, B. Kinsella, A. Furey, and F. Regan. 2017. Occurrence of Selected Metals in Wastewater Effluent and Surface Water in Ireland. *Analytical Letters* 50: 724–737. doi:10.1080/00032719.2016.1194854.

Joo, S. H., and W. A. Mitch. 2007. Nitrile, Aldehyde, and Halonitroalkane Formation during Chlorination/Chloramination of Primary Amines. *Environmental Science & Technology* 41: 1288–1296. doi:10.1021/es0612697.

Karvelas, M., A. Katsoyiannis, and C. Samara. 2003. Occurrence and fate of heavy metals in the wastewater treatment process. *Chemosphere*, *53*(10), 1201-1210.

Kelly, D., P. Norris, and C. Brierley. 1979. Microbiological methods for the extraction and recovery of metals. Microbial Technology: Current State, Future Prospects (pp. 263–308).

Kempton, S., R. M. Sterritt, and J. N. Lester. 1987. Heavy metal removal in primary sedimentation II. The influence of metal speciation and particle size distribution. *Science of The Total Environment* 63: 247–258. doi:10.1016/0048-9697(87)90049-0.

Koehler, A. 2008.Water use in LCA: managing the planet's freshwater resources. *International Journal of Life Cycle Assessment.* 13: 451-455.

Krasner, S., P. Westerhoff, B. Chen, G. Amy, S. N. Nam, Z. K. Chowdhury, S. Sinha, and B. E. Rittmann. 2008. *Contribution of wastewater to DBP formation*. Water Environment Research Foundation.

Krasner, S. W., P. Westerhoff, B. Chen, B. E. Rittmann, S.-N. Nam, and G. Amy. 2009a. Impact of Wastewater Treatment Processes on Organic Carbon, Organic Nitrogen, and DBP Precursors in Effluent Organic Matter. *Environmental Science & Technology* 43: 2911–2918. doi:10.1021/es802443t.

Krasner, S. W., P. Westerhoff, B. Chen, B. E. Rittmann, and G. Amy. 2009b. Occurrence of Disinfection Byproducts in United States Wastewater Treatment Plant Effluents. *Environmental Science & Technology* 43: 8320–8325. doi:10.1021/es901611m.

Lakshminarasimman, N., O. Quiñones, B. J. Vanderford, P. Campo-Moreno, E. V. Dickenson, and D. C. McAvoy. 2018. Biotransformation and sorption of trace organic compounds in biological nutrient removal treatment systems. *Science of The Total Environment* 640–641: 62–72. doi:10.1016/j.scitotenv.2018.05.145.

Lawson, P. S., R. M. Sterritt, and J. N. Lester. 1984. Factors affecting the removal of metals during activated sludge wastewater treatment II. The role of mixed liquor biomass. *Archives of Environmental Contamination and Toxicology* 13: 391–402. doi:10.1007/BF01056254.

Lee, W., P. Westerhoff, and J.-P. Croué. 2007. Dissolved Organic Nitrogen as a Precursor for Chloroform, Dichloroacetonitrile, N-Nitrosodimethylamine, and Trichloronitromethane. *Environmental Science & Technology* 41: 5485–5490. doi:10.1021/es070411g.

Lester, J. N. 1983. Significance and behaviour of heavy metals in waste water treatment processes I. Sewage treatment and effluent discharge. *Science of The Total Environment* 30: 1–44. doi:10.1016/0048-9697(83)90002-5.

Levis, J.W., and M.A. Barlaz. 2013. Anaerobic Digestion Process Model Documentation. North Carolina State University. http://www4.ncsu.edu/~jwlevis/AD.pdf. Accessed 5 April, 2016

Linstedt, K. D., C. P. Houck, and J. T. O'Connor. 1971. Trace Element Removals in Advanced Wastewater Treatment Processes. *Journal (Water Pollution Control Federation)* 43: 1507–1513. JSTOR.

Lippiatt, B.C., J. Kneifel, P. Lavappa, S. Suh, and A.L. Greig. 2013. Building Industry Reporting and Design for Sustainability (BIRDS): Technical Manual and User Guide. NIST Technical Note 1814. National Institute of Standards and Technology.

Liu, Z., Y. Kanjo, and S. Mizutani. 2009. Removal mechanisms for endocrine disrupting compounds (EDCs) in wastewater treatment - physical means, biodegradation, and chemical advanced oxidation: A review. *Science of the Total Environment* 407: 731–748. doi:10.1016/j.scitotenv.2008.08.039.

Liwarska-Bizukojc, E., M. Galamon, and P. Bernat. 2018. Kinetics of Biological Removal of the Selected Micropollutants and Their Effect on Activated Sludge Biomass. *Water, Air, & Soil Pollution* 229: 356. doi:10.1007/s11270-018-4015-7.

Lo, S.-L., C. Y. Lin, and J. O. Leckie. 1989. The mass transfer-adsorption model of metal ions uptake by waste activated sludge. *Proc. Natl. Sci. Counc.* 13.

Luo, Y., W. Guo, H. H. Ngo, L. D. Nghiem, F. I. Hai, J. Zhang, S. Liang, and X. C. Wang. 2014. A review on the occurrence of micropollutants in the aquatic environment and their fate and removal during wastewater treatment. *Science of the Total Environment* 473–474: 619–641.

Makepeace, D., D. Smith, and S. Stanley. 1995. Urban Stormwater Quality - Summary of Contaminant Data. *Critical Reviews in Environmental Science and Technology* 25: 93–139. doi:10.1080/10643389509388476.

Malamis, S., E. Katsou, K. Takopoulos, P. Demetriou, and M. Loizidou. 2012. Assessment of metal removal, biomass activity and RO concentrate treatment in an MBR–RO system. *Journal of Hazardous Materials* 209–210: 1–8. doi:10.1016/j.jhazmat.2011.10.085.

Malmborg, J., and J. Magnér. 2015. Pharmaceutical residues in sewage sludge: Effect of sanitization and anaerobic digestion. *Journal of Environmental Management* 153: 1–10. doi:10.1016/j.jenvman.2015.01.041.

Martin Ruel, S., J.-M. Choubert, H. Budzinski, C. Miège, M. Esperanza, and M. Coquery. 2012. Occurrence and fate of relevant substances in wastewater treatment plants regarding Water Framework Directive and future legislations. *Water Science and Technology* 65: 1179–1189. doi:10.2166/wst.2012.943.

Metcalf and Eddy. 2014. Wastewater Engineering: Treatment and Resource Recovery. 5th Edition, McGraw-Hill, New York.

Miege, C., J. M. Choubert, L. Ribeiro, M. Eusebe, and M. Coquery. 2009. Fate of pharmaceuticals and personal care products in wastewater treatment plants. Conception of a database and first results. *Environmental Pollution* 157: 1721–1726.

Mizgireuv, I. V., I. G. Majorova, V. M. Gorodinskaya, V. V. Khudoley, and S. Y. Revskoy. 2004. Carcinogenic Effect of N-Nitrosodimethylamine on Diploid and Triploid Zebrafish (Danio rerio). *Toxicologic Pathology* 32: 514–518. doi:10.1080/01926230490496311.

Mohsen-Nia, M., P. Montazeri, and H. Modarress. 2007. Removal of Cu2+ and Ni2+ from wastewater with a chelating agent and reverse osmosis processes. *Desalination*, *217*(1-3), 276-281.

Montes-Grajales, D., M. Fennix-Agudelo, and W. Miranda-Castro. 2017. Occurrence of personal care products as emerging chemicals of concern in water resources: A review. *Science of The Total Environment* 595: 601–614. doi:10.1016/j.scitotenv.2017.03.286.

Muellner, M. G., E. D. Wagner, K. McCalla, S. D. Richardson, Y.-T. Woo, and M. J. Plewa. 2007. Haloacetonitriles vs. Regulated Haloacetic Acids: Are Nitrogen-Containing DBPs More Toxic? *Environmental Science & Technology* 41: 645–651. doi:10.1021/es0617441.

Myhre, G., D. Shindell, F.M. Breon, W. Collins, J. Fugleststvedt, J. Huang, D. Koch, and J.F. Lamarque et al. 2013. Anthropogenic and Natural Radiative Forcing, in Climate Change 2013: The Physical Science Basis, edited by D. Jacob, A.R. Ravishankara, and K. Shine. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, U.K. and New York, NY.

Nelson, P. O., A. K. Chung, and M. C. Hudson. 1981. Factors Affecting the Fate of Heavy Metals in the Activated Sludge Process. *Journal (Water Pollution Control Federation)* 53: 1323–1333. JSTOR.

Neufeld, R. D., and E. R. Hermann. 1975. Heavy Metal Removal by Acclimated Activated Sludge. *Journal (Water Pollution Control Federation)* 47: 310–329. JSTOR.

Nieuwenhuijsen, M. J., M. B. Toledano, N. E. Eaton, J. Fawell, and P. Elliott. 2000. Chlorination disinfection byproducts in water and their association with adverse reproductive outcomes: a review. *Occupational and Environmental Medicine* 57: 73–85. doi:10.1136/oem.57.2.73.

Noble, C., T. Horan, E. Brown, M. Shaffer, and J. Lopez. 2003. Microfiltration Pilot Studies for Aquifer Storage and Recovery Pretreatment." *Florida Water Resources Journal*. November 2003: 33-37.

Norberg, A. B., and H. Persson. 1984. Accumulation of heavy-metal ions by Zoogloea ramigera. *Biotechnology and Bioengineering* 26: 239–246. doi:10.1002/bit.260260307.

Norris, G. 2003. Impact Characterization in the Tool for the Reduction and Assesment of Chemical and Other Environmental Impacts. *Journal of Industrial Ecology*. 6(3-4): 79-101.

NRC. 2002. *Biosolids applied to land: advancing standards and practices*. National Research Council. National Academies Press.

NREL. 2015. US Life Cycle Inventory Database. National Renewable Energy Laboratory. https://www.nrel.gov/lci/. Accessed 28 June, 2016.

Obarska-Pempkowiak, H., and M. Gajewska. 2007. Influence of sludge treatment processes on heavy metal speciation. *Management of Pollutant Emission from Landfills and Sludge*: 141.

Ogunlaja, M. O., W. J. Parker, C. Metcalfe, and P. Seto. 2013. Impact of activated sludge process configuration on removal of micropollutants and estrogenicity. *Proceedings of the Water Environment Federation* Session 47-53: 3501–3516.

Oliver, B. G., and E. G. Cosgrove. 1974. The efficiency of heavy metal removal by a conventional activated sludge treatment plant. *Water Research* 8: 869–874. doi:10.1016/0043-1354(74)90099-2.

Ong, M. D.; Williams, R. B.; Kaffka, S. R. 2017. *Comparative Assessment of Technology Options for Biogas Clean-up*; 500-11-020; California Energy Commission: Davis, California; p 164.

Oppenheimer, J., R. Stephenson, A. Burbano, and L. Liu. 2007. Characterizing the Passage of Personal Care Products Through Wastewater Treatment Processes. *Water Environment Research* 79: 2564–2577. doi:10.2175/106143007X184573.

Orange County Water District. 2010. Initial Expansion of the Groundwater Replenishment System, Engineer's Report. http://www.water.ca.gov/irwm/grants/docs/Archives/Prop84/Submitted_Applications/P84_Round1_Implementation/Santa%20Ana%20Watershed%20Project%20Authority/Attach%203/A-OCWD/OCWD%20Proj%20Pkt.pdf. Accessed 28 June, 2016.

Parker, Wayne J., Monteith, Hugh D., Bell, John P., Melcer, Henryk, and Berthouex, P. Mac. 1994. Comprehensive Fate Model for Metals in Municipal Wastewater Treatment. *Journal of Environmental Engineering* 120: 1266–1283. doi.org:10.1061/(ASCE)0733-9372(1994)120:5(1266).

Pehlivanoglu-Mantas, E., and D. L. Sedlak. 2008. Measurement of dissolved organic nitrogen forms in wastewater effluents: Concentrations, size distribution and NDMA formation potential. *Water Research* 42: 3890–3898. doi:10.1016/j.watres.2008.05.017.

Peters, M.S. and K.D. Timmerhaus. 1991. *Plant Design and Economics for Chemical Engineers*. Fourth Edition. McGraw-Hill Inc.

Pivato, Alberto. 2011. Landfill liner failure: an open question for landfill risk analysis. *Journal of Environmental Protection* 2.03: 287.

Plewa, M. J., and E. D. Wagner. 2009. Quantitative comparative mammalian cell cytotoxicity and genotoxicity of selected classes of drinking water disinfection by-products. *Water Research Foundation, Denver*.

Pomiès, M., J.-M. Choubert, C. Wisniewski, and M. Coquery. 2013. Modelling of micropollutant removal in biological wastewater treatments: A review. *Science of The Total Environment* 443: 733–748. doi:10.1016/j.scitotenv.2012.11.037.

Qdais, H. A., and H. Moussa. 2004. Removal of heavy metals from wastewater by membrane processes: a comparative study. *Desalination* 164: 105–110. doi:10.1016/S0011-9164(04)00169-9.

Rahman, S. M., M. J. Eckelman, A. Onnis-Hayden, and A. Z. Gu. 2018. Comparative Life Cycle Assessment of Advanced Wastewater Treatment Processes for Removal of Chemicals of Emerging Concern. *Environmental Science & Technology* 52: 11346–11358. doi:10.1021/acs.est.8b00036.

Reddy, K. R., T. Xie, and S. Dastgheibi. 2014. Removal of heavy metals from urban stormwater runoff using different filter materials. *Journal of Environmental Chemical Engineering* 2: 282–292. doi:10.1016/j.jece.2013.12.020.

Redfield, A.C. 1934. On the proportions of organic derivatives in sea water and their relation to the composition of plankton. In James Johnstone memorial volume, edited by F.J. Cole. University Press of Liverpool, Liverpool, U.K.

Renman, A., G. Renman, J. P. Gustafsson, and L. Hylander. 2009. Metal removal by bed filter materials used in domestic wastewater treatment. *Journal of Hazardous Materials* 166: 734–739. doi:10.1016/j.jhazmat.2008.11.127.

Richardson, S. D., M. J. Plewa, E. D. Wagner, R. Schoeny, and D. M. DeMarini. 2007. Occurrence, genotoxicity, and carcinogenicity of regulated and emerging disinfection by-products in drinking water: A review and roadmap for research. *Mutation Research/Reviews in Mutation Research* 636. The Sources and Potential Hazards of Mutagens in Complex Environmental Matrices - Part II: 178–242. doi:10.1016/j.mrrev.2007.09.001.

Rosenbaum, R.K., T.M. Bachmann, L.S. Gold, M.A.J. Huijbregts, O. Jolliet, R. Juraske, A. Koehler, and H.F. Larsen et al. 2008. USEtox™ —the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle assessment. *International Journal of Life Cycle Assessment.* 13: 532–546.

Rosenbaum, R.K., M.A. Huijbregts, A.D. Henderson, M. Margni, T.E. McKone, D. van der Meent, M.Z. Hauschild, and S. Shaked et al. 2011. USEtox™ human exposure and toxicity factors for comparative assessment of toxic emissions in life cycle analysis: sensitivity to key chemical properties. *International Journal of Life Cycle Assessment.* 16(8): 710-727.

Rossin, A. C., R. M. Sterritt, and J. N. Lester. 1982. The influence of process parameters on the removal of heavy metals in activated sludge. *Water, Air, and Soil Pollution* 17: 185–198. doi:10.1007/BF00283301.

Roy, P.O., L. Deschênes, and M. Margni. 2014. Uncertainty and spatial variability in characterization factors for aquatic acidification at the global scale. *The International Journal of Life Cycle Assessment* 19(4): 882–890.

RSMeans. 2010. RSMeans Building Construction Cost Data, 68th Edition.

RSMeans. 2017. RSMeans Historical Construction Cost Index.

Rudd, T., R. M. Sterritt, and J. N. Lester. 1984. Formation and conditional stability constants of complexes formed between heavy metals and bacterial extracellular polymers. *Water Research* 18: 379–384. doi:10.1016/0043-1354(84)90115-5.

Ruel, S. M., J. M. Choubert, M. Esperanza, C. Miège, P. Navalón Madrigal, H. Budzinski, K. Le Ménach, V. Lazarova, et al. 2011. On-site evaluation of the removal of 100 micro-pollutants through advanced wastewater treatment processes for reuse applications. *Water Science and Technology* 63: 2486–2497. doi:10.2166/wst.2011.470.

Ryberg, M., M.D.M. Vieira, M. Zgola, J. Bare, and R.K. Rosenbaum. 2014. Updated US and Canadian normalization factors for TRACI 2.1. Clean Technologies and Environmental Policy. 16(2).

Salihoglu, N. K. 2013. Assessment of urban source metal levels in influent, effluent, and sludge of two municipal biological nutrient removal wastewater treatment plants of Bursa, an industrial City in Turkey. CLEAN–Soil, Air, Water 41: 153–165.

Schroeder, D. C., & Lee, G. F. (1975). Potential transformations of chromium in natural waters. Water, Air, and Soil Pollution, 4(3-4), 355-365.

Sedlak, D. L., and U. von Gunten. 2011. The Chlorine Dilemma. Science 331: 42–43. doi:10.1126/science.1196397.

Stasinakis, A. S., and N. S. Thomaidis. 2010. Fate and Biotransformation of Metal and Metalloid Species in Biological Wastewater Treatment Processes. *Critical Reviews in Environmental Science and Technology* 40: 307–364. doi:10.1080/10643380802339026.

Stasinakis, A. S., N. S. Thomaidis, D. Mamais, M. Karivali, and T. D. Lekkas. 2003. Chromium species behaviour in the activated sludge process. *Chemosphere* 52: 1059–1067. doi:10.1016/S0045-6535(03)00309-6.

Stensel, H. D., and G. L. Shell. 1974. Two Methods of Biological Treatment Design. *Journal (Water Pollution Control Federation)* 46: 271–283. JSTOR.

Stephenson, T., and J. N. Lester. 1987. Heavy metal behavior during the activated sludge process I. Extent of soluble and insoluble metal removal. *Science of The Total Environment* 63: 199–214. doi:10.1016/0048-9697(87)90046-5.

Sterritt, R., and J. Lester. 1983. Mechanisms of heavy metal concentration into sewage sludge. Processing and Use of Sewage Sludge. Proceedings of the 3rd Int. Symposium, Brighton.

Stoveland, S., and J. N. Lester. 1980. A study of the factors which influence metal removal in the activated sludge process. *Science of The Total Environment* 16: 37–54. doi:10.1016/0048-9697(80)90101-1.

Tang, H., Y.-C. Chen, J. M. Regan, and Y. F. Xie. 2012. Disinfection by-product formation potentials in wastewater effluents and their reductions in a wastewater treatment plant. *Journal of Environmental Monitoring* 14: 1515–1522. doi:10.1039/C2EM00015F.

Tchobanoglous, G. and F.L. Burton. 1991. Wastewater Engineering: Treatment, Disposal, and Reuse. Metcalf & Eddy.

Tchobanoglous, G., H.D. Stensel, R. Tsuchihashi, F. Burton, M. Abu-Orf, G. Bowden, and W. Pfrang. 2014. Wastewater Engineering: Treatment and Resource Recovery. Fifth Edition. McGraw-Hill Education, New York, NY.

Tetra Tech. 2013. Cost Estimate of Phosphorus Removal at Wastewater Treatment Plants. Ohio Environmental Protection Agency. http://epa.ohio.gov/Portals/35/wqs/nutrient_tag/OhioTSDNutrientRemovalCostEstimate_05_06_13.pdf. Accessed 28 June, 2016.

Thornton, L., D. Butler, P. Docx, M. Hession, C. Makropoulos, M. McMullen, M. Nieuwenhuijsen, A. Pitman, et al. 2001. Pollutants in urban waste water and sewage sludge. Final report prepared by ICON. Office for Official Publications of the European Communities, Luxembourg. ISBN 92-894-1735-8.

Tien, C.-T., and C. Huang. 1991. Kinetics of heavy metal adsorption on sludge particulate. *Heavy metal in the environment, Vernet, JP (Ed.). Elesvier Science Publishers, USA*: 313–328.

Udo de Haes, H.A., O. Jolliet, G. Finnveden, M. Hauschild, W. Krewitt, and R. Mueller-Wenk. 1999. Best available practices regarding impact categories and category indicators in life cycle impact assessment–Part 1 and 2. *International Journal of Life Cycle Assessment J. of LCA*. 4: 66-74, 167-174.

UNFCCC. 2012. Clean Development Mechanism: Methodological Tool, Project and Leakage Emissions from Anaerobic Digestion; CDM Methodology; UNFCCC EB 66, Annex 32.

USDA (US Department of Agriculture) and U.S. EPA (US Environmental Protection Agency). 2015. US Federal LCA Digital Commons Life Cycle Inventory Template. https://data.nal.usda.gov/dataset/us-federal-lca-commons-life-cycle-inventory-unit-process-template. Accessed January 2015.

U.S. EIA (U.S. Energy Information Administration). 2015. Electric Power Monthly–Table 5.6.A. Average Price of Electricity to Ultimate Customers by End-Use Sector.

U.S. DOE. 2016. U.S. DOE Combined Heat and Power Installation Database. https://doe.icfwebservices.com/chpdb/ (accessed March 5, 2018).

U.S. DOL (U.S. Department of Labor, Bureau of Labor Statistics). 2017. May 2016 National Industry-Specific Occupational Employment and Wage Estimates for NAICS 221300 – Water, Sewage and Other Systems.

U.S. EPA. 1980. Construction Costs for Municipal Wastewater Treatment Plants: 1973-1978. EPA/430/9-80-003. Washington, DC.

U.S. EPA. 2000. Wastewater Technology Fact Sheet–Dechlorination. EPA 832-F-00-022. Washington, DC.

U.S. EPA ORD. 2002. Onsite Wastewater Treatment System Manual. EPA/625/R-00/008. Washington, DC.

U.S. EPA. 2003a. *Biosolids Technology Fact Sheet – Gravity Thickening*. EPA 832-F-03-022. Washington, DC.

U.S. EPA. 2003b. Wastewater Technology Fact Sheet – Screening and Grit Removal. EPA 832-F-03-011. Washington, DC.

U.S. EPA. 2008a. National Ambient Air Quality Standards (NAAQS). http://www3.epa.gov/ttn/naaqs/criteria.html. Accessed 21 December 2015.

U.S. EPA OWM. 2008b. Municipal Nutrient Removal Technologies Reference Document. EPA 832-R-08-006. Washington, DC. http://water.epa.gov/scitech/wastetech/upload/mnrt-volume1.pdf. Accessed 28 June, 2016

U.S. EPA ORD. 2010. Nutrient Control Design Manual. EPA/600/R-10/100. Washington, DC.

U.S. EPA. 2012a. Notes on Conference Call with EPA and ERG Staff and with Bill Hays, Dave Jenkins, and Terry Smerks of North Star Disposal, Inc.

U.S. EPA. 2012b. 2012 Guidelines for Water Reuse. EPA/600/R-12/618. Washington, DC.

U.S. EPA. 2014. LFG Energy Benefits Calculator. Landfill Methane Outreach Program. https://www3.epa.gov/lmop/projects-candidates/lfge-calculator.html. Accessed 28 June, 2016.

U.S. EPA OST. 2015a. A Compilation of Cost Data Associated with the Impacts and Control of Nutrient Pollution. EPA 820-F-15-096. Washington, DC. http://www2.epa.gov/sites–/production/files/2015-04/documents/nutrient-economics-report-2015.pdf. Accessed 28 June, 2016.

U.S. EPA. 2015b. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013**.** http://www.epa.gov/climatechange/emissions/usinventoryreport.html**.** Accessed 28 June, 2016.

U.S. EPA. 2015c. Contaminants of Emerging Concern. Reports and Assessments. *USEPA*.

U.S. EPA. 2015d. Drinking Water Contaminants – Standards and Regulations. Collections and Lists. *US EPA*. August 12.

U.S. EPA. 2015e. Stage 1 and Stage 2 Disinfectants and Disinfection Byproducts Rules. Policies and Guidance. *US EPA*. October 13.

U.S. EPA. 2015f. ORD LCA Database. LCA Research Center, National Risk Management Research Laboratory.

U.S. EPA. 2016a. LFG Energy Project Profiles. Landfill Methane Outreach Program. https://www3.epa.gov/lmop/projects-candidates/profiles.html. Accessed 28 June, 2016.

U.S. EPA. 2016b. Clean Water Sate Revolving Fund (SWSRF) Results. https://www.epa.gov/cwsrf/clean-water-state-revolving-fund-cwsrf-results. Accessed 19 April, 2016.

U.S. EPA. 2016c. *Drinking Water Contaminant Candidate List 4-Final*. 81 FR 81099. Federal Register.

U.S. EPA. 2017. CWA Analytical Methods: Contaminants of Emerging Concern.

U.S. EPA. 2019a. National Pretreatment Program. https://www.epa.gov/npdes/national-pretreatment-program. Visited May, 2019.

U.S. EPA. 2019b. National Recommended Water Quality Criteria – Aquatic Life Criteria Table. https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table. Accessed September 1, 2019

U.S. EPA. 2019c. National Recommended Water Quality Criteria - Human Health Criteria Table. https://www.epa.gov/wqc/national-recommended-water-quality-criteria-human-health-criteria-table. Accessed September 1, 2019

USGCRP (United States Global Change Research Program). 2015. The Impacts of Climate Change on Change on Human Health in The United States: A Scientific Assessment, edited by A. Crimmins, J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, and N. Fann et al. https://health2016.globalchange.gov/. Accessed 21 June, 2016.

Varnier, D. 2014. Life cycle cost analysis as a decision support tool for managing municipal infrastructure. in Proceedings of the CIB 2004 Triennial Congress. Toronto, Ontario, May 2-9, 2004: International Council for Research and Innovation Building and Construction, Rotterdam, Netherlands.

Villanueva, C. M., K. P. Cantor, S. Cordier, J. J. Jaakkola, W. D. King, C. F. Lynch, S. Porru, and M. Kogevinas. 2004. Disinfection byproducts and bladder cancer: a pooled analysis. *Epidemiology* 15: 357–367.

Wang, J. 1997. Equilibrium aspects of heavy metal interactions with wastewater and wastewater particulates.

Wang, J., C. P. Huang, and H. E. Allen. 2006. Predicting metals partitioning in wastewater treatment plant influents. *Water Research* 40: 1333–1340. doi:10.1016/j.watres.2005.12.044.

WRRF (Water Reuse Research Foundation). 2014. The Opportunities and Economics of Direct Potable Reuse. WRRF-14-08.

Water Surplus. 2015. Internet provider of new, remanufactured and rental water and wastewater treatment equipment and components. http://www.watersurplus.com/. Accessed 28 June, 2016.

Watson, K., G. Shaw, F. D. L. Leusch, and N. L. Knight. 2012. Chlorine disinfection by-products in wastewater effluent: Bioassay-based assessment of toxicological impact. *Water Research* 46: 6069–6083. doi:10.1016/j.watres.2012.08.026.

Weidema, B.P., C. Bauer, R. Hischier, C.L. Mutel, T. Nemecek, C.O. Vadenbo, and G. Wernet. 2011. Overview and methodology: Data quality guideline for the ecoinvent database version 3 (final draft_revision 1). http://www.ecoinvent.org/fileadmin/documents/en/ecoinvent_v3_elements/01_DataQualityGuideline_FinalDraft_rev1.pdf. Accessed 28 June, 2016.

Westerhoff, P., and H. Mash. 2002. Dissolved organic nitrogen in drinking water supplies: a review. *Journal of Water Supply: Research and Technology-Aqua* 51: 415–448. doi:10.2166/aqua.2002.0038.

Wiser, J. R., P. E.; Schettler, J. W., P. E.; Willis, J. L., P. E. 2010. *Evaluation of Combined Heat and Power Technologies for Wastewater Treatment Facilities*. EPA 832-R-10-006. Washington, D.C.

World Bank. 2016. Population, total (2008). http://data.worldbank.org/indicator/SP.POP.TOTL?page=1. Accessed 10 May, 2016.

Yamada, M., M. Dazai, and K. Tonomura. 1969. Change of mercurial compounds in activated sludge. *Journal of Fermentation Technology* 47: 155.

Yost, K. J., R. F. Wukasch, T. G. Adams, and B. Michalczyk. 1981. Heavy Metal Sources and Flows in a Municipal Sewage System: Literature Survey and Field Investigation of the Kokomo, Indiana, Sewage System.

Ziolko, D., O. V. Martin, M. D. Scrimshaw, and J. N. Lester. 2011. An Evaluation of Metal Removal During Wastewater Treatment: The Potential to Achieve More Stringent Final Effluent Standards. *Critical Reviews in Environmental Science and Technology* 41: 733–769. doi:10.1080/10643380903140299.

APPENDIX A
SELECTION OF WASTEWATER TREATMENT CONFIGURATIONS

Appendix A: Selection of Wastewater Treatment Configurations

ERG searched the literature to compile performance information on wastewater treatment configurations which remove both TN and TP from municipal wastewater. ERG recorded the type of biological treatment used and the use or absence of chemical addition for phosphorus precipitation, fermenter, sand filter, and other technology components. ERG assumed preliminary treatment with screens, a grit chamber, and primary clarification. Sludge management was assumed to include gravity thickening, anaerobic digestion, dewatering (centrifugation), and transport of wastewater solids to a landfill. ERG gathered performance data from nine key sources:

- Bickler, S. Wigen Water Technologies. 2015. Technical Feedback Requested Regarding Reverse Osmosis. Email from S. Bickler, to A. Allen, ERG. (June).
- Bott, C. and Parker, D. 2011. Nutrient Management Volume II: Removal Technology Performance & Reliability. Water Environment Research Federation Report NUTR1R06k. IWA Publishing, London, U.K.
- Dukes, S. and von Gottberg, A. Koch Membrane Systems. 2006. Membrane Bioreactors for RO Pretreatment. Water Environment Foundation. WEFTEC® 2006.
- Eastern Research Group, Inc. 2009. Draft Technical Support Document: Analysis of Secondary Treatment and Nutrient Control at POTWs. (December).
- Eastern Research Group, Inc. 2015b. Personal communication between Amber Allen, Debra Falatko, and Mark Briggs of ERG and Stacey Bickler of Wigen Water Technologies.
- Falk, M.W., Neethling, J.B., and Reardon, D.J. 2011. Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability. Water Environment Research Federation Report NUTR1R06n. IWA Publishing, London, U.K.
- Hartman, P. and Cleland, J. ICF International. 2007. Wastewater Treatment Performance and Cost Data to Support an Affordability Analysis for Water Quality Standards. Montana Department of Environmental Quality. (May). Available online at http://www.kysq.org/docs/Wastewater_2007.pdf.
- Tetra Tech. 2013. Cost Estimate of Phosphorus Removal at Wastewater Treatment Plants. Ohio Environmental Protection Agency. (May). Available online at http://epa.ohio.gov/Portals/35/wqs/nutrient_tag/OhioTSDNutrientRemovalCostEstimate_05_06_13.pdf.
- U.S. EPA OWM. 2008b. Municipal Nutrient Removal Technologies Reference Document. EPA 832-R-08-006. Washington, DC. (September). Available online at http://water.epa.gov/scitech/wastetech/upload/mnrt-volume1.pdf.

- U.S. EPA OST. 2015a. A Compilation of Cost Data Associated with the Impacts and Control of Nutrient Pollution. EPA 820-F-15-096. Washington, DC. (May). Available online at http://www2.epa.gov/sites/production/files/2015-04/documents/nutrient-economics-report-2015.pdf.

ERG recorded performance data for all wastewater treatment configurations and assigned each a performance level as defined in Falk et al. (2011), Table ES-1:

- Level 1 – No target effluent concentration specified;
- Level 2 – 8 mg N/L, 1 mg P/L;
- Level 3 – 4-8 mg N/L, 0.1-0.3 mg P/L;
- Level 4 – 3 mg N/L, 0.1 mg P/L; and
- Level 5 – 2 mg N/L, <0.02 mg P/L.

In many cases, performance levels for wastewater treatment configurations differ for TN and TP (i.e., a configuration achieves a certain level for TN and a different level for TP).

ERG examined the set of identified wastewater treatment configurations for which TN and TP performance levels match to identify nine which are commonly used and provide contrast. Contrast was defined by differences in terms of performance level, type of biological nutrient reduction, combinations of additional treatment steps, costs (capital and operating), and other contrasting parameters such as energy requirements, chemical usage, and sludge generation. For level 1, ERG recommended one wastewater treatment configuration, and for each of levels 2 to 5 ERG recommended two wastewater treatment configurations. ERG's rationale for these recommendations is described below.

A.1 Results and Recommendations

ERG identified 37 wastewater treatment configurations that achieve the same performance level for both TN and TP (see Table A-1). The technologies used in these wastewater treatment configurations include a variety of biological nutrient removal and enhanced nutrient removal technologies.

The sections below describe the wastewater treatment configurations identified for each performance level and discuss ERG's rationale for selection of specific wastewater treatment configurations to be evaluated in the LCA. Selected configurations generally represent those most commonly used to achieve the desired performance levels, and that also provide contrast in biological processes, capital and/or annual costs, or other factors such as energy requirements and sludge generation. The most common reasons wastewater treatment configurations were not selected include: 1) they are unique retrofits and otherwise not commonly used, 2) they are very similar to another selected technology, or 3) they exhibit a wide range of performance, spanning multiple performance levels, which raises uncertainty as to the reliability with which the process can achieve a specific performance level.

Table A-1. Identified Wastewater Treatment Configurations

🟩 Recommended wastewater treatment configuration

All configurations assumed to also include preliminary/primary treatment and sludge management.

No.	Type of Biological Treatment	Phosphorus Precipitation	Fermenter	Sand Filter	Additional Treatment	Long Term Average Effluent TN Concentration (mg/L as N)	TN Level	Long Term Average Effluent TP Concentration (mg/L)	TP Level	Performance Source [1]
1	3-stage Westbank					3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
2	3-stage Westbank	x				3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
3	4-stage Bardenpho	x				3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
4	5-stage Bardenpho (Level 3)	x	x	x		4 to 8	2,3	0.1 to 0.3	3	b, Table 3-1 and 2-b, pages 56, 57, 59.
5	5-stage Bardenpho (Level 4)	x	x	x	Denitrification filter	3	4	0.1	4	b, Table 3-1 and 2-b, pages 56, 57, 60-61; also a, Table 5-d, page 237
6	5-stage Bardenpho	x		x		3	4	0.1	4	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
7	5-stage Bardenpho (Level 5)	x	Not listed in reference (Falk et al), but may be appropriate	x	Denitrification filter (10% flow) + ultrafiltration and reverse osmosis (90% flow)	<2	5	<0.02	5	b, Table 3-1 and 2-b, pages 56, 57, 61; also a, Table 5-d, page 237
8	Activated sludge + Modified Ludzack-Ettinger				Biological activated filter	4	3	<=0.3	3	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
9	Activated sludge + Modified Ludzack-Ettinger	x				3	4	0.1	4	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
10	Activated sludge (Level a, assuming conventional activated sludge treatment)					3 to 9	a,2,3	0.3 to 2	a,2	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)

Table A-1. Identified Wastewater Treatment Configurations

🟩 Recommended wastewater treatment configuration

All configurations assumed to also include preliminary/primary treatment and sludge management.

No.	Type of Biological Treatment	Phosphorus Precipitation	Fermenter	Sand Filter	Additional Treatment	Long Term Average Effluent TN Concentration (mg/L as N)	TN Level	Long Term Average Effluent TP Concentration (mg/L)	TP Level	Performance Source [1]
11	Activated sludge, 3-sludge system (Level 2)	x				6 to 8	2	0.43	2	a, pages 2-5 and 3-5/6 (pg 59 and 151/152)
12	Aerobic lagoons					3 to 8	2,3	0.1 to 1	2,3	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
13	Anaerobic/Anoxic/Oxic (Level 2)					8; 3 to 8	2; 2,3	1; 0.5 to 1	2; 2	b, Table 3-1 and 2-b, pages 56, 57, 58.; a, Table 5-d, page 237
14	Anaerobic/Oxic, Phoredox					3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
15	Cyclic activated sludge	x				3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
16	Integrated fixed-film activated sludge	x				3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
17	Extended aeration					3 to 8	2,3	0.1 to 1 (2)	2,3	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
18	Facultative lagoon					3 to 8	2,3	0.1 to 1	2,3	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
19	Membrane bioreactor (Level 4)	x				<3	4	<=0.1	4	a, Table 5-d, page 237
20	Membrane bioreactor (Level 5)	x	Not listed in reference (Falk et al), but may be appropriate		Reverse osmosis (85% flow)	<2; <0.1	5	<0.02; -	5	b, Table 3-1 and 2-b, pages 56, 57, 61; a, Table 5-d, page 237; 8, page 6127; 9, page 1

Table A-1. Identified Wastewater Treatment Configurations

🟩 Recommended wastewater treatment configuration

All configurations assumed to also include preliminary/primary treatment and sludge management.

No.	Type of Biological Treatment	Phosphorus Precipitation	Fermenter	Sand Filter	Additional Treatment	Long Term Average Effluent TN Concentration (mg/L as N)	TN Level	Long Term Average Effluent TP Concentration (mg/L)	TP Level	Performance Source [1]
21	Membrane bioreactor		x		Land application/ infiltration bed	<3	4	<=0.1	4	a, Table 5-d, page 237, also land application note on pages 13d, 27, and 39
22	Modified Ludzack-Ettinger	x				3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
23	Modified Ludzack-Ettinger	x	x	x	Denitrification filter	<3	4	<=0.1	4	a, Table 5-d, page 237, page 63
24	Moving-bed biofilm reactor (Level 2)	x				3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
25	Phased isolation ditch					3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
26	PhoStrip II					3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
27	Post-aeration anoxic with methanol (Blue Plains process, a retrofit system)	x				3 to 8; 4 to 8	2,3	0.5 to 1; 0.18	2; 3	a, Table 5-d, page 237; 7, page 3-43 (pg 83)
28	Rotating biological contactor (assume Level 3 performance)					3 to 8	2,3	0.1 to 1	2,3	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
29	Sequencing batch reactor					3 to 8	2,3	0.1 to 1	2,3	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
30	Sequencing batch reactor			x		3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
31	Sequencing batch reactor	x				3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
32	Step-feed activated sludge					3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237

Table A-1. Identified Wastewater Treatment Configurations

🟩 Recommended wastewater treatment configuration

All configurations assumed to also include preliminary/primary treatment and sludge management.

No.	Type of Biological Treatment	Phosphorus Precipitation	Fermenter	Sand Filter	Additional Treatment	Long Term Average Effluent TN Concentration (mg/L as N)	TN Level	Long Term Average Effluent TP Concentration (mg/L)	TP Level	Performance Source [1]
33	Step-feed activated sludge (Level 4)	x	x	x	Chemically assisted clarification	<3	4	<=0.1	4	a, Table 5-d, page 237
34	Trickling filter				Submerged biological filter	3	4	0.1	4	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
35	Suspended growth activated sludge	x	x		Inclined plate settling tanks, deep bed sand filter	3 to 6	3	0.18	3	d, page 3-39 (pg 79-80)
36	University of Cape Town process, modified					3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
37	University of Cape Town process, modified (Level 3)	x	x	x		<3	3	0.1 to 0.5	3	a, Table 5-d, pages 5-5 (pg 237), ES-22 (pg 40), UCTm equivalent to technologies in Table 5-2 on page 5-4 (pg 236)

1 – Sources: a – U.S. EPA OWM, 2008b; b – Falk et al., 2011; c – U.S. EPA OST, 2015a; d – Bott and Parker, 2011.

2 – This phosphorus removal capability is unexpected, but is included as reported in the cited wastewater treatment configuration source document.

A.1.1 Level 1

Level 1 technologies are not designed to specifically remove nutrients, although some removal of nutrients occurs with the wastewater treatment configuration. ERG recommended the conventional plug flow activated sludge system to represent level 1 performance.

A.1.2 Level 2

Twenty-two wastewater treatment configurations performed at level 2 for both TN and TP. These wastewater treatment configurations included the biological and enhanced nutrient reduction technologies listed in Table A-1. ERG selected the anaerobic/anoxic/oxic (A2O) system as a typical level 2 wastewater treatment configuration and then reviewed the remaining level 2 wastewater treatment configurations for contrast, performance, and likelihood of use.

ERG considered and rejected the moving-bed biofilm reactor because it is most frequently used as a retrofit but otherwise is not commonly used. The integrated fixed-film activated sludge and anaerobic/oxic Phoredox systems were rejected as too similar to the selected A2O system. The Modified University of Cape Town process and 4-stage Bardenpho were rejected at level 2 to allow for their selection as contrasting wastewater treatment configurations for other performance levels.

The sequencing batch reactor, 3-stage Westbank, cyclic activated sludge, step-feed activated sludge, phased isolation ditch, modified Ludzack-Ettinger (MLE), and PhoStrip II were rejected due to concerns that their performance ranges were too wide, raising uncertainty regarding their ability to reliably achieve level 2 performance. The extended aeration system was rejected because of concerns about the performance data presented in the reference. The Blue Plains Process was rejected because it is a unique retrofit system. The aerobic and facultative lagoons were rejected because lagoons are not applicable for all publicly owned treatment works (POTWs). A rotating biological contactor (RBC) system was initially considered because it offers the advantages of low energy usage, low solids generation, and good settling. However, the RBC technology was ultimately rejected because its use is predominately restricted to small plants; the technology also exhibited a number of problems in the 1970s and 1980s, some of which remain unresolved today.

After eliminating the other level 2 options for the reasons discussed above, ERG recommended a common alternative level 2 configuration of plug flow activated sludge followed by separate stage nitrification and separate stage denitrification with chemical phosphorus removal. This technology contrasts with the recommended A2O system in its relative ease of operation and control (due to segregated treatment components for BOD, ammonia, and nitrate removal) and relatively higher cost due to multiple biological reactors and associated clarifiers/sludge recycling.

In summary, ERG recommended the following two technologies to represent level 2 performance in the LCA:

- 2-1) A2O with chemical phosphorus precipitation; and
- 2-2) 3-Sludge activated sludge system with chemical phosphorus precipitation.

A.1.3 Level 3

Ten wastewater treatment configurations performed within the level 3 range. Of these, six were rejected from further consideration because their TN/TP performance spans levels two and three (included in the level 2 description above). The remaining four wastewater treatment configurations perform at level 3 for both TN and TP. The first system, which uses activated sludge, MLE, and a biological activated filter, was not recommended because it is a unique retrofit system. The second system, which uses suspended growth in high purity oxygen activated sludge, inclined plate setting tanks, and a deep bed sand filter, was rejected because suspended growth systems are not applicable for all POTWs. The remaining two systems are commonly used systems that ERG recommended to represent level 3 performance in the LCA:

- 3-1) 5-Stage Bardenpho with chemical phosphorus precipitation, fermenter, and sand filter; and
- 3-2) Modified University of Cape Town process with chemical phosphorus precipitation, fermenter, and sand filter.

A.1.4 Level 4

Eight wastewater treatment configurations perform at level 4 for both TN and TP. These processes included a 5-stage Bardenpho activated sludge coupled with a MLE unit, 4- and 5-stage Bardenpho systems coupled with membrane filtration, denitrification filters coupled with a MLE unit or with a 5-stage Bardenpho, a trickling filter coupled with a submerged biological filter, and a step-feed activated sludge process with chemically assisted clarification. Most of these wastewater treatment configurations also include chemical phosphorus precipitation, and half also include either a fermenter or a sand filter.

ERG selected the 5-stage Bardenpho with denitrification filter as a typical level 4 wastewater treatment configuration. For the contrasting level 4 wastewater treatment configuration, ERG considered and rejected the membrane bioreactor with land infiltration and the trickling filter because neither is applicable for all POTWs. The activated sludge coupled with a MLE unit was rejected as a unique retrofit system. The 5-stage Bardenpho without denitrification filter was rejected as too similar to the typical level 4 configuration. Of the remaining three options (step-feed activated sludge, MLE with denitrification filter, and 4-stage Bardenpho with membrane filter), ERG selected the membrane bioreactor (MBR) system as a contrasting alternative because of its increasing popularity.

In summary, ERG recommended the following technologies to represent level 4 performance in the LCA:

- 4-1) 5-Stage Bardenpho with chemical phosphorus precipitation, fermenter, sand filter, and denitrification filter; and
- 4-2) 4-Stage Bardenpho MBR and chemical phosphorus precipitation.

A.1.5 Level 5

Two wastewater treatment configurations performed at level 5 for both TN and TP. The first configuration includes 5-stage Bardenpho, chemical precipitation, and fermentation. The wastestream is then split with a portion of the flow undergoing side stream treatment by reverse osmosis (RO) and the remainder of the flow undergoing side stream treatment by a denitrification filter and sand filter. The second wastewater treatment configuration is a 5-stage Bardenpho MBR with chemical phosphorus precipitation and fermenter followed by a portion of the flow to RO and the remainder of the flow not requiring additional side stream treatment. This second process is a modification of the first, substituting a 5-stage Bardenpho MBR for the 5-stage Bardenpho and clarifier. The MBR allows the wastewater treatment configuration to achieve similar TN and TP performance without a denitrification filter and sand filter.

ERG conducted additional literature reviews and communications with RO vendors to determine RO pretreatment requirements. For the first configuration, RO pretreatment includes solids removal (ultrafiltration, UF), biofouling control (chlorination followed by dechlorination), and scale control (antiscalant addition). RO pretreatment for the second configuration is similar to the first, except that use of the 5-stage Bardenpho MBR precludes the need for solids removal via UF.

ERG performed calculations to determine the percentage of flow requiring side stream treatment for each configuration to achieve the target TN and TP effluent concentrations. For TN, ERG assumed the following effluent quality achieved by nutrient control technologies:

- A 5-stage Bardenpho TN effluent concentration of 4 - 8 mg/L (based on the performance of the level 3 5-stage Bardenpho configuration).
- A denitrification and sand filter TN effluent concentration of 3 mg/L (based on the performance of the level 4 5-stage Bardenpho configuration).
- A 5-stage Bardenpho MBR TN effluent concentration of 3 mg/L (based on the performance of the level 4 5-stage Bardenpho MBR configuration).
- A RO removal of 95 percent (based on information from RO vendors).

Using these assumptions, and a target overall TN effluent concentration of 2 mg/L, approximately 35 to 40 percent of flow would need to undergo side stream treatment by RO.

For TP, ERG assumed the following effluent quality achieved by nutrient control technologies:

- A 5-stage Bardenpho TP effluent concentration of 0.1 to 0.3 mg/L (based on the performance of the level 3 5-stage Bardenpho configuration).
- A denitrification and sand filter TP effluent concentration of 0.1 mg/L (based on the performance of the level 4 5-stage Bardenpho configuration).
- A 5-stage Bardenpho MBR TP effluent concentration of 0.1 mg/L (based on the performance of the level 4 5-stage Bardenpho MBR configuration).
- A RO removal of 95 percent (based on information from RO vendors).

Using these assumptions, and a target overall TP effluent concentration of 0.02 mg/L, approximately 85 to 90 percent of flow (for the second and first configurations, respectively) would need to undergo side stream treatment by RO.[9]

These calculations demonstrate that TP removal, rather than TN removal, drives the percentage of wastewater requiring RO treatment to achieve level 5 performance.

In summary, ERG recommended the following technologies to represent level 5 performance in the LCA:

- 5-1) 5-stage Bardenpho with chemical phosphorus precipitation, fermenter, and sand filter followed by 10 percent of the flow to a denitrification filter and sand and 90 percent of the flow to UF and RO; and
- 5-2) 5-stage Bardenpho MBR with chemical phosphorus precipitation and fermenter followed by 85 percent of the flow to RO.

A summary of these recommendations is found in Table A-2 below.

Table A-2. Recommended Technologies

Performance Level	Type of Biological Treatment	Phosphorus Precipitation	Fermenter	Sand Filter	Other Technical Components	Reference
1	Plug Flow Activated Sludge					OST, 2015
2	Anaerobic/Anoxic/Oxic					Falk, 2011
2	Activated Sludge, 3-Sludge System	X				OWM, 2008
3	5-Stage Bardenpho	X	X	X		Falk, 2011
3	University of Cape Town Process, Modified	X	X	X		OWM, 2008
4	5-stage Bardenpho	X	X	X	Denitrification Filter	Falk, 2011
4	4-stage Bardenpho MBR	X				OWM, 2008
5	5-Stage Bardenpho	X	X	X	10%: Denitrification Filter 90%: UF and RO	Falk, 2011 and OWM, 2008
5	5-stage Bardenpho MBR	X	X		85% RO	Falk, 2011 and OWM, 2008

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[9] Note that RO effluent quality expressed as a percentage of TP removal may not be the most appropriate measure of RO performance, but rather an effluent concentration of non-detect (detection limit 0.02 mg/L). Under this scenario, assuming an average effluent concentration equal to the detection limit, ½ the detection limit, and zero, approximately 80 to 100 percent of flow would need to undergo side stream treatment by reverse osmosis.

A.2 Technology Selection Data Quality

In accordance with the project's Quality Assurance Project Plan (QAPP) entitled *Quality Assurance Project Plan for Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants* (ERG, 2015c) approved by EPA on March 25, 2015, ERG collected existing data[10] via a literature search to determine the performance of identified wastewater treatment configurations. The literature search focused on peer-reviewed literature, EPA projects, and publicly available equipment specifications from and communications with technology vendors. ERG evaluated the collected information for completeness, accuracy, and reasonableness. In addition, ERG considered publication date, accuracy/reliability, and nutrient concentrations (reported as TN and TP) when reviewing data quality. Finally, ERG performed conceptual, developmental, and final product internal technical reviews of the data compilation and this Appendix.

Completeness. The descriptions of wastewater treatment configurations in the literature vary in level of detail. Descriptions used in this analysis were limited to those sufficiently detailed to be classified into one of the performance level categories and to identify the major technology components (e.g., type of biological treatment, chemical treatments, sand filter). ERG reviewed the treatment system descriptions, and did not include data for incomplete treatment systems.

Accuracy. ERG evaluated sources to ensure that the descriptions of each treatment system represent current operations at municipal treatment systems, and that nutrient reductions reflect the performance of the identified control technologies rather than other design or operational factors.

Reasonableness. ERG evaluated sources to ensure that the type of treatment correlates with expected nutrient reduction performance; for example, treatment systems with nutrient control should have lower nutrient concentrations than systems with secondary treatment only.

The criteria ERG used in evaluating the quality of information collected during the literature review are summarized in Table A-3.

Table A-3. Literature Review Data Quality Criteria

Quality Criterion	Description/Definition
Current (up to date)	Report the time period of the data. Year of publication (or presentation, if a paper presented at a conference) is 2005 or after.
Accurate/Reliable	U.S. government publications assumed accurate. For academic researcher: • Publication in peer reviewed journal. • Presentation at professional technical conference. For vendor researcher: • Publication in peer reviewed journal.

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[10] *Existing data* means information and measurements that were originally produced for one purpose that are recompiled or reassessed for a different purpose. Existing data are also called secondary data. Sources of existing data may include published reports, journal articles, LCI and government databases, and industry publications.

Table A-3. Literature Review Data Quality Criteria

Quality Criterion	Description/Definition
Analyte Scope	Nutrient concentrations, reported as TN and TP.

In accordance with the QAPP, ERG performed conceptual, developmental, and final product technical reviews of the spreadsheet included as Table A-1. These reviews included the following general steps:

- The spreadsheet developer verified the accuracy of any data that were transcribed into the spreadsheet;
- The team member reviewer also verified the accuracy of any data that were transcribed into the spreadsheet;
- The team member reviewer evaluated the technical soundness of methods and approaches used;
- The ERG spreadsheet developer maintained version control of interim spreadsheets; and
- The ERG spreadsheet developer maintained documentation in the project files.

APPENDIX B
DETAILED CHARACTERIZATION OF HEAVY METALS BEHAVIOR IN STUDY TREATMENT CONFIGURATIONS

Appendix B: Detailed Characterization of Heavy Metals Behavior in Study Treatment Configurations

B.1 Introduction

The discharge of metals to the environment represents an ever-present concern, given their potential toxicity at even trace levels. Wastewater treatment plants (WWTP) receive variable but sometimes high loads of metals depending on the mix of sources in their watershed, which can include industrial activities, domestic sources and stormwater (Yost et al. 1981; Rule et al. 2006; J.-M. Choubert et al. 2011b). Given a WWTP's position as a final barrier between source and environmental discharge, they are an opportunity for smart management of potentially toxic substances like metals.

The direct management of metals in conventional, municipal WWTPs has traditionally not been a focus of WWTP design and operation as measures like the National Pretreatment Program[11] are in place to limit the concentration and load of metals coming from industrial facilities. Rather, most discussion surrounding the treatment of metals by municipal WWTPs has dealt with the ancillary benefits afforded by existing processes that impact metals as well as the organics and nutrients these processes were designed to address (Choubert et al. 2011a; Choubert et al. 2011b; Ziolko et al. 2011; Cantinho et al. 2016). Additionally, little to no attention has been paid to the life cycle impacts of metal emissions associated with upstream processes, especially in conjunction with and relative to direct effluent emissions. To date, the most comprehensive study performed to address the 'co-benefits' of various treatment processes from a life cycle perspective only qualitatively discussed the effects of metals from both upstream and direct discharge impact calculations (Rahman et al. 2018). This study is therefore intended to address these gaps, which will help to both characterize the ability of a variety of commonly used wastewater treatment practices to partition metals from the liquid phase, as well as to help inform the full potential benefits of these treatment trains from a comprehensive life cycle perspective.

The metals reviewed for this study were selected based on two main criteria: the metal's recurrent presence in lists of regulated substances and its prevalence in the literature regarding treatability in the study treatment configurations. Indirectly, these two criteria were assumed to be indicators of demonstrated potential of the metal to cause environmental or human health impacts. The resulting list of metals includes Cadmium (Cd), Chromium (Cr), Copper (Cu), Mercury (Hg), Nickel (Ni), Lead (Pb), and Zinc (Zn). Each of these metals have been regulated in different countries. Four of them (Cd, Hg, Ni and Pb) were classified by the European Water Framework Directive (EUWFD) as priority substances and two (Hg and Cd) were additionally classified as hazardous substances (EU 2013; Cantinho et al. 2016). In the United States (US), guidance is provided for concentration limits of each of these metals in WWTP effluent through National Recommended Water Quality Criteria (EPA 2009). Table B-1 summarizes relevant regulatory criteria for the metals included in this study. Metal concentrations in land-applied sludge are also regulated in the US through the Part 503 Rule (NRC 2002).

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[11] https://www.epa.gov/npdes/national-pretreatment-program

Elevated levels of metals in the environment can result from both natural and anthropogenic sources. In the urban environment, metals are present in mixed municipal wastewater owing to the contribution of commercial and industrial sources, residential sources, contact with piping, and stormwater runoff (Yost et al. 1981; Thornton et al. 2001; Jones et al. 2017). Often, domestic inputs tend to be the largest sources of Cu, Zn and Pb, whereas commercial and industrial sources contribute greater proportions of Hg and Cr (Makepeace et al. 1995; Cantinho et al. 2016). Table B-1 summarizes ranges of influent concentrations established in several literature reviews, along with the ranges that were compiled from the case study data reviewed as part of this effort. These concentrations, as well as concentrations throughout this document, represent total concentrations (as opposed to specific fractions) unless otherwise noted.

Table B-1. Summary of Literature and Case Study Metal Influent Concentrations and Regulatory Effluent Concentrations

Value		Concentrations in µg/L							Notes	Source
		Pb	**Cu**	**Zn**	**Ni**	**Cr**	**Cd**	**Hg**		
Influent Concentrations - Literature Reviews		5.7	63	181	11	10	0.21	0.36	19 Plants, France	1
		25	78	155	14	12.0	0.8	0.5	30 Plants, UK	2
		140-600	--	--	--	--	--	--	Combined WW	3
		232	489	968	455	378	19	--	12+ Cities, US	4
Case Study Ranges	High	68	118	493	77	290	10	7.0	This Study	5
	Medium	21	65	350	24	59	4.9	3.8	This Study	5
	Low	10.8	25	204	11	19	0.94	0.37	This Study	5
US CCC[a]		2.5	9	120	52	74/11[b]	0.25	0.77	Effluent Limits	6
US CMC[a]		65	13	120	470	570/16[b]	2	1.4	Effluent Limits	6

a - Criterion Continuous Concentration/Criteria Maximum Concentration, hardness dependent except for Cr (VI) and Hg. Values shown assume a hardness of 100 mg/L.

b - Chromium (III/VI)

1 - Choubert et al., 2011b; Ruel et al., 2012

2 - Rule et al., 2006

3 - Metcalf and Eddy, 2014

4 – Yost et al., 1981

5 - Linstedt et al., 1971; Brown et al., 1973; Chen et al., 1974; Oliver and Cosgrove, 1974; Aulenbach and Chan, 1988; Huang et al., 2000; Innocenti et al., 2002; Chipasa, 2003; Karvelas et al., 2003; Qdais and Moussa, 2004; Buzier et al., 2006; da Dilva Oliveira et al., 2007; Mohsen et al., 2007; Obarska-Pempkowiak and Gajewska, 2007; Carletti et al, 2008; Johnson et al., 2008; Dialynas and Diamadopoulos, 2009; Renman et al., 2009; Malamis et al., 2012; Arevalo et al., 2013; Garcia et al., 2013; Salihoglu, 2013; Inna et al., 2014; Reddy et al., 2014

6 - U.S. EPA, 2019b

B.2 Metal Chemistry

With the exception of Cr, the metals selected in this study are commonly found in the 2+ oxidation state (Huang et al. 2000). Chromium mainly occurs in the Cr(III) and Cr(VI) oxidation states. While the Cr(VI) form is more labile and toxic to a number of organisms, it is generally associated with industrial effluent and is therefore less prevalent in both raw municipal wastewater and WWTP effluent (Jan and Young 1978; Stasinakis et al. 2003; Stasinakis and Thomaidis 2010). Moreover, Cr(VI) can be reduced to Cr(III) in the presence of suitable electron donors (e.g., organic substrates), whereas experimental results have shown that Cr(III) is not oxidized to Cr(VI) under the aerobic conditions found in AS plants (Stasinakis et al. 2003). A possible explanation is that oxidation of Cr(III) may be so slow that biosorption occurs before any oxidation can occur (Schroeder and Lee 1975).

With respect to treatability, the fraction in which the metal exists (solid or dissolved) is more important than its oxidation state which, under average municipal wastewater conditions, tends not to vary. Throughout the wastewater treatment process, metals generally exist in precipitated (strong complex), organically complexed (weak complex) or soluble forms (Nelson et al. 1981; Huang et al. 2000; Buzier et al. 2006). The type and fraction of precipitates present, which are considered insoluble and often the strongest of the complexes, depend on pH, solubility of the metal species, and the availability of complexing reagents including hydroxides, carbonates, and phosphates (Stoveland and Lester 1980; Huang et al. 2000; Wang et al. 2006). However, the solubility coefficients and products of metals reported in the literature vary markedly (Cheng et al. 1975) and direct application to study systems may not be appropriate as site-specific calculated solubilities can be up to two orders of magnitude different than experimental determinations (Nelson et al. 1981; Parker et al. 1994).

The unprecipitated fraction of metals tend to form weak organic complexes, which can be both settleable or dissolved (distinguished by the fraction passing through a 0.45 µm filter). The process of metal ion sorption to organic material is typically referred to as biosorption, and its effectiveness varies with the type of metal, ambient water quality, and the source of the organic material (Cheng et al. 1975; Huang et al. 2000; Arican et al. 2002; Chang et al. 2007). With the exception of Ni and Cd, which show an intermediate and variable affinity to solids partitioning (Cheng et al. 1975; Wang et al. 2006), the study metals tend to readily adsorb to particulate matter in raw, mixed municipal wastewater (mean dissolved fractions below 30%) (Goldstone et al. 1990a; Goldstone et al. 1990b; Goldstone et al. 1990c; Buzier et al. 2006; Choubert et al. 2011b). Accordingly, processes that remove solids or metal-organic complexes are often effective at removing metals as well.

Extracellular polymers (ECPs) have been found to play a key role in biosorption (Brown and Lester 1979; Hunter et al. 1983; Lawson et al. 1984; Norberg and Persson 1984; Rudd et al. 1984) as they contain negatively charged functional groups such as phosphoryl, carboxyl, sulphydryl, and hydroxyl groups which can serve as adsorption sites (Kelly et al. 1979; Nelson et al. 1981). Additionally, the metal affinity of ECPs has been shown to depend on the microorganism (MO) or MO consortium that produced them. In general, slower growing MOs produce more ECPs (Nelson et al. 1981; Hunter et al. 1983; Ghosh and Bupp 1992). Operationally, solids retention time (SRT) is typically used (along with ambient redox and nutrient conditions) to hold the bacterial growth rate constant, which in turn maintains consistent sorption characteristics of the biosolids. Conversely, increasing the SRT tends to select for slower-growing MOs, which in turn can increase the metal sorption capacity of the biosolids (Stensel and Shell 1974; Chao and Keinath 1979; Nelson et al. 1981). For example, the floc produced by slow-growing phosphate accumulating organisms (PAOs) and denitrifying organisms (DNOs) that are selected for in biological nutrient removal (BNR) processes with high SRTs have been found to have greater affinity towards Cd and Ni than conventional activated sludge floc (Chang et al. 2007). Notably, biosorption is a passive process taking place on the order of minutes to hours and does not depend on the viability of biological floc (Cheng et al. 1975; Neufeld and Hermann 1975; Nelson et al. 1981); the influence of active metabolic processes can therefore be considered unimportant (Huang et al. 2000). Moreover, for this study, hydraulic retention time (HRT) is maintained on the order of hours rather than minutes and will likely have little effect on the removal of metals by the different treatment levels.

Dissolved organic matter (DOM), for which COD can be considered a surrogate, also has a significant effect on metal sorption by biosolids (Sterritt and Lester 1983; Rudd et al. 1984; Tien and Huang 1991). High DOM can prevent both metal precipitation and metal uptake by sludge particulates by lowering ambient pH and competing for sorption sites, respectively (Cheng et al. 1975; Lo et al. 1989). In a detailed study of the factors influencing metals removal in four full-scale conventional activated sludge (AS) wastewater treatment (WWT) systems, Huang et al. (2000) found COD and SS concentrations to be the most important as indicators of effective biosorption of the dissolved fraction to biosolids, and biosolids removal, respectively.

B.3 Fate of Metals During Wastewater Treatment

The fate of metals during wastewater treatment depends on a number of chemical, physical, and operational parameters of the treatment process. Many processes commonly found in municipal wastewater treatment plants result in the effective removal of certain metals from the liquid fraction, thus limiting emissions to receiving waters. Depending on the type of unit processes present, the metals removed from the liquid fraction are partitioned to either the solids (sludge) fraction or in the case of this study where reverse osmosis is used, the brine solution. Although volatilization was proposed as a loss pathway for Hg in the early wastewater treatment literature (Yamada et al. 1969), results from full-scale systems indicate that this is likely an artifact of startup conditions. In continuously operating full scale WWTPs, adsorption to biomass is the dominant partitioning mechanism and volatilization is negligible (Goldstone et al. 1990c; Pomiès et al. 2013).

In general, metal concentrations tend to decrease during primary treatment. Metals present as precipitated species or adsorbed to settleable solids (i.e. the non-dissolved fraction) are the main fractions that are removed. As such, many authors have found a correlation between primary treatment solids removal and metal removal, with reported metal removals ranging from 40-70% when solids removal is high (Rossin et al. 1982; Lester 1983; Kempton et al. 1987). However, where primary solids removal is lower or concentrated supernatant is recirculated to the headworks (in effect increasing internal, dissolved metal loadings), reported total metal removals can be on the order of 1-10% (Oliver and Cosgrove 1974) and can even be negative depending on the strength of recirculated supernatant (Huang et al. 2000; Inna et al. 2014). Due to the variability of this documented performance, the similarity of primary treatment unit processes and the incorporation of internal circulation within most study configurations, it was conservatively assumed that no metals removal was directly attributed to primary treatment. Primary treatment performance was instead aggregated with secondary biological processes, both because proper functioning of secondary processes implicitly assumes proper primary treatment or pretreatment, and because most performance data obtained for secondary processes implicitly accounted for the presence of standard primary treatment.

In secondary biological unit processes, SRT, COD, and TSS tend to be important indicators of metals partitioning (Lo et al. 1989; Huang et al. 2000). Systems that provide better COD removal tend to allow for greater sorption potential between metals and biological flocs, which can then be removed through efficient suspended solids removal. The sorption process varies by metal type as well, depending on the affinity of metal species to sludge and the stability of the sludge metal complexes. Results from batch equilibrium adsorption experiments using solids from conventional activated sludge (CAS) systems indicate that the stability constants of the sludge-metal complexes follow the order of Hg(II)≈Pb(II)≈Cu(II)≈Cr(II)>Zn(II)> Cd(II)>Ni(II) (Wang 1997). This is supported by results from full scale case studies as well, with removals of Hg, Pb, Cu, Cr, Cd, and Zn often in the range of 40-60% and the removal of Ni often less than 40% for sorption-based processes like CAS (Lester 1983; Cantinho et al. 2016). For more advanced biological treatment processes like Bardenpho or Modified University Cape Town (MUCT) systems, much less work has been done to characterize the biosorption and metals partitioning dynamics, however the limited case studies available suggest that due to the greater SRT, COD removal and diversity of microbial consortiums (and by extension variety of metal-binding ECPs), overall metal removal performances are marginally better than CAS, ranging from approximately 60-80% for all metals except Cd and Ni, which are around 30-40% (Chipasa 2003; Obarska-Pempkowiak and Gajewska 2007; Salihoglu 2013; Emara et al. 2014). Aside from potential detection limit influences on full removal potentials, no mechanistic explanations of the lower Cd and Ni removal efficiencies were given (Chipasa 2003; Salihoglu 2013)

Following biological treatment, advanced filtration in the form of sand filters, MBR, and RO can be effective in physically removing the remaining soluble or colloidal fractions, as well as what remains of the insoluble fraction. Of the three, sand filters tend to be the least effective, owing to the larger pore spaces through which water can travel. Still, as a tertiary treatment process, removals of remaining organics can be on the order of 10-50%, and metals 0-35% (Linstedt et al. 1971; Aulenbach and Chan 1988; Renman et al. 2009). Next, MBRs have proven very effective as a tertiary polishing step, with removals of most metals on the order of 50% to greater than 95% (Innocenti et al. 2002; Carletti et al. 2008; Dialynas and Diamadopoulos 2009; Malamis et al. 2012; Arévalo et al. 2013). Last, with the smallest effective pore size, RO is the most effective unit process for metals removal with the case study literature indicating consistent removal efficiencies of 90% or greater (Dialynas and Diamadopoulos 2009; Malamis et al. 2012; Arévalo et al. 2013; Garcia et al. 2013).

For this study there are also several unit processes that through either limited, contradictory or inconclusive evidence, were not assigned any removal credit. Chemical phosphorus precipitation is a unit process that can be effective at removing metals, however it is dependent upon the chemicals used for precipitation and the conditions of the plant. In a study of three WWTPs using only alum or sodium aluminate for enhanced phosphorus removal, Aulenbach et al. (1984) found statistically insignificant effects for Pb and Cr removal and only a minor benefit to Cu removal (less than a 10% difference), noting that Cd, Hg, and Zn were removed to undetectable levels prior to alum dosing. Accordingly, chemical phosphorus precipitation using alum salts alone (U9, Table B-2) was not considered to provide an additional metals removal benefit.

The metals removal performance of tertiary biological nutrient removal processes, including nitrification reactors, denitrification reactors and tertiary clarification, has also not been extensively researched. Conceptually, the additional contact time between remaining soluble metal species and a new, distinct biological consortium (compared to upstream secondary unit processes) could reasonably be thought to provide for additional metals removal. However, in a study using copper as an indicator of the comparative metal removing performance of tertiary vs. secondary WWTPs, Inna et al. (2014) found that while tertiary processes like biological aerated flooded filters and nitrifying trickling filters provided some degree of additional copper removal, the tertiary return flows tended to have adverse and somewhat unpredictable effects on the performance of upstream unit processes. While they found total removal efficiencies of 57% for the three secondary plants and 78% for the two tertiary plants with nitrifying filters, the removal attributed directly to the nitrifying trickling filters was just 11% (-15% to 37%). Given the lack of information obtained for other metals, the marginal performance documented by Inna et al. (2014) and the potential for adverse effects from concentrated return flows, tertiary biological nutrient removal processes (U11-U14) were assumed to have no net effect on metals.

Table B-2. Unit Process Composition of Study Treatment Configurations

Unit Process		Wastewater Treatment Configuration								
		Level 1, AS	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
U1	Preliminary Treatment – Screening and grit removal	✓	✓	✓	✓	✓	✓	✓	✓	✓
U2	Primary Clarification	✓	✓	✓	✓	✓	✓	✓	✓	✓
U3	Fermenter				✓	✓	✓		✓	✓
U4	Plug Flow Activated Sludge	✓		✓						
U5	Biological Nutrient Removal – 3-Stage		✓							
U6	Biological Nutrient Removal – 5-Stage				✓		✓		✓	✓
U7	Biological Nutrient Removal – 4-Stage (Bardenpho)							✓		
U8	Biological Nutrient Removal – 4-Stage (MUCT)					✓				
U9	Chemical Phosphorus Removal			✓	✓	✓	✓	✓	✓	✓
U10	Secondary Clarifier	✓	✓	✓	✓	✓	✓		✓	
U11	Nitrification – Suspended Growth			✓						
U12	Tertiary Clarification			✓ [c]						
U13	Denitrification – Suspended Growth			✓						
U14	Denitrification – Attached Growth						✓		✓	
U15	Membrane Filtration [a, b]							✓		✓
U16	Final Clarification									
U17	Filtration – Sand Filter				✓	✓	✓		✓	
U18	Reverse Osmosis [a, d]								✓	✓
U19	Ultrafiltration [a]								✓	
U20	Chlorination	✓	✓	✓	✓	✓	✓	✓	✓	✓
U21	Dechlorination	✓	✓	✓	✓	✓	✓	✓	✓	✓
U22	WWTP Effluent Discharge	✓	✓	✓	✓	✓	✓	✓	✓	✓
U23	Sludge – Gravity Thickening	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table B-2. Unit Process Composition of Study Treatment Configurations

Unit Process		Wastewater Treatment Configuration								
		Level 1, AS	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
U24	Sludge – Anaerobic Digestion	✓	✓	✓	✓	✓	✓	✓	✓	✓
U25	Sludge – Centrifugation	✓	✓	✓	✓	✓	✓	✓	✓	✓
U26	Sludge – Haul and Landfill	✓	✓	✓	✓	✓	✓	✓	✓	✓
U27	Brine – Underground Inject								✓	✓

✓ Indicates unit process is relevant for select wastewater treatment configuration.

a – Periodic chemical cleaning is included for all membranes.

b – Membrane bioreactor wastewater treatment configurations use a membrane filter for the solid-liquid separation process instead of a traditional secondary clarifier.

c – This configuration includes two instances of tertiary clarification.

d – Includes chlorination and dechlorination pretreatment.

B.4 Metals Removal Performance Estimation Methods

Metal removal efficiencies for study system configurations were estimated based on a detailed literature review of performance results from similar systems. Sources reviewed include peer-reviewed literature, government reports and book chapters, covering a range of bench-scale experiments to performance characterization of full-scale treatment systems. Given the complexity of conditions and partitioning processes that can occur within WWTPs, empirical results were prioritized where the demonstrated metals removal performance of comparable treatment configurations or unit processes could be used to estimate performance of the study configurations. Where possible, mechanistic discussion was provided, though it is qualitative in nature as the factors affecting metal partitioning and removal are highly site specific (Cheng et al. 1975; Nelson et al. 1981; Huang et al. 2000) and mechanistic modelling is beyond the capability of the existing CAPDETWorks models used to develop the LCA and cost analysis.

For system levels where no representative equivalent was identified but the important components were characterized, a composite removal efficiency was calculated based upon case study performance data of its major unit processes. For example, Level 3-1 includes a 5-stage Bardenpho process with subsequent sand filtration. However, results of the literature review only identified 5-stage Bardenpho WWTPs without sand filtration. Therefore, Equation B-1 below represents a two-step linear process and was used to combine these results with removal efficiencies identified for sand filtration as a standalone process.

$$R_{total} = f_1 R_1 + f_2 (1 - R_1) R_2$$

Equation B-1

where

R_{total} = composite metal removal efficiency

f_1 = fraction of flow diverted to process 1

R_1 = removal efficiency of process 1

f_2 = fraction of flow diverted to process 2

R_2 = removal efficiency of process 2

In this example, R_1 would be representative of the combined effects of U1, U2, U6, and U10 (pretreatment + 5-stage Bardenpho + secondary clarification), while R_2 would be representative of U17 (sand filter). The functional form has also been adapted to account for more than two stepwise processes (e.g. Level 5-2) or parallel streams (e.g. Level 5-1), as demonstrated below. Note that the unit code descriptions are provided in Table B-2.

B.5 Metals Removal Performance Estimation Results

Following the approach outlined in Section B.4, Table B-3 shows how removal efficiencies for each study configuration were calculated based on major unit process combinations and supporting literature. Final composite removal efficiencies for each metal, by treatment configuration, are provided in Table B-4 and illustrated in Figure B-1. A more detailed discussion of each treatment configuration follows.

Table B-3. Summary of Composite Removal Calculations used in Equation 1

Level	Level Unit Processes[a]	Case Study Unit Process(es)[b]	R[c]	f[d]	Description
Level 1, AS	**U1**+**U2**+**U4**+**U10**	**U1**+**U2**+**U4**+**U10**	N/A	100%	Conventional Activated Sludge[e]
Level 2-1, A2O	**U1**+**U2**+**U5**+**U10**	**U5**	q	100%	Anaerobic/Anoxic/ Oxic[f]
Level 2-2, AS3	**U1**+**U2**+**U4**+*U9*+**U10**+*U11*+*U12*+*U13*	**U1**+**U2**+**U4**+**U10**	q	100%	3-Sludge System[g]
Level 3-1, B5	**U1**+**U2**+*U3*+**U6**+*U9*+**U10**+**U17**	**U1**+**U2**+**U6**+**U10**	R1	100%	5-stage Bardenpho[h]
		U17	R2	100%	Sand filter[i]
Level 3-2, MUCT	**U1**+**U2**+*U3*+**U8**+*U9*+**U10**+**U17**	**U1**+**U2**+**U8**+**U10**	R1	100%	Modified University Cape Town process[j]
		U17	R2	100%	Sand filter[i]
Level 4-1, B5/Denit	**U1**+**U2**+*U3*+**U6**+*U9*+**U10**+*U14*+**U17**	**U1**+**U2**+**U6**+**U10**	R1	100%	5-stage Bardenpho[h]
		U17	R2	100%	Sand filter[i]
Level 4-2, MBR	**U1**+**U2**+**U7**+*U9*+**U15**	**U7**	q	100%	4-stage Bardenpho[k]
		U15	R2	100%	Membrane bioreactor[l]
Level 5-1, B5/RO	**U1**+**U2**+*U3*+**U6**+*U9*+**U10**+*U14*+**U17**+**U18** +*U19*	**U1**+**U2**+**U6**+**U10**	R1	100%	5-stage Bardenpho[h]
		U17	R2a	10%	Sand filter[i]
		U18	R2b	90%	Reverse osmosis[m]
Level 5-2, MBR/RO	**U1**+**U2**+*U3*+**U6**+*U9*+**U15**+**U18**	**U1**+**U2**+**U6**+**U10**	R1	100%	5-stage Bardenpho[h]
		U15	R2	100%	Membrane bioreactor[l]
		U18	R3	85%	Reverse osmosis[m]

a - Bold unit processes affect metals removal, italicized unit processes were determined to have no significant effect.

b - Unit process or unit process configurations represented in the case study literature.

c - Removal efficiency determined from the literature and used in stepwise removal calculations (see Equation B-1. 'NA' indicates that Equation B-1 was not used, as documented removal efficiencies could be used directly to represent the entire treatment system. 'q' indicates that only qualitative conclusions can be drawn from the applicable literature.

d - Proportion of flow directed to unit process(es), see Equation B-1.

e - Brown et al., 1973; Oliver and Cosgrove, 1974; da Silva Oliveira et al., 2007; Carletti et al., 2008; Karvelas et al., 2003

f - Chang et al., 2007

g - Metal-affecting unit processes same as Level 1, use Level 1 for conservative estimation

h - Salihoglu et al., 2013

i - Linstedt et al., 1971; Aulenbach and Chan, 1988; Renman et al., 2009; Reddy et al., 2014

j - Chipasa, 2003; Obarska-Pempkowiak and Gajewska, 2007. Data describe the metals removal performance of membrane bioreactors. Data were assumed to be representative of membrane filtration as well, as the physical filtration is the dominant partitioning mechanism of metals sorbed to dissolved organic complexes.

k - Emara et al., 2014

l - Innocenti et al., 2002; Carletti et al., 2008; Dialynas and Diamadopoulos, 2009; Malamis et al., 2012; Arevalo et al., 2013

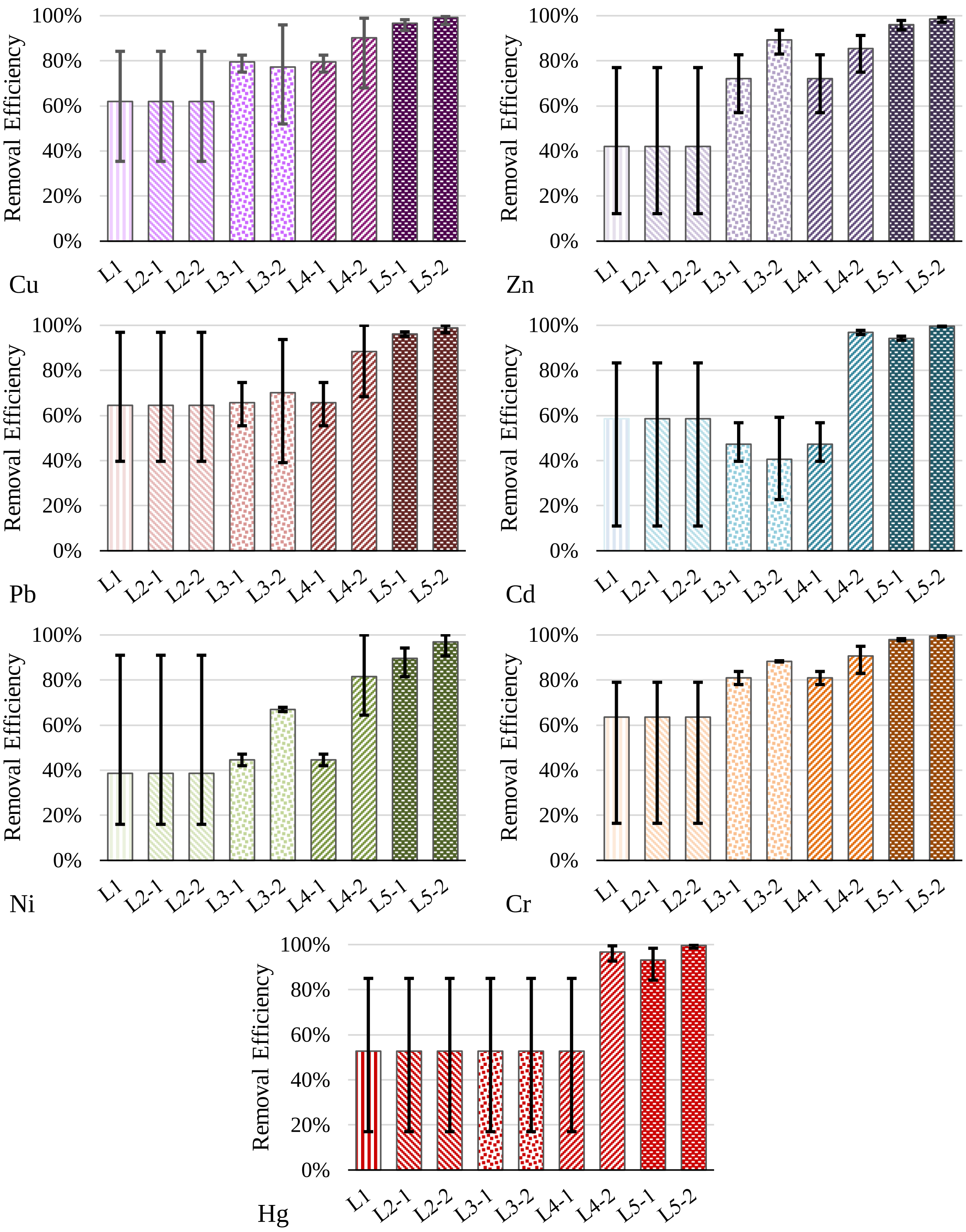
m - Dialynas and Diamadopoulos, 2009; Malamis et al., 2012; Garcia et al., 2013; Arévalo et al. 2013

Table B-4. Summary of Estimated Metal Removal Efficiencies[a]

Metal		Level 1 AS	Level 2-1 A2O	Level 2-2 AS3	Level 3-1 B5	Level 3-2 MUCT	Level 4-1 B5/Denit	Level 4-2 MBR	Level 5-1 B5/RO	Level 5-2 MBR/RO
Cu	Min	35%	35%	35%	75%	52%	75%	68%	93%	96%
	Mean	62%	62%	62%	80%	77%	80%	90%	97%	99%
	Max	84%	84%	84%	83%	96%	83%	99%	98%	100%
Pb	Min	40%	40%	40%	55%	39%	55%	68%	95%	97%
	Mean	65%	65%	65%	66%	70%	66%	88%	96%	99%
	Max	97%	97%	97%	75%	94%	75%	100%	97%	100%
Ni	Min	16%	16%	16%	42%	66%	42%	64%	82%	91%
	Mean	39%	39%	39%	45%	67%	45%	82%	90%	97%
	Max	91%	91%	91%	47%	68%	47%	100%	94%	100%
Zn	Min	12%	12%	12%	57%	83%	57%	75%	94%	97%
	Mean	42%	42%	42%	72%	89%	72%	85%	96%	99%
	Max	77%	77%	77%	83%	94%	83%	91%	98%	99%
Cd	Min	11%	11%	11%	40%	23%	40%	96%	93%	99%
	Mean	59%	59%	59%	47%	41%	47%	97%	94%	100%
	Max	83%	83%	83%	57%	59%	57%	98%	95%	100%
Cr	Min	16%	16%	16%	78%	88%	78%	83%	97%	99%
	Mean	64%	64%	64%	81%	88%	81%	91%	98%	100%
	Max	79%	79%	79%	84%	89%	84%	95%	98%	100%
Hg[1]	Min	17%	17%	17%	17%	17%	17%	93%	84%	98%
	Mean	53%	53%	53%	53%	53%	53%	97%	93%	100%
	Max	85%	85%	85%	85%	85%	85%	99%	98%	100%

a – “Removal Efficiency” used loosely; data more explicitly represents partitioning to sludge. Min and max represent minimum and maximum removal efficiencies reported in the literature. Where removal efficiencies are composites of multiple processes, minimum represents the composite of both contributing minimums, likewise for maximum.

b – No data for Hg removal found for 4-stage Bardenpho, 5-stage Bardenpho or MUCT. Therefore, conservatively assumed same removal for these biological treatment processes as documented for CAS (Level1). Data for Levels 4-2, 5-1 and 5-2 represent the effect of tertiary polishing step alone, i.e. MBR and RO.



a – Distinct bar patterns are used to distinguish treatment systems in each of the five nutrient removal levels.
b - Error bars represent the minimum and maximum removal efficiencies reported in the literature.

Figure B-1. Summary of Estimated Metal Treatment Performance[a, b]

B.5.1 Level 1: Conventional Plug Flow Activated Sludge (AS)

Level 1 is the most commonly represented treatment configuration within the case study literature. Overall, seven conventional activated sludge (CAS) systems were reviewed providing a range of performance results. Metals with the highest mean removals were Pb, Cr and Cu, each with a mean removal >60%. Intermediate mean removals of 40-60% were determined for Cd, Hg and Zn, while Ni returned the lowest mean removal of 39%. This pattern is to be expected, with previous reviews showing good (>50%) removals of Cd, Cr, Cu and Pb, and lower removals (<30%) for Ni (Stephenson and Lester 1987). For all metals, variability in results was high, with ranges from less than half to more than double the mean for most metals.

B.5.2 Level 2-1: Anaerobic/Anoxic/Oxic (A2O)

Level 2-1 is differentiated from Level 1 by its three-stage biological nutrient removal system which consists of sequential anaerobic, anoxic, and oxic basins. No performance data for A2O systems were found in the literature review, however a study conducted to determine the metal affinity of A2O sludge was reviewed (Chang et al. 2007). While data were not provided that could provide an input/output removal performance, results indicated that A2O sludge exhibited higher biosorption affinities than CAS sludge for Cd and Ni, and similar affinity for Zn (only three metals were evaluated). Based on these relative conclusions and in combination with the slightly longer SRT (Table 1-5) and better removal performance of COD (Table 1-4), it was conservatively assumed that the metal removal performance of Level 2-1 was equivalent to Level 1.

B.5.3 Level 2-2: Activated Sludge, 3-Sludge System (A3S)

Level 2-2 is similar to Level 1, with the addition of post-secondary suspended growth nitrification and denitrification reactors, as well as chemical phosphorus precipitation. No performance data for A3S systems were found in the literature review. Despite the greater SRT (Table 1-5) and better removal performance of COD (Table 1-4), in the absence of literature specifically documenting effects of this process on metal concentrations, it was conservatively assumed that the metal performance of Level 2-2 was equivalent to Level 1.

B.5.4 Level 3-1: 5-Stage Bardenpho System (B5)

Level 3-1 is characterized by a combination of case studies that are representative of its major metal-affecting unit processes, including the 5-stage Bardenpho process and sand filtration. Salihoglu (2013) reviewed the metals removal performance of two WWTPs that utilized the 5-stage Bardenpho process in the Turkish city of Bursa. The treatment plants, which serve populations of 170,000 and 85,000 in mixed urban areas, consist of pretreatment (screening and grit removal) followed by an equalization tank, 5-stage Bardenpho process and a clarifier. In terms of applicability to Level 3-1, the plants describe the beginning of the treatment train including pretreatment (U1), 5-stage Bardenpho process (U6) and secondary clarification (U10). Although primary sedimentation (U2) is not included, it is assumed that the level of treatment conferred by the particular combination of unit processes (U1+U6+U10) allows for sufficient settleable solids removal such that the absence of U2 can be considered negligible.

Data for sand filtration came from a range of studies, including pilot- or bench-scale tests of sand filtration as a tertiary treatment unit process (Linstedt et al. 1971; Aulenbach and Chan

1988), as a polishing step for septic effluent (Renman et al. 2009) and for the treatment of stormwater (Reddy et al. 2014). Although stormwater is compositionally different than wastewater, it is arguably closer to secondary effluent than raw wastewater and the inclusion of these results helped fill data gaps left by the wastewater-specific studies.

Reported removal efficiencies for the 5-stage Bardenpho system for all metals except Cd and Pb (data were not given for Hg) tended to be similar to those reported for CAS, while the removal efficiency for Cd was lower than CAS and Pb was higher (Salihoglu 2013). No mechanistic explanations were provided for these deviations by Salihoglu (2013), though possible reasons may have to do with the relatively high affinity of Pb and relatively low affinity of Cd to organic matter, respectively (e.g., Wang, 1997) Mean removal efficiencies for sand filtration case studies ranged from 2% to 29%, bounded by Cr (2%) and Ni (3%) at the low end and Pb (22%) and Zn (29%) at the high end. Composite removal efficiencies for L3-1 were greater than Level 1 for all metals except Cd (and Hg, as no data were reported for U6 or U17 unit processes), owing to low removals of Cd in both 5-stage Bardenpho (41%) and sand filtration (11%).

B.5.5 Level 3-2: Modified University of Cape Town (MUCT)

Level 3-2 is characterized by a combination of case studies that are representative of its major metal-affecting unit processes, including the Modified University of Cape Town process and sand filtration. Metals performance data for MUCT systems come from a pair of case studies conducted in Poland (Chipasa 2003; Obarska-Pempkowiak and Gajewska 2007). The first system, reviewed by Chipasa (2003), includes screening and grit removal (U1), primary sedimentation (U2), MUCT reactors (U8), and secondary clarification (U10). The second system, reviewed in Obarska-Pempkowiak and Gajewska (2007), refers to a 23 MGD plant receiving mixed municipal wastewater with roughly 10% coming from industrial sources. Primary treatment consists of screening, an aerated sand trap and primary sedimentation, which was assumed equivalent to screening and grit removal (U1) and primary sedimentation (U2). Biological treatment consists of six sequential reactors that make up the MUCT process (U8) followed by secondary sedimentation (U10).

Data for sand filtration come from a range of studies, including pilot- or bench-scale tests of sand filtration as a tertiary treatment unit process (Linstedt et al. 1971; Aulenbach and Chan 1988), as a polishing step for septic effluent (Renman et al. 2009) and for the treatment of stormwater (Reddy et al. 2014). Although stormwater is compositionally different than wastewater, it is arguably closer to secondary effluent than raw wastewater and the inclusion of these results helped fill data gaps left by the wastewater-specific studies.

Mean removal efficiencies for the MUCT systems ranged from 66% to 88% with the exception of Cd, which had a mean removal of 34%. Mean removal efficiencies for sand filtration case studies ranged from 2% to 29%, bounded by Cr (2%) and Ni (3%) at the low end and Pb (22%) and Zn (29%) at the high end. Composite removal efficiencies for Level 3-2 were slightly better than Level 3-1 for Pb, Zn, Ni and Cr and slightly worse for Cu and Cd. No data were reported for Hg.

B.5.6 Level 4-1: 5-Stage Bardenpho System with Denitrification Filter (B5/Denit)

The unit process configuration of Level 4-1 is identical to Level 3-1, with the exception of an attached growth denitrification reactor. Although no data were identified to directly characterize the metals removal performance of this unit process, it is likely that it provides some degree of metals removal as it allows for additional contact time between secondary effluent and a new, biologically distinct consortium. However, in the absence of literature specifically documenting effects of an attached growth denitrification reactor on metal concentrations, it was conservatively assumed that the performance of Level 4-1 was equivalent to that of Level 3-1.

B.5.7 Level 4-2: 4-Stage Bardenpho Membrane Bioreactor System (MBR)

Level 4-2 is characterized by a 4-stage Bardenpho system followed by a membrane bioreactor. The 4-stage Bardenpho system of Level 4-2 differs from the 5-stage Bardenpho system of Level 4-1, lacking the first anaerobic stage and having a total SRT of 19 days as opposed to 15 days for the 5-stage system. No data were found characterizing the metals performance of a 4-stage Bardenpho system, rather performance was estimated based on the comparative design and operation of the study configurations as well as results from a bench-scale study performed to directly compare the performance of 4-stage and 5-stage Bardenpho systems using Ni and Fe as indicators of metal removal (Emara et al. 2014). The study showed that after incorporation of the upstream anaerobic tank, thus modifying the 4-stage to a 5-stage system, Ni removal increased from 68% to 86% and Fe removal increased from 82% to 92%. This is to be expected, as the incorporation of the anaerobic stage is done to improve phosphorus removal through the promotion of phosphorus accumulating organisms, which produce floc that provides for an additional degree of biosorption. As such, it was conservatively assumed that the metal removal efficiency of the 4-stage system was 50% of the 5-stage system described by Salihoglu (2013). The greater SRT of the Level 4-2, 4-stage system compared to the Level 4-1, 5-stage system, adds a further degree of conservatism as it would suggest better performance than what is being assumed.

The metals removal performance of MBRs has been well characterized, with five applicable studies identified representing six different systems (Innocenti et al. 2002; Carletti et al. 2008; Dialynas and Diamadopoulos 2009; Malamis et al. 2012; Arévalo et al. 2013). The systems all treated mixed municipal primary effluent, ranged in size from a 100 gpd pilot plant to a 5.3 MGD full-scale plant, and had membrane pore sizes of either 0.020 µm or 0.040 µm. Average removal efficiencies across all studies were high, ranging from 76% (Ni) to 96% (Cd and Hg). That the removals are high relative to other unit processes discussed thus far is reasonable when considering the pore size of MBRs (0.020 to 0.040 µm) relative to the filter pore size generally used to delineate between dissolved and non-dissolved fractions (0.45 µm). This comparison suggests an ability to remove smaller dissolved organic complexes in the 0.04-0.45 µm range that may be missed by processes that rely on settling or clarification.

Although a conservative assumption was made regarding the treatment performance of the 4-stage Bardenpho system, composite removal efficiencies for the Level 4-2 configuration are greater than those of Level 4-1 for all metals reviewed, owing to the high removal efficiency of the MBR unit process. Moreover, although Hg was not included in any Bardenpho study, the two MBR studies that did evaluate Hg found an average removal of 96%, which could reasonably be interpreted as a total Hg removal efficiency for Level 4-2.

B.5.8 Level 5-1: 5-Stage Bardenpho with Sidestream Reverse Osmosis (B5/RO)

Level 5-1 is characterized by a 5-stage Bardenpho system followed by two parallel processes. The first, treating 90% of the 5-stage Bardenpho effluent, consists of an ultrafilter followed by a reverse osmosis (RO) system. The remaining 10% is treated by a sand filter, similar to Level 3-1.

For the 5-stage Bardenpho system, Salihoglu (2013) reviewed the metals removal performance of two WWTPs that utilize this process in the Turkish city of Bursa. The treatment plants, which serve populations of 170,000 and 85,000 in mixed urban areas, consist of pretreatment (screening and grit removal) followed by a selector tank, 5-stage Bardenpho process and a clarifier. In terms of applicability to Level 5-1, the plants describe the beginning of the treatment train including pretreatment (U1), 5-stage Bardenpho process (U6) and secondary clarification (U10). Although primary sedimentation (U2) is not included, it is assumed that the level of treatment conferred by the particular combination of unit processes (U1+U6+U10) allows for sufficient settleable solids removal that the absence of U2 can be considered negligible.

For the first parallel process, consisting of an ultrafilter followed by an RO system, four studies were found evaluating the performance of five distinct RO systems (Qdais and Moussa 2004; Dialynas and Diamadopoulos 2009; Malamis et al. 2012; Garcia et al. 2013). The systems reviewed were mostly pilot scale treating mixed municipal primary effluent, with the exception of a 0.3 MGD full scale system (Garcia et al. 2013) and a pilot scale study evaluating synthetic industrial wastewater (Qdais and Moussa 2004). Ultrafiltration was not explicitly included as, in the case of most case study systems and study configurations, this step serves as a pretreatment step allowing for proper RO functioning and its performance was generally not characterized. Mean removal of each metal across all systems for which data were available were greater than 90%. The lowest removal efficiencies reported for any single system, and the only rates less than 90%, were those for the pilot plant treating pretreated, mixed municipal wastewater evaluated by Malamis et al. (2012) at 82% for Cu and 76% for Ni.

Data for sand filtration come from a range of studies, including pilot- or bench-scale tests of sand filtration as a tertiary treatment unit process (Linstedt et al. 1971; Aulenbach and Chan 1988), as a polishing step for septic effluent (Renman et al. 2009) and for the treatment of stormwater (Reddy et al. 2014). Although stormwater is compositionally different than wastewater, it is arguably closer to secondary effluent than raw wastewater and the inclusion of these results helped fill data gaps left by the wastewater-specific studies.

Composite removal efficiencies for Level 5-1 are 90-98% for all metals reviewed. Also, although sufficient data were not obtained for the full characterization of Hg removal in 5-stage Bardenpho or RO systems, Ruel et al. (2011) measured effluent concentrations in two full-scale municipal WWTPs that incorporated RO for advanced nutrient removal and found Hg to be below the level of detection in both cases.

B.5.9 Level 5-2: 5-Stage Bardenpho Membrane Bioreactor with Sidestream Reverse Osmosis (MBR/RO)

Level 5-2, the most advanced study configuration, consists of a 5-stage Bardenpho system followed by an MBR, then treatment of 85% of MBR effluent by an RO system with the remaining 15% discharged with no further treatment.

For the 5-stage Bardenpho system, Salihoglu (2013) reviewed the metals removal performance of two WWTPs that utilized this process in the Turkish city of Bursa. The treatment plants, which serve populations of 170,000 and 85,000 in mixed urban areas, consist of pretreatment (screening and grit removal) followed by a selector tank, 5-stage Bardenpho process and a clarifier. In terms of applicability to Level 5-2, the plants describe the beginning of the treatment train including pretreatment (U1), 5-stage Bardenpho process (U6) and secondary clarification (U10). Although primary sedimentation (U2) is not included, it is assumed that the level of treatment conferred by the particular combination of unit processes (U1+U6+U10) allows for sufficient settleable solids removal that the absence of U2 can be considered negligible.

The metals removal performance of MBRs has been well characterized, with 5 applicable studies identified representing 6 different systems (Innocenti et al. 2002; Carletti et al. 2008; Dialynas and Diamadopoulos 2009; Malamis et al. 2012; Arévalo et al. 2013). The systems all treated mixed municipal primary effluent, ranged from a 100 gpd pilot plant to a 5.3 MGD full-scale plant and had membrane pore sizes of either 0.020 µm or 0.040 µm. Average removal efficiencies across all studies were high, ranging from 76% (Ni) to 96% (Cd and Hg). That the removals are high relative to other unit processes discussed thus far is reasonable when considering the pore size of MBRs (0.020 to 0.040 µm) relative to the filter pore size generally used to delineate between dissolved and non-dissolved fractions (0.45 µm). This comparison suggests an ability to remove much smaller, dissolved organic complexes missed by processes that rely on settling or clarification.

For the characterization of RO systems, four studies were found evaluating the performance of 5 distinct RO systems (Qdais and Moussa 2004; Dialynas and Diamadopoulos 2009; Malamis et al. 2012; Garcia et al. 2013). The systems reviewed were mostly pilot scale treating pretreated mixed municipal wastewater, with the exception of a 0.3 MGD full scale system (Garcia et al. 2013) and a pilot scale evaluating synthetic industrial wastewater (Qdais and Moussa 2004). Ultrafiltration was not explicitly included as, in the case of most case study systems and study configurations, this step serves as a pretreatment step allowing for proper RO functioning and its performance was generally not characterized. Mean removal of each metal across all systems for which data were available were greater than 90%. The lowest removal efficiencies reported for any single system, and the only rates less than 90%, were those for the pilot plant treating pretreated, mixed municipal wastewater evaluated by Malamis et al. (2012) at 82% for Cu and 76% for Ni.

Composite removal efficiencies for Level 5-2 are 97% to >99% for all metals reviewed. Also, although sufficient data were not obtained for the full characterization of Hg removal in 5-stage Bardenpho or RO systems, Ruel et al. (2011) measured effluent concentrations in two full-scale municipal WWTPs that incorporated RO for advanced nutrient removal and found Hg to be below the level of detection in both cases.

B.6 Heavy Metals Toxicity Characterization Factors

Table B-5 presents the characterization factors used to estimate toxicity impacts associated with heavy metals in treatment plant effluent and sludge. Not all heavy metals included in this study have associated characterization factors listed in the most recent versions of USEtox™, versions 2.02 and 2.11. Characterization factors that were not otherwise available were estimated using the median value of all other heavy metals for which data was available. Sources for individual characterization factors are listed in Table C-8.

Table B-5. Heavy Metals Toxicity Characterization Factors, USEtox™ version 2.11

Chemical Name	**USETox Chemical Name**	**Freshwater Ecotoxicity, (CTUe, PAF m3.day/kg emitted)**		**Human Health cancer, freshwater (CTUh, cases/kg emitted)**		**Human Health noncancer, freshwater (CTUh, cases/kg emitted)**	
		Emissions to Freshwater	**Emissions to Natural Soil**	**Emissions to Freshwater**	**Emissions to Natural Soil**	**Emissions to Freshwater**	**Emissions to Natural Soil**
Lead	Pb(II)	6.9E+2	4.1E+2	1.4E-7	8.5E-8	5.0E-5	3.0E-5
Copper	Cu(II)	9.9E+6	5.2E+6	8.8E-6[a]	4.5E-6[a]	1.4E-7	7.2E-8
Zinc	Zn(II)	1.3E+5	7.3E+4	-	-	2.6E-4	1.4E-4
Nickel	Ni(II)	3.0E+5	1.5E+5	1.2E-4	6.1E-5	6.7E-6	3.4E-6
Chromium	Cr(III)	8.1E+3	4.1E+3	-	-	2.1E-11	1.0E-11
Cadmium	Cd(II)	2.3E+6	1.2E+6	1.7E-5	8.9E-6	4.7E-3	2.4E-3
Mercury	Hg(II)	2.2E+4	1.6E+4	1.5E-4	1.1E-4	0.02	0.01

a - Estimated using the median of heavy metals with available characterization factors.

APPENDIX C
DETAILED CHARACTERIZATION OF TOXIC ORGANICS BEHAVIOR IN STUDY TREATMENT CONFIGURATIONS

Appendix C: Detailed Characterization of Toxic Organics Behavior in Study Treatment Configurations

C.1 Toxic Organics: Introduction

This section presents background information and methods used to estimate the environmental impact associated with select trace organic chemical releases in the Level 1 through 5 treatment systems.

Toxic organics are a diverse and growing category of chemical substances that includes other commonly referred to pollutant groups such as contaminants of emerging concern (CECs), pharmaceuticals and personal care products (PPCPs), and endocrine disrupting chemicals (EDCs). The pollutant category includes medications, fragrances, insect repellents and other household items that can be harmful to environmental and human health at even trace levels (U.S. EPA 2015c; Montes-Grajales et al. 2017).

Many toxic organics have a documented presence in surface waters, groundwater, wastewater and WWTP effluent, both in the U.S. and globally (Ellis 2008; Ebele et al. 2017; Montes-Grajales et al. 2017). No comprehensive list exists, though based on the diverse literature the number of contaminants is at least in the hundreds (if not thousands) and is continually being expanded upon as analytical techniques for measuring both presence and toxicity are continually refined. In order to provide a targeted analysis of their behavior in WWTPs, a restricted group of 43 pollutants (Table C-1) has been selected for specific treatment in this analysis. The selected pollutant group uses the chemical list from Rahman et al. (2018) as a starting point. Rahman et al. (2018) performed a comparative LCA that examines the effect of toxic organics removal on life cycle human health and ecotoxicity impacts for treatment systems that correspond to three levels of nutrient removal, focusing on the use of advanced tertiary processes for toxic organics removal. Their selection of toxic organics was based on frequency of presence in WWTPs and availability of information regarding concentration, chemical degradation, transformation and removal. Several additional common chemicals, including triclocarban, tonalide, celestolide, phantolide and musk ketone, were added based on the assessment of Montes-Grajales et al. (2017), which looked at the presence of PPCPs in global water resources and found these compounds to be the most widely reported. Per- and Polyfluoroalkyl Substances (PFAS) are not included in this toxic organics' assessment.

The concentration of trace pollutants can vary considerably on a daily and seasonal basis and between WWTPs (Martin Ruel et al. 2012). Urban WWTPs have also been shown to receive higher influent concentrations of some toxic organics that are less common in rural water systems. As such, the median influent concentrations from Table C-1 were used as input to subsequent calculations as the averages had a tendency to be strongly influenced by a small number of very high influent concentration records. Figure C-1 and Figure C-2 present boxplots of the influent concentration of toxic organics. The figures divide the pollutants into two subgroups to allow better visualization across pollutants with considerably different influent concentrations. Acetaminophen is excluded from these figures due to its notably greater median influent concentration, 97 µg/L, as compared to the other included pollutants. The figures show the tendency for some pollutant distributions to skew towards large outlier values, causing a disparity between the median and average values.

Table C-1. Occurrence of the Selected Toxic Organic Compounds in WWTP Influent

Chemical Name	Chemical Type/Use	Influent Concentration (μg/L)				Sample Size
		Average	Median	Minimum	Maximum	
acetaminophen[a]	pain reliever, anti-inflammatory	97	19	0.02	400	12
androstendione[a]	steroid hormone	0.29	0.10	0.02	1.3	7
atenolol	beta blocker	4.3	1.1	0.03	26	10
atorvastatin	lipid regulator	0.49	0.22	0.07	1.6	6
atrazine[b]	pesticide	0.02	0.02	1.0E-3	0.06	5
benzophenone	PCP, sunscreen	0.24	0.27	7.0E-3	0.42	4
bisphenol A	EDC, plasticizer	4.6	0.84	0.01	44	16
butylated hydroxyanisole[c]	beta blocker	1.3	0.16	0.13	3.5	3
butylated hydroxytoluene	beta blocker, cosmetic	0.93	0.41	0.05	3.5	5
butylbenzyl phthalate[d]	plasticizer	0.11	0.11	0.08	0.14	2
carbamazepine[a]	Anti-convulsant	0.92	0.69	0.04	3.8	28
N,N-diethyl-meta-toluamide (DEET)	insect repellent	1.4	0.40	0.02	6.9	6
diclofenac	Analgesics, anti-inflammatory	2.1	0.96	1.0E-3	17	20
dilantin	anti-seizure medication	0.16	0.17	0.05	0.24	4
dioctyl phthalate[b]	plasticizer, industry	23	1.4	1.1	67	3
estradiol[a,c]	EDC, steroid hormone	0.59	0.03	8.0E-3	5.0	11
estrone[a,c]	EDC, steroid hormone	0.17	0.05	0.01	1.0	9
galaxolide	beta blocker, PCP, fragrance	4.3	2.3	1.4E-3	25	16
gemfibrozil[a]	lipid regulator	3.1	1.6	0.02	22	15
hydrocodone	analgesic, opioid	0.08	0.11	0.02	0.12	5
ibuprofen[a]	Analgesics, anti-inflammatory	7.8	2.4	1.0E-3	39	27
iopromide	contrast agent	7.4	0.05	0.01	38	6
meprobamate	tranquilizer, medication	0.40	0.35	0.01	0.97	5
naproxen[a]	Analgesics, anti-inflammatory	8.5	2.5	2.0E-3	53	20
nonylphenol[b,c]	EDC, disinfectant, surfactant, solvent	3.4	2.3	0.02	9.7	14

Table C-1. Occurrence of the Selected Toxic Organic Compounds in WWTP Influent

Chemical Name	Chemical Type/Use	Influent Concentration (µg/L)				Sample Size
		Average	Median	Minimum	Maximum	
octylphenol[b]	EDC, surfactant, solvent	1.9	0.41	0.12	8.7	12
o-hydroxy atorvastatin	lipid regulator	0.12	0.12	0.10	0.14	2
oxybenzone	PCP	1.2	0.39	0.03	3.8	4
p-hydroxy atorvastatin	lipid regulator	0.12	0.12	0.10	0.14	2
progesterone[a]	EDC	0.02	0.01	3.1E-3	0.06	4
sulfamethoxazole[a]	antibiotic	1.1	0.43	0.04	4.5	14
tris(2-chloroethyl) phosphate (TCEP)	flame retardant, plasticizer	0.35	0.24	0.17	0.65	3
tris(2-chloroisopropyl) phosphate (TCPP)	flame retardant	1.2	1.2	1.1	1.3	2
testosterone[a]	EDC	0.06	0.05	0.01	0.14	5
triclosan[a]	pesticide, disinfectant	2.7	0.80	2.3E-3	24	17
trimethoprim[a]	antibiotic	0.52	0.53	0.10	1.4	8
triclocarban[a]	disinfectant	0.42	0.42	0.29	0.54	2
tonalide	beta blocker, PCP, fragrance	1.5	0.80	5.0E-5	7.6	13
celestolide	PCP, fragrance	5.1	0.07	0.04	15	3
phantolide	fragrance	0.10	0.10	0.04	0.15	2
clofibric acid	lipid regulator	0.46	0.29	0.03	1.1	3
musk ketone	fragrance	0.12	0.12	0.10	0.15	3
diuron[b,c]	fragrance	0.14	0.11	0.05	0.25	3

a - Identifies substances with EPA developed analytical methods for detection of contaminants of emerging concern per (U.S. EPA, 2017).

b - Identifies substances with a European Quality Standard per (EP 2008).

c - Identifies substances identified in EPA's Candidate Contaminant List (CCL), version 4 (U.S. EPA, 2016). The CCL identifies chemicals that are currently unregulated but may pose a risk to drinking water.

d - Identifies substances identified as human health criteria in Section 304(a) of the Clean Water Act (U.S. EPA, 2019c).

Table Acronyms: EDC – endocrine disrupting chemical, PCP – personal care product.

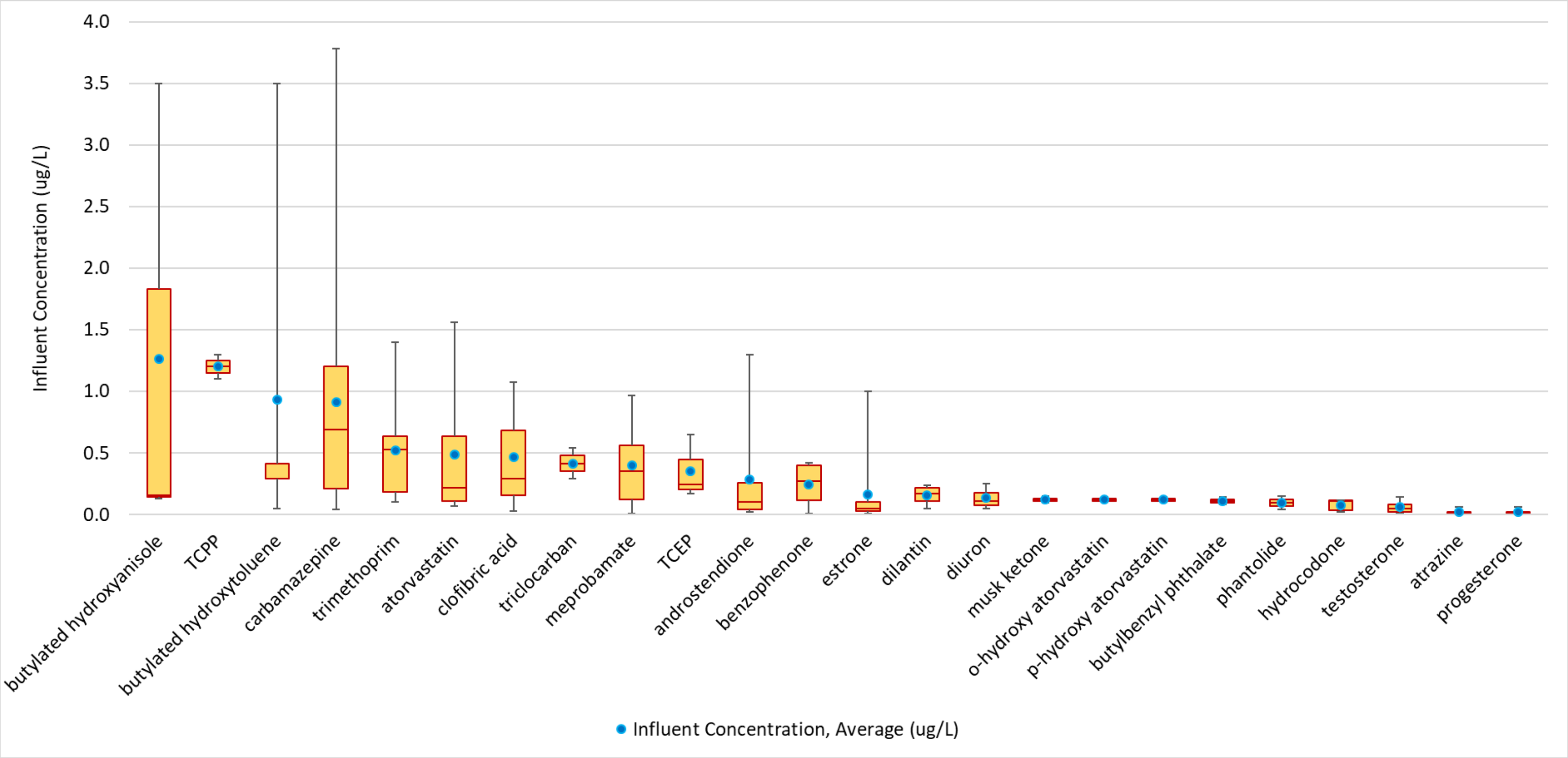


Figure C-1. Boxplot of the Influent Concentration of Toxic Organics with Maximum Concentration Less than 4 μg/L.

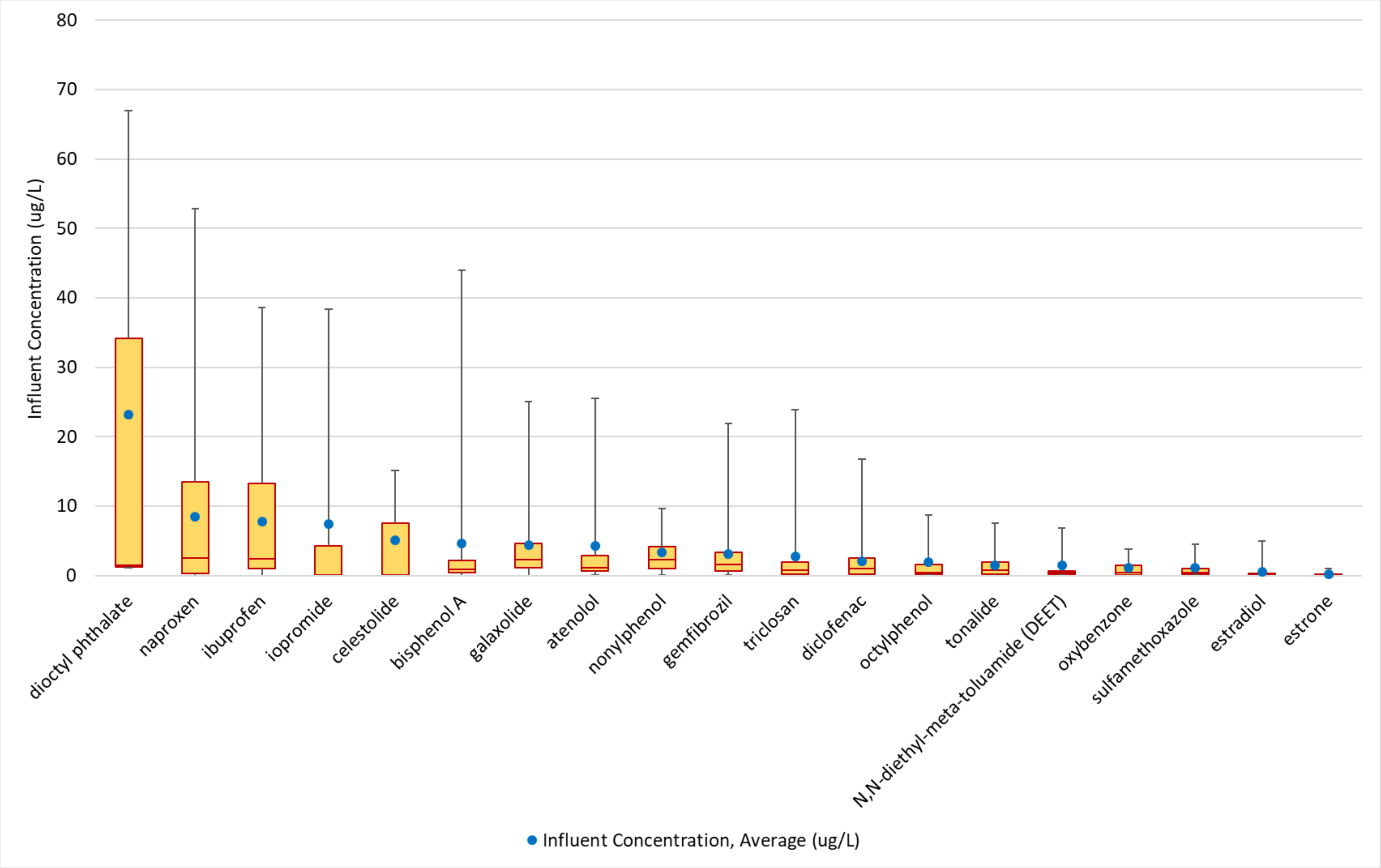


Figure C-2. Boxplot of the Influent Concentration of Toxic Organics with Maximum Concentration Greater than 4 µg/L.

C.2 Fate of Toxic Organics during Wastewater Treatment

A great deal of work has been done regarding the degradation and partitioning of toxic organics within municipal WWTPs. The extent of degradation as well as the mechanisms of removal can vary widely, reflecting the underlying diversity in the pollutants themselves and conditions and operational procedures practiced at WWTPs. For example, some chemicals such as acetaminophen and bisphenol A are highly degradable and exhibit excellent removal, often greater than 90 percent, in conventional (Level 1) treatment works (Liwarska-Bizukojc et al. 2018). Conversely, chemicals such as diclofenac and trimethoprim are more recalcitrant, exhibiting removal efficiencies of less than 80 percent in conventional treatment systems (Ahmed et al. 2017, Ogunlaja et al. 2013). The term removal efficiency is used to refer to the combined effect of biodegradation and partitioning to solids, unless otherwise specified.

As a general rule-of-thumb, Level 1 treatment systems remove approximately 80 percent of the toxic organic load from the liquid stream (Martin Ruel et al. 2012). Removal that is attributable to solids partitioning versus biodegradation varies according to pollutant. The reason for this variation is not well agreed upon within the literature. Martin Ruel et al. (2012) states that roughly two-thirds of pollutant removal can be accounted for by partitioning to sludge, while Jelic et al. (2011) found that this pathway was considerably less important. Biodegradation is a second important removal pathway, especially for chemicals that remain dissolved in the liquid fraction of wastewater. Volatilization of organic pollutants is expected to contribute negligibly to removal of most pollutants. Of the reviewed pollutants only celestolide is known to count volatilization as a significant loss pathway, accounting for up to 16% of total pollutant removal (Luo et al. 2014). Generally, volatilization is only expected to be relevant for treatment systems that have a large surface area (Liwarska-Bizukojc et al. 2018), which is not the case for any of the studied treatment configurations.

Several chemical properties of trace organics including the octanol-water coefficient (K_{ow}) and acid dissociation constant (pKa) affect the partitioning of individual organic pollutants between the solid and liquid phase in a WWTP (Alvarino et al. 2018). Pollutants with a high log K_{ow} should preferentially adsorb to the solid fraction of wastewater (Alvarino et al. 2018). Luo et al. (2014) identified a log K_{ow} threshold of 4, above which pollutants have a high sorption potential. Trace pollutants with a log K_{ow} of less than 2.5 (hydrophilic) have a low sorption potential and will tend to remain in the dissolved phase. For example, many pesticides have a log K_{ow} of less than three, are hydrophilic and predominantly exist in the dissolved phase (Martin Ruel et al. 2012). The solid-water distribution coefficient (K_d) is defined as the ratio between the concentration in the liquid and solid phases of a solution under equilibrium conditions and has been used to determine the fraction of trace pollutants that partition to sludge (Alvarino et al. 2018). For pollutants with a log K_d value of less than 2.5, sorption onto sludge can be considered negligible (Luo et al. 2014). Other authors indicate that K_{ow} alone does not provide a consistent indicator of removal performance (Oppenheimer et al. 2007), indicating that generalized approaches should be used with caution and interpreted appropriately. For example, Alvarino et al. (2018) state that hormones with high K_{ow} will tend to partition to sludge, however Martin Ruel et al. (2012) found that the majority of hormones are generally found in the dissolved phase, highlighting the complexity of these interactions.

Within the literature, there are three unit-process parameters most commonly found to affect pollutant degradation rates: (1) solids retention time (SRT), (2) hydraulic retention time (HRT), and (3) redox condition. Biomass conformation (i.e., size and type), use of adsorbents, pH, and temperature are additional unit process parameters that may vary between treatment configurations and affect pollutant degradation or removal (Alvarino et al. 2018). The pH of wastewater can affect removal of some micropollutants, particularly acidic pharmaceuticals for which the affinity to biosolids was pH affected (Luo et al. 2014). These additional factors were excluded from the current study as they are not expected to vary considerably between the nine treatment configurations, or are unknown, as in the case of biomass conformation.

Solids retention time is a measure of sludge age in secondary biological treatment processes. Longer SRT, in general, allows the growth and proliferation of slower growing microbial partners, and is thought to increase the diversity of organisms present in mixed liquor suspended solids (Luo et al. 2014). Biodegradation of organic pollutants has been shown to exhibit a variable dependence on SRT according to specific chemical characteristics. Oppenheimer et al. (2007) calculated the minimum SRT value required for 80 percent CEC removal (SRT80) for several common CECs. Easily degradable compounds such as ibuprofen and oxybenzone had an SRT80 of less than 5 days, while poorly degradable substances such as galaxolide had SRT80 values of greater than 15 days. Results showed a pronounced plateau in removal performance for SRTs greater than the SRT80 value for each respective chemical.

Hydraulic retention time measures the average period that water is retained in a given treatment unit. Longer HRT allows more time for biodegradation and partitioning to solids. HRT often correlates with SRT and it can therefore be difficult to determine the predominant factor contributing to variations in pollutant removal. The literature shows variable pollutant removal responses to HRT, which in some cases can be marginal (Oppenheimer et al. 2007).

Redox conditions are defined as the tendency of a given redox reaction to occur. In wastewater treatment, redox conditions are categorized into the three broad conditions of aerobic, anoxic, and anaerobic. Aerobic is the presence of free oxygen and indicates positive redox values. Anoxic indicates the presence of bound oxygen (e.g., nitrate) and redox values around zero. Negative redox conditions indicate the absence of free and/or bound oxygen. Redox values are indicators of what types of microbial communities may be active and which chemical reactions may occur in a given wastewater. Research has shown that the removal rate of specific organic pollutants varies according to the redox environment. Overall, aerobic conditions have been shown to more effectively degrade the broadest range of substances. Anaerobic environments had greater removal performance for a small number of compounds, some of which were not degraded in aerobic environments (Alvarino et al. 2018). Anoxic conditions were in many cases found to be a less effective environment for removal of toxic organics, however some chemicals such as diclofenac, clofibric acid, and contrast agents exhibited improved removal under anoxic conditions (Luo et al. 2014). It is suspected that anoxic conditions often found in advanced biological treatment systems, intended for nitrogen removal, are not particularly effective in the degradation of organic micropollutants (Alvarino et al. 2018). The effect of variable redox conditions, such as those present in the level 2 through 5 treatment systems assessed in this study, on toxic organics removal are still understudied (Alvarino et al. 2018).

The preceding unit process and chemical characteristics are some of the primary determinants of the fate of toxic organics within wastewater treatment systems. Those chemicals that partition readily to solids will tend to settle out with the sludge, be subject to anaerobic digestion and exit the plant heading to landfills or land application. Un-degraded dissolved chemicals will exit with the WWTP effluent and enter receiving surface waters.

C.3 Toxic Organics Removal Performance Estimation Methodology

This section describes the data and methods used to quantify a range of estimated removal efficiencies for individual unit processes that compose the 9 WWTP configurations of this study and to combine unit level removal efficiency data to estimate cumulative removal efficiency for each of the 9 WWTP configurations. Low, medium and high estimates of removal efficiency were developed for each unit process and are used to define corresponding estimates of cumulative removal efficiency for each configuration. Limited data were found to define chemical specific removal efficiencies for the advanced biological treatment units of Levels 2 through 5. Therefore, sensitivity approaches were used to assess the importance of biodegradation and solids partitioning in advanced biological treatment units to the overall environmental impact of each respective system described below.

C.3.1 Biological Treatment

Biological treatment processes contribute to both the degradation of toxic organic compounds and additional partitioning to solids by creating biological flocculants that provide adsorption sites and allow time for metabolic degradation and adsorption to take place. Owing to these processes, Miege et al. (2009) note that removal of toxic organics from the liquid portion of biological wastewater treatment is typically in the range of 50-90%, and that nitrogen removal improves the removal efficiency of many pharmaceutical compounds. Additionally, the work of Alvarino et al. (2018) concludes that hybrid biological reactors offer a “good alternative to enhance the removal of organic micropollutants.” This is expected to be especially true for pollutants that are not readily degraded in aerobic conditions such as sulfamethoxazole and trimethoprim.

Table C-2 presents a summary of the Level 1, activated sludge removal efficiency of the toxic organics considered in this study. To facilitate discussion of diverse and sometimes divergent treatment performances, this study adopts a classification system for biological treatment systems developed by Oppenheimer et al. (2007) that characterizes overall treatment performance as “good”, “moderate” or “low”. Good removal efficiency is defined as 80% or greater. Moderate removal efficiency is classified as being in the range of 50-80% removal, while less than 50% removal efficiency is considered poor.

Based on Table C-2, Level 1 treatment systems promote “Good” removal efficiency of at least 30% of the toxic organics examined. The table also includes low, medium and high estimates of removal efficiency for the Level 1 treatment system, which includes the combined effect of primary and secondary treatment processes. Removal efficiency includes both biodegradation and the fraction of toxic organics that partition to solids and are removed in primary and waste activated sludge. Low, medium and high estimates in the table were defined as the 25th percentile, median and 75th percentile of the documented removal efficiencies. In instances where removal efficiencies are negative (i.e. formation), a value of zero has been substituted for use in this study (e.g. carbamazepine).

No removal efficiency data were found for eight of the 43 chemicals including: butylated hydroxyanisole, butylated hydroxytoluene, dilantin, hydrocodone, o-hydroxy atorvastatin, p-hydroxy atorvastatin, TCPP and triclocarban (marked with italics in Table C-2). Proxy values that bracket the extreme values for removal efficiency were used to determine if the removal of these chemicals is significant in the LCA results. Proxy removal efficiency values of 0%, 50%, and 100% were applied in the low, medium and high removal efficiency scenarios, respectively. The selection of 0% and 100% in the low and high removal efficiency scenarios was based on the minimum and maximum removal across the 35 pollutants with reported level 1 removal efficiency data. The removal efficiency estimate in the medium removal efficiency scenario is halfway between the minimum and maximum values.

Preliminary screening and grit removal were assumed to have no effect on partitioning and degradation of toxic organics. Reported removal performance of biological treatment units was assumed to include operation of the secondary clarifier, which is not assessed separately. It is important to note that within the literature it is often not clear whether pollutant removal is the result of solids partitioning or biodegradation.

Studies have shown that expected changes in toxic organic influent concentrations do not produce a noticeable effect on removal efficiency (Oppenheimer et al. 2007). One study looking at estradiol, diclofenac, and nonylphenol showed indistinguishable removal rates at influent concentrations of 1 and 10 µg/L (Liwarska-Bizukojc et al. 2018). Based on this observation, we utilized all available removal data for a given unit process, regardless of reported influent concentration.

Table C-2. Degradation and Removal of Toxic Organics within the Level 1 Biological Treatment System

Chemical Name	Removal – Class[a]	Removal Efficiency - Level 1		
		Low	Medium	High
acetaminophen	Good	92%	100%	100%
androstendione	Good	96%	98%	99%
atenolol	Medium	30%	70%	81%
atorvastatin	Good	88%	90%	92%
atrazine	Poor	26%	28%	29%
benzophenone	Good	79%	80%	80%
bisphenol A	Good	77%	85%	98%
*butylated hydroxyanisole**	N/A	*0%*	*50%*	*100%*
*butylated hydroxytoluene**	N/A	*0%*	*50%*	*100%*
butylbenzyl phthalate	Good	80%	80%	80%
carbamazepine	Poor	0%	0%	22%
N,N-diethyl-meta-toluamide (DEET)	Medium	50%	50%	50%
diclofenac	Poor	22%	49%	68%

Table C-2. Degradation and Removal of Toxic Organics within the Level 1 Biological Treatment System

Chemical Name	Removal – Class[a]	Removal Efficiency - Level 1		
		Low	Medium	High
*dilantin**	N/A	*0%*	*50%*	*100%*
dioctyl phthalate	Medium	70%	70%	70%
estradiol	Good	73%	96%	98%
estrone	Good	14%	81%	95%
galaxolide	Medium	47%	77%	87%
gemfibrozil	Medium	67%	70%	75%
*hydrocodone**	N/A	*0%*	*50%*	*100%*
ibuprofen	Good	80%	96%	99%
iopromide	Poor	0%	0%	8%
meprobamate	Poor	0%	0%	0%
naproxen	Medium	56%	73%	94%
nonylphenol	Medium	62%	78%	89%
octylphenol	Good	63%	80%	95%
*o-hydroxy atorvastatin**	N/A	*0%*	*50%*	*100%*
oxybenzone	Good	72%	80%	89%
*p-hydroxy atorvastatin**	N/A	*0%*	*50%*	*100%*
progesterone	Good	92%	93%	95%
sulfamethoxazole	Poor	31%	50%	66%
tris(2-chloroethyl)phosphate (TCEP)	Medium	50%	50%	50%
*tris(2-chloroisopropyl) phosphate (TCPP)**	N/A	*0%*	*50%*	*100%*
testosterone	Good	86%	90%	95%
triclosan	Medium	58%	71%	76%
trimethoprim	Poor	18%	20%	29%
*triclocarban**	N/A	*0%*	*50%*	*100%*
tonalide	Good	61%	84%	86%
celestolide	Medium	0%	60%	68%
phantolide	Poor	0%	9%	34%
clofibric acid	Medium	50%	52%	53%
musk ketone	Poor	0%	25%	38%
diuron	Poor	30%	30%	30%

a - Removal class refers to the qualitative removal efficiency classification thresholds defined by (Oppenheimer et al. 2007). Poor = <50% removal, Medium = 50-80% removal, Good = >80% removal. Classifications were assigned based on the median removal efficiency.

* Marked and italicized chemicals lack data on removal efficiency and use 0%, 50%, and 100% as proxy removal efficiency values to determine significance in LCA results.

C.3.2 Advanced Biological Treatment

The majority of literature related to degradation and removal of toxic organics considers the removal efficiency of entire WWTPs or advanced tertiary processes (e.g. RO, ozonation). Because of this limitation it was not possible to determine individualized removal efficiencies that correspond to each of the advanced biological treatment units. Therefore, a more generalized approach was used to define low, medium and high estimates of removal efficiency for advanced biological treatment works.

As a conservative estimate, the low removal efficiency of the advanced treatment systems was set equal to the low removal efficiency of the Level 1 treatment system, which was based on the 25th percentile of documented values. The medium removal efficiency scenario value for Levels 2 through 5 was established assuming an increase in removal performance that is 25% ($EF_{\text{inc.y}}$) beyond the Level 1 median removal efficiency. The high removal efficiency scenario value assumes a removal performance that is 50% ($EF_{\text{inc.y}}$) above the Level 1 median removal efficiency as calculated in Equation C-1. For example, assuming a median removal efficiency for Level 1 treatment of 50%, the removal efficiency of advanced biological treatment units would be 62.5% and 75% (EF_x) in the medium and high removal efficiency scenarios. The proposed increases in removal efficiency attributed to Levels 2 through 5 are indicative of increased HRT, SRT and variable redox conditions that are known to increase removal efficiency of many toxic organics as discussed in Section C.2 and document in the removal notes of Table C-3.

$$EF_x = EF_{med} + [(1 - EF_{med}) \times EF_{\text{inc.y}}]$$

Equation C-1

Where:

EF_x = Adjusted removal efficiency of scenario x

EF_{med} = Level 1 median removal efficiency

$EF_{\text{inc.y}}$ = Removal efficiency increase factor y (varies by scenario)

Table C-3 summarizes the calculated advanced biological process removal efficiency values for individual organic pollutants used in the sensitivity analysis. The notes in Table C-3 describe additional information that sheds light on how the studied compounds may respond to alternate redox conditions and longer HRTs and SRTs that characterize the advanced biological treatment units of Levels 2 through 5. As noted above, several authors state that current evidence indicates that comparable or improved removal efficiencies can be expected in advanced biological treatment works. Examination of removal notes in Table C-3 often confirms this perspective, however, there are also numerous instances where the findings of authors contradict one another. For example, Lakshminarasimman et al. (2018) identified improved removal of bisphenol A at high SRTs, whereas (Luo et al. 2014) identified no significant effect of SRT on removal efficiency. What is clear from Table C-2 and Table C-3 is the conclusion that individual toxic organics respond differently to the range of conditions that characterize both activated sludge and advance nutrient removal WWTPs. The sensitivity approach described in this section will allow the analysis to judge the importance of removal efficiency estimates on final LCA results.

Table C-3. Toxic Organic Removal Efficiency of Advanced Biological Treatment Process

Chemical Name	**Level 1**	**Removal Efficiency - Advanced Biological Processes (Levels 2-5)**			**Removal Notes**
	Median	**Low**	**Medium**	**High**	
acetaminophen	100%	92%	100%	100%	
androstendione	98%	96%	98%	99%	
atenolol	70%	30%	78%	90%	Biodegrades in all three redox conditions. Degradation was greatest under aerobic conditions (Lakshminarasimman et al. 2018) Better removal at high SRT (Lakshminarasimman et al. 2018) Less than 20% removal under aerobic conditions (Miege et al. 2009) Poor to moderate removal in activated sludge, 45-80% (Martin Ruel et al. 2012)
atorvastatin	90%	88%	93%	96%	
atrazine	28%	26%	46%	64%	
benzophenone	80%	79%	85%	90%	
bisphenol A	85%	77%	89%	99%	Biotransformation is catalyzed by nitrifying conditions (Lakshminarasimman et al. 2018) Not affected by SRT (Luo et al. 2014) Better removal at high SRT (Lakshminarasimman et al. 2018)
*butylated hydroxyanisole**	*50%*	*0%*	*63%*	*100%*	
*butylated hydroxytoluene**	*50%*	*0%*	*63%*	*100%*	
butylbenzyl phthalate	80%	80%	85%	90%	
carbamazepine	0%	0%	25%	61%	Poor removal (Miege et al. 2009; Martin Ruel et al. 2012) Removal less than 20% under all redox conditions (Alvarino et al. 2018; Lakshminarasimman et al. 2018) Removal less than 25% under aerobic conditions (Jelic, (Miege et al. 2009; Jelic et al. 2011)
N,N-diethyl-meta-toluamide (DEET)	50%	50%	63%	75%	Degradation is primarily aerobic (Lakshminarasimman et al. 2018) Poor removal in anaerobic conditions

Table C-3. Toxic Organic Removal Efficiency of Advanced Biological Treatment Process

Chemical Name	**Level 1**	**Removal Efficiency - Advanced Biological Processes (Levels 2-5)**			**Removal Notes**
	Median	**Low**	**Medium**	**High**	
					(Lakshminarasimman et al. 2018) Better removal at high SRT (Lakshminarasimman et al. 2018)
diclofenac	49%	22%	62%	84%	Removal <20% under all redox conditions (Alvarino et al. 2018) Anoxic conditions have a positive influence on removal (Luo et al. 2014) Exhibited inconsistent overall removal. (Jelic et al. 2011) Poor to moderate removal in activated sludge, less than 60% (Miege et al. 2009) Poor removal in activated sludge, <50% (Martin Ruel et al. 2012)
*dilantin**	*50%*	*0%*	*63%*	*100%*	
dioctyl phthalate	70%	70%	78%	85%	Poor to moderate removal in all three redox conditions (Luo et al. 2014) High HRT increases removal to sludge (Luo et al. 2014)
estradiol	96%	73%	97%	99%	Biotransformation is catalyzed by nitrifying conditions (Lakshminarasimman et al. 2018) Better removal at high SRT (Lakshminarasimman et al. 2018) Moderate to good removal in activated sludge, 65-100% (Miege et al. 2009) Good degradation in aerobic conditions (Alvarino et al. 2018) Moderate degradation in anaerobic conditions (Alvarino et al. 2018)

Table C-3. Toxic Organic Removal Efficiency of Advanced Biological Treatment Process

Chemical Name	**Level 1**	**Removal Efficiency - Advanced Biological Processes (Levels 2-5)**			**Removal Notes**
	Median	**Low**	**Medium**	**High**	
estrone	81%	14%	85%	98%	Biotransformation is catalyzed by nitrifying conditions (Lakshminarasimman et al. 2018) Better removal at high SRT (Lakshminarasimman et al. 2018) Moderate to good removal in activated sludge, 45-100% (Miege et al. 2009) Good degradation in aerobic conditions (Alvarino et al. 2018) Moderate degradation in anaerobic conditions (Alvarino et al. 2018)
galaxolide	77%	47%	83%	93%	Poor degradation (Oppenheimer et al. 2007) Good aerobic degradation (Alvarino et al. 2018) Moderate anoxic degradation (Alvarino et al. 2018) Poor anaerobic degradation (Alvarino et al. 2018) Poor to moderate removal in activated sludge, 25-75% (Miege et al. 2009)
gemfibrozil	70%	67%	78%	87%	Moderate removal in activated sludge (Miege et al. 2009)
*hydrocodone**	*50%*	*0%*	*63%*	*100%*	
ibuprofen	96%	80%	97%	100%	Good degradation (Oppenheimer et al. 2007) Good aerobic degradation (Alvarino et al. 2018) Poor anaerobic and anoxic degradation (Alvarino et al. 2018) Biotransformation is catalyzed by nitrifying conditions (Lakshminarasimman et al. 2018) Better removal at high SRT (Lakshminarasimman et al. 2018) Moderate to good removal in activated sludge, 50-100% (Miege et al. 2009)

Table C-3. Toxic Organic Removal Efficiency of Advanced Biological Treatment Process

Chemical Name	**Level 1**	**Removal Efficiency - Advanced Biological Processes (Levels 2-5)**			**Removal Notes**
	Median	**Low**	**Medium**	**High**	
iopromide	0%	0%	25%	54%	Anoxic conditions have a positive influence on removal (Luo et al. 2014) Biotransformation is catalyzed by nitrifying conditions (Lakshminarasimman et al. 2018) Demonstrated no removal in activated sludge (Miege et al. 2009)
meprobamate	0%	0%	25%	50%	
naproxen	73%	56%	79%	97%	Good degradation in aerobic and anaerobic conditions (Alvarino et al. 2018) Poor degradation in anoxic conditions (Alvarino et al. 2018) Biotransformation is catalyzed by nitrifying conditions (Lakshminarasimman et al. 2018) Better removal at high SRT (Lakshminarasimman et al. 2018) Good degradation. Does not accumulate in sludge (Jelic et al. 2011) Moderate to good removal in activated sludge, 65-95% (Miege et al. 2009)
nonylphenol	78%	62%	83%	94%	SRT greater than 20 hours improves removal (Luo et al. 2014)
octylphenol	80%	63%	85%	98%	
*o-hydroxy atorvastatin**	*50%*	*0%*	*63%*	*100%*	
oxybenzone	80%	72%	85%	95%	Good degradation (Oppenheimer et al. 2007)
*p-hydroxy atorvastatin**	*50%*	*0%*	*63%*	*100%*	
progesterone	93%	92%	95%	97%	

Table C-3. Toxic Organic Removal Efficiency of Advanced Biological Treatment Process

Chemical Name	Level 1	Removal Efficiency - Advanced Biological Processes (Levels 2-5)			Removal Notes
	Median	Low	Medium	High	
sulfamethoxazole	50%	31%	62%	83%	Good degradation in anaerobic conditions (Alvarino et al. 2018) Poor degradation in anoxic and aerobic conditions (Alvarino et al. 2018) Comparable degradation under varying redox conditions (Lakshminarasimman et al. 2018) Mixed results on the effect of SRT (Lakshminarasimman et al. 2018) Poor to good removal in activated sludge, 35-80% (Miege et al. 2009)
tris(2-chloroethyl)phosphate (TCEP)	50%	50%	63%	75%	
*tris(2-chlorisopropyl) phosphate (TCPP)**	*50%*	*0%*	*63%*	*100%*	
testosterone	90%	86%	93%	97%	
triclosan	71%	58%	78%	88%	Better degradation under aerobic conditions (Lakshminarasimman et al. 2018) SRT greater than 20 hours improves removal (Luo et al. 2014) Removal rates do not vary with increasing SRT (Lakshminarasimman et al. 2018)
trimethoprim	20%	18%	40%	65%	Good degradation anaerobic conditions (Alvarino et al. 2018) Poor degradation under aerobic and anoxic conditions (Alvarino et al. 2018) Poor degradation under aerobic conditions, <40% (Miege et al. 2009) Demonstrated degradation under anaerobic and anoxic conditions (Lakshminarasimman et al. 2018) Mixed results on the effect of SRT (Lakshminarasimman et al. 2018)

Table C-3. Toxic Organic Removal Efficiency of Advanced Biological Treatment Process

Chemical Name	**Level 1**	**Removal Efficiency - Advanced Biological Processes (Levels 2-5)**			**Removal Notes**
	Median	**Low**	**Medium**	**High**	
					No significant removal under aerobic conditions (Jelic et al. 2011)
*triclocarban**	*50%*	*0%*	*63%*	*100%*	
tonalide	84%	61%	88%	93%	Good degradation under aerobic conditions (Alvarino et al. 2018) Moderate degradation under anaerobic and anoxic conditions (Alvarino et al. 2018) Poor to good degradation in activated sludge, 35-85% (Miege et al. 2009)
celestolide	60%	0%	70%	84%	Good degradation under aerobic conditions (Alvarino et al. 2018) Moderate degradation under anaerobic and anoxic conditions (Alvarino et al. 2018) Poor to moderate removal in activated sludge, less than 60% (Miege et al. 2009) Volatilization is a significant loss pathway, approximately 16% (Luo et al. 2014)
phantolide	9%	0%	32%	67%	
clofibric acid	52%	50%	64%	76%	Anoxic conditions have a positive influence on removal (Luo et al. 2014) Poor removal in activated sludge, less than 50% (Miege et al. 2009)
musk ketone	25%	0%	44%	69%	Poor degradation under aerobic conditions (Miege et al. 2009)
diuron	30%	30%	48%	65%	Poor degradation in activated sludge (Martin Ruel et al. 2012)

* Marked and italicized chemicals lack data on removal efficiency and use 0%, 50%, and 100% as proxy removal efficiency values to determine significance in LCA results.

It was also necessary to estimate the fraction of pollutant removal that is attributable to solids partitioning as opposed to biological degradation. Miege et al. (2009) performed an in-depth review of studies looking at the fate of PPCPs in WWTPs and noted that the vast majority (87%) of studies focus on the aqueous phase. None of the reviewed studies looked at both aqueous and solid phases of PPCPs simultaneously. As noted earlier, (Martin Ruel et al. 2012) proposed that up to two-thirds of pollutant removal can be attributed to solids partitioning. Other authors disagree with this conclusion, proposing that the majority of removal efficiency is due to biodegradation (Liu et al. 2009). It is beyond the scope of this analysis to attempt to resolve this discrepancy.

In the low efficiency scenario, it was assumed that two-thirds of removal efficiency is due to solids partitioning (one-third biodegradation). The analysis does not specify if this removal occurs during primary or secondary clarification. The medium removal efficiency estimates assume a 50-50 split between solids partitioning and biodegradation, while the high removal efficiency estimates assume that one-third of removal is attributable to solids partitioning (two-thirds biodegradation). All assumptions related to solids partitioning were applied to the corresponding removal efficiency as documented in Table C-2.

C.3.3 Anaerobic Digestion

All 9 treatment systems include anaerobic digestion as a sludge processing step, and a low, medium and high estimate of removal efficiency was established for each of the 43 pollutants using the 25th percentile, median and 75th percentile degradation values. The reviewed research on anaerobic digestion deals more consistently with pollutants in both the liquid and solid phase. Removal efficiency measurements for anaerobic digestion tend to refer to biodegradation explicitly. Pollutant specific data were identified for 20 of the 43 pollutants and are summarized in Table C-4. Removal efficiency was set as zero for pollutants reporting negative values. Proxy values that bracket the extreme values for removal efficiency were used to determine if the removal of the 23 remaining chemicals is significant in the LCA results. Proxy removal efficiency values of 0%, 50%, and 100% were applied in the low, medium and high removal efficiency scenarios, respectively. The selection of 0% and 100% in the low and high removal efficiency scenarios was based on the minimum and maximum removal across the 20 pollutants with reported AD removal efficiency data. The removal efficiency estimate in the medium removal efficiency scenario is halfway between the minimum and maximum values.

A study by Malmborg and Magnér (2015) looked at several sludge treatment steps including pasteurization, thermal hydrolysis, advanced oxidation and ammonia treatment, concluding that anaerobic digestion was the most effective at removing organic substances. Toxic organics pollutants not degraded in anaerobic digestion remain with the solids for disposal in landfills.

Table C-4. Toxic Organic Removal Efficiency of Anaerobic Digestion

Chemical Name	**Removal Efficiency (%)**			
	Low	**Medium**	**High**	**Range (min-max)**
acetaminophen	89%	89%	96%	85-100
*androstendione**	*0%*	*50%*	*100%*	*N/A*
atenolol	61%	77%	89%	39-96

Table C-4. Toxic Organic Removal Efficiency of Anaerobic Digestion

Chemical Name	Removal Efficiency (%)			
	Low	**Medium**	**High**	**Range (min-max)**
*atorvastatin**	*0%*	*50%*	*100%*	*N/A*
*atrazine**	*0%*	*50%*	*100%*	*N/A*
*benzophenone**	*0%*	*50%*	*100%*	*N/A*
bisphenol A	12%	30%	84%	0-100
*butylated hydroxyanisole**	*0%*	*50%*	*100%*	*N/A*
*butylated hydroxytoluene**	*0%*	*50%*	*100%*	*N/A*
butylbenzyl phthalate	93%	93%	93%	93-93
carbamazepine	0%	0%	7%	0-15
N,N-diethyl-meta-toluamide (DEET)	0%	0%	0%	0-0
diclofenac	21%	34%	55%	0-78
*dilantin**	*0%*	*50%*	*100%*	*N/A*
*dioctyl phthalate**	*0%*	*50%*	*100%*	*N/A*
estradiol	85%	93%	96%	75-100
estrone	75%	79%	85%	70-95
galaxolide	58%	65%	73%	50-80
gemfibrozil	0%	0%	0%	0-0
*hydrocodone**	*0%*	*50%*	*100%*	*N/A*
ibuprofen	21%	27%	44%	0-70
iopromide	16%	23%	31%	8-38
*meprobamate**	*0%*	*50%*	*100%*	*N/A*
naproxen	86%	89%	93%	76-96
nonylphenol	43%	86%	100%	0-100
*octylphenol**	*0%*	*50%*	*100%*	*N/A*
*o-hydroxy atorvastatin**	*0%*	*50%*	*100%*	*N/A*
*oxybenzone**	*0%*	*50%*	*100%*	*N/A*
*p-hydroxy atorvastatin**	*0%*	*50%*	*100%*	*N/A*
*progesterone**	*0%*	*50%*	*100%*	*N/A*
sulfamethoxazole	79%	99%	100%	23-100
*tris(2-chloroethyl)phosphate (TCEP)**	*0%*	*50%*	*100%*	*N/A*
*tris(2-chloroisopropyl) phosphate (TCPP)**	*0%*	*50%*	*100%*	*N/A*
*testosterone**	*0%*	*50%*	*100%*	*N/A*
triclosan	45%	53%	55%	30-55
trimethoprim	90%	96%	99%	80-100
triclocarban	20%	40%	53%	0-65
tonalide	59%	65%	67%	52-68
*celestolide**	*0%*	*50%*	*100%*	*N/A*
*phantolide**	*0%*	*50%*	*100%*	*N/A*
*clofibric acid**	*0%*	*50%*	*100%*	*N/A*
*musk ketone**	*0%*	*50%*	*100%*	*N/A*
*diuron**	*0%*	*50%*	*100%*	*N/A*

* Marked and italicized chemicals lack data on removal efficiency and use 0%, 50%, and 100% as proxy removal efficiency values to determine significance in LCA results.

C.3.4 Chemical Phosphorus Removal

The effect of chemical phosphorus removal was considered to the extent that it is expected to enhance partitioning and settling of toxic organics. Alexander et al. (2012) reviewed the available literature on the effect of chemical coagulation on trace organic pollutant removal. They found that chemical phosphorus removal (i.e. chemical coagulation) has been demonstrated to be an inefficient means of removing trace organics from the liquid phase of wastewater. Across different categories of organic chemicals, average removal efficiency of chemical coagulation varies between six and 77%.

Table C-5 lists low, medium and high removal efficiency scenario values used in this study. Pollutant specific data was identified for 9 of the 43 toxic organic compounds. Twenty-eight of the 43 chemicals were assigned removal efficiency data based on their assigned chemical class, as listed in Table C-5. No data was identified for 15 of the toxic organic chemicals, and they were assigned the median removal efficiency across all chemical classes of 34% (Alexander et al. 2012).

Six of the nine treatment systems included in this study utilize chemically enhanced secondary clarification. The low removal efficiency scenario assumes no increase in removal efficiency relative to secondary clarification without a preceding alum addition. The medium and high removal efficiency scenarios assume that 50% and 100% of the identified chemical coagulation removal efficiencies are in addition to the removal realized by the combined biological process and secondary clarification (without alum addition). The range of these assumptions is wide to accommodate the fact that Alexander et al. (2012) presents chemical coagulation as a stand-alone unit process. The precise relationship between the removal efficiency of stand-alone chemical coagulation and chemically enhanced secondary clarification is not known.

Table C-5. Toxic Organic Removal Efficiency of Chemical Coagulation

Chemical Name	**Chemical Class**[a]	**Removal Efficiency - Chemical Coagulation**[b]		
		Low	**Medium**	**High**
acetaminophen[3]	N/A	-	24%	48%
androstendione	hormone	-	9.5%	19%
atenolol[3]	beta-blocker	-	9.5%	19%
atorvastatin	hypolipidemic agent	-	13%	26%
atrazine	pesticide	-	15%	30%
*benzophenone**	*N/A*	-	*17%*	*34%*
*bisphenol A**	*N/A*	-	*17%*	*34%*
butylated hydroxyanisole	beta-blocker	-	17%	34%
butylated hydroxytoluene	beta-blocker	-	17%	34%
butylbenzyl phthalate	phthalate	-	25%	49%
carbamazepine[c]	N/A	-	15%	30%
N,N-diethyl-meta-toluamide (DEET)	pesticide	-	15%	30%
diclofenac[c]	anti-inflammatory	-	25%	50.0%
*dilantin**	*N/A*	-	*17%*	*34%*
dioctyl phthalate	phthalate	-	25%	49%
estradiol[c]	hormone	-	1.0%	2.0%

Table C-5. Toxic Organic Removal Efficiency of Chemical Coagulation

Chemical Name	Chemical Class[a]	Removal Efficiency - Chemical Coagulation[b]		
		Low	Medium	High
estrone[c]	hormone	-	6.0%	12%
galaxolide	beta-blocker	-	39%	77%
gemfibrozil	musk fragrance	-	13%	26%
hydrocodone[c]	N/A	-	12%	24%
ibuprofen	anti-inflammatory	-	18%	35%
*iopromide**	*N/A*	-	*17%*	*34%*
*meprobamate**	*N/A*	-	*17%*	*34%*
naproxen[c]	anti-inflammatory	-	11%	23%
*nonylphenol**	*N/A*	-	*17%*	*34%*
*octylphenol**	*N/A*	-	*17%*	*34%*
o-hydroxy atorvastatin	hypolipidemic agent	-	13%	26%
*oxybenzone**	*N/A*	-	*17%*	*34%*
p-hydroxy atorvastatin	hypolipidemic agent	-	13%	26%
progesterone[c]	hormone	-	6.3%	13%
sulfamethoxazole	antibiotic	-	20%	39%
*tris(2-chloroethyl)phosphate (TCEP)**	*N/A*	-	*17%*	*34%*
*tris(2-chloroisopropyl) phosphate (TCPP)**	*N/A*	-	*17%*	*34%*
testosterone	hormone	-	9.5%	19%
triclosan	pesticide	-	15%	30%
trimethoprim	antibiotic	-	20%	39%
*triclocarban**	*N/A*	-	*17%*	*34%*
tonalide	musk fragrance	-	28%	56%
celestolide	musk fragrance	-	39%	77%
phantolide	musk fragrance	-	39%	77%
clofibric acid	hypolipidemic agent	-	13%	26%
musk ketone	musk fragrance	-	39%	77%
*diuron**	*N/A*	-	*17%*	*34%*

a - Chemical classes are based on trace organic compound classes defined in Table 4 of (Alexander et al. 2012).

b - Removal efficiency of chemical coagulation is in addition to the removal efficiencies for combined biological treatment and secondary clarification listed in Table 1-3 and Table 1-4.

c - Chemical specific removal efficiency data was drawn from (Alexander et al. 2012).

* Marked values use median removal efficiency of all chemical classes defined in Alexander et al. (2012) as the proxy removal efficiency value.

C.3.5 Membrane Filtration

For the fraction of toxic organics that remain in the dissolved phase there are subsequent unit processes to consider following biological treatment. Media filters and ultrafiltration membranes do not physically screen toxic organic compounds as the molecules are often two orders of magnitude smaller than the membrane pores (Oppenheimer et al. 2007; Alvarino et al. 2018), or more in the case of sand filters. Ultrafiltration membranes replace traditional secondary clarifiers in Levels 4-2 and 5-2. In this capacity they increase total suspended solids removal by approximately 0.5%, which was considered negligible from the perspective of increasing the fraction of toxic organics exiting the WWTP with the sludge fraction. There is however evidence that certain toxic organics can be sorbed onto hydrophobic filtration membranes via electrostatic interactions and within the cake layer (Alvarino et al. 2018). Retention of toxic organics on filtration membranes was not able to be assessed in this study.

Reverse osmosis has been shown to be effective at removing residual toxic organics in secondary effluent to less-than-detectable levels (Oppenheimer et al. 2007). Reverse osmosis removal efficiency measurement data was found for 37 of the 43 toxic organic chemicals considered. Table C-6 lists the low, medium and high removal efficiency estimates calculated using the 25th percentile, median and 75th percentile of documented values. Data on the removal efficiency of reverse osmosis was not found for six chemicals. Proxy values that bracket the extreme values for removal efficiency were used to determine if the removal of these chemicals is significant in the LCA results. Proxy removal efficiency values of 0%, 49.9%, and 99.9% were applied in the low, medium and high removal efficiency scenarios, respectively. The selection of 0% and 99.9% in the low and high removal efficiency scenarios was based on the minimum and maximum removal across the 37 pollutants with reported RO removal efficiency data. The removal efficiency estimate in the medium removal efficiency scenario is halfway between the minimum and maximum values.

Table C-6. Toxic Organic Removal Efficiency of Reverse Osmosis

Chemical Name	Removal Efficiency - Reverse Osmosis		
	Low	Medium	High
acetaminophen	89%	90%	91%
androstendione	31%	62%	71%
atenolol	98%	98%	99%
atorvastatin	98%	98%	99%
atrazine	49%	97%	98%
benzophenone	40%	69%	98%
bisphenol A	98%	99%	99%
butylated hydroxyanisole	98%	98%	99%
butylated hydroxytoluene	98%	98%	99%
butylbenzyl phthalate	98%	98%	99%
carbamazepine	99%	99%	99%
N,N-diethyl-meta-toluamide (DEET)	94%	95%	99%
diclofenac	95%	97%	97%
dilantin	99%	99%	100%
dioctyl phthalate	98%	98%	99%
estradiol	-	80%	92%
estrone	90%	91%	95%
galaxolide	54%	88%	99%
gemfibrozil	98%	99%	100%
hydrocodone	98%	98%	99%
ibuprofen	97%	99%	99%
iopromide	98%	99%	99%
meprobamate	99%	100%	100%
naproxen	94%	96%	99%
nonylphenol	98%	98%	99%

Table C-6. Toxic Organic Removal Efficiency of Reverse Osmosis

Chemical Name	Removal Efficiency - Reverse Osmosis		
	Low	Medium	High
octylphenol	98%	98%	99%
o-hydroxy atorvastatin	98%	98%	99%
oxybenzone	85%	93%	95%
p-hydroxy atorvastatin	98%	98%	99%
progesterone	-	80%	97%
sulfamethoxazole	98%	99%	100%
TCEP	93%	95%	96%
TCPP	98%	98%	99%
testosterone	49%	97%	98%
triclosan	89%	92%	95%
trimethoprim	99%	99%	100%
*triclocarban**	*98%*	*98%*	*100%*
*tonalide**	*98%*	*98%*	*100%*
*celestolide**	*98%*	*98%*	*100%*
*phantolide**	*98%*	*98%*	*100%*
*clofibric acid**	*98%*	*98%*	*100%*
musk ketone	56%	68%	79%
*diuron**	*98%*	*98%*	*100%*

* Marked and italicized chemicals lack data on removal efficiency and use 0%, 50%, and 100% as proxy removal efficiency values to determine significance in LCA results.

C.3.6 Other Processes

Media filtration has not been shown to provide considerable removal beyond that provided by preceding secondary treatment processes, less than 15 percent (Oppenheimer et al. 2007). Removal efficiency data of standalone sand filters were identified for eight of the 43 pollutants. The low and medium removal efficiency scenarios both assume zero percent removal based on the 25th percentile and median of the eight identified values. The high removal efficiency scenarios assume 11% removal, based on the 75th percentile. The described values were applied to all 43 pollutants and were assumed to constitute additional biodegradation.

Chlorination, dechlorination and the sludge thickening processes were assumed not to affect the fate of toxic organics within the WWTP.

C.3.7 Total System Level Performance

Removal efficiency estimates for individual unit processes listed in Table C-2 through Table C-6 were used as inputs to Equation C-2 to calculate cumulative removal from the liquid effluent. The fraction of influent toxic organics that accumulate in sludge was estimated by adding the fraction of removal efficiency attributable to solids partitioning from the combined primary and secondary biological unit processes ($r_b \times r_s$) to the additional sludge removal that results from chemically enhanced secondary clarification (r_c) less the fraction of each compound that is degraded during anaerobic digestion ($1-r_{AD}$) as summarized in Equation C-2.

$$\boldsymbol{R_{s-total}} = [(\boldsymbol{r_b} \times \boldsymbol{r_s}) + \boldsymbol{r_c}] \times (\boldsymbol{1} - \boldsymbol{r_{AD}})]$$

Equation C-2

where

$R_{s\text{-}total}$ = total fraction of pollutant (in influent) that accumulates in sludge

r_b = fraction of pollutant removed in primary and secondary treatment, includes degradation and partitioning to solids.

r_s = fraction of primary and secondary removal efficiency attributable to solids partitioning and sludge removal (percentage of r_b).

r_c = additional fraction of pollutant removed by chemically enhanced secondary clarification.

r_{AD} = fraction of pollutant degraded during anaerobic digestion.

Table C-7 summarizes the cumulative fate of toxic organics across the nine system configurations. The presented values represent weighted average degradation and removal efficiencies across the 43 included chemicals and include the estimated effect of the listed unit processes. The median influent concentration of the 43 toxic organic chemicals was used as the weighting factor.

- Primary clarification, biological treatment and secondary/tertiary clarification - combined removal efficiency. Median values for the Level 1 low, medium and high removal efficiency scenarios range from 47 to 87% removal. Median values for the Level 2 through 5 low, medium and high removal efficiency scenarios range from 47 to 93%. Removal efficiency includes partitioning to solids and biodegradation.
- Chemical phosphorus removal – contributes additional partitioning to solids. Median values for the low, medium and high removal efficiency scenarios range from zero to 34% additional partitioning to solids.
- Sand filtration – assumed to increase biodegradation (minor). Low, medium and high removal efficiency scenario values range from 0 to 11% removal.
- Anaerobic digestion – biodegrades a fraction of toxic organics that partition to sludge. Median values for the low, medium and high removal efficiency scenarios range from 0 to 100% biodegradation.
- Reverse Osmosis – physically separates toxic organics from the liquid stream of wastewater, concentrating these substances in the brine solution for underground injection. Median values for the low, medium and high removal efficiency scenarios range from 98 to 99% removal from the liquid fraction of wastewater.

Table C-7. Summary of Total Toxic Organics Fate in the Nine Treatment Systems[a]

Treatment Level	Fraction Degraded			Fraction Removed (includes solids)		
	Low	Mid	High	Low	Mid	High
L1	51.7%	69.9%	84.8%	67.1%	81.1%	89.1%

Table C-7. Summary of Total Toxic Organics Fate in the Nine Treatment Systems[a]

Treatment Level	Fraction Degraded			Fraction Removed (includes solids)		
	Low	Mid	High	Low	Mid	High
L2-1	51.7%	73.5%	89.7%	67.1%	85.8%	94.6%
L2-2	51.7%	73.5%	89.7%	67.1%	85.8%	94.6%
L3-1	51.7%	74.9%	91.6%	67.1%	88.5%	97.0%
L3-2	51.7%	74.9%	91.6%	67.1%	88.5%	97.0%
L4-1	51.7%	74.9%	91.6%	67.1%	88.5%	97.0%
L4-2	51.7%	74.9%	91.2%	67.1%	88.5%	96.7%
L5-1	51.7%	74.9%	91.2%	94.2%	98.5%	99.7%
L5-2	51.7%	74.9%	91.2%	92.7%	98.0%	99.5%

a - Table values represent the cumulative effect of all the described treatment processes, calculated as a weighted average of the 43 toxic organics using influent concentration as the weighting factor.

C.3.8 Toxicity Characterization Factors

Table C-8 presents the characterization factors used to estimate toxicity impacts associated with toxic organics in treatment plant effluent and sludge. Not all toxic organics included in this study have associated characterization factors listed in the most recent versions of USEtox™, versions 2.02 and 2.11. Characterization factors for several of the pollutants were previously calculated by other authors (Rahman et al. 2018, Alfonsín et al. 2014). Characterization factors that were not otherwise available were estimated using the median value of all other toxic organic pollutants for which data was available. Sources for individual characterization factors are listed in Table C-8.

Table C-8. Toxic Organics Toxicity Characterization Factors, USEtox™ version 2.11

Chemical Name	USETox Chemical Name	Freshwater Ecotoxicity, (CTUe, PAF m^3.day/kg emitted)		Human health cancer, freshwater (CTUh, cases/kg emitted)		Human Health noncancer, freshwater (CTUh, cases/kg emitted)	
		Emissions to Freshwater	**Emissions to Natural Soil**	**Emissions to Freshwater**	**Emissions to Natural Soil**	**Emissions to Freshwater**	**Emissions to Natural Soil**
acetaminophen	acetamide	2.6	0.88	2.5E-7	8.5E-8	3.5E-6[d]	1.4E-7[d]
androstendione	androstenedione	5.1E+3	5.7E+2	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
atenolol	N/A[c]	1.2E+2[a]	57	-[d]	-[d]	8.0E-3[a]	4.0E-3[a]
atorvastatin	N/A[c]	8.4E+3[a]	4.2E+3[a]	-[d]	-[d]	9.6E-8[a]	4.8E-8[a]
atrazine	atrazine	8.7E+4	3.4E+3	3.7E-6	1.5E-7	4.3E-6	1.7E-7
benzophenone	benzophenone	5.2E+3	94	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
bisphenol A	bisphenol A	8.dE+3	2.0E+2	-	-	1.1E-6[d]	2.6E-8[d]
butylated hydroxyanisole	butylated hydroxyanisole	8.8E+3	1.6E+2	3.4E-7	1.0E-8	3.5E-6[d]	1.4E-7[d]
butylated hydroxytoluene	2,6-DI-T-BUTYL-4-METHYLPHENOL (BHT)	1.8E+3	3.6	3.4E-7	3.6E-9	3.5E-6[d]	1.4E-7[d]
butylbenzyl phthalate	phthalate, butyl-benzyl-	5.7E+3	9.1	5.0E-8	1.0E-9	7.3E-8	1.5E-9
carbamazepine	carbamazepine	7.8E+2	93	-	-	2.3E-6	2.8E-7
N,N-diethyl-meta-toluamide (DEET)	DEET [N,N,-DIET-3-ME BENZAMIDE]	2.2E+2	11	-	-	3.5E-6[d]	1.4E-7[d]
diclofenac	diclofenac	1.9E+3	1.5E+2	-	-	1.6E-4	1.2E-5
dilantin	phenytoin	1.0E+5[a]	5.0E+4[a]	2.9E-6	1.8E-7	5.3E-4[a]	2.7E-4[a]
dioctyl phthalate	phthalate, dioctyl-	30	0.01	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
estradiol	estradiol	2.2E+8	2.3E+6	-	-	1.0E-3[b]	1.4E-6[b]
estrone	estrone	2.4E+4	5.7E+2	-[d]	-[d]	3.2E-4[b]	5.4E-7[b]
galaxolide	N/A[3]	3.3E+5[b]	17[b]	-[d]	-[d]	5.0E-7[b]	4.7E-9[b]
gemfibrozil	gemfibrozil	7.0E+3[d]	1.6E+2[d]	3.1E-6	1.3E-7	3.5E-6[d]	1.4E-7[d]
hydrocodone	N/A	1.4E+4[a]	7.0E+3[a]	-[d]	-[d]	2.1E-5[a]	1.1E-4[a]
ibuprofen	ibuprofen	2.3E+2	7.3	-	-	3.7E-7[2]	1.7E-8[2]

Table C-8. Toxic Organics Toxicity Characterization Factors, USEtox™ version 2.11

Chemical Name	**USETox Chemical Name**	**Freshwater Ecotoxicity, (CTUe, PAF m^3.day/kg emitted)**		**Human health cancer, freshwater (CTUh, cases/kg emitted)**		**Human Health noncancer, freshwater (CTUh, cases/kg emitted)**	
		Emissions to Freshwater	**Emissions to Natural Soil**	**Emissions to Freshwater**	**Emissions to Natural Soil**	**Emissions to Freshwater**	**Emissions to Natural Soil**
iopromide	iopromide	24	10	-	-	2.4E-7	1.0E-7
meprobamate	N/A[c]	9.2E+2[a]	4.6E+2[a]	-[d]	-[d]	1.0E-c[a]	5.2E-4[a]
naproxen	N/A[c]	9.6E+2[b]	4.9[b]	-[d]	-[d]	3.0E-7[b]	6.6E-9[b]
nonylphenol	nonylphenol	1.6E+4	8.8	-[d]	-[d]	5.6E-6[b]	7.1E-10[b]
octylphenol	N/A[c]	3.3E+5[b]	1.4E+2[b]	-[d]	-[d]	4.3E-6[b]	3.3E-9[b]
o-hydroxy atorvastatin	N/A[c]	7.0E+3[d]	1.6E+2[d]	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
oxybenzone	N/A[c]	4.4E+4[a]	2.2E+4[a]	-[d]	-[d]	2.4E-6[a]	1.3E-6[a]
p-hydroxy atorvastatin	N/A[c]	7.0E+3[d]	1.6E+2[d]	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
progesterone	N/A[c]	1.6E+4[a]	7.7E+3[a]	-[d]	-[d]	1.3E-5[a]	6.1E-6[a]
sulfamethoxazole	sulfamethoxazole	4.7E+3	1.2E+3	-	-	4.7E-7	1.2E-7
tris(2-chloroethyl)phosphate (TCEP)	tris(2-carboxyethyl)phosphine	7.0E+3[d]	1.6E+2[d]	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
tris(2-chloroisopropyl) phosphate (TCPP)	TRI-2-CHLOROETHYL PHOSPHATE	4.4E+2	1.1E+2	1.1E-6	2.8E-7	3.5E-6[d]	1.4E-7[d]
testosterone	testosterone	1.3E+4	4.0E+2	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
triclosan	5-CHLORO-2-(2,4-DICHLOROPHENOXY)PHENOL	1.3E+5	8.9E+2	-[d]	-[d]	2.2E-7[b]	5.0E-10[b]
trimethoprim	trimethoprim	1.0E+3	13	-	-	2.8E-6	3.7E-8
triclocarban	triclocarban	1.4E+6	7.7E+3	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
tonalide	N/A[c]	7.0E+3[d]	1.6E+2[d]	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
celestolide	N/A[c]	7.0E+3[d]	1.6E+2[d]	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
phantolide	N/A[c]	7.0E+3[d]	1.6E+2[d]	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]

Table C-8. Toxic Organics Toxicity Characterization Factors, USEtox™ version 2.11

Chemical Name	USETox Chemical Name	Freshwater Ecotoxicity, (CTUe, PAF m^3.day/kg emitted)		Human health cancer, freshwater (CTUh, cases/kg emitted)		Human Health noncancer, freshwater (CTUh, cases/kg emitted)	
		Emissions to Freshwater	**Emissions to Natural Soil**	**Emissions to Freshwater**	**Emissions to Natural Soil**	**Emissions to Freshwater**	**Emissions to Natural Soil**
clofibric acid	N/A[c]	7.0E+3[d]	1.6E+2[d]	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
musk ketone	N/A[c]	7.0E+3[d]	1.6E+2[d]	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
diuron	diuron	6.0E+4	4.6E+3	-	-	6.6E-6	5.1E-7

a – Characterizations factors sourced from Rahman et al. 2018.

b – Characterization factors sourced from Alfonsín et al. 2014.

c – Chemical is not present in the current USEtox™ LCIA method.

d **-** Estimated using the median of toxic organics with available characterization factors.

APPENDIX D

DETAILED CHARACTERIZATION OF DISINFECTION BYPRODUCT FORMATION POTENTIAL IN STUDY TREATMENT CONFIGURATIONS

Appendix D: Detailed Characterization of Disinfection Byproduct Formation Potential in Study Treatment Configurations

D.1 Disinfection Byproducts

Disinfection of wastewater treatment plant (WWTP) effluent is a necessary practice to minimize the acute risk associated with exposure to microbial pathogens, however it must be balanced with the chronic risk posed by the creation of disinfection byproducts (DBPs). DBPs are a class of chemical compounds that can be harmful to both aquatic and human health (Boorman G A 1999; Nieuwenhuijsen et al. 2000; Mizgireuv et al. 2004; Villanueva et al. 2004; Muellner et al. 2007; Richardson et al. 2007; Watson et al. 2012). Similar to other emerging contaminants, the understanding of the occurrence and variety of this class of chemicals is continually expanding as new analytical techniques enable finer characterization of individual compounds, though even by 2007 over 600 DBPs had been reported in the literature (Richardson et al. 2007).

DBPs are formed when DBP precursors, generally organic carbonaceous or nitrogenous compounds, are oxidized during chlorination or chloramination (Christman et al. 1983). By regulation, DBPs are managed at drinking water treatment plants, as their presence in water supplies poses a direct threat to human health (Sedlak and Gunten 2011; U.S. EPA 2015d). However, as water recycling and reclamation programs expand (and as indirect potable reuse continues), management of DBPs and DBP precursors has become increasingly important at the WWTP as well (Krasner et al. 2008; L. Tang et al. 2012).

In the U.S., DBPs are mainly regulated by the U.S. EPA through the Stage 1 and 2 Disinfectants/DBP Rules (U.S. EPA 2015e), which include maximum contaminant levels for the sum of four trihalomethanes (THM4) and the sum of five haloacetic acids (HAA5) (Table D-1).

Regulation focuses on these two groups, in part, as they generally have the highest occurrence in drinking water. More importantly however, they serve as indicators for the presence of other less common, though potentially more toxic, DBPs (Muellner et al. 2007; Richardson et al. 2007; Krasner et al. 2008). More recently, the US EPA has begun to focus on these emerging, high priority DBPs (Richardson et al. 2002). Additionally, the California Department of Health Services established notification levels for several highly toxic nitrosamines, including *N*-Nitrosodimethylamine (NDMA) (Table D-1).

The importance of DBP and DBP precursor control at WWTPs has been growing in recent years for several reasons. First, the type of precursors formed through biological wastewater treatment are complex and, although overlapping with, are in many ways dissimilar from the natural organic matter (NOM)-derived precursors of drinking water-based DBPs. For example, effluent organic matter (EfOM) is generally composed of NOM, synthetic organic compounds and soluble microbial products (SMP) (Doederer et al. 2014), the latter of which can be further decomposed into organic compounds generated during biological treatment processes including (but not limited to) humic and fulvic acids, polysaccharides, proteins, nucleic acids, organic acids, amino acids, structural components of cells and products of energy metabolism (Barker and Stuckey 1999). Given this potential chemical diversity, lessons learned in drinking water DBP formation prediction and control are not directly translatable (Drewes and Croue 2002; L. Tang et al. 2012).

In addition to precursor complexity, there has been increasing concern over emerging and more toxic nitrogenous DBPs such as nitrosamines, halonitroalkanes, haloacetonitriles (HANs) and haloacetamides (Westerhoff and Mash 2002; Joo and Mitch 2007; Lee et al. 2007). Haloacetamides and HANs in particular are approximately two orders of magnitude more cytotoxic and genotoxic than the regulated THMs and HAAs (Muellner et al. 2007; Plewa and Wagner 2009). The precursors for these nitrogenous DBPs are mostly dissolved organic nitrogen (DON) compounds, which are removed to varying degrees depending on the type of treatment process utilized. Secondary effluents are particularly rich in DON (Huang et al. 2016), which can be removed to varying degrees through the addition of nitrification and denitrification biological nutrient removal (BNR) processes (Huo et al. 2013). However, in a study of an A2O (anaerobic, anoxic, oxic), AO (anaerobic, oxic) and MBR treatment, it was found that approximately half of wastewater-derived DON was of low molecular weight (capable of passing through a 1 kDa ultrafilter) which is not effectively removed by BNR processes (Huo et al. 2013). Moreover, the low molecular weight fraction that remains after biological treatment also tends to be hydrophilic, which is challenging for even chemical and physical methods to remove (Pehlivanoglu-Mantas and Sedlak 2008; Huo et al. 2013).

A further complication is the effect of nitrogen, ammonia in particular, on the reaction kinetics of chlorination and chloramination. For example, formation of halogenated DBPs like THMs and HAAs can be greatly reduced if free chlorine is minimized in the disinfection process (Krasner et al. 2009b). This is done by either using chloramines directly or maintaining the Cl_2/N (mass/mass) ratio below 10 so that any free chlorine is quenched by ammonia. Ironically however, this effective control of halogenated DBPs favors the formation of more toxic nitrogenous DBPs like NDMA, especially when applied to poorly nitrified (high DON) effluent (Krasner et al. 2008; Sedlak and Gunten 2011). Thus, the presence of precursors does not necessarily entail DBP formation, which further depends on site-specific operational characteristics like disinfection practices.

Last, DBP precursors formed in biological treatment processes can potentially be recalcitrant, as they are generally composed of cellular debris leftover from substrate metabolism and biomass decay (Barker and Stuckey 1999). Owing to this potential recalcitrance, there is evidence of persistence at least on the order of days, which is of relevance for a typical river indirect potable reuse scenario. In a multi-season survey of a river determined to be effluent dominated (determined through use of primidone, a conservative wastewater tracer), Krasner et al. (2008) documented the presence of EfOM-derived nitrogenous DBP precursors at downstream locations, including the intake of a water treatment plant, with concentrations that suggested dilution, not degradation, to be the primary attenuation mechanism. Results for carbonaceous precursors, which tend to be humic compounds, were masked by the naturally high humic content of the river water.

Given that the formation potential of DBPs is dependent upon numerous variables which can change daily, for purposes of this study, it was decided to use the formation potential (FP) of DBPs (DBPFP) as a more conservative indicator of the concentration of DBPs that could be formed by the various treatment configurations used in this study. Moreover, FP is determined using a standardized procedure, eliminating variability that may arise owing to different disinfection practices, allowing for a clearer distinction between the effects of different treatment approaches on precursor control. Accordingly, to characterize the effects of the nine Study configurations on DBP formation, a comprehensive dataset linking effluent water quality to DBPFP was used for this analysis (Krasner et al. 2008). The DBP and DBP groups included in the study included the regulated carbonaceous DBPs (THMs and HAAs) along with emerging and more toxic carbonaceous and nitrogenous DBPs and are outlined in Table D-1. The general approach is discussed further below.

Table D-1. Summary of Regulated Disinfection Byproducts

DBP (group/compound)	Characteristics	Precursors	Limit	Regulatory Authority
Trihalomethanes (THM)[1,2]				
Chloroform	carbonaceous, halogenated	influent refractory NOM, EfOM, nitrified effluent, humic compounds	80 µg/L (TTHM)	U.S. EPA, Stage 1/2 DBP Rule
Bromodichloromethane (BDCM)				
Chlorodibromomethane (DBCM)				
Bromoform				
Haloacetic Acids (HAA)[2,3]				
Monochloroacetic acid	carbonaceous, halogenated	influent refractory NOM, EfOM, nitrified effluent, humic compounds	60 µg/L (HAA5)	U.S. EPA, Stage 1/2 DBP Rule
Dichloroacetic acid (DXAA)				
Trichloroacetic acid (TXAA)				
Bromoacetic acid				
Dibromoacetic acid				
Nitrosamines[4]				
N-nitrosodimethylamine (NDMA)	nitrogenous, unhalogenated	DON, dimethylamine	10 ng/L	CA (action level)
Aldehydes				
Formaldehyde	carbonaceous, halogenated	DON, amino acids	NA	NA
Acetaldehyde				
Chloroacetaldehyde				
Dichloroacetaldehyde				
Trichloroacetaldehyde (chloral hydrate)				
Haloacetonitriles (HANs)				
Chloroacetonitrile	nitrogenous, halogenated	DON, amino acids	NA	NA
Bromoacetonitrile				
Iodoacetonitrile				
Trichloroacetonitrile				
Bromodichloroacetonitrile				
Dibromochloroacetonitrile				
Tribromoacetonitrile				

[1] The four compounds together comprise the four primary trihalomethanes, sometimes referred to as TTHM or THM4

[2] (U.S. EPA 2015d)

[3] These five compounds together comprise the five primary haloacetic acids, sometimes referred to as HAA5

[4] California Department of Health Services, action level

D.2 Methods

The results of a comprehensive survey of the effluent DBPFP of 23 U.S. WWTPs (Survey) were used to construct multiple linear regression models (Models) for the prediction of DBPFP based on effluent water quality (Krasner et al. 2008; Krasner et al. 2009a). The Survey was conducted at WWTPs that utilize a range of common treatment technologies with differing abilities to control DBP precursors, including humic substances, amino acids and other organic nitrogen compounds. The treatment processes included oxidation ditch, aerated lagoon, trickling filter, activated sludge, nitrification/denitrification, soil aquifer treatment (SAT), powdered activated carbon (PAC) and granular activated carbon (GAC), MBR, RO and various combinations. A primary objective of the Survey was to establish a database of water quality and operational parameters that could be used to evaluate global and site-specific correlations between water quality and DBPFP.

In order to draw meaningful conclusions from the Survey, the authors divided the 23 WWTPs into nine general categories according to the dominant biological or physical treatment process. Figure D-1 shows the resulting water quality ranges of Survey categories (25th, 50th and 75th percentiles), along with effluent quality of the nine Study configurations plotted against their most similar Survey category. Although additional water quality parameters were measured in the Survey, only those relevant parameters (i.e. carbonaceous or nitrogenous) that were also defined for Study configurations (Table 1-4) were used in this analysis.

As can be seen from Figure D-1, although many Study configurations fit within the ~~second~~ first and third quartiles (between the 25th and 75th percentile of results) of at least one Survey category, some parameters fall outside of any range. This is especially true for COD, which is particularly important as a surrogate for carbonaceous DBP precursors. Accordingly, a direct translation of Survey categories to Study configurations is not fully appropriate. Therefore, a multiple linear regression modelling approach was used to estimate which water quality parameters were most appropriate for predicting DBPFP, and their approximate effect.

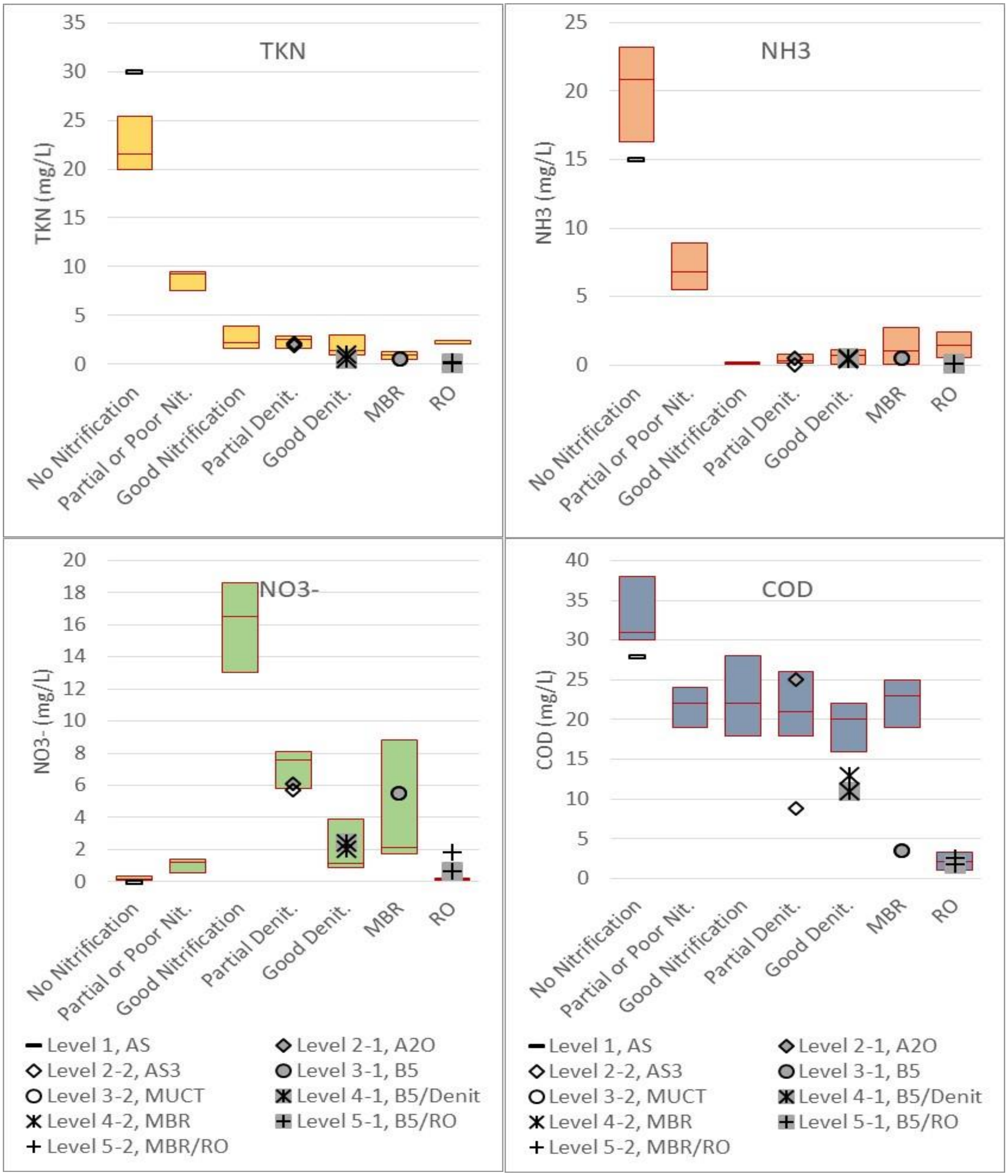


Figure D-1. Statistical summary of Survey category water quality, along with Study configuration water quality plotted within the most applicable Survey category. Ranges represent second and third quartiles, or 25th/50th/75th percentiles (Krasner et al. 2008; Krasner et al. 2009).

First, a linear correlation analysis was performed between relevant water quality parameters and DBPFP, using median values from each Survey category as input. Table D-2 shows the resulting correlations, in terms of the coefficient of determination (R^2). As shown, COD is the largest predictor of DBPFP for each DBP group, followed in most cases by TKN.

Table D-2. Linear Correlation Analysis between Median Water Quality Parameters and Median DBPFP for Survey Categories

DBPFP	Coefficient of Determination (R^2)			
	COD	TKN	NH_3	$NO3^-$
THMs	0.86	0.09	0.07	0.05
HANs	0.79	0.72	0.68	0.01
DXAAs	0.99	0.29	0.26	0.03
TXAAs	0.86	0.24	0.20	0.05
dihaloacetaldehydes	0.88	0.59	0.57	0.00
trihaloacetaldehydes	0.85	0.55	0.50	0.01
NDMA	0.73	0.18	0.20	0.00

Given the predictive ability of both COD and TKN especially, multiple linear regression models were constructed for each DBP group. Models were constructed in a stepwise fashion. Starting with COD as a single predictor, additional predictors were incorporated following the order of their coefficient of determination (Table D-2). Final Models reflect the combination of predictors that resulted in the greatest adjusted R^2. Although NH_3 was in many cases nearly as predictive as TKN, its contribution to overall model fit was generally less than TKN (i.e. the adjusted R^2 of models with COD and TKN were generally greater than that of models with COD and NH_3). Resulting Model coefficients, adjusted R^2 and overall significance (F) are provided in Table D-3. For DXAAs and TXAAs, COD alone provided the greatest predictive power (adjusted R^2). To illustrate the Models' predictive capabilities, Figure D-2 shows Model results using median water quality values for each Survey category as input, plotted against their actual DBPFP ranges (~~second~~ first and third quartiles). As shown, the Models are capable of predicting DBPFP within the 25th to 75th percentile ranges for most DBP categories, with the main exception of the Partial or Poor Nitrification and Good Nitrification categories for NDMA. Importantly however, the Models capture the low DBPFP provided by RO, which ultimately will provide for greater predictive capability in the water quality ranges not represented by Survey categories but occupied by many of the Study configurations (recall Figure D-1).

Table D-3. Multiple Linear Regression Model Parameters, Fit and Significance

DBP	Coefficient			Adjusted R^2	F (Signif.)
	COD	TKN	Intercept		
THMs	11.09	-3.68	3.66	0.89	0.005
HANs	0.59	0.58	-1.58	0.96	0.001
DXAAs	5.31		-4.15	0.99	0.000
TXAAs	4.57		-0.87	0.83	0.003
dihaloacetaldehydes	0.21	0.12	-0.63	0.95	0.001

Table D-3. Multiple Linear Regression Model Parameters, Fit and Significance

DBP	Coefficient			Adjusted R^2	F (Signif.)
	COD	TKN	Intercept		
trihaloacetaldehydes	2.30	1.19	-5.34	0.89	0.006
NDMA	27.92	-2.52	-13.65	0.60	0.072

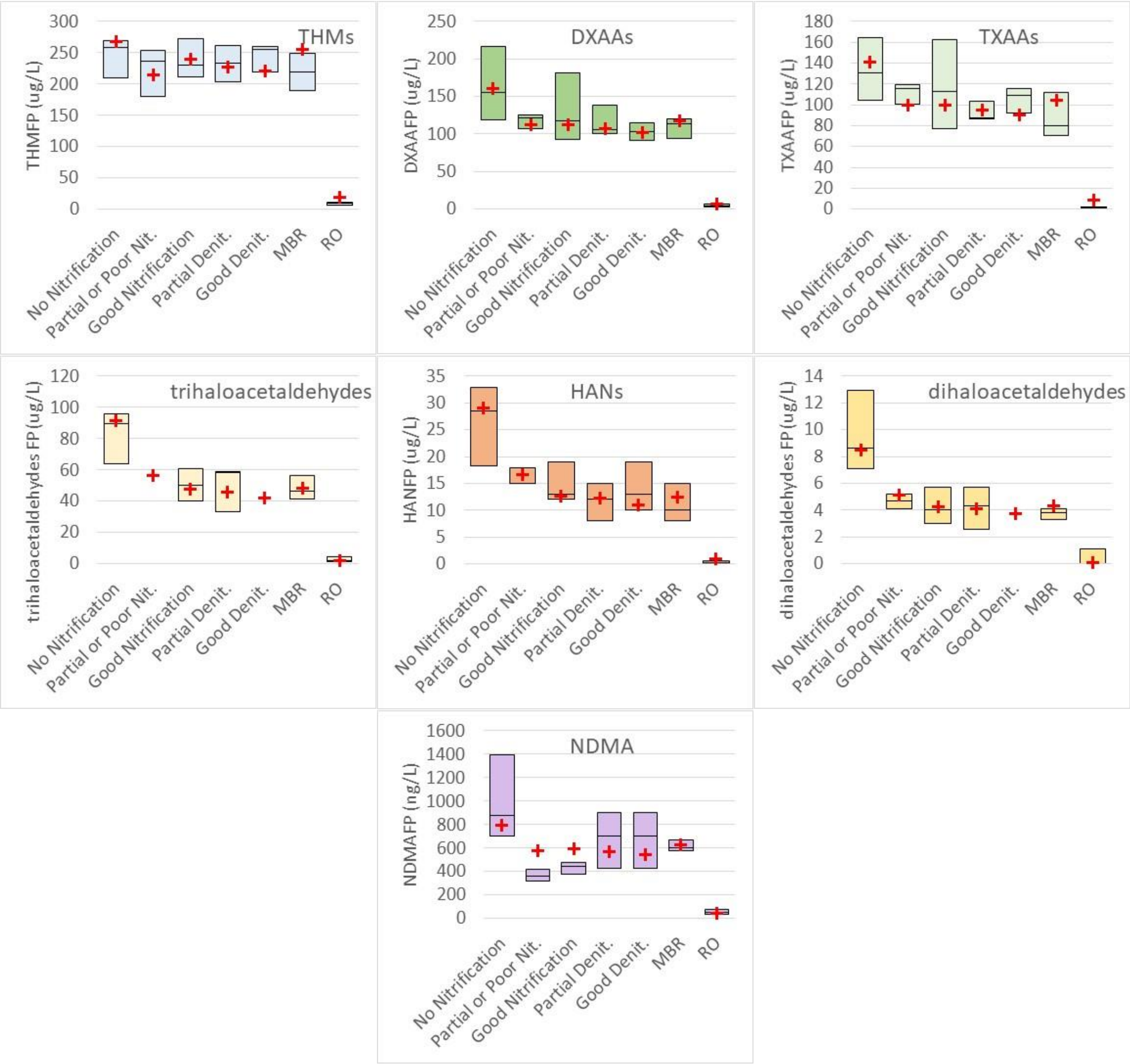


Figure D-2. Multiple linear regression model verification. Red crosses represent model results using median water quality values for each Survey category. DBPFP ranges represent second and third quartiles, or 25th/50th/75th percentiles (Krasner et al. 2008; Krasner et al. 2009a).

Table D-4 presents the characterization factors used to estimate toxicity impacts associated with DBPs in treatment plant effluent. Not all DBPs included in this study have associated characterization factors listed in the most recent versions of USEtox™, versions 2.02 and 2.11. Characterization factors that were not otherwise available were estimated using the median value of all other DBPs for which data was available. Sources for individual characterization factors are listed in Table D-4.

Table D-4. DBP Toxicity Characterization Factors, USEtox™ version 2.11

Chemical Name/Class	USEtox Chemical Name	Freshwater Ecotoxicity, (CTUe, PAF m^3.day/kg emitted)	Human Health cancer, freshwater (CTUh, cases/kg emitted)	Human Health noncancer, freshwater (CTUh, cases/kg emitted)
		Emissions to Freshwater		
trihalomethanes[a]	N/A[c]	90	5.2E-7	8.0E-7
haloacetonitriles	chloroacetonitrile	7.6E+3	3.6E-7[b]	4.5E-7[b]
dichloroacetic Acid	dichloroacetic acid	52	6.7E-7	1.1E-6
trichloroacetic acid	trichloroacetic acid	34	2.9E-7	4.5E-7[b]
dihaloacet-aldehydes	N/A[c]	1.9E+2[b]	3.6E-7[b]	4.5E-7[b]
trihaloacet-aldehydes	chloral hydrate	2.5E+2	3.6E-7[b]	4.5E-7[b]
nitrosamines	N-nitrosodimethylamine	25	7.9E-4	N/A

a – Average of trichloromethane/chloroform, bromodichloromethane, dibromochloromethane, and tribromomethane.

b – Estimated using the median of DBPs with available characterization factors.

c – Chemical is not present in the current USEtox™ LCIA method.

D.3 Results and Discussion

Table D-5 and Figure D-3 give Model results for the nine Study treatment configurations. Effluent COD and TKN values (Table 1-4) were used as input, along with coefficients and intercepts given in Table D-3.

Table D-5. DBPFP Model Results for Study Treatment Configurations

Study Configuration	THMs	HANs	DXAAs	TXAAs	dihaloacet-aldehydes	trihaloacet-aldehydes	NDMA
	µg/L						ng/L
Level 1, AS	204	32	145	127	8.8	95	692
Level 2-1, A2O	274	14	129	113	4.9	54	680
Level 2-2, AS3	95	4.9	43	40	1.5	18	230
Level 3-1, B5	41	0.78	14	15	0.16	3.3	83
Level 3-2, MUCT	41	0.78	14	15	0.16	3.3	83
Level 4-1, B5/Denit	124	5.2	54	49	1.7	21	292
Level 4-2, MBR	144	6.6	65	59	2.2	26	347
Level 5-1, B5/RO	23	0.01	5.4	7.4	0.01	0.01	36
Level 5-2, MBR/RO	32	0.07	10	11	0.01	0.87	58

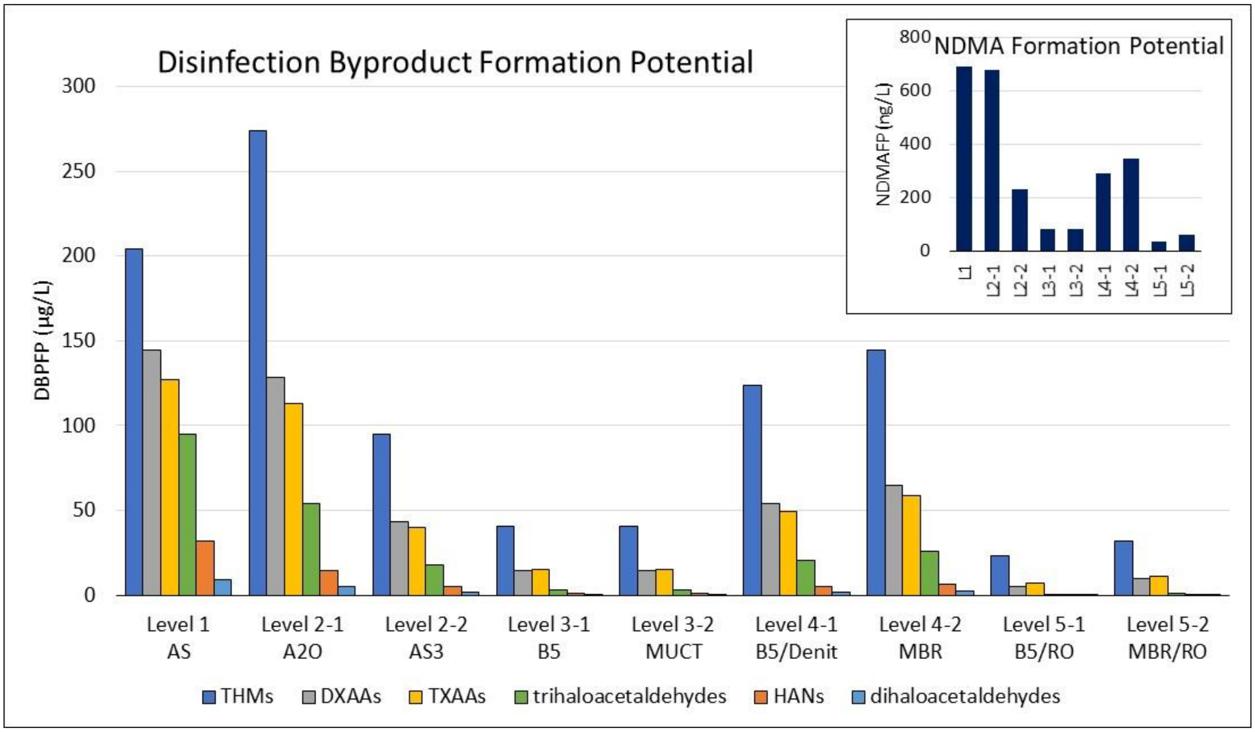


Figure D-3. DBPFP Model results for Study treatment configurations.

The formation potentials presented above are an upper bound to what could be formed at the WWTP. Using THMs as an example, ranges of THMs that actually formed at the surveyed WWTPs were also a function of chlorine dose and the Cl_2/N ratio. When the Cl_2/N ratio was above 10, allowing for the creation of free chlorine and enhanced THM formation, the 10th and 90th percentile concentrations of THMs were 20 µg/L and 80 µg/L, respectively (Krasner et al. 2009b). Compared to the formation potentials determined for each of the Survey groups (illustrated in Figure D-2) with medians largely in the range of 200-250 µg/L, this implies that upon discharge, there remains considerable additional formation potential in the form of unreacted precursors. Similarly, when the Cl_2/N ratio was less than 10, favoring chloramine creation and NDMA formation, the 10th and 90th percentile of observed concentrations of NDMA were 4 and 122 ng/L, compared to formation potentials that were sometimes an order of magnitude greater (also illustrated in Figure D-2). Thus, depending on factors like chlorination, temperature and pH (Doederer et al. 2014), which are assumed constant in Study configurations, formation of DBPs prior to discharge may be on the order of 10-50% of the formation potentials indicated above in Table D-5 and Figure D-3.

APPENDIX E
DETAILED COST METHODOLOGY

Appendix E: Detailed Cost Methodology

Appendix E includes supporting details for the methodology used to estimate costs associated with the nine wastewater treatment configurations. Appendix E.1 presents the unit design values for the unit processes included in CAPDETWorks^{TM}. Appendices E.2, E.4, B.4, E.6, and E.7 present the detailed cost methodologies for the dechlorination, ultrafiltration, reverse osmosis, and deep well injection, respectively. Appendix E.8 presents the CAPDETWorks™ file used to develop the direct cost factors discussed in Section 3.3.1.

E.1 CAPDETWorks™ Process Unit Design Values

This appendix includes the initial CAPDETWorks™ design values for the unit processes included in the nine wastewater treatment configurations. As discussed in Section 3.2.2, ERG revised some of the design values during development of the CAPDETWorks™ models to achieve the effluent wastewater objectives for each treatment level and/or address warnings in the CAPDETWorks^{TM}. For example, CAPDETWorks™ calculates the number of mixers for the Biological Nutrient Removal 3/5 Stage and provides a warning if the horsepower (HP) per mixer exceeds the CAPDETWorks™ recommended 5 HP/mixer. In this instance, ERG increased the number of mixers to eliminate the warning so the design reflected all of the equipment necessary. The final design values used for each wastewater treatment configuration are included in the final CAPDETWorks™ cost output discussed in Section 5. The following unit processes are not in CAPDETWorks^{TM}: modified University of Cape Town, 4-stage Bardenpho, fermentation, ultrafiltration, reverse osmosis (including pretreatment), deep well injection for brine disposal, and dechlorination. Costs for these unit processes were developed outside of CAPDETWorks™ and are documented in Sections 3.2.3.1 through 3.2.3.7 of this report.

ERG reviewed *EPA's Municipal Nutrient Removal Technologies Reference Document (U.S. EPA OWM, 2008b), WERF's Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability* (Falk, 2011), EPA/ORD's Nutrient Control Design Manual (U.S. EPA ORD, 2010), and additional EPA wastewater treatment process fact sheets to confirm that the CAPDETWorks™ default design values (Hydromantis, 2014) are appropriate for use for this study. Based on our review, ERG used the CAPDETWorks™ default design values for the unit processes below that are included in one or more of the wastewater treatment configurations. Appendix E.1.14 includes key parameters and the default design values for these unit processes (Hydromantis, 2014).

- Membrane Bioreactor
- Sand Filter
- Centrifugation – Sludge

The remainder of Section E.1 provides the initial design values used for each of the remaining CAPDETWorks™ unit processes included in the nine wastewater treatment configurations.

E.1.1 Preliminary Treatment – Screening and Grit Removal

The default Preliminary Treatment design values were used. Key parameters and default design values for Preliminary Treatment – Screening include:

- Cleaning Method: Mechanically Cleaned

Key parameters and default design values for Preliminary Treatment – Grit Removal include:

- Type of Grit Removal: Horizontal
- Number of Units: 2
- Volume of Grit: 4.0 ft^3/MGal
- Detention Time: 2.5 min

However, the resulting purchased equipment costs were about half the construction costs presented in *Wastewater Technology Fact Sheet – Screening and Grit Removal* (U.S. EPA, 2003b). As a result, ERG doubled the CAPDETWorks^{TM} Preliminary Treatment purchased equipment costs for all nine wastewater treatment configurations.

E.1.2 Primary Clarifier

The default Primary Clarifier design values were modified as follows, as recommended in *Wastewater Engineering: Treatment and Resource Recovery* (Tchobanoglous et al., 2014):

- Sidewater depth: 12.0 ft (instead of 9.0 ft)
- Underflow concentration: 3.5% (instead of 4.0%)

Note that this sidewater depth and underflow concentration are within CAPDETWorks^{TM}'s recommended ranges (7-12 ft and 3-6%, respectively) (Hydromantis, 2014).

Additional key parameters and default design values for Primary Clarifier include:

- Type of Clarifier: Circular
- Surface Overflow Rate: 1,000 gal/ft2-d
- Weir Overflow Rate: 15,000 gal/ft-d
- Suspended Solids Removal: 58%
- BOD Removal: 32%
- COD Removal: 40%
- TKN Removal: 5%
- Phosphorous Removal: 5%

E.1.3 Plug Flow Activated Sludge

Because the Level 1 wastewater treatment configuration represents a system that is not designed for nitrogen removal, and Level 2-2 requires higher effluent ammonia levels for the subsequent nitrification/denitrification processes, the default Plug Flow Activated Sludge design values was modified as follows:

- Process Design: Carbon Removal Only (instead of default Carbon Plus Nitrification)

Additional key parameters and default design values for Plug Flow Activated Sludge include:

- Aeration Type: Diffused Aeration
- Bubble Size: Fine Bubble
- Solids Retention Time (SRT): 10 days
- Mixed Liquor Suspended Solids (MLSS): 2,500 mg/L

E.1.4 Biological Nutrient Removal 3/5 Stage

When used for the Anaerobic/Anoxic/Oxic (A2O) unit process in Level 2-1, the default Biological Nutrient Removal 3/5 Stage design values were modified as follows:

- Number of Stages: 3-Stage (instead of 5-Stage)
- Internal Recycle from Anoxic to Anaerobic Zone: No (the A2O process does not include this recycle)
- Internal Recycle from the Oxic to Anoxic Zone: Yes
- Assume sufficient carbon in the wastewater to denitrify without an additional carbon source
- Effluent Total Kjeldahl Nitrogen (TKN): modified to achieve the 8 mg/L target effluent total nitrogen (TN) concentration
- Effluent Total Phosphorous (TP): modified to achieve the 1 mg/L target effluent TP concentration

When used for the 5-Stage Bardenpho unit process in Levels 3-1, 4-1, 5-1, and 5-2, the default Biological Nutrient Removal 3/5 Stage design values were modified as follows:

- Number of Stages: 5-Stage (instead of 3-Stage)
- Internal Recycle from Anoxic to Anaerobic Zone: No
- Internal Recycle from the Oxic to Anoxic Zone: Yes
- Effluent TKN: modified to achieve the target effluent total nitrogen concentrations of:
  - Level 3-1: 4–8 mg/L TN
  - Level 4-1: 3 mg/L TN

  - Levels 5-1 and 5-2: 2 mg/L TN
- Effluent TP: modified to achieve the target effluent total phosphorous concentrations of:
  - Level 3-1: 0.1–0.3 mg/L TP
  - Level 4-1: 0.1 mg/L TP
  - Levels 5-1 and 5-2: <0.2 mg/L TP

In addition to the specific modifications proposed above, for instances when CAPDETWorks™ provided a warning that the number of mixers was insufficient for each mixer to be less than 5 HP/mixer, the CAPDETWorks™ default number of mixers per tank was increased until the mixers were less than 5 HP/mixer.

Additional key parameters and default design values for Biological Nutrient Removal 3/5 Stage include:

- Aeration Type: Diffused Aeration
- Bubble Size: Fine Bubble
- Total Reactor SRT: 15 days

E.1.5 Denitrification – Suspended Growth

The default Denitrification – Suspended Growth design values were modified for effluent nitrate to achieve the effluent total nitrogen concentration target for Level 2-2 of 8 mg/L TN.

In addition to the specific modifications proposed above, for instances when CAPDETWorks™ provided a warning that the number of mixers was insufficient for each mixer to be less than 5 HP/mixer, the CAPDETWorks™ default number of mixers per tank was increased until the mixers were less than 5 HP/mixer.

Additional key parameters and default design values for Denitrification – Suspended Growth include:

- Design SRT: 10 d
- MLSS: 2,500 mg/L

E.1.6 Denitrification – Attached Growth

The default Denitrification – Attached Growth design values were modified as follows:

- Allowable Effluent Nitrate:
  - Level 4-1: 3 mg/L TN
  - Levels 5-1 and 5-2: <0.02 mg/L TN (taking into consideration the RO TN removal)
- Application Rate: 1.5 gal/ft^2-min (instead of 1.0 gal/ft^2-min)

The recommended application rate matches that used in the analysis in WERF's *Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability* (Falk, 2011) and is more aligned with actual plant application rates of 2.2 and 3.0 gal/ft^2-min, as presented for two plants in the *Municipal Nutrient Removal Technologies Reference Document* (U.S. EPA OWM, 2008b). Note that this application rate is outside of CAPDETWorks^{TM}' recommended range (0.5 to 1.0 gal/ft^2-min). ERG reviewed the underlying cost curves for CAPDETWorks^{TM}' construction and O&M costs and considers the outputs to be reasonable at the 1.5 gal/ft^2-min application rate.

Additional key parameters and default design values for Denitrification – Attached Growth include:

- Methanol Requirement: 3 lb/lb NO_3
- Backwash Rate: 12 gal/ft^2-min

E.1.7 Nitrification – Suspended Growth

Because SRT is a key factor for achieving nitrification, the default Nitrification – Suspended Growth design values were modified as follows for the reasons described below:

- Design Basis: Specify Design SRT (instead of default Temperature Specific Growth Rates or pH Ammonia Sensitive Rates)
- Design SRT: 50 d (instead of 10 d)

Note that using a design basis that specifies the default Temperature Specific Growth Rates returned a unit design with a SRT of 5.89 hrs and hydraulic residence time (HRT) of 1.27 hrs, well below recommended SRT and HRT values[12]. Using a SRT of 24 d and the default MLSS of 2,500 mg/L returns a unit design with a HRT of 3.11 hrs, which is still below CAPDETWorks™ recommended minimum. A SRT of 50 d and the default MLSS of 2,500 mg/L returns a unit design with a HRT of 6.31 hours. These values are similar to those of the Western Branch WWTP with a 3-sludge system designed to achieve 1.0 mg/L effluent TP and 3.0 mg/L effluent TN. The Western Branch WWTP has nitrifying activated sludge system SRT ranging from 21.4 days (June) to 84.6 days (September), with an average of 47.6 days (U.S. EPA OWM, 2008b). As a result, ERG's recommended 50 d design SRT is reasonable.

Additional key parameters and default design values for Nitrification – Suspended Growth include:

- Aeration Type: Diffused Aeration
- Bubble Type: Fine Bubble
- MLSS: 2,500 mg/L

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[12] A SRT of 24 days is recommended for general nitrification systems from *Municipal Nutrient Removal Technologies Reference Document* (U.S. EPA OWM, 2008b) and a minimum HRT of 6 hrs from CAPDETWorks^{TM} (Hydromantis, 2014).

E.1.8 Chemical Phosphorus Removal

The default effluent phosphorus concentration target for each level that includes chemical phosphorous removal was adjusted to achieve the following effluent total phosphorous concentration targets:

- Level 2-2: 1 mg/L TP
- Levels 3-1 and 3-2: 0.3 mg/L TP
- Levels 4-1, 4-2, 5-1, and 5-2: 0.1 mg/L TP (remaining TP to achieve <0.02 mg/L effluent target for Level 5 configurations will be achieved with RO)

In addition, ERG revised the default chemical dosage to two times the stoichiometric alum dose, as recommended by the *Municipal Nutrient Removal Technologies Reference Document* (U.S. EPA OWM, 2008b).

Additional key parameters and default design values for Chemical Phosphorous Removal include:

- Metal Precipitant: Equivalent Aluminum

E.1.9 Secondary Clarifier

The default Secondary Clarifier design values were modified as followed:

- Surface overflow rate: 600 gal/ft^2-d (instead of 500 gal/ft^2-d)
- Sidewater depth: 14.5 ft (instead of 9.0 ft)

The surface overflow rate was modified to match WERF's *Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability* (Falk et al, 2011). Note that this surface overflow rate is within CAPDETWorks^{TM}' recommended range (200 to 800 gal/ft^2-day) (Hydromantis, 2014). CAPDETWorks^{TM}' background documentation generally describes that lower overflow rates are more appropriate for smaller plants and higher overflow rates are more appropriate for larger plants (Hydromantis, 2014). The sidewater depth and underflow concentrations were modified to within ranges recommended in *Wastewater Engineering: Treatment and Resource Recovery* (Tchobanoglous et al., 2014). Note that the sidewater depth is within CAPDETWorks^{TM}'s recommended ranges (7-15 ft) (Hydromantis, 2014).

Additional key parameters and default design values for Secondary Clarifier include:

- Underflow concentration: 1%
- Weir Overflow Rate – Maximum 15,000 gal/ft-d
- Effluent Suspended Solids: 20 mg/L

E.1.10 Chlorination

Chlorination using liquid hypochlorite is more common that gaseous chlorine due to safety concern and regulations on the handling and storage of pressurized liquid chlorine (Tchobanoglous et al., 2014). However, this analysis assumes use of gaseous chlorine because that is the only disinfection alternative used by CAPDETWorks^{TM} (Hydromantis, 2014).

When used for wastewater treatment configurations where solids removal is completed with clarifiers (Level 1, Level 2-1, and Level 2-2), the default Chlorination design values were modified as follows:

- Contact Time at Peak Flow: 30 min
- Chlorine Dose: 10 mg/L

When used for wastewater treatment configurations where solids removal is completed with a sand filter or membrane bioreactor (Level 3-1, Level 3-2, Level 4-1, and Level 4-2), the default Chlorination design values were modified as follows:

- Contact Time at Peak Flow: 30 min
- Chlorine Dose: 8 mg/L

When used for wastewater treatment configurations with the majority of the flow going through reverse osmosis (Level 5-1 and Level 5-2), the default Chlorination design values were modified as follows:

- Contact Time at Peak Flow: 30 min
- Chlorine Dose: 5 mg/L

ERG developed these design input value recommendations based on consideration of CAPDETWorks™ default design values (Hydromantis, 2014) and assumptions provided in *Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability* (Falk et al, 2011), which were further supported based on an evaluation of design information provided in EPA’s *Onsite Wastewater Treatment Systems Manual* (EPA, 2002).

E.1.11 Gravity Thickener

The default Gravity Thickener design values were modified as follows:

- Based On: Mass Loading (instead of Settling)
- Mass Loading: 30 lb/ft^2-d (instead of 10 lb/ft^2-d)
- Underflow Concentration: 4.0% (instead of 5.0%)
- Depth: 11.5 ft (instead of 9 ft)
- Standard 90 ft Diameter Thickener: $1,000,000 (instead of $154,000)

Note that using the default Settling design basis returned a unit design with a HRT of 20.3 hr, well above recommended HRT values (maximum HRT of 6 hrs from CAPDETWorks™ (Hydromantis, 2014)). As a result, ERG used CAPDETWorks™ maximum recommended mass loading rate rather than the default design value of 10 lb/ft^2-d to reduce the gravity thickener HRT and the risk of creating anaerobic conditions that can lead to phosphorous release from the sludge. Using the recommended mass loading results in a HRT of 6.78 hrs, which is reasonable compared to CAPDETWorks™ recommended 6 hr maximum (Hydromantis, 2014).

The underflow concentration was modified to within the range in *Wastewater Engineering: Treatment and Resource Recovery* (Tchobanoglous et al., 2014). The depth was modified to within the range recommended in *Biosolids Technology Fact Sheet – Gravity Thickening* (U.S. EPA, 2003a). The standard 90 ft diameter thickener cost was modified to $1,000,000 so the gravity thickener purchased equipment cost was comparable to the costs in *Biosolids Technology Fact Sheet – Gravity Thickening* (U.S. EPA, 2003a).

E.1.12 Anaerobic Digestion

The default Anaerobic Digestion design values were modified to match the Gravity Thickener underflow concentration (see Section E.1.11) as follows:

- Concentration in Digester: 4.0% (instead of 5.0%)

Note that this concentration in digester is within CAPDETWorks™’ recommended range (3 to 7%) (Hydromantis, 2014).

Additional key parameters and default design values for Anaerobic Digestion include:

- Percent Volatile Solids Destroyed: 50%
- Minimum Detention Time in Digester: 15 d
- Fraction of Influent Flow Returned as Supernatant: 2%
- Supernatant Concentrations:
    - Suspended Solids: 6,250 mg/L
    - BOD: 1,000 mg/L
    - COD: 2,150 mg/L
    - TKN: 950 mg/L
    - Ammonia: 650 mg/L

E.1.13 Haul and Landfill - Sludge

ERG modified the following default design values as follows to correspond with the 25 mi one-way distance used in the ORCR CCR rule (ERG, 2013):

- Distance to Disposal Site: 25 mi one way

- Disposal Cost Based On: Sludge Disposal per Ton

E.1.14 Key Default Design Parameters for Select Unit Processes

Membrane Bioreactor

Key parameters and default design values for Membrane Bioreactor include:

- Average Net Flux: 20 L/m2-hr
- Effluent Suspended Solids: 1.0 mg/L
- Underflow Concentration: 1.2%
- Scour Air Cycle Time: 20 s
- Scour Air On Time: 10 s
- Physical Cleaning Interval: 9 min
- Physical Cleaning Duration: 1 min
- Chemical Cleaning Interval: 7 days
- Backflush Flow Factor: 1.25

Sand Filter

Key parameters and default design values for Sand Filter include:

- Number of Layers: 4
- Layer 1: Anthracite
- Layers 2, 3, and 4: Sand
- Loading Rate: 6 gpm/ft^2
- Backwash Time: 10 min

Centrifugation – Sludge

Key parameters and default design values for Centrifugation – Sludge include:

- Cake Solids Content: 9%
- Solids Capture: 90%
- Number of Units: 2
- Operation: 8 hr/d for 5 d/wk

E.2 Dechlorination

Listed below are the capital cost elements included for dechlorination using sodium bisulfite ($NaHSO_3$), with a general description of the basis of estimate, followed by the O&M cost elements and the basis of estimate.

Capital Costs

1. Dechlorination Contact Tank, Dechlorination Building, Chemical Storage Building, and Miscellaneous Items (e.g., grass seeding, site cleanup, piping).

   Costed in 2014 $ using the CAPDETWorks™ chlorination unit process and selecting unit process input values to simulate dechlorination rather than chlorination.

   - Revised the CAPDETWorks™ input contact time at peak flow to 5 minutes to reflect the dechlorination unit contact time:
     - CAPDETWorks™ uses the contact time at peak flow to calculate the contact tank volume (Hydromantis, 2014).
     - EPA’s Wastewater Technology Fact Sheet – Dechlorination recommends dechlorination contact times of one to five minutes to react with free chlorine and inorganic chloramines (U.S. EPA, 2000). ERG selected five minutes to ensure adequate dechlorination prior to discharge.
   - Revised the CAPDETWorks™ input chemical dose to 3.75 mg/L to reflect the sodium bisulfite solution dose:
     - CAPDETWorks™ uses the chemical dose to size the chemical feed storage building (Hydromantis, 2014).
     - ERG selected the input chlorine dose for each wastewater treatment configuration to achieve approximately 1 mg/L residual chlorine. Specifically, for the chlorination unit process, ERG used 10 mg/L for Levels 1, 2-1, and 2-2; 8 mg/L for levels 3-1, 3-2, 4-1, and 4-2; and 5 mg/L for Levels 5-1 and 5-2 (see Appendix E.1.8).
     - EPA’s Wastewater Technology Fact Sheet – Dechlorination indicates that, on a mass basis, 1.46 parts of sodium bisulfite is required to dechlorinate 1.0 parts of residual chlorine (U.S. EPA, 2000), which ERG rounded to 1.5 parts of sodium bisulfite. Assuming a 40% by weight sodium bisulfide in solution results in a sodium bisulfite dose of 3.75 mg/L, as presented in Equation E-1.

$$3.75\ \mathrm{NaHSO_3}\ 40\%\ \mathrm{Solution}\ \left(\frac{\mathrm{mg}}{\mathrm{L}}\right) = 1.5\ \mathrm{NaHSO_3}\ 100\%\ \mathrm{Solution}\ \left(\frac{\mathrm{mg}}{\mathrm{L}}\right) \times \frac{100\%\ \mathrm{NaHSO_3\ Solution}}{40\%\ \mathrm{NaHSO_3\ Solution}}$$

Equation E-1

2. Sodium Bisulfite Liquid Feed System
    - See Table E-1 for calculation of sodium bisulfite liquid feed rates for each wastewater treatment configuration.
    - For sodium bisulfite liquid feed rates less than 100 gph, purchase cost of $5,000, plus $300 for transport, in 2011 $, based on telephone contact with EnPro Technologies (ERG, 2011b). Escalated to 2014 $ using RSMeans Construction Cost Index and the calculation presented in Section 3.2.1 (RSMeans, 2017).
    - Used the installation factor of 0.3 from CAPDETWorks™ for the installation of the dechlorination system to account for installation and other costs such as electrical, piping, painting, etc. associated with the sodium bisulfite system (Hydromatis, 2014).

3. Total capital costs were estimated by applying the CAPDETWorks™ direct and indirect cost factors to the purchase costs, using the factors and methodology described in Section 3.3 of this report.

Table E-1. Sodium Bisulfite Liquid Feed Rate Calculation

Level	$NaHSO_3$Rate (gph) =	Sodium Bisulfite Dose (mg/L)	× Gram to Milligram Factor (g/mg)	× $NaHSO_3$ Dose Factor (calculated in Table E-2)	× Estimated Wastewater Treatment Flow (MGD)	× 1,000,000 gal/Mgal	× Day to Hour Factor (day/hr)
Level 1	2.6	3.8	1.0E-3	1.7E-3	10	1.0E+6	0.04
Level 2-1	2.6	3.8	1.0E-3	1.7E-3	10	1.0E+6	0.04
Level 2-2	2.6	3.8	1.0E-3	1.7E-3	10	1.0E+6	0.04
Level 3-1	2.6	3.8	1.0E-3	1.7E-3	10	1.0E+6	0.04
Level 3-2	2.6	3.8	1.0E-3	1.7E-3	10	1.0E+6	0.04
Level 4-1	2.6	3.8	1.0E-3	1.7E-3	10	1.0E+6	0.04
Level 4-2	2.6	3.8	1.0E-3	1.7E-3	10	1.0E+6	0.04
Level 5-1	4.3	7.5	1.0E-3	1.7E-3	8.2	1.0E+6	0.04
Level 5-2	4.4	7.5	1.0E-3	1.7E-3	8.3	1.0E+6	0.04

Table E-2. Sodium Bisulfite Dose Factor Calculation

$NaHSO_3$ Dose Factor =	1	/ (NaHSO3 Concentration (%)	× NaHSO3 Density (kg/L)	× 1,000 g/kg)
0.00168919	1	0.4	1.48	1000

E.3 Annual Costs

1. Operating Labor, Maintenance Labor, Materials and Supplies[13]
   - Costed in 2014 $ using the CAPDETWorks™ chlorination unit process to simulate dechlorination rather than chlorination.
   - Revised the CAPDETWorks™ input contact time at peak flow to 5 minutes and chemical dose to 3.75 mg/L to reflect the dechlorination unit contact time and dose (see justification in the Capital Cost section item #1).

2. Energy
   - One 0.5 HP feed system pump operated continuously for a calculated annual electrical requirement of approximately 6,500 kWh/yr (ERG, 2011b).
   - Using the CAPDETWorks™ energy rate of $0.10/kWh (2014 $) (Hydromantis, 2014), total energy costs are approximately $650/yr.

3. Sodium Bisulfite
   - Calculated using:
     - Dosage rate of:
       - 1.5 mg/L for Levels 1, 2-1, 2-2, 3-1, 3-2, 4-1, and 4-2 (see justification in the Capital Cost section #1)
       - 3.0 mg/L for Levels 5-1 and 5-2 to also account for the chemicals required for RO pretreatment.[14]
     - Effluent flow rate from the chlorination unit process for each wastewater treatment configuration modeled in CAPDETWorks™.
   - Assumed a 40% by weight sodium bisulfide in solution.
   - Chemical cost of $344/ton of 40% sodium bisulfide solution in 2010 $ (ERG, 2014). This cost includes freight and assumes the chemical will be delivered in drums or totes. Escalated to 2014 $ using RSMeans Construction Cost Index (RSMeans, 2017.

E.4 Methanol Addition

Listed below are the capital cost elements included for dechlorination using sodium bisulfite ($NaHSO_3$), with a general description of the basis of estimate, followed by the O&M cost elements and the basis of estimate.

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[13] Materials and supplies include materials and replacement parts required to keep the facilities in proper operating conditions.

[14] The RO system requires 1 mg/L chlorine pretreatment and a corresponding sodium bisulfite dechlorination. ERG assumed the majority of the 1 mg/L chlorine would remain as chlorine residual. Therefore, the dechlorination sodium bisulfite dose is 1.5 mg/L neat. Capital costs for the RO pretreatment sodium bisulfite system are included in Appendix E.5.

Capital Costs

1. Methanol Storage Tank, Feed Pump, Control System, and Miscellaneous Items (e.g., piping).

   Costed in 2014 $ using the CAPDETWorks^{TM} denitrification – attached growth (i.e., denitrification filter) unit process that includes methanol addition. Selected unit process input values to match the required nitrate reduction and used only the output associated with the methanol system.

   - Revised the CAPDETWorks^{TM} influent wastewater average and minimum flow rates to 10.1 MGD and maximum flow rate to 20.1 MGD to match the influent flow rates for the 4-stage Bardenpho. CAPDETWorks^{TM} uses the influent wastewater flow rates to calculate the methanol system capital cost (Hydromantis, 2014).
   - Revised the CAPDETWorks^{TM} influent nitrate concentration to 8.24 mg/L to match the effluent from the 4-stage Bardenpho and the denitrification – attached growth input allowable effluent nitrate to 1.95 mg/L to match the necessary effluent nitrate concentration to achieve 3 mg/L total nitrogen (TKN effluent is 1.05 mg/L) for Level 4-2, MBR. CAPDETWorks^{TM} uses the difference between the influent and allowable effluent nitrate concentration to calculate the methanol feed rate, which is used to calculate the methanol system capital cost (Hydromantis, 2014).

2. Methanol feed system cost (2014 $) from the CAPDETWorks^{TM} output were added to the 4-stage Bardenpho capital costs for the Level 4-2, MBR.

3. Total capital costs for the 4-stage Bardenpho were estimated by applying the CAPDETWorks™ direct and indirect cost factors to the purchase costs, using the factors and methodology described in Section 3.3 of this report.

Annual Costs

1. Operating Labor, Maintenance Labor, Materials and Supplies[15], and Energy
   - CAPDETWorks^{TM} does not calculate costs for operating labor, maintenance labor, materials and supplies, and energy for the methanol feed system separately from the denitrification – attached growth unit process. As a result, assumed the 4-stage Bardenpho operating labor, maintenance labor, materials and supplies, and energy include costs for the methanol feed system.
2. Methanol
   - CAPDETWorks^{TM} calculates the methanol cost based on the influent nitrate and allowable effluent nitrate concentrations, as discussed in the

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[15] Materials and supplies include materials and replacement parts required to keep the facilities in proper operating conditions.

Capital Costs section above. Used the default methanol cost of \$0.60/lb from CAPDETWorks™.

E.5 Ultrafiltration

Listed below are the capital cost elements included for ultrafiltration, with a general description of the basis of estimate, followed by the O&M cost elements and the basis of estimate. Table E-3 and Table E-4 summarize the capital and O&M cost calculations, respectively.

Capital Costs

1. Membrane Filtration System – cost basis obtained from email contacts with Evoqua Water Technologies LLC, 2015 (ERG, 2015a). Escalated to 2014 \$ using RSMeans Construction Cost Index (RSMeans, 2017). For a 9 MGD system for this project[16], purchase costs for membrane equipment and appurtenances are approximately \$3.7 million. Total capital costs were estimated by applying the CAPDETWorks™ installation factor, and direct and indirect cost factors, to the purchase costs, after incorporating the purchase costs into the CAPDETWorks™ outputs.
2. Membrane Filtration Building – using equipment dimensions provided by Evoqua (ERG, 2015a), calculated a required building footprint of 8,040 square feet to house the system. Using the CAPDETWorks™ building unit cost of \$110/square foot, calculated a total capital building cost of approximately \$880,000.

Operating and Maintenance Costs

1. Operating Labor – transferred the operating labor costs from reverse osmosis (RO) (see Appendix E.6).
2. Maintenance Labor – transferred the operating labor costs from RO (see Appendix E.6).
3. Materials – membrane replacement cost of \$1,650 per membrane times an estimated 768 membranes for a 9 MGD system based on Evoqua (ERG, 2015a). Assumed membranes have a 7-year life based on Evoqua (ERG, 2015a). Escalated to 2014 \$ using RSMeans Construction Cost Index (RSMeans, 2017). Calculated materials costs of approximately \$240,000/yr.
4. Chemicals – membrane cleaning chemical costs estimated using chemical usage rates and costs per Evoqua (ERG, 2015a) and a \$0.03/lb freight cost from FreightCenter.com (ERG, 2011a), which were escalated to 2014 \$ using RSMeans Construction Cost Index (RSMeans, 2017), resulting in a total annual chemicals cost of approximately \$91,000/yr. Cleaning chemicals include citric acid, sodium hypochlorite, sulfuric acid, sodium hydroxide, and sodium bisulfite.

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[16] Based on side stream treatment of 90 percent of the 10 MGD flow for Level 5-1 5-Stage Bardenpho with Sidestream Reverse Osmosis.

5. Energy – energy usage equal to the average of estimates provided by two sources:
   - Evoqua (ERG, 2015a) estimated energy usage of 0.5 kWh/kgal
   - WateReuse Research Foundation, 2014 estimated energy usage ranging from 0.75 to 1.1 kWh/kgal (average of 0.925 kWh/kgal)

   Used the average of the average estimated energy usage from these two sources, 0.7125kWh/kgal (average of 0.5 kWh/kgal and 0.925 kWh/kgal). For a 9 MGD system, and using the CAPDETWorks™ energy rate of $0.10/kWh (2014 $), total annual energy costs are approximately $230,000.

Table E-3. Ultrafiltration Capital Costs

Equipment Cost Item	Size or Number	Units	Unit Cost	Total Cost	Year	2014 Purchased Cost	Total Capital Cost	Source
Ultrafiltration	9	MGD		$3,750,000	2015	$3,717,344		Evoqua (ERG, 2015a).
Ultrafiltration Building	8,040	sq. foot	$110	$884,400	2014		$884,400	Evoqua, 2015; building unit cost from CAPDETWorks™.

Table E-4. Ultrafiltration Operating and Maintenance Costs

Operating Labor	Labor (hrs/day)	Labor Rate ($/hr)	Days/yr	Annual Operating Labor Cost ($/yr)	Source
Ultrafiltration	1	$51.50	365	$18,798	Evoqua (ERG, 2015a); transferred 1 hour/day operating labor from RO (see Table B.4-3); labor rate from CAPDETWorks™ for Operator.
Maintenance Labor	**Labor (hrs/day)**	**Labor Rate ($/hr)**	**Days/yr**	**Annual Maintenance Labor Cost ($/yr)**	**Source**
Ultrafiltration	1	$51.50	365	$18,798	Evoqua (ERG, 2015a); transferred 1 hour/day maintenance labor from RO (see Table B.4.3); labor rate from CAPDETWorks™ for Operator.
Material	**Annual Materials Cost ($/yr)**				**Source**
Membrane Replacement	$124,473				Evoqua (ERG, 2015a).

Table E-5. Ultrafiltration Operating and Maintenance Costs

Membrane Cleaning Chemicals	Usage (gal/yr)	Cost ($/gal)	Annual Chemicals Cost ($/yr)	Source
50% Citric Acid	4,551	$10.41	$47,369	Evoqua (ERG, 2015a); freight per FreightCenter.com (ERG, 2011a).
50% Sulfuric Acid	2,891	$4.56	$13,183	Evoqua (ERG, 2015a); freight per FreightCenter.com (ERG, 2011a).
12.5% Sodium Hypochlorite	2,997	$0.89	$2,674	Evoqua (ERG, 2015a); freight per FreightCenter.com (ERG, 2011a).
25% Sodium Hydroxide	10,366	$2.43	$25,176	Evoqua (ERG, 2015a) (multiplied usage by 2 as usage data based on 50% solution and cost data based on 25% solution); freight per FreightCenter.com (ERG, 2011a).
12.5% Sodium Bisulfite	1,223	$2.43	$2,970	Evoqua (ERG, 2015a); freight per FreightCenter.com (ERG, 2011a).

Table E-6. Ultrafiltration Operating and Maintenance Costs

Energy	Rate (kWh/day)	Annual Energy (kWh/yr)	Energy Rate ($/kWh)	Annual Energy Cost ($/yr)	Source
Ultrafiltration	6,413	2,340,563	$0.10	$234,056	Evoqua (ERG, 2015a); WateReuse, 2014; and CAPDETWorks^{TM}.

E.6 Reverse Osmosis (RO)

Listed below are the capital cost elements included for RO, with a general description of the basis of estimate, followed by the O&M cost elements and the basis of estimate. Table E-7 and Table E-8 summarize the capital cost calculations for the 90 and 85 percent flow options, respectively (Levels 5-1 and 5-2), while Table E-9 and Table E-12 summarize the O&M cost calculations for the 90 and 85 percent flow options, respectively (Levels 5-1 and 5-2).

Capital Costs

1. RO System – cost basis obtained from telephone contacts with Wigen Water Technologies, 2015 (ERG, 2015b). Prepared a cost curve based on purchase costs provided for 2.5, 5, and 10 MGD systems (see Figure E-1).

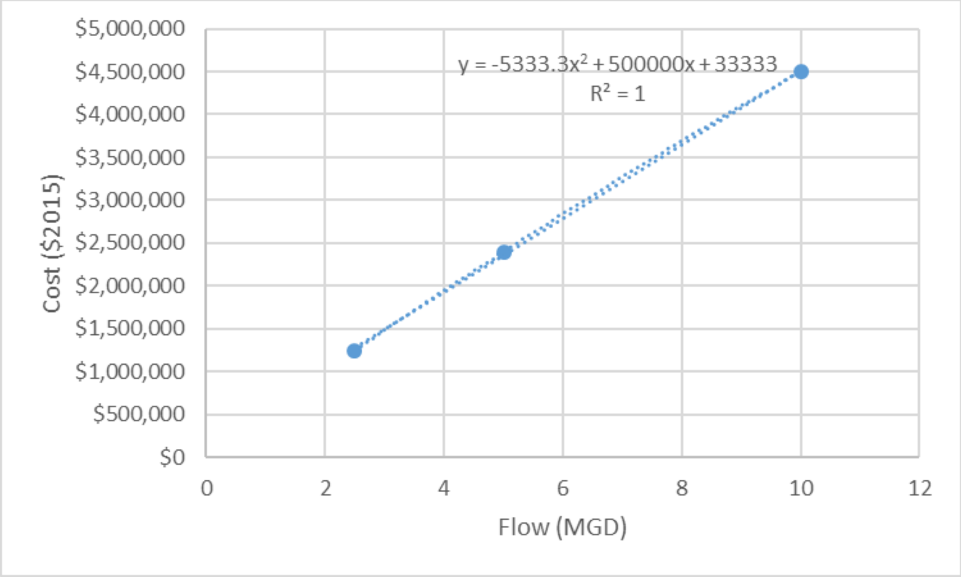

Figure E-1. RO Purchase Cost Curve

Escalated to 2014 $ using RSMeans Construction Cost Index (RSMeans, 2017). For a 9 MGD and 8.5 MGD system for this project[17], purchase costs for membrane equipment and appurtenances are approximately $4.4 million and $4.2 million, respectively. Total capital costs were estimated by applying the CAPDETWorks™ installation factor, and direct and indirect cost factors, to the purchase costs, after incorporating the purchase costs into the CAPDETWorks™ outputs.

2. RO Building – using equipment dimensions provided by Wigen (ERG, 2015b), calculated a required building footprint of 4,960 square feet to house the system.

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[17] Based on side stream treatment of 85% and 90% of the 10 MGD flow for Level 5-1 5-Stage Bardenpho with Sidestream Reverse Osmosis and Level 5-2 5-Stage Bardenpho Membrane Bioreactor with Sidestream Reverse Osmosis, respectively.

Using the CAPDETWorks™ building unit cost of $110/square foot, calculated a total capital building cost of approximately $550,000.

3. Chlorine Feed System – assumed a single, shared chlorine feed system for the RO biofouling control pretreatment and final wastewater disinfection. Costs for the shared chlorine feed system were estimated as part of the CAPDETWorks™ chlorine wastewater disinfection module.

4. Dechlorination and Antiscalant Feed Systems – purchase cost of $5,000, plus $300 for transport, for each feed system based on telephone contact with EnProTechnologies (ERG, 2011b). Escalated to 2014 $ Using RSMeans Construction Cost Index (RSMeans, 2017), resulting in a 2014 purchase cost of approximately $5,900 for each of these two systems. Total capital costs were estimated by applying the CAPDETWorks™ installation factor, and direct and indirect cost factors, to the purchase costs, after incorporating the purchase costs into the CAPDETWorks™ outputs.

5. Brine Surge Sump – estimated an in-ground concrete brine collection sump volume based on an assumed 60-minute residence time (best professional judgement) and a RO rejection rate of 20 percent based on telephone contacts with Wigen (ERG, 2015b). Calculated a total capital cost of approximately $190,000 for the 90% side stream treatment option, and approximately $180,000 for the 85% side stream treatment option, using a concrete basin cost curve developed using *RSMeans Building Construction Cost Data* (see Figure E-2). Escalated from $2010 to 2014 $ using RSMeans Construction Cost Index (RSMeans, 2017).

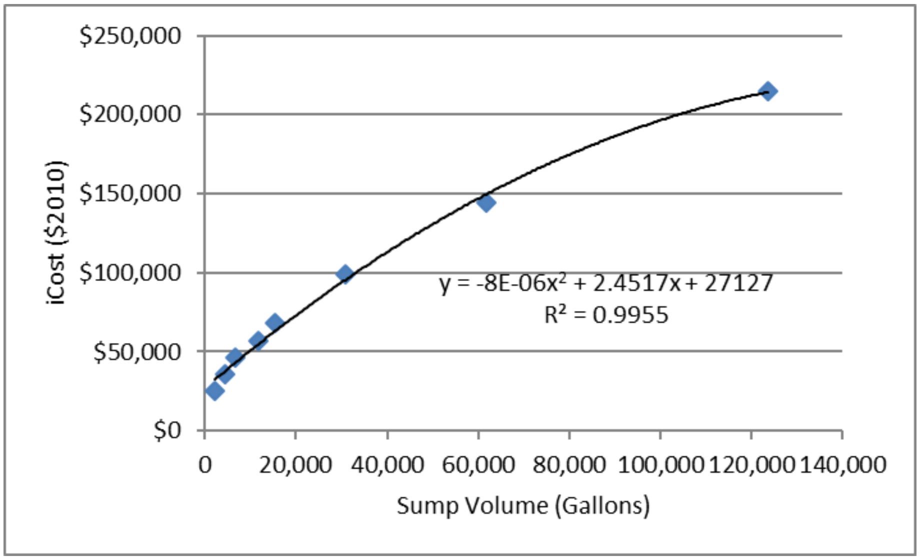

Figure E-2. Brine Surge Sump Total Capital Cost Curve

Operating and Maintenance Costs

1. Operating Labor – One labor hour per day based on Wigen (ERG, 2015b) and CAPDETWorks™ operator labor rate of $51.50/hour (2014 $) for a total operating labor cost of approximately $19,000/yr.
2. Maintenance Labor – One labor hour per day based on best professional judgement that maintenance labor requirements would be similar to, and not greater than, operating labor requirements, and sufficient for maintenance activities such as lubrication, troubleshooting, and installing replacement parts. Used the CAPDETWorks™ operator labor rate of $51.50/hour (2014 $), for a total annual maintenance labor cost of approximately $19,000/yr.
3. Materials – membrane replacement cost of $450 per membrane times an estimated 2,000 membranes for a 10 MGD system based on Wigen (ERG, 2015b), scaled to 9 MGD and 8.5 MGD systems for this project. Assumed membranes has a 4-year life based on Wigen (ERG, 2015b). Escalated to 2014 $ using RSMeans Construction Cost Index (RSMeans, 2017). Calculated materials costs of approximately $162,000/yr for the 90% side stream treatment option, and approximately $150,000/yr for the 85% side stream treatment option.
4. Antiscalant Chemicals – calculated using dosage rate of 3 mg/L of Vitec 3000 per Wigen (ERG, 2015b). Vitec 3000 chemical cost of approximately $1,300/500 lb provided by Water Surplus, 2015 and a $0.03/lb freight cost from FreightCenter.com (ERG, 2011a), for a total antiscalant chemicals cost of approximately $220,000/yr and $200,000/yr for the 90% and 85% side stream treatment options, respectively.
5. Membrane Cleaning Chemicals – per Wigen (ERG, 2015b), two cleaning chemicals are each 4,000 lb/yr for a 2.5 MGD system at a cost of $5/lb. Scaled to 9 MGD and 8.5 MGD for this project and added a $0.03/lb freight cost from FreightCenter.com (ERG, 2011a), for a total membrane cleaning chemicals cost of approximately $145,000/yr and $137,000/yr for the 90% and 85% side stream treatment options, respectively.
6. Chlorine and Sodium Bisulfite Pretreatment Chemicals – modified the CAPDETWorks™ chlorine wastewater disinfection module, and the supplemental dechlorination module developed for this project, to incorporate the additional chemical requirements associated with RO pretreatment. Assumed a 1 mg/L chlorine dosage rate per Wigen (ERG, 2015b) and a corresponding dechlorination dosage rate.
7. RO System Energy – energy usage equal to the average of estimates provided by two sources:
    - Wigen (ERG, 2015b) estimated energy usage ranging from 3,000 to 6,000 kWh/day for a 2.5 MGD system (average of 4,500 kWh for a 2.5 MGD system, or 1.8 kWh/kgal)
    - WateReuse Research Foundation, 2014 estimated energy usage ranging from 1.9 to 2.3 kWh/kgal (average of 2.1 kWh/kgal)

Used the average of the average estimated energy usage from these two sources, 1.95kWh/kgal (average of 1.8 kWh/kgal and 2.1 kWh/kgal). For a 9 MGD system, and using the CAPDETWorks™ energy rate of $0.10/kWh (2014 $), total annual energy costs are approximately $640,000/yr and $600,000/yr for the 90% and 85% side stream treatment options, respectively.

8. Dechlorination and Antiscalant Feed System Energy – Two 0.5 HP feed system pumps operated continuously for a calculated annual electrical requirement of approximately 6,500 kWh/yr. Using the CAPDETWorks™ energy rate of $0.10/kWh (2014 $), total energy costs are approximately $650/yr.

Table E-7. RO Capital Costs, 90 Percent of Flow

Equipment Cost Item	Size or number	Units	Unit Cost	Total Cost	Year	2014 Purchased Cost	Total Capital Cost	Source
RO System	9	MGD		$4,460,136	2015	$4,421,296		Wigen (ERG, 2015b).
RO System Building	4,960	sq. foot	$110	$545,600	2014		$545,600	Wigen (ERG, 2015b); building unit cost from CAPDETWorks^{TM}.
Chlorination Feed System						$0	$0	
Dechlorination Feed System	1	Each	$5,300	$5,300	2010	$5,918		EnPro (ERG, 2011b).
Anti-Scale Feed System	1	Each	$5,300	$5,300	2010	$5,918		EnPro (ERG, 2011b).
Brine Surge Sump	75,000	gallons		$166,005	2010		$185,364	RSMeans Building Construction Cost Data; RO rejection rate from Wigen (ERG, 2015b).

Table E-8. RO Capital Costs, 85 Percent of Flow

Equipment Cost Item	Size or number	Units	Unit Cost	Total Cost	Year	2014 Purchased Cost	Total Capital Cost	Source
RO System	8.5	MGD		$4,214,802	2015	$4,178,098		Wigen (ERG, 2015b).
RO System Building	4,960	sq. foot	$110	$545,600	2014		$545,600	Wigen (ERG, 2015b); building unit cost from CAPDETWorks^{TM}.
Chlorination Feed System						$0	$0	
Dechlorination Feed System	1	Each	$5,300	$5,300	2010	$5,918		EnPro (ERG, 2011b).
Anti-Scale Feed System	1	Each	$5,300	$5,300	2010	$5,918		EnPro (ERG, 2011b).
Brine Surge Sump	70,833	gallons		$160,650	2010		$179,385	RSMeans Building Construction Cost Data; RO rejection rate from Wigen (ERG, 2015b).

Table E-9. RO Operating and Maintenance Costs, 90 Percent of Flow

Operating Labor	Labor (hrs/day)	Labor Rate ($/hr)	Days/yr	Annual Operating Labor Cost ($/yr)	Source
RO System	1	$51.50	365	$18,798	Wigen (ERG, 2015b).
Maintenance Labor	**Labor (hrs/day)**	**Labor Rate ($/hr)**	**Days/yr**	**Annual Maintenance Labor Cost ($/yr)**	**Source**
RO System	1	$51.50	365	$18,798	Best Professional Judgement and CAPDETWorks™
Materials	**Annual Materials Cost ($/yr)**				**Source**
RO System	$162,044				Wigen (ERG, 2015b).

Table E-10. RO Operating and Maintenance Costs, 90 Percent of Flow

Chemicals	Dose Rate (lbs/gal)	Total Flow (gal/yr)	Annual Anti-Scale Chemicals (lbs/yr)	Cost ($/lb)	Annual Chemicals Cost ($/yr)	Source	Chemical Consumption
Pretreatment Anti-Scale	0.00002	3,285,000,000	82,063	$2.64	$216,317	Dose per Wigen (ERG, 2015b); cost per Water Surplus, 2015; freight per FreightCenter.com (ERG, 2011a).	Annual Vitec 3000 Consumption: 91,181 lb/yr Annual Citric Acid Consumption: 16,000 lb/yr Annual Sodium Hypochlorite Consumption: 16,000 lb/yr
Membrane Cleaning	0.00001	3,285,000,000	28,800	$5.03	$144,864	Wigen (ERG, 2015b); freight per FreightCenter.com (ERG, 2011a).	
Pretreatment Chlorine					$0.00	Incorporated into wastewater disinfection module.	
Pretreatment Sodium Bisulfite					$0.00	Incorporated into wastewater dechlorination module.	

Table E-11. RO Operating and Maintenance Costs, 90 Percent of Flow

Energy	**Rate (kWh/day)**	**Annual Electrical (kWh/yr)**	**Energy Rate ($/kWh)**	**Annual Energy Cost ($/yr)**	**Source**
RO System	17,550	6,405,750	$0.10	$640,575	Wigen (ERG, 2015b); WateReuse, 2014; CAPDETWorks^{TM}.
Chemical Feed Systems	18	6,531	$0.10	$653	EnPro (ERG, 2011b); CAPDETWorks^{TM}.

Table E-12. RO Operating and Maintenance Costs, 85 Percent of Flow

Operating Labor	**Labor (hrs/day)**	**Labor Rate ($/hr)**	**Days/yr**	**Annual Operating Labor Cost ($/yr)**	**Source**
RO System	1	$51.50	365	$18,798	Wigen (ERG, 2015b).
Maintenance Labor	**Labor (hrs/day)**	**Labor Rate ($/hr)**	**Days/yr**	**Annual Maintenance Labor Cost ($/yr)**	**Source**
RO System	1	$51.50	365	$18,798	Best Professional Judgement and CAPDETWorks^{TM}
Materials	**Annual Materials Cost ($/yr)**				**Source**
RO System	$153,041				Wigen (ERG, 2015b).

Table E-13. RO Operating and Maintenance Costs, 85 Percent of Flow

Chemicals	Dose Rate (lbs/gal)	Total Flow (gal/yr)	Annual Anti-Scale Chemicals (lbs/yr)	Cost ($/lb)	Annual Chemicals Cost ($/yr)	Source	Chemical Consumption
Pretreatment Anti-Scale	0.00002	3,102,500,000	77,504	$2.64	$204,299	Dose per Wigen (ERG, 2015b); cost per Water Surplus, 2015; freight per FreightCenter.com (ERG, 2011a).	Annual Vitec 3000 Consumption: 91,181 lb/yr Annual Citric Acid Consumption: 16,000 lb/yr Annual Sodium Hypochlorite Consumption: 16,000 lb/yr
Membrane Cleaning	0.00001	3,102,500,000	27,200	$5.03	$136,816	Wigen (ERG, 2015b); freight per FreightCenter.com (ERG, 2011a).	
Pretreatment Chlorine					$0.00	Incorporated into wastewater disinfection module.	
Pretreatment Sodium Bisulfite					$0.00	Incorporated into wastewater dechlorination module.	

Table E-14. RO Operating and Maintenance Costs, 85 Percent of Flow

Energy	Rate (kWh/day)	Annual Electrical (kWh/yr)	Energy Rate ($/kWh)	Annual Energy Cost ($/yr)	Source
RO System	16,575	6,049,875	$0.10	$604,988	Wigen (ERG, 2015b); WateReuse, 2014; CAPDETWorks™.
Chemical Feed Systems	18	6,531	$0.10	$653	EnPro (ERG, 2011b) and CAPDETWorks™.

E.7 Deep Well Injection

Listed below are the capital cost elements included for deep well injection, with a general description of the basis of estimate, followed by the O&M cost elements and the basis of estimate. Table E-15 and Table E-16 summarize the capital and O&M cost calculations, respectively.

Capital Costs

1. Deep Injection Well – cost basis obtained from telephone contact with North Star Disposal, Inc (U.S. EPA, 2012a). Drilling a new underground injection well costs $3.5 million for a deep well, which was escalated to 2014 $ using RSMeans Construction Cost Index (RSMeans, 2017), resulting in a 2014 total capital cost of approximately $3.7 million.
2. Injection Pump/Electrical Building – estimated pump house dimensions (12'x14') based on best professional judgement to house the 3 pumps and control panel, as informed by domestic wastewater deep well injection proposal prepared by the Santa Clarita Valley Sanitation District, 2015[18]. Using the CAPDETWorks™ building unit cost of $110/square foot, calculated a total capital building cost of approximately $18,000.
3. Injection Well Pumps – cost basis of approximately $49,000 for a 786 gpm multistate pump obtained from Water Surplus, 2015, which was escalated to 2014 $ using RSMeans Construction Cost Index (RSMeans, 2017). Assumed 2 pumps in operation and 1 spare for a total purchase cost of approximately $140,000. Total capital costs were estimated by applying the CAPDETWorks™ installation factor, and direct and indirect cost factors, to the purchase costs, after incorporating the purchase costs into the CAPDETWorks™ outputs.
4. Injection Well Pumps Freight – cost basis of approximately $1,750 per flatbed truckload to transport all three pumps (total of 10 tons) obtained from Siemens (ERG, 2011c), which we escalated to 2014 $ using RSMeans Construction Cost Index (RSMeans, 2017). Total capital costs were estimated by applying the CAPDETWorks™ installation factor, and direct and indirect cost factors, to the purchase costs, after incorporating the purchase costs into the CAPDETWorks™ outputs.

Operating and Maintenance Costs

1. Operating Labor – 0.5 labor hour per day based on best professional judgement to inspect the pump motors and to record data, and CAPDETWorks™ operator labor rate of $51.50/hour (2014 $), for a total annual operating labor cost of approximately $9,400.

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[18] Santa Clarity Valley Sanitation District. 2015. *Information Sheet – Deep Well Injection Site for Brine Disposal*. DOC #2970311. Accessed from http://www.lacsd.org/civicax/filebank/blobdload.aspx?blobid=9556.

2. Maintenance Labor – 0.5 labor hour per day based on best professional judgement that maintenance labor requirements would be similar to, and not greater than, operating labor requirements, and sufficient for maintenance activities such as lubrication, troubleshooting, and installing replacement parts. Used the CAPDETWorks™ operator labor rate of $51.50/hour (2014 $), for a total annual maintenance labor cost of approximately $9,400/yr.
3. Materials – calculated total annual maintenance materials cost as 2 percent of injection well pump purchase cost based on CAPDETWorks™ methodology. Calculated a maintenance materials cost of approximately $3,000/yr.
4. Energy – Two 350 HP injection well pumps operated continuously for a calculated annual electrical requirement of approximately 4.5 million kWh/yr. Using the CAPDETWorks™ energy rate of $0.10/kWh (2014 $), total energy costs are approximately $460,000/yr.

Table E-15. Deep Well Injection Capital Costs

Equipment Cost Item	Number	Units	Unit Cost	Total Cost	Year	2014 Cost	Total Capital Cost	Data Source
Deep Injection Well	1	Each	$3,500,000	$3,500,000	2012		$3,685,252	North Star Disposal (U.S. EPA, 2012a).
Injection pump building to house pumps and electrical	168	square feet	$110	$18,480	2014		$18,480	Best professional judgement; building unit cost from CAPDETWorks$^{\text{TM}}$.
Injection Well Pumps	3	Each	$48,730	$146,190	2015	$144,917		Water Surplus, 2015.
Injection Well Pumps Freight	1	Flatbed Truck	$1,750	$1,750	2011	$1,875		Siemens (ERG, 2011c).

Table E-16. Deep Well Injection Operating and Maintenance Costs

Operating Labor	**Labor (hrs/day)**	**Labor Rate ($/hr)**	**Days/yr**	**Annual Operating Labor Cost ($/yr)**	**Source**
	0.5	$51.50	365	$9,399	Best Professional Judgement and CAPDETWorks$^{\text{TM}}$.
Maintenance Labor	**Labor (hrs/day)**	**Labor Rate ($/hr)**	**Days/yr**	**Annual Operating Labor Cost ($/yr)**	**Source**
	0.5	$51.50	365	$9,399	Best Professional Judgement and CAPDETWorks$^{\text{TM}}$.
Material	**Purchased Pump Cost**	**Rate (% of Purchase)**	**Annual Materials Cost ($/yr)**		**Source**
	$144,917	2	$2,898		CAPDETWorks$^{\text{TM}}$.
Chemicals	**Dose Rate (lbs/gal)**	**Total Flow (gallons/yr)**	**Annual Anti-Scale Chemicals (lbs/yr)**	**Cost ($/lb)**	**Annual Chemicals Cost ($/yr)**
No chemical requirements					
Energy	**Rate (kWh/day)**	**Annual Electrical (kWh/yr)**	**Energy Rate ($/kWh)**	**Annual Energy Cost ($/yr)**	**Source**
	12,526	4,572,019	$0.10	$457,202	Water Surplus, 2015 and CAPDETWorks$^{\text{TM}}$.

E.8 CAPDETWorks™ Direct Cost Factor Development

See Companion PDF File.

APPENDIX F
DETAILED AIR EMISSIONS METHODOLOGY

Appendix F: Detailed Air Emissions Methodology

F.1 Greenhouse Gas Analysis

This section details the calculations used to determine the process-level GHG emissions from the wastewater treatment and sludge handling stages, from the effluent, and from landfilled sludge. GHG emissions from background and upstream fuel and material processes already exist within the LCI databases used, and while incorporated in the study results, are not discussed here.

F.1.1 Methane Emissions from Biological Treatment

The methodology for calculating CH_4 emissions associated with the wastewater treatment configurations evaluated as part of this study is generally based on the guidance provided in the IPCC Guidelines for national inventories. CH_4 emissions are estimated based on the amount of organic material (i.e., BOD) entering the unit operations that may exhibit anaerobic activity, an estimate of the theoretical maximum amount of methane that can be generated from the organic material (B_o), and a methane correction factor that reflects the ability of the treatment system to achieve that theoretical maximum. In general, the IPCC does not estimate CH_4 emissions from well managed centralized aerobic treatment systems. However, there is acknowledgement that some CH_4 can be emitted from pockets of anaerobic activity, and more recent research suggests that dissolved CH_4 in the influent wastewater to the treatment system is emitted when the wastewater is aerated.

For this analysis, some of the wastewater treatment configurations include anaerobic zones within the treatment system. For these configurations, a methane correction factor (MCF) was used. The methodological equation is:

$$CH_{4\ PROCESS} = BOD\ (mg/L) \times Flow\ (MGD) \times 3.785\ L/gal \times 365.25\ days/yr \times 1x10^{-6}\ kg/mg \times B_o \times MCF$$

Equation F-1

where:

$CH_{4\ PROCESS}$ = CH_4 emissions from wastewater treatment process (kg CH_4 /yr)

BOD = Concentration of BOD entering biological treatment process (mg/L)

Flow = Wastewater treatment flow entering biological treatment process (MGD)

B_o = maximum CH_4 producing capacity, kg CH_4/kg BOD

MCF = methane correction factor (fraction)

For this analysis, there was no relevant MCF provided in the IPCC guidance for centralized aerobic treatment with the wastewater treatment configurations included in this study. Instead, MCFs were developed based on GHG emission studies that were conducted at two U.S. WWTPs. The first study (Czepiel, 1995) evaluated emissions associated with a conventional activated sludge treatment plant, resulting in an MCF of 0.005, which was used for Level 1. The second study (Daelman et al., 2013) evaluated emissions associated with a municipal treatment plant with biological nutrient removal (specifically nitrification and denitrification), resulting in an MCF of 0.05, which was used for all other levels of treatment. No other studies were available and acceptable for use to allow differentiating CH_4 emissions between Levels 2 through 5.

The annual emissions per system were than translated to emissions per m^3 of wastewater treated, using the following calculation and displayed in Table F-1.

$$CH_4 \text{ Process Emissions (kg } CH_4 /m^3 \text{ wastewater)} = CH_{4\,PROCESS} \div [10 \text{ MGD x } 365 \text{ days/yr x } 0.00378541 \text{ m}^3\text{/gal}]$$

Equation F-2

Table F-1. Methane Emissions from Biological Treatment

System Configuration Level	Influent BOD to biotreatment, mg/L	Flow, MGD	MCF	CH_4 Emitted by Process, kg CH_4/yr	CH_4 Process Emissions, kg CH_4/m^3 wastewater
1	1.6E+2	10	5.0E-3	6.8E+3	5.0E-4
2-1	1.6E+2	10	0.05	6.6E+4	4.8E-3
2-2	1.6E+2	10	0.05	6.8E+4	4.9E-3
3-1	1.7E+2	10	0.05	7.1E+4	5.1E-3
3-2	1.7E+2	10	0.05	7.1E+4	5.1E-3
4-1	1.7E+2	10	0.05	7.1E+4	5.1E-3
4-2	1.6E+2	10	0.05	6.6E+4	4.8E-3
5-1	1.7E+2	10	0.05	7.1E+4	5.1E-3
5-2	1.7E+2	10	0.05	7.0E+4	5.1E-3

F.1.2 Nitrous Oxide Emissions from Biological Treatment

The methodology for calculating N_2O emissions associated with wastewater treatment is based on estimates of emissions reported in the literature. The guidance provided in the IPCC Guidelines for national inventories does not provide a sufficient basis to distinguish N_2O emissions from varying types of wastewater treatment configurations, particularly related to biological nutrient reduction. More recent research has highlighted the fact that emissions from these systems can be highly variable based on operational conditions, specific treatment configurations, and other factors (Chandran, 2012).

For this analysis, data collected from 12 WWTPs were reviewed to identify which wastewater treatment configuration they may best represent (Chandran, 2012). Using the emissions measured from these systems, an average emission factor (EF) was calculated and applied to the modeled data for the nine system configurations. The methodological equation is:

$$N_2O_{PROCESS} = \text{TKN (mg/L)} \times \text{Flow (MGD)} \times 3.785 \text{ L/gal} \times 365.25 \text{ days/yr} \times 1\text{x}10^{-6} \text{ kg/mg} \times \text{EF\%} \times 44/14$$

Equation F-3

where:

$N_2O_{PROCESS}$ = N_2O emissions from wastewater treatment process (kg N_2O /yr)

TKN = Concentration of TKN entering biological treatment process (mg/L)

Flow = Wastewater treatment flow entering biological treatment process (MGD)

EF% = average measured % of TKN emitted as N_2O, %

44/14 = molecular weight conversion of N to N_2O

As displayed in Table F-2, the annual emissions per system were translated to emissions per m^3 of wastewater treated, using the following calculation.

$$N_2O \text{ Process Emissions (kg } N_2O/m^3 \text{ wastewater)} = N_2O_{PROCESS} \div [10 \text{ MGD} \times 365 \text{ days/yr} \times 0.00378541\ m^3/\text{gal}]$$

Equation F-4

Table F-2. Nitrous Oxide Emissions from Biological Treatment

System Configuration Level	Influent TKN to biotreatment, mg/L[a]	Flow, MGD[a]	EF%, % Emitted as N_2O	Source of EF	Unit Operation Basis	N_2O Emitted by Process, kg N_2O/yr	N_2O Process Emissions, kg N_2O/m^3 wastewater
1	43	10	0.035%	Czepiel (1995)	conventional activated sludge	6.6E+2	4.8E-5
2-1	41	10	0.160%	Chandran (2012)	MLE	2.9E+3	2.1E-4
2-2	43	10	0.020%	Chandran (2012)	separate stage BNR	3.9E+2	2.8E-5
3-1	42	10	0.425%	Chandran (2012)	4-stage Bardenpho	7.8E+3	5.7E-4
3-2	42	10	0.160%	Chandran (2012)	MLE	3.0E+3	2.1E-4
4-1	43	10	0.425%	Chandran (2012)	4-stage Bardenpho	8.2E+3	5.9E-4
4-2	41	10	0.425%	Chandran (2012)	4-stage Bardenpho	7.7E+3	5.6E-4
5-1	42	10	0.425%	Chandran (2012)	4-stage Bardenpho	7.8E+3	5.7E-4
5-2	42	10	0.425%	Chandran (2012)	4-stage Bardenpho	7.7E+3	5.6E-4

a – Flow and influent TKN to biotreatment is based on CAPDETWorks™ modeling

F.1.3 Methane Emissions due to Anaerobic Digestion

The methodology for calculating CH_4 emissions associated with anaerobic sludge digestion is based on the guidance provided in the IPCC Guidelines for national inventories. CH_4 emissions from anaerobic digestion of sludge were estimated based on the amount of biogas generated by the digester, an estimation of the biogas composition, and an estimation of the amount of CH_4 destroyed through flaring.

CH_4 emissions from anaerobic digesters were estimated by multiplying the amount of biogas generated by wastewater sludge treated in anaerobic digesters by the proportion of CH_4 in digester biogas (0.65), the density of CH_4 (662 g CH_4/m^3 CH_4), and the destruction efficiency associated with burning the biogas in an energy/thermal device (0.99). For this analysis, ERG is assuming the biogas is flared, and not recovered for energy use. The methodological equation is:

$$CH_{4\ DIGESTER} = \text{Biogas Flow} \times \text{conversion to } m^3 \times (525960 \text{ min/year}) \times (FRAC\_CH_4) \times (\text{density of } CH_4) \times (1\text{-}DE) \times 1/10\text{^}3$$

Equation F-5

where:

$CH_{4\ DIGESTER}$ = CH_4 emissions from anaerobic digestion (kg CH_4 /yr)

Biogas Flow = Cubic feet of digester gas produced by digester (ft^3/min)

conversion to m^3 = Conversion factor, ft^3 to m^3 (0.0283)

$FRAC\_CH_4$ = Proportion CH_4 in biogas (0.65)

density of CH_4 = 662 (g CH_4/m^3 CH_4)

DE = CH_4 destruction efficiency from flaring (0.99 for enclosed flares)

1/10^3 = Conversion factor, g to kg

As shown in Table F-3 the annual emissions per system were translated to emissions per m^3 of wastewater treated, using the following calculation.

$$CH_4 \text{ Digester Emissions (kg } CH_4/m^3 \text{ wastewater)} = CH_{4\ DIGESTER} \div [10 \text{ MGD x } 365 \text{ days/yr x } 0.00378541\ m^3/\text{gal}]$$

Equation F-6

Table F-3. Methane Emissions due to Anaerobic Digestion

System Configuration Level	Biogas Flow, ft^3/min^a	CH_4 Generated by Digester, kg CH_4/yr	CH_4 Emitted by Digester, kg CH_4/yr	CH_4 Digester Emissions, kg CH_4/m^3 wastewater
1	1.1E+2	6.9E+5	6.9E+3	5.0E-4
2-1	88	5.6E+5	5.6E+3	4.1E-4
2-2	1.2E+2	7.6E+5	7.6E+3	5.5E-4
3-1	85	5.4E+5	5.4E+3	3.9E-4
3-2	85	5.4E+5	5.4E+3	3.9E-4
4-1	85	5.4E+5	5.4E+3	3.9E-4
4-2	87	5.6E+5	5.6E+3	4.1E-4
5-1	85	5.4E+5	5.4E+3	3.9E-4
5-2	82	5.2E+5	5.2E+3	3.8E-4

a – Biogas flow is based on CAPDETWorks™ modeling.

Air emissions other than CH_4 associated with flaring the digester biogas are covered at the end of this Appendix.

F.1.4 Nitrous Oxide Emissions from Effluent Discharged to Receiving Waters

The methodology for calculating nitrous oxide emissions associated with effluent discharge is based on the guidance provided in the IPCC Guidelines for national inventories. N_2O emissions from domestic wastewater (wastewater treatment) were estimated based on the amount of nitrogen discharged to aquatic environments from each of the system configurations, which accounts for nitrogen removed with sewage sludge.

$$N_2O_{EFFLUENT} = N_{EFFLUENT} \times \text{Flow} \times 3.785 \text{ L/gal} \times 365.25 \text{ days/yr} \times 1\text{x}10^{-6} \text{ kg/mg} \times EF_3 \times 44/28$$

Equation F-7

where:

$N_2O_{EFFLUENT}$ = N_2O emissions from wastewater effluent discharged to aquatic environments (kg N_2O/yr)

$N_{EFFLUENT}$ = N in wastewater discharged to receiving stream, mg/L

Flow = Effluent flow, MGD

EF_3 = Emission factor (0.005 kg N_2O -N/kg sewage-N produced)

44/28 = Molecular weight ratio of N_2O to N_2

As presented in Table F-4, the annual emissions per system were then translated to emissions per m^3 of wastewater treated, using the following calculation.

$$N_2O \text{ Effluent Emissions (kg } N_2O/m^3 \text{ wastewater)} = N_2O_{EFFLUENT} \div [10 \text{ MGD x } 365 \text{ days/yr x } 0.00378541 \text{ m}^3\text{/gal}]$$

Equation F-8

Table F-4. Nitrous Oxide Emissions from Effluent Discharged to Receiving Waters

System Configuration Level	Effluent Total Nitrogen, mg/L[a]	N_2O Effluent Emissions, kg N_2O /yr	N_2O Effluent Emissions, kg N_2O/m^3 wastewater
1	30	3.2E+3	2.3E-4
2-1	8.0	8.7E+2	6.3E-5
2-2	7.8	8.4E+2	6.1E-5
3-1	6.0	6.5E+2	4.7E-5
3-2	6.0	6.5E+2	4.7E-5
4-1	3.0	3.2E+2	2.4E-5
4-2	3.0	3.3E+2	2.4E-5
5-1	0.78	69	5.0E-6
5-2	1.9	1.7E+2	1.3E-5

a – Effluent nitrogen is based on CAPDETWorks™ modeling and calculated as TKN + nitrate + nitrite.

F.1.5 Methane Emissions and Energy Recovery from Sludge Disposal in Landfills

The methodology for calculating CH_4 emissions associated with landfill disposal are based on the general presumption that the portion of the landfill receiving anaerobic digester sludge operates as a "bioreactor landfill" due to the high BOD and water loading. As such, the anaerobic digestion process will reach steady state quickly. In addition, the anaerobic conversion of BOD to CH_4 will be very similar between anaerobic sludge digesters and anaerobic bioreactor landfills. As such, the ratio of CH_4 evolution to BOD removal in an anaerobic digester will also be applicable to sewage sludge degradation in anaerobic landfills. ERG calculated an emission factor for landfill emissions based on the conversion of organic material to CH_4, as seen in the anaerobic sludge digester. Using modeled outputs from Level 1, ERG calculated an emission factor of 0.61 kg CH_4 emitted per kg BOD added using the following equation:

$$CH_4EF_{\text{LANDFILL}} = \text{Digester } CH_4 \text{ Generated} \times [(\text{Digester BOD Inlet} – \text{Digester BOD Outlet}) \times 365.25 \text{ days/yr}] \qquad \text{Equation F-9}$$

where:

CH_4EF_{LANDFILL} = CH_4 emission factor for landfills receiving municipal sludge (kg CH_4/kg BOD removed)

Digester CH_4 Generated = CH_4 emissions generated in anaerobic sludge digester for Level 1 system, kg CH_4/yr

Digester BOD Inlet = BOD entering the digester, kg/day

Digester BOD Outlet = BOD exiting the digester, kg/day

CH_4 emissions from domestic wastewater (wastewater treatment) were estimated based on the amount of BOD transferred to the landfill in digested sludge.

$$CH_{4\,\text{LANDFILL}} = \text{Sludge Volume} \times \text{BOD} \times 3.785 \text{ L/gal} \times 365.25 \text{ days/yr} \times 1\text{x}10^{-6} \text{ kg/mg} \times CH_4EF_{\text{LANDFILL}} \qquad \text{Equation F-10}$$

where:

$CH_{4\,\text{LANDFILL}}$ = CH_4 emissions from landfilled sludge (kg CH_4/yr)

Sludge Volume = Volume of sludge transferred to landfill, MGD

BOD = BOD concentration in digested sludge, mg/L

CH_4EF_{LANDFILL} = CH_4 emission factor for landfills receiving municipal sludge (kg CH_4/kg BOD)

As displayed in Table F-5, the annual emissions per system were then translated per m^3 of wastewater treated, using the following calculation. These values assume no capture of landfill gas.

$$CH_4 \text{ Landfill Emissions (kg } CH_4/m^3 \text{ wastewater)} = CH_{4\,LANDFILL} \div [10 \text{ MGD x 365 days/yr x 0.00378541 } m^3/\text{gal}]$$

Equation F-11

Table F-5. Raw Methane Emissions from Sludge Disposal in Landfills

System Configuration Level	Sludge Volume, MGD[a]	Sludge BOD, mg/L[a]	CH_4 Landfill Emissions, kg CH_4/yr	Raw CH_4 Landfill Emissions, kg CH_4 /m^3 wastewater
1	0.02	7.2E+3	1.2E+5	8.9E-3
2-1	0.02	7.0E+3	1.0E+5	7.3E-3
2-2	0.03	5.4E+3	1.4E+5	9.8E-3
3-1	0.02	5.6E+3	9.7E+4	7.0E-3
3-2	0.02	5.6E+3	9.7E+4	7.0E-3
4-1	0.02	5.5E+3	9.7E+4	7.0E-3
4-2	0.02	5.7E+3	1.0E+5	7.3E-3
5-1	0.02	5.5E+3	9.7E+4	7.0E-3
5-2	0.02	5.5E+3	9.4E+4	6.8E-3

a – Sludge volume and sludge BOD is based on CAPDETWorks™ modeling.

However, currently, about 71 percent of CH_4 generated from municipal solid waste landfills is converted to CO_2 before it is released to the environment. 10.6 percent is flared, 56.8 percent is burned with energy recovery, and about 3.8 percent is oxidized as it travels through the landfill cover based on the Inventory of U.S. GHG emissions and sinks (U.S. EPA, 2015b). Overall, only approximately 29 percent of the total CH_4 generated is released as methane without treatment. The net CH_4 emissions from sludge in a landfill, calculated by applying the percentage of CH_4 released without treatment to raw CH_4 emissions reported in Table F-5, is provided in Table F-6.

Table F-6. Methane Emissions from Sludge Disposal in Landfills after Treatment

System Configuration Level	Raw CH_4 Landfill Emissions, kg CH_4 /m^3 wastewater[a]	% CH_4 Released without Treatment	kg CH_4 Released without Treatment/m^3 wastewater
1	8.9E-3	29%	2.6E-3
2-1	7.3E-3	29%	2.1E-3
2-2	9.8E-3	29%	2.8E-3
3-1	7.0E-3	29%	2.0E-3
3-2	7.0E-3	29%	2.0E-3
4-1	7.0E-3	29%	2.0E-3
4-2	7.3E-3	29%	2.1E-3
5-1	7.0E-3	29%	2.0E-3
5-2	6.8E-3	29%	1.9E-3

a – Derived from Table F-5 results.

The U.S. EPA's Landfill Methane Outreach Program Landfill Database indicates that the majority of landfill gas burned with energy recovery is used to produce electricity (U.S. EPA, 2016). The gross energy recovered from combustion of sludge landfill is converted to displaced quantities of grid electricity using an efficiency factor of 1 kWh generated per 11,700 Btu (or 12.34 MJ) of landfill CH_4 burned (U.S. EPA, 2014). Each system configuration is credited with avoiding the GWP associated with production of the offset quantity of grid electricity. The calculations to derive this offset or avoided electricity per system configuration level are shown in Table F-7.

Table F-7. Electricity Generation from Landfill Methane Energy Recovery

System Configuration Level	Raw CH_4 Landfill Emissions, kg CH_4 /m^3 wastewater	% CH_4 Burned with Energy Recovery	kg CH_4 Burned with Energy Recovery/m^3 wastewater	Gross MJ from Landfill Gas Energy Recovery[a]/m^3 wastewater	Net kWh from Landfill CH_4 Energy Recovery/m^3 wastewater[b]
1	8.9E-3	57%	5.0E-3	0.28	0.02
2-1	7.3E-3	57%	4.1E-3	0.23	0.02
2-2	9.8E-3	57%	5.6E-3	0.31	0.03
3-1	7.0E-3	57%	4.0E-3	0.22	0.02
3-2	7.0E-3	57%	4.0E-3	0.22	0.02
4-1	7.0E-3	57%	4.0E-3	0.22	0.02
4-2	7.3E-3	57%	4.1E-3	0.23	0.02
5-1	7.0E-3	57%	4.0E-3	0.22	0.02
5-2	6.8E-3	57%	3.8E-3	0.21	0.02

a – HHV of methane = 11.47 MJ/kg

b – Modeled as avoided electricity with a negative value in the LCA.

F.2 Anaerobic Digester Biogas Flaring

Biogas production for each treatment level is a calculated based on the output of the CAPDETWorks™ model. Emissions inventory information for biogas flaring is compiled from three resources with the maximum reported emission value for each compound being taken as the emission factor for this project. Table F-8 shows the data extracted from each study with the last column displaying the emission factor selected for inclusion in this study. All emission factors in the table are included as kg of compound emitted per cubic meter of biogas flared. Emission factors from Levis and Barlaz 2013 are presented in the original study per cubic meter of biogas CH_4 content.

Table F-8. Biogas Flaring Emission Factors (All values are kg/m^3 Biogas Flared)

Compound	Levis & Barlaz [a]	Alberta Environment [b]	Environment Canada [c]	This Study (Max Value)
Nitrous Oxide	1.1E-5	3.5E-5	4.5E-4	4.5E-4
PM-Total	6.0E-5		8.5E-4	8.5E-4
PM10	1.0E-5		8.5E-4	8.5E-4
PM-2.5	4.7E-6		8.5E-4	8.5E-4
Nitrogen Oxides	0.01			0.01
NMVOCs	2.0E-5			2.0E-5

Table F-8. Biogas Flaring Emission Factors (All values are kg/m^3 Biogas Flared)

Compound	Levis & Barlaz [a]	Alberta Environment [b]	Environment Canada [c]	This Study (Max Value)
Sulfur Oxides	4.3E-4		9.2E-5	4.3E-4
Carbon Monoxide	6.2E-3		5.6E-5	6.2E-3
Ammonia	1.8E-5			1.8E-5
Hydrogen Sulfide	3.9E-6			3.9E-6
PAH			8.7E-6	8.7E-6

Sources:

a – Levis, J.W., and Barlaz, M.A. 2013. Anaerobic Digestion Process Model Documentation. North Carolina State University. http://www4.ncsu.edu/~jwlevis/AD.pdf. Accessed 5 April, 2016

b – Alberta Environment. 2007. Quantification Protocol for the Anaerobic Decomposition of Agricultural Materials Project: Excel Biogas Calculator. http://environment.gov.ab.ca/info/library/7917.pdf. Accessed 5 April, 2016.

c – Environment Canada. 2005. Biogas Flare. https://www.ec.gc.ca/inrp-npri/14618D02-387B-469D-B1CD-42BC61E51652/biogas_flare_e_04_02_2009.xls. Accessed 5 April, 2016

APPENDIX G
EXAMPLE LCI DATA CALCULATIONS

Appendix G: Example LCI Data Calculations

CAPDETWorks™ design and costing software (Hydromantis, 2014) provides the main source of LCI data for treatment plant unit process construction and operation. The relevant elements of the CAPDETWorks™ model output were imported into an Excel document where supplemental calculations were performed to standardize flows to be on the basis of physical units per cubic meter of treated wastewater. Calculation procedures were similar regardless of treatment level. Output LCI associated with the Level 1 treatment system is included in Table G-1 to provide an example of the procedure applied to all treatment levels. Supplementary LCI calculations not associated with CAPDETWorks™ output (e.g., process-level air emissions) are described elsewhere in the report.

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Table G-1. Example Standardization of CAPDETWorks™ Output to LCI per m3 of Treated Wastewater (Level 1)

	CAPDETWorks™ Model Output			***Calculated LCI Values***			
Unit	**Description**	**Value**	**Units**	**Calculated Flow**	**Units**	**Value**	**Assumptions**
Grit Removal	Energy cost	4,690	$/yr	Electricity	kwh/m^3	3.0E-3	$0.10/kWh
Primary Clarifier	Structural	40	years	Building	m^2/m^3	3.4E-8	structural lifespan 40 years
	Area of pump building	201	sqft				
	Electrical energy required	10,100	kWh/yr	Electricity, Total	kwh/m^3	8.4E-4	
	Electrical energy required	1,510	kWh/yr				
	Volume of earthwork required	129,000	cuft	Earthwork, Total	m^3/m^3	2.7E-6	plant lifespan of 100 years
	Volume of earthwork required	1,610	cuft				
	Volume of slab concrete required	10,700	cuft	Concrete, Total	m^3/m^3	9.5E-7	structural lifespan 40 years
	Volume of wall concrete required	7,810	cuft				
Plug Flow Activated Sludge	Electrical energy required	1,880,000	kWh/yr	Electricity, Total	kwh/m^3	0.14	
	Electrical energy required	113,000	kWh/yr				
	Volume of earthwork required	176,000	cuft	Earthwork, Total	m^3/m^3	3.7E-6	plant lifespan of 100 years
	Volume of earthwork required	2,670	cuft				
	Structural	40	years	Concrete	m^3/m^3	5.9E-6	structural lifespan 40 years
	Volume of slab concrete required	75,900	cuft				
	Volume of wall concrete required	38,200	cuft				
	Handrail length	1,290	ft	Steel	kg/m^3	6.4E-6	lifespan of 40 years
	Area of pump building	334	sqft	Building	m^2/m^3	5.6E-8	lifespan of 40 years
Secondary Clarifier	Electrical energy required	11,100	kWh/yr	Electricity, Total	kwh/m^3	1.0E-3	
	Electrical energy required	6,500	kWh/yr				
	Volume of earthwork required	216,000	cuft	Earthwork, Total	m^3/m^3	4.5E-6	plant lifespan of 100 years
	Volume of earthwork required	1,630	cuft				
	Structural	40	years	Concrete, Total	m^3/m^3	1.4E-7	structural lifespan 40 years
	Volume of slab concrete required	17,000	cuft				
	Volume of wall concrete required	9,830	cuft				
	Area of pump building	204	sqft	Building	m2/m3	3.4E-8	structural lifespan 40 years

Table G-1. Example Standardization of CAPDETWorks™ Output to LCI per m3 of Treated Wastewater (Level 1)

Unit	***CAPDETWorks™ Model Output***			***Calculated LCI Values***			
	Description	**Value**	**Units**	**Calculated Flow**	**Units**	**Value**	**Assumptions**
Chlorination	Average chlorine required	832	lb/d	Chlorine	kg/m^3	0.01	operates 365 days per year
	Electrical energy required	131,000	kWh/yr	Electricity	kwh/m^3	9.5E-3	
	Volume of earthwork required	11,900	cuft	Earthwork	m^3/m^3	2.4E-7	plant lifespan of 100 years
	Structural	40.0	years	Concrete, Total	m^3/m^3	4.0E-7	structural lifespan 40 years
	Volume of slab concrete required	2,790	cuft				
	Volume of wall concrete required	4,980	cuft				
	Chlorination building area	220	sqft	Building	m^2/m^3	3.4E-7	structural lifespan 40 years
	Area of chlorine storage building	1,820	sqft				
Dechlorination	Sodium Bisulfite 40% Solution	3.75	mg/L	Sodium bisulfite	kg/m^3	3.8E-3	
	Electrical energy required	131,000	kWh/yr	Electricity	kwh/m^3	9.5E-3	
	Volume of earthwork required	1,980	cuft	Earthwork	m^3/m^3	4.1E-8	plant lifespan of 100 years
	Structural	40.0	years	Concrete, Total	m^3/m^3	1.4E-7	structural lifespan 40 years
	Volume of slab concrete required	464	cuft				
	Volume of wall concrete required	2,330	cuft				
	Dechlorination building area	220	sqft	Building	m^2/m^3	1.5E-7	structural lifespan 40 years
	Area of sodium bisulfite 40% solution storage building	700	sqft				
Gravity Thickening	Electrical energy required	10,300	kWh/yr	Electricity	kwh/m^3	7.5E-4	
	Volume of earthwork required	14,400	cuft	Earthwork	m^3/m^3	3.0E-7	plant lifespan of 100 years
	Structural	40.0	years	Concrete, Total	m^3/m^3	1.6E-7	structural lifespan 40 years
	Volume of slab concrete required	1,260	cuft				
	Volume of wall concrete required	1,860	cuft				

Table G-1. Example Standardization of CAPDETWorks™ Output to LCI per m3 of Treated Wastewater (Level 1)

Unit	*CAPDETWorks™ Model Output*				*Calculated LCI Values*			
	Description	**Value**	**Units**		**Calculated Flow**	**Units**	**Value**	**Assumptions**
Anaerobic Digester	Gas produced	107	cuft/min		Biogas, production	m^3/m^3	0.12	continuous production
	Electrical energy required	253,000	kWh/yr		Electricity	kwh/m^3	0.02	
	Volume of earthwork required	196,000	cuft		Earthwork	m^3/m^3	4.0E-6	plant lifespan of 100 years
	Structural	40.0	years		Concrete, Total	m^3/m^3	1.8E-6	structural lifespan 40 years
	Volume of slab concrete required	6,860	cuft					
	Volume of wall concrete required	27,300	cuft					
	Length of total piping system	833	ft		Steel	kg/m^3	2.4E-5	8" steel pipe, 16.2 kg/ft, lifespan 40 years
	Surface area/floor of 2-story control bldg..	1,180	sqft		Building	m^2/m^3	2.0E-7	
	Heat required	1,350,000	BTU/hr		Natural Gas	m^3/m^3	0.02	38.4 MJ/m^3 Gas HHV
Centrifuge	Polymer dosage	248	lb/d		Polymer	kg/m^3	2.1E-3	operates 5 days per week
	Electrical energy required	237,000	kWh/yr		Electricity	kwh/m^3	0.02	
	Area of building	453	sqft		Building	m^2/m^3	7.6E-8	structural lifespan 40 years
Sludge Hauling & Landfill	Volume of earthwork required	26,700	cuft		Earthwork	m^3/m^3	5.5E-7	plant lifespan of 100 years
	Structural	40	years		Concrete	m^3/m^3	5.7E-7	structural lifespan 40 years
	Volume of slab concrete required	11,100	cuft					
	Sludge storage shed area	10,100	sqft		Building, Total	m^2/m^3	3.4E-6	structural lifespan 40 years
	Surface area of canopy roof	10,100	sqft					
	Sludge hauled	80,286	kg/day		Truck Transport	ton-km/m^3	0.09	25 km haul distance, 365 days per year

APPENDIX H
SUMMARY LCI RESULTS

Appendix H: Summary LCI Result

Table H-1. LCI for Level 1: Conventional Plug Flow Activated Sludge Wastewater Treatment Configuration (per m3 wastewater treated)

	Operation										**Infrastructure**			
	Electricity	**Natural Gas**	**Chlorine Gas**	**Polymer**	**Sodium Bisulfite (40%)**	**Truck Transport**	**Digester Gas, Flared** [c]	**CH_4 Emissions**	**N_2O Emissions**	**Electricity (Avoided)**	**Earthwork**	**Concrete**	**Building**	**Steel**
Unit:	***kWh/m^3***	***m^3/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***tkm/m^3*** [b]	***m^3/m^3***	***kg/m^3***	***kg/m3***	***kWh/m3***	***m^3/m^3***	***m^3/m^3***	***m^2/m^3***	***kg/m^3***
Screening and Grit Removal	3.4E-3													
Primary Clarifier	8.6E-4										2.7E-6	1.2E-6	3.4E-8	
Plug Flow Activated Sludge	0.14							3.3E-4	4.8E-5		3.7E-6	5.8E-6	5.6E-8	6.4E-6
Secondary Clarifier	1.3E-3										4.5E-6	1.9E-6	3.4E-8	
Chlorination	9.5E-3		1.0E-2								4.9E-7	7.0E-7	3.4E-7	
Dechlorination	9.5E-3				3.8E-3						8.1E-8	1.9E-7	1.5E-7	
Effluent Release [a]									2.4E-4					
Gravity Thickener	7.5E-4										3.0E-7	1.9E-7		
Anaerobic Digester	0.02	0.04					0.12	2.5E-3			5.0E-6	2.0E-6	2.4E-7	2.6E-5
Centrifuge	0.02			2.1E-3									8.4E-8	
Sludge Hauling and Landfill						0.09		2.6E-3		0.02	5.5E-7	5.7E-7	3.4E-6	
Totals	0.20	0.04	1.0E-2	2.1E-3	3.8E-3	**0.09**	**0.12**	5.4E-3	2.9E-4	0.02	1.7E-5	1.3E-5	4.4E-6	3.2E-5

a – All effluent release emissions are presented in Table 1-4.

b – tkm is an abbreviation for ton-kilometers.

c – Biogas flaring emissions are presented in Table F-8

Table H-2. LCI for Level 2-1: Anaerobic/Anoxic/Oxic Wastewater Treatment Configuration(per m3 wastewater treated)

	Operation										**Infrastructure**			
	Electricity	**Natural Gas**	**Chlorine Gas**	**Polymer**	**Sodium Bisulfite (40%)**	**Truck Transport**	**Digester Gas, Flared** [c]	**CH_4 Emissions**	**N_2O Emissions**	**Electricity (Avoided)**	**Earthwork**	**Concrete**	**Building**	**Steel**
Unit:	***kWh/m³***	***m³/m³***	***kg/m³***	***kg/m³***	***kg/m³***	***tkm/m³*** [b]	***m³/m³***	***kg/m³***	***kg/m³***	***kWh/m³***	***m³/m³***	***m³/m³***	***m²/m³***	***kg/m³***
Screening and Grit Removal	3.4E-3													
Primary Clarifier	8.5E-4										2.6E-6	1.1E-6	3.4E-8	
Biological Nutrient Removal–3-Stage	0.43							3.3E-3	2.1E-4		9.5E-6	1.2E-5	1.2E-7	1.6E-5
Secondary Clarifier	1.1E-3										4.5E-6	1.9E-6	3.4E-8	
Chlorination	9.5E-3		1.0E-2								4.9E-7	7.0E-7	3.4E-7	
Dechlorination	9.5E-3				3.8E-3						8.1E-8	1.9E-7	1.5E-7	
Effluent Release [a]									6.3E-5					
Gravity Thickener	7.1E-4										2.6E-7	1.8E-7		
Anaerobic Digester	0.02	0.04					0.10	2.1E-3			5.0E-6	2.0E-6	2.4E-7	2.6E-5
Centrifuge	0.01			1.8E-3									7.8E-8	
Sludge Hauling and Landfill						0.07		2.1E-3		0.02	4.7E-7	4.9E-7	2.9E-6	
Totals	0.48	0.04	1.0E-2	1.8E-3	3.8E-3	0.07	0.10	7.5E-3	2.8E-4	0.02	2.3E-5	1.9E-5	3.9E-6	4.2E-5

a – All effluent release emissions are presented in Table 1-4.

b – tkm is an abbreviation for ton-kilometers.

c – Biogas flaring emissions are presented in Table F-8.

Table H-3. LCI for Level 2-2: Activated Sludge, 3-Sludge System Wastewater Treatment Configuration (per m3 wastewater treated)

	Operation													**Infrastructure**			
	Electricity	**Natural Gas**	**Chlorine Gas**	**Polymer**	**Sodium Bisulfite (40%)**	**Al Sulfate**	**Calcium Carbonate**	**Methanol**	**Truck Transport**	**Digester Gas, Flared [c]**	**CH_4 Emissions**	**N_2O Emissions**	**Electricity (Avoided)**	**Earthwork**	**Concrete**	**Building**	**Steel**
Unit:	***kWh/m^3***	***m^3/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***tkm/m^3 [b]***	***m^3/m^3***	***kg/m^3***	***kg/m^3***	***kWh/m^3***	***m^3/m^3***	***m^3/m^3***	***m^2/m^3***	***kg/m^3***
Screening and Grit Removal	3.4E-3																
Primary Clarifier	8.8E-4													2.7E-6	1.2E-6	3.4E-8	
Plug Flow Activated Sludge	0.15										3.3E-3	2.8E-5		3.8E-6	6.1E-6	5.6E-8	6.6E-6
Chemical Phosphorus Removal						0.08											
Nitrification - Suspended Growth	0.16						0.21							3.8E-6	6.1E-6	5.6E-8	6.6E-6
Denitrification - Suspended Growth	0.13							0.05						2.3E-6	1.8E-6	5.6E-8	
Secondary Clarifier	1.3E-3													4.5E-6	1.9E-6	3.4E-8	
Tertiary Clarification (Nitrification)	8.3E-4													4.5E-6	1.9E-6	3.4E-8	
Tertiary Clarification (Denitrification)	1.0E-3													4.5E-6	1.9E-6	3.4E-8	
Chlorination	9.5E-3		1.0E-2											4.9E-7	7.0E-7	3.4E-7	
Dechlorination	9.5E-3				3.8E-3									8.1E-8	1.9E-7	1.5E-7	
Effluent Release [a]												6.1E-5					
Gravity Thickener	8.2E-4													3.8E-7	2.3E-7		
Anaerobic Digester	0.02	0.06								0.13	2.8E-3			6.6E-6	2.7E-6	3.0E-7	3.5E-5
Centrifuge	0.02			3.2E-3												9.0E-8	
Sludge Hauling and Landfill									0.13		2.8E-3		0.03	8.1E-7	8.4E-7	5.1E-6	
Totals	0.51	0.06	1.0E-2	3.2E-3	3.8E-3	0.08	0.21	0.05	0.13	0.13	8.9E-3	8.9E-5	0.03	3.4E-5	2.5E-5	6.3E-6	4.8E-5

a – All effluent release emissions are presented in Table 1-4.

b – tkm is an abbreviation for ton-kilometers.

c – Biogas flaring emissions are presented in Table F-8.

Table H-4. LCI for Level 3-1: 5-Stage Bardenpho System Wastewater Treatment Configuration (per m3 wastewater treated)

	Operation											**Infrastructure**						
	Electricity	**Natural Gas**	**Chlorine Gas**	**Polymer**	**Sodium Bisulfite (40%)**	**Al Sulfate**	**Truck Transport**	**Digester Gas, Flared** [c]	**CH_4 Emissions**	**N_2O Emissions**	**Electricity (Avoided)**	**Earthwork**	**Concrete**	**Building**	**Steel**	**Sand**	**Gravel**	**Anthracite**
Unit:	kWh/m^3	m^3/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	tkm/m^3 [b]	m^3/m^3	kg/m^3	kg/m^3	kWh/m^3	m^3/m^3	m^3/m^3	m^2/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3
Screening and Grit Removal	3.4E-3																	
Primary Clarifier	8.5E-4											2.6E-6	1.1E-6	3.4E-8				
Fermenter	8.8E-4											2.1E-7	1.4E-7					
Biological Nutrient Removal–5-Stage	0.46								8.4E-3	5.7E-4		1.1E-5	1.4E-5	1.2E-7	1.9E-5			
Chemical Phosphorus Removal						4.2E-3												
Secondary Clarifier	1.2E-3											4.5E-6	1.9E-6	3.4E-8				
Filtration–Sand Filter	5.6E-3											2.7E-6	1.6E-6			1.1E-3	4.0E-4	2.7E-4
Chlorination	9.5E-3		8.0E-3									4.9E-7	7.0E-7	2.7E-7				
Dechlorination	9.5E-3				3.8E-3							8.1E-8	1.9E-7	1.5E-7				
Effluent Release [a]										4.7E-5								
Gravity Thickener	7.1E-4											2.6E-7	1.8E-7					
Anaerobic Digester	0.02	0.04						0.09	2.0E-3			5.0E-6	2.0E-6	2.4E-7	2.6E-5			
Centrifuge	0.01			1.8E-3										7.9E-8				
Sludge Hauling and Landfill							0.07		2.0E-3		0.02	4.7E-7	4.9E-7	2.9E-6				
Totals	0.52	0.04	8.0E-3	1.8E-3	3.8E-3	4.2E-3	0.07	0.09	0.01	6.2E-4	0.02	2.7E-5	2.2E-5	3.9E-6	4.5E-5	1.1E-3	4.0E-4	2.7E-4

a – All effluent release emissions are presented in Table 1-4.

b – tkm is an abbreviation for ton-kilometers.

c – Biogas flaring emissions are presented in Table F-8.

Table H-5. LCI for Level 3-2: Modified University of Cape Town Process Wastewater Treatment Configuration (per m3 wastewater treated)

	Operation											**Infrastructure**						
	Electricity	**Natural Gas**	**Chlorine Gas**	**Polymer**	**Sodium Bisulfite (40%)**	**Al Sulfate**	**Truck Transport**	**Digester Gas, Flared** [c]	**CH_4 Emissions**	**N_2O Emissions**	**Electricity (Avoided)**	**Earthwork**	**Concrete**	**Building**	**Steel**	**Sand**	**Gravel**	**Anthracite**
Unit:	kWh/m^3	m^3/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	tkm/m^3 [b]	m^3/m^3	kg/m^3	kg/m^3	kWh/m^3	m^3/m^3	m^3/m^3	m^2/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3
Screening and Grit Removal	3.4E-3											-	-	-	-			
Primary Clarifier	8.5E-4											2.6E-6	1.1E-6	3.4E-8	-			
Fermenter	8.8E-4											2.1E-7	1.4E-7	-	-			
Biological Nutrient Removal–4-Stage	0.51								8.4E-3	2.2E-4		1.1E-5	1.4E-5	1.1E-7	1.9E-5			
Chemical Phosphorus Removal						4.2E-3						-	-	-	-			
Secondary Clarifier	1.2E-3											4.5E-6	1.9E-6	3.4E-8	-			
Filtration–Sand Filter	5.6E-3											2.7E-6	1.6E-6	-	-	1.1E-3	4.0E-4	2.7E-4
Chlorination	9.5E-3		8.0E-3									4.9E-7	7.0E-7	2.7E-7	-			
Effluent Release [a]										4.7E-5								
Dechlorination	9.5E-3				3.8E-3							8.1E-8	1.9E-7	1.5E-7	-			
Gravity Thickener	7.1E-4											2.6E-7	1.8E-7	-	-			
Anaerobic Digester	0.02	0.04						0.09	2.0E-3			5.0E-6	2.0E-6	2.4E-7	2.6E-5			
Centrifuge	0.01			1.8E-3								-	-	7.9E-8	-			
Sludge Hauling and Landfill							0.07		2.0E-3		0.02	4.7E-7	4.9E-7	2.9E-6	-			
Totals	0.57	0.04	8.0E-3	1.8E-3	3.8E-3	4.2E-3	0.07	0.09	0.01	2.6E-4	0.02	2.7E-5	2.2E-5	3.9E-6	4.5E-5	1.1E-3	4.0E-4	2.7E-4

a – All effluent release emissions are presented in Table 1-4.

b – tkm is an abbreviation for ton-kilometers.

c – Biogas flaring emissions are presented in Table F-8.

Table H-6. LCI for Level 4-1: 5-Stage Bardenpho System with Denitrification Filter Wastewater Treatment Configuration (per m3 wastewater treated)

	Operation												**Infrastructure**						
	Electricity	**Natu-ral Gas**	**Chlorine Gas**	**Polym-er**	**Sodium Bisulfite (40%)**	**Al Sulfate**	**Methanol**	**Truck Trans-port**	**Digester Gas, Flared** [c]	**CH_4 Emissions**	**N_2O Emissions**	**Elect-ricity (Avo-i-ded)**	**Earth-work**	**Concrete**	**Building**	**Steel**	**Sand**	**Gravel**	**Anthracite**
Unit:	***kWh/m^3***	***m^3/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***tkm/m^3*** [b]	***m^3/m^3***	***kg/m^3***	***kg/m^3***	***kWh/m^3***	***m^3/m^3***	***m^3/m^3***	***m^2/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***
Screening and Grit Removal	3.4E-3																		
Primary Clarifier	8.5E-4												2.6E-6	1.1E-6	3.4E-8				
Fermenter	8.8E-4												2.1E-7	1.4E-7	-				
Biological Nutrient Removal–5-Stage	0.46									8.4E-3	5.7E-4		1.1E-5	1.4E-5	1.2E-7	1.9E-5			
Chemical Phosphorus Removal						4.2E-3													
Secondary Clarifier	1.2E-3												4.5E-6	1.9E-6	3.4E-8				
Denitrification - Attached Growth	0.13						0.02						1.5E-6	1.1E-6	1.9E-7		2.8E-4	1.2E-4	
Filtration–Sand Filter	5.6E-3												2.7E-6	1.6E-6			1.1E-3	4.0E-4	2.7E-4
Chlorination	9.5E-3		8.0E-3										4.9E-7	7.0E-7	2.7E-7				
Dechlorination	9.5E-3				3.8E-3								8.1E-8	1.9E-7	1.5E-7				
Effluent Release [a]											2.3E-5								
Gravity Thickener	7.1E-4												2.6E-7	1.8E-7					
Anaerobic Digester	0.02	0.04							0.09	2.0E-3			5.0E-6	2.0E-6	2.4E-7	2.6E-5			
Centrifuge	0.01			1.8E-3											7.9E-8				
Sludge Hauling and Landfill								0.07		2.0E-3		0.02	4.7E-7	4.9E-7	2.9E-6				
Totals	0.65	0.04	8.0E-3	1.8E-3	3.8E-3	4.2E-3	0.02	0.07	0.09	0.01	6.0E-4	0.02	2.9E-5	2.3E-5	4.1E-6	4.5E-5	1.4E-3	5.3E-4	2.7E-4

a – All effluent release emissions are presented in Table 1-4.

b – tkm is an abbreviation for ton-kilometers.

c – Biogas flaring emissions are presented in Table C-8.

Table H-7. LCI for Level 4-2: 4-Stage Bardenpho Membrane Bioreactor System Wastewater Treatment Configuration (per m3 wastewater treated)

	Operation											Infrastructure			
	Electricity	**Natural Gas**	**Chlorine Gas**	**Polymer**	**Sodium Bisulfite (40%)**	**Al Sulfate**	**Truck Transport**	**Digester Gas, Flared** [c]	**CH_4 Emissions**	**N_2O Emissions**	**Electricity (Avoided)**	**Earthwork**	**Concrete**	**Building**	**Steel**
Unit:	***kWh/m³***	***m³/m³***	***kg/m³***	***kg/m³***	***kg/m³***	***kg/m³***	***tkm/m³*** [b]	***m³/m³***	***kg/m³***	***kg/m³***	***kWh/m³***	***m³/m³***	***m³/m³***	***m²/m³***	***kg/m³***
Screening and Grit Removal	3.4E-3											-	-	-	-
Primary Clarifier	8.5E-4											2.6E-6	1.1E-6	3.4E-8	-
Biological Nutrient Removal–4-Stage	0.35								8.4E-3	5.6E-4		5.5E-6	7.8E-6	1.2E-7	9.4E-6
Chemical Phosphorus Removal						2.2E-3						-	-	-	-
Membrane Filter	0.23											1.5E-6	3.1E-6	8.2E-8	5.4E-6
Chlorination	9.5E-3		8.0E-3									4.9E-7	7.0E-7	2.7E-7	-
Dechlorination	9.5E-3				3.8E-3							8.1E-8	1.9E-7	1.5E-7	-
Effluent Release [a]										2.4E-5		-	-	-	-
Gravity Thickener	7.0E-4											2.6E-7	1.8E-7	-	-
Anaerobic Digester	0.02	0.03						0.09	2.0E-3			4.5E-6	1.9E-6	2.2E-7	2.5E-5
Centrifuge	0.01			1.8E-3								-	-	7.8E-8	-
Sludge Hauling and Landfill							0.07		2.1E-3		0.02	4.6E-7	4.8E-7	2.9E-6	-
Totals	0.64	0.03	8.0E-3	1.8E-3	3.8E-3	2.2E-3	0.07	0.09	0.01	5.9E-4	0.02	1.5E-5	1.5E-5	3.8E-6	4.0E-5

a – All effluent release emissions are presented in Table 1-4.

b – tkm is an abbreviation for ton-kilometers.

c – Biogas flaring emissions are presented in Table C-8.

Table H-8. Operational LCI for Level 5-1: 5-Stage Bardenpho with Sidestream Reverse Osmosis Wastewater Treatment Configuration (per m3 wastewater treated)

	Electricity	**Natural Gas**	**Chlorine Gas**	**Polymer**	**Sodium Bisulfite (40%/12.5 %)**	**Al Sulfate**	**Methanol**	**Antiscalant**	**Brine Injection (Water Loss)**	**Truck Transport**	**Citric Acid**	**Sodium Hypochlorite**	**Sulfuric Acid**	**Sodium Hydroxide**	**Digester Gas, Flared [c]**	**CH_4 Emissions**	**N_2O Emissions**	**Electricity (Avoided)**
Unit:	***kWh/m^3***	***m^3/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***m^3/m^3***	***tkm/m^3 [b]***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***m^3/m^3***	***kg/m^3***	***kg/m^3***	***kWh/m^3***
Screening and Grit Removal	3.4E-3																	
Primary Clarifier	8.5E-4																	
Fermenter	8.8E-4																	
Biological Nutrient Removal – 5-Stage	0.46															8.4E-3	5.7E-4	
Chemical Phosphorus Removal						4.2E-3												
Secondary Clarifier	1.2E-3																	
Denitrification – Attached Growth	0.01						2.3E-3											
Filtration – Sand Filter	5.9E-4																	
Chlorination	9.1E-3		4.9E-3															
Dechlorination	9.1E-3				7.5E-3													
Ultrafiltration	0.17				4.0E-4						1.6E-3	9.9E-4	1.2E-3	3.9E-3				
Reverse Osmosis	0.46							2.7E-3			9.5E-4							
Effluent Release [a]																	5.0E-6	
Gravity Thickener	7.1E-4																	
Anaerobic Digester	0.02	0.04													0.09	2.0E-3		
Centrifuge	0.01			1.8E-3														
Sludge Hauling and Landfill										0.07						2.0E-3		0.02
Underground Injection of Brine	0.33								0.18	2.7E-5								
Totals	1.5	0.04	4.9E-3	1.8E-3	7.9E-3	4.2E-3	2.3E-3	2.7E-3	0.18	0.07	2.5E-3	9.9E-4	1.2E-3	3.9E-3	0.09	0.01	5.8E-4	0.02

a – All effluent release emissions are presented in Table 1-4.

b – tkm is an abbreviation for ton-kilometers.

c – Biogas flaring emissions are presented in Table C-8.

Table H-9. Infrastructure LCI for Level 5-1: 5-Stage Bardenpho with Sidestream Reverse Osmosis Wastewater Treatment Configuration (per m3 wastewater treated)

	Earthwork	**Concrete**	**Building**	**Steel**	**Sand**	**Gravel**	**Anthracite**
Unit:	***m3/m3***	***m3/m3***	***m2/m3***	***kg/m3***	***kg/m3***	***kg/m3***	***kg/m3***
Screening and Grit Removal							
Primary Clarifier	2.6E-6	1.1E-6	3.4E-8				
Fermenter	2.1E-7	1.4E-7					
Biological Nutrient Removal – 5-Stage	1.1E-5	1.4E-5	1.2E-7	1.9E-5			
Chemical Phosphorus Removal							
Secondary Clarifier	4.5E-6	1.9E-6	3.4E-8				
Denitrification – Attached Growth	3.2E-7	4.1E-7	8.5E-8		2.8E-5	1.2E-5	
Filtration – Sand Filter	3.9E-7	2.2E-7			1.1E-4	4.0E-5	2.7E-5
Chlorination	4.0E-7	5.9E-7	2.0E-7				
Dechlorination	6.7E-8	1.8E-7	2.3E-7				
Ultrafiltration	2.6E-6	-	2.7E-6				
Reverse Osmosis	1.6E-6	-	1.7E-6				
Gravity Thickener	2.6E-7	1.8E-7					
Anaerobic Digester	5.0E-6	2.0E-6	2.4E-7	2.6E-5			
Centrifuge			7.9E-8				
Sludge Hauling and Landfill	4.7E-7	4.9E-7	2.9E-6				
Underground Injection of Brine			2.8E-8	2.7E-5			
Totals	2.9E-5	2.1E-5	8.4E-6	7.2E-5	1.4E-4	5.3E-5	2.7E-5

Table H-10. LCI for Level 5-2: 5-Stage Bardenpho Membrane Bioreactor with Sidestream Reverse Osmosis Wastewater Treatment Configuration (per m3 wastewater treated)

	Operation														Infrastructure			
	Electricity	**Natural Gas**	**Chlorine Gas**	**Polymer**	**Sodium Bisulfite (40%)**	**Al Sulfate**	**Antiscalant**	**Brine Injection (Water Loss)**	**Truck Transport**	**Citric Acid**	**Digester Gas, Flared** [c]	**CH4 Emissions**	**N2O Emissions**	**Electricity (Avoided)**	**Earthwork**	**Concrete**	**Building**	**Steel**
Unit:	***kWh/m^3***	***m^3/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***m^3/m^3***	***tkm/m^3*** [b]	***kg/m^3***	***m^3/m^3***	***kg/m^3***	***kg/m^3***	***kWh/m^3***	***m^3/m^3***	***m^3/m^3***	***m^2/m^3***	***kg/m^3***
Screening and Grit Removal	3.4E-3																	
Primary Clarifier	8.5E-4														2.6E-6	1.1E-6	3.4E-8	
Fermenter	8.8E-4														2.1E-7	1.4E-7		
Biological Nutrient Removal – 5-Stage	0.39											8.4E-3	5.7E-4		5.3E-6	7.6E-6	1.2E-7	9.1E-6
Chemical Phosphorus Removal						2.1E-3												
Membrane Filter	0.23														1.5E-6	3.1E-6	8.3E-8	5.4E-6
Chlorination	9.1E-3		5.0E-3												4.8E-7	6.9E-7	2.0E-7	
Dechlorination	9.1E-3				7.5E-3										8.0E-8	1.9E-7	2.3E-7	
Reverse Osmosis	0.44						2.5E-3			8.9E-4					1.6E-6	-	1.7E-6	
Effluent Release [a]													1.3E-5					
Gravity Thickener	7.0E-4														2.1E-7	1.5E-7		
Anaerobic Digester	0.02	0.03									0.09	1.9E-3			4.0E-6	1.8E-6	2.0E-7	2.4E-5
Centrifuge	0.01			1.7E-3													7.7E-8	
Sludge Hauling and Landfill									0.07			2.0E-3		0.02	4.5E-7	4.7E-7	2.8E-6	
Underground Injection of Brine	0.33							0.17	2.7E-5								2.8E-8	2.7E-5
Totals	1.4	0.03	5.0E-3	1.7E-3	7.5E-3	2.1E-3	2.5E-3	0.17	0.07	8.9E-4	0.09	0.01	5.8E-4	0.02	1.6E-5	1.5E-5	5.4E-6	6.6E-5

Table H-11. Sludge Quantity Produced by Wastewater Treatment Configuration

Wastewater Treatment Configuration	kg Sludge/m^3 Wastewater Treated[a]	% Change to Level 1, AS
Level 1, AS	0.26	-
Level 2-1, A2O	0.22	-15%
Level 2-2, AS3	0.38	48%
Level 3-1, B5	0.22	3%
Level 3-2, MUCT	0.22	3%
Level 4-1, B5/Denit	0.22	4%
Level 4-2, MBR	0.22	4%
Level 5-1, B5/RO	0.22	4%
Level 5-2, MBR/RO	0.21	0%

[a] 21 percent moisture

APPENDIX I
COST RESULTS BY UNIT PROCESS

Appendix I: Cost Results by Unit Process

This Appendix provides cost results by unit process using the 3% interest and discount rates. Table I-1 and Table I-2 display the detailed results for the total construction costs and total annual costs by unit process. Table I-3 through Table I-7 display the detailed results by total annual cost component (e.g., operational labor, maintenance labor) by unit process. Net present value was not calculated by unit process.

Table I-1. Total Construction Costs by Detailed Unit Process (2014 $)

Process	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Screening and grit removal	$1,890,000	$1,890,000	$1,900,000	$1,890,000	$1,890,000	$1,888,000	$1,890,000	$1,888,000	$1,890,000
Primary clarifier	$1,260,000	$1,230,000	$1,260,000	$1,230,000	$1,230,000	$1,230,000	$1,230,000	$1,230,000	$1,230,000
Activated Sludge	$5,100,000		$5,260,000						
Biological nutrient removal-3-stage		$12,500,000							
Biological nutrient removal-4-stage					$14,800,000		$7,580,000		
Biological nutrient removal-5-stage				$13,800,000		$13,800,000		$13,800,000	$8,550,000
Blower System	$715,000	$770,000	$1,150,000	$787,000	$787,000	$787,000	$2,490,000	$787,000	$2,520,000
Secondary Clarifier	$1,880,000	$1,880,000	$1,890,000	$1,880,000	$1,880,000	$1,880,000		$1,880,000	
Membrane Filter							$13,300,000		$13,300,000
Nitrification, suspended growth			$5,330,000						
Tertiary clarification, nitrification			$1,860,000						
Denitrification, suspended growth			$1,830,000						
Tertiary clarification, denitrification			$1,880,000						
Fermenter				$788,000	$788,000	$788,000		$788,000	$788,000
Chemical Phosphorus Removal			$0	$0	$0	$0	$0	$0	$0
Alum Feed System			$302,000	$214,000	$214,000	$214,000	$214,000	$214,000	$214,000
Denitrification, attached growth						$2,580,000		$560,000	
Sand Filter				$3,810,000	$3,810,000	$3,810,000		$1,100,000	
Ultrafiltration								$11,430,000	
Reverse Osmosis								$12,990,000	$12,340,000
Chlorination	$977,000	$977,000	$977,000	$954,000	$954,000	$954,000	$955,000	$795,000	$860,000
$0Dechlorination	$213,000	$213,000	$213,000	$213,000	$213,000	$213,000	$213,000	$224,000	$235,000
Effluent Release	$0	$0	$0	$0	$0	$0	$0	$0	$0
Gravity Thickener	$1,090,000	$1,010,000	$1,240,000	$1,010,000	$1,010,000	$1,010,000	$1,010,000	$1,010,000	$901,000
Anaerobic Digester	$5,440,000	$5,320,000	$7,450,000	$5,320,000	$5,320,000	$5,320,000	$4,570,000	$5,320,000	$4,830,000
Centrifuge	$2,720,000	$2,370,000	$3,760,000	$2,380,000	$2,380,000	$2,380,000	$2,350,000	$2,390,000	$2,320,000
Sludge Hauling and Landfill	$988,000	$649,000	$1,320,000	$651,000	$651,000	$651,000	$644,000	$651,000	$639,000
Brine Injection Well								$7,790,000	$7,790,000
Other Costs	$33,000,000	$42,600,000	$55,500,000	$51,500,000	$53,000,000	$55,300,000	$53,700,000	$95,400,000	$86,000,000
Total	**$55,300,000**	**$71,400,000**	**$93,100,000**	**$86,400,000**	**$88,900,000**	**$92,800,000**	**$90,100,000**	**$160,000,000**	**$144,000,000**

Table I-2. Total Annual Costs by Detailed Unit Process (2014 $)

Process	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Screening and grit removal	$170,000	$170,000	$174,000	$170,000	$171,000	$172,000	$171,000	$171,000	$171,000
Primary clarifier	$117,000	$117,000	$120,000	$120,000	$117,000	$118,000	$118,000	$118,000	$118,000
Activated Sludge	$518,000		$532,000						
Biological nutrient removal-3-stage		$1,300,000							
Biological nutrient removal-4-stage					$1,540,000		$1,120,000		
Biological nutrient removal-5-stage				$1,380,000		$1,380,000		$1,380,000	$1,140,000
Blower System	$0	$0	$0	$0	$0	$0	$0	$0	$0
Secondary Clarifier	$157,000	$156,000	$160,000	$157,000	$157,000	$158,000		$158,000	
Membrane Filter							$1,230,000		$1,230,000
Nitrification, suspended growth			$554,000						
Tertiary clarification, nitrification			$148,000						
Denitrification, suspended growth			$1,370,000						
Tertiary clarification, denitrification			$155,000						
Fermenter				$72,000	$72,100	$72,800		$72,500	$72,400
Chemical Phosphorus Removal			$1,210,000	$61,500	$61,500	$61,500	$31,000	$61,500	$61,300
Alum Feed System			$124,000	$37,300	$37,300	$37,300	$35,200	$37,300	$37,300
Denitrification, attached growth						$1,030,000		$372,000	
Sand Filter				$128,000	$128,000	$129,000		$47,400	
Ultrafiltration								$487,000	
Reverse Osmosis								$1,200,000	$1,140,000
Chlorination	$313,000	$313,000	$313,000	$266,000	$267,000	$267,000	$267,000	$189,000	$193,000
Dechlorination	$121,000	$122,000	$122,000	$122,000	$122,000	$122,000	$122,000	$171,000	$173,000
Effluent Release	$0	$0	$0	$0	$0	$0	$0	$0	$0
Gravity Thickener	$75,000	$67,000	$92,800	$66,000	$66,600	$67,200	$66,800	$66,900	$64,900
Anaerobic Digester	$591,000	$526,000	$804,000	$523,000	$523,000	$525,000	$510,000	$524,000	$489,000
Centrifuge	$797,000	$717,000	$1,060,000	$720,000	$720,000	$721,000	$711,000	$720,000	$704,000
Sludge Hauling and Landfill	$1,990,000	$1,680,000	$2,910,000	$1,690,000	$1,690,000	$1,680,000	$1,660,000	$1,690,000	$1,640,000
Brine Injection Well								$479,000	$479,000
Other Costs	$288,000	$288,000	$290,000	$288,000	$288,000	$288,000	$288,000	$361,000	$360,000
Total	**$5,140,000**	**$5,470,000**	**$10,150,000**	**$5,800,000**	**$5,960,000**	**$6,840,000**	**$6,330,000**	**$8,320,000**	**$8,080,000**

Table I-3. Total Operational Labor Costs by Detailed Unit Process (2014 $)

Process	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Screening and grit removal	$100,000	$100,000	$101,000	$100,000	$100,000	$100,000	$99,800	$100,000	$99,800
Primary clarifier	$68,900	$68,700	$69,500	$68,700	$68,700	$68,700	$68,600	$68,700	$68,600
Activated Sludge	$148,000		$149,000						
Biological nutrient removal-3-stage		$316,000							
Biological nutrient removal-4-stage					$348,000		$276,000		
Biological nutrient removal-5-stage				$320,000		$320,000		$320,000	$288,000
Blower System	$0	$0	$0	$0	$0	$0	$0	$0	$0
Secondary Clarifier	$90,800	$89,800	$91,400	$90,300	$90,300	$90,300		$90,300	
Membrane Filter							$440,000		$440,000
Nitrification, suspended growth			$154,000						
Tertiary clarification, nitrification			$84,900						
Denitrification, suspended growth			$129,000						
Tertiary clarification, denitrification			$88,500						
Fermenter				$38,600	$38,600	$38,600		$38,600	$38,400
Chemical Phosphorus Removal			$0	$0	$0	$0	$0	$0	$0
Alum Feed System			$118,000	$33,000	$33,000	$33,000	$30,900	$33,000	$33,000
Denitrification, attached growth						$554,000		$221,000	
Sand Filter				$15,400	$15,400	$15,400		$4,140	
Ultrafiltration								$18,800	
Reverse Osmosis								$18,800	$18,800
Chlorination	$74,400	$74,400	$74,400	$66,100	$66,100	$66,100	$66,100	$51,000	$51,400
Dechlorination	$44,200	$44,200	$44,100	$44,200	$44,200	$44,200	$44,200	$57,400	$57,800
Effluent Release	$0	$0	$0	$0	$0	$0	$0	$0	$0
Gravity Thickener	$40,000	$34,900	$50,300	$34,700	$34,700	$34,700	$34,600	$34,700	$34,000
Anaerobic Digester	$134,000	$115,000	$171,000	$114,000	$114,000	$114,000	$113,000	$114,000	$111,000
Centrifuge	$570,000	$521,000	$730,000	$523,000	$523,000	$523,000	$517,000	$523,000	$512,000
Sludge Hauling and Landfill	$204,000	$173,000	$302,000	$174,000	$174,000	$173,000	$171,000	$174,000	$168,000
Brine Injection Well								$9,400	$9,400
Other Costs	$288,000	$288,000	$288,000	$288,000	$288,000	$288,000	$288,000	$361,000	$357,000
Total	**$1,760,000**	**$1,830,000**	**$2,650,000**	**$1,910,000**	**$1,940,000**	**$2,460,000**	**$2,150,000**	**$2,240,000**	**$2,290,000**

Table I-4. Total Maintenance Labor Costs by Detailed Unit Process (2014 $)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	$41,700	$42,200	$44,100	$42,400	$42,500	$43,800	$43,300	$43,200	$43,400
Primary clarifier	$34,500	$34,900	$36,500	$35,100	$35,200	$36,200	$35,800	$35,700	$36,000
Activated Sludge	$74,100		$78,900						
Biological nutrient removal-3-stage		$168,000							
Biological nutrient removal-4-stage					$191,000		$149,000		
Biological nutrient removal-5-stage				$171,000		$176,000		$174,000	$158,000
Blower System	$0	$0	$0	$0	$0	$0	$0	$0	$0
Secondary Clarifier	$45,500	$45,600	$48,000	$46,100	$46,200	$47,700		$47,000	
Membrane Filter							$239,000		$241,000
Nitrification, suspended growth			$81,300						
Tertiary clarification, nitrification			$43,300						
Denitrification, suspended growth			$70,200						
Tertiary clarification, denitrification			$46,100						
Fermenter				$24,300	$24,400	$25,100		$24,800	$24,900
Chemical Phosphorus Removal			$0	$0	$0	$0	$0	$0	$0
Alum Feed System			$0	$0	$0	$0	$0	$0	$0
Denitrification, attached growth						$216,000		$120,000	
Sand Filter				$9,090	$9,110	$9,390		$2,410	
Ultrafiltration								$18,800	
Reverse Osmosis								$18,800	$18,800
Chlorination	$15,600	$15,800	$16,300	$12,800	$12,900	$13,200	$13,100	$8,140	$8,310
Dechlorination	$6,020	$6,120	$6,310	$12,800	$6,160	$13,200	$6,290	$10,100	$10,300
Effluent Release	$0	$0	$0	$0	$0	$0	$0	$0	$0
Gravity Thickener	$22,900	$20,700	$29,000	$20,700	$20,800	$21,400	$21,100	$21,100	$20,900
Anaerobic Digester	$72,100	$63,600	$96,100	$63,500	$63,600	$65,500	$64,500	$64,700	$63,300
Centrifuge	$31,800	$29,800	$44,400	$30,100	$30,200	$31,000	$30,500	$30,600	$30,300
Sludge Hauling and Landfill	$0	$0	$0	$0	$0	$0	$0	$0	$0
Brine Injection Well								$9,400	$9,400
Other Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total	**$344,000**	**$427,000**	**$641,000**	**$461,000**	**$482,000**	**$692,000**	**$603,000**	**$629,000**	**$665,000**

Table I-5. Total Material Costs by Detailed Unit Process (2014 $)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	$23,600	$23,600	$23,700	$23,600	$23,600	$23,600	$23,600	$23,600	$23,600
Primary clarifier	$12,500	$12,200	$12,500	$12,200	$12,200	$12,200	$12,200	$12,200	$12,200
Activated Sludge	$97,400		$100,000						
Biological nutrient removal-3-stage		$228,000							
Biological nutrient removal-4-stage					$259,000		$132,000		
Biological nutrient removal-5-stage				$253,000		$253,000		$253,000	$152,000
Blower System	$0	$0	$0	$0	$0	$0	$0	$0	$0
Secondary Clarifier	$18,700	$18,700	$18,700	$18,700	$18,700	$18,700		$18,700	
Membrane Filter							$130,000		$130,000
Nitrification, suspended growth			$102,000						
Tertiary clarification, nitrification			$18,500						
Denitrification, suspended growth			$6,830						
Tertiary clarification, denitrification			$18,600						
Fermenter				$7,880	$7,880	$7,880		$7,875	$7,875
Chemical Phosphorus Removal			$0	$0	$0	$0	$0	$0	$0
Alum Feed System			$6,040	$4,280	$4,280	$4,280	$4,280	$4,280	$4,280
Denitrification, attached growth						$14,200		$3,270	
Sand Filter				$96,200	$96,200	$96,200		$40,000	
Ultrafiltration								$124,000	
Reverse Osmosis								$162,000	$153,000
Chlorination	$30,600	$30,600	$30,600	$31,400	$31,400	$31,400	$31,400	$29,300	$31,600
Dechlorination	$20,200	$20,200	$20,200	$20,200	$20,200	$20,200	$20,200	$20,600	$20,900
Effluent Release	$0	$0	$0	$0	$0	$0	$0	$0	$0
Gravity Thickener	$10,900	$10,100	$12,400	$10,100	$10,100	$10,100	$10,100	$10,100	$9,010
Anaerobic Digester	$42,400	$40,800	$59,400	$40,800	$40,800	$40,800	$39,100	$40,800	$37,400
Centrifuge	$86,400	$73,500	$128,000	$73,800	$73,800	$73,800	$72,300	$73,800	$71,400
Sludge Hauling and Landfill	$1,790,000	$1,510,000	$2,610,000	$1,520,000	$1,520,000	$1,510,000	$1,490,000	$1,520,000	$1,470,000
Brine Injection Well								$2,900	$2,900
Other Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total	**$2,130,000**	**$1,970,000**	**$3,170,000**	**$2,110,000**	**$2,120,000**	**$2,120,000**	**$1,970,000**	**$2,350,000**	**$2,130,000**

Table I-6. Total Chemical Costs by Detailed Unit Process (2014 $)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	$0	$0	$0	$0	$0	$0	$0	$0	$0
Primary clarifier	$0	$0	$0	$0	$0	$0	$0	$0	$0
Activated Sludge	$0		$0						
Biological nutrient removal-3-stage		$0							
Biological nutrient removal-4-stage					$0		$77,300		
Biological nutrient removal-5-stage				$0		$0		$0	$0
Blower System	$0	$0	$0	$0	$0	$0	$0	$0	$0
Secondary Clarifier	$0	$0	$0	$0	$0	$0		$0	
Membrane Filter							$103,000		$103,000
Nitrification, suspended growth			$0						
Tertiary clarification, nitrification			$0						
Denitrification, suspended growth			$991,000						
Tertiary clarification, denitrification			$0						
Fermenter				$0	$0	$0		$0	$0
Chemical Phosphorus Removal			$1,210,000	$61,500	$61,500	$61,500	$31,000	$61,500	$61,300
Alum Feed System			$0	$0	$0	$0	$0	$0	$0
Denitrification, attached growth						$74,300		$7,430	
Sand Filter				$0	$0	$0		$0	
Ultrafiltration								$91,400	
Reverse Osmosis								$361,000	$341,000
Chlorination	$179,000	$179,000	$179,000	$143,000	$143,000	$143,000	$143,000	$88,200	$89,300
Dechlorination	$50,400	$50,400	$50,400	$50,400	$50,400	$50,400	$50,400	$82,500	$83,500
Effluent Release	$0	$0	$0	$0	$0	$0	$0	$0	$0
Gravity Thickener	$0	$0	$0	$0	$0	$0	$0	$0	$0
Anaerobic Digester	$0	$0	$0	$0	$0	$0	$0	$0	$0
Centrifuge	$84,700	$71,800	$126,000	$72,100	$72,100	$72,100	$70,700	$72,200	$69,800
Sludge Hauling and Landfill	$0	$0	$0	$0	$0	$0	$0	$0	$0
Brine Injection Well								$0	$0
Other Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total	**$314,000**	**$301,000**	**$2,560,000**	**$327,000**	**$327,000**	**$401,000**	**$475,000**	**$764,000**	**$748,000**

Table I-7. Total Energy Costs by Detailed Unit Process (2014 $)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	$4,700	$4,680	$4,720	$4,690	$4,690	$4,690	$4,680	$4,690	$4,680
Primary clarifier	$1,190	$1,180	$1,210	$1,180	$1,180	$1,180	$1,180	$1,180	$1,180
Activated Sludge	$198,000		$204,000						
Biological nutrient removal-3-stage		$592,000							
Biological nutrient removal-4-stage					$737,000		$483,000		
Biological nutrient removal-5-stage				$635,000		$635,000		$635,000	$541,000
Blower System	$0	$0	$0	$0	$0	$0	$0	$0	$0
Secondary Clarifier	$1,760	$1,590	$1,820	$1,660	$1,660	$1,660		$1,660	
Membrane Filter							$319,000		$320,000
Nitrification, suspended growth			$217,000						
Tertiary clarification, nitrification			$1,140						
Denitrification, suspended growth			$175,000						
Tertiary clarification, denitrification			$1,400						
Fermenter				$1,220	$1,220	$1,220		$1,223	$1,220
Chemical Phosphorus Removal			$0	$0	$0	$0	$0	$0	$0
Alum Feed System			$0	$0	$0	$0	$0	$0	$0
Denitrification, attached growth						$174,000		$20,400	
Sand Filter				$7,690	$7,690	$7,690		$820	
Ultrafiltration								$234,000	
Reverse Osmosis								$641,000	$606,000
Chlorination	$13,100	$13,100	$13,100	$13,100	$13,100	$13,100	$13,100	$12,600	$12,600
Dechlorination	$650	$650	$650	$650	$650	$650	$650	$650	$650
Effluent Release	$0	$0	$0	$0	$0	$0	$0	$0	$0
Gravity Thickener	$1,030	$977	$1,130	$975	$975	$975	$972	$975	$965
Anaerobic Digester	$342,320	$306,861	$477,457	$304,875	$304,875	$304,875	$293,400	$304,875	$277,773
Centrifuge	$24,000	$20,500	$34,500	$20,600	$20,600	$20,600	$20,300	$20,600	$20,000
Sludge Hauling and Landfill	$0	$0	$0	$0	$0	$0	$0	$0	$0
Brine Injection Well								$457,000	$457,000
Other Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total	**$587,000**	**$942,000**	**$1,130,000**	**$992,000**	**$1,090,000**	**$1,170,000**	**$1,140,000**	**$2,340,000**	**$2,240,000**

APPENDIX J
LCIA RESULTS BY UNIT PROCESS

Appendix J: LCIA Results by Unit Process

This Appendix provides LCIA results by unit process. Table J-1 through Table J-12 display the detailed results for the twelve impact categories by unit process on the basis of a cubic meter of wastewater treated.

Table J-1. Eutrophication Potential Results by Detailed Unit Process (kg N eq/m^3 Wastewater Treated)

Process	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Screening and grit removal	1.2E-5	1.2E-5	1.2E-5	1.2E-5	1.2E-5	1.2E-5	1.2E-5	1.2E-5	1.2E-5
Primary clarifier	3.4E-6	3.4E-6	3.5E-6	3.4E-6	3.4E-6	3.3E-6	3.3E-6	3.4E-6	3.3E-6
Activated sludge	5.0E-4		5.1E-4						
Secondary clarifier	5.1E-6	4.6E-6	5.2E-6	4.8E-6	4.8E-6	4.8E-6		4.8E-6	
Biological nutrient removal-3-stage		1.5E-3							
Biological nutrient removal-4-stage					1.8E-3		1.2E-3		
Biological nutrient removal-5-stage				1.6E-3		1.6E-3		1.6E-3	1.4E-3
Filtration				2.2E-5	2.2E-5	2.2E-5		2.3E-6	
Tertiary clarification, denitrification			4.2E-6						
Tertiary clarification, nitrification			3.5E-6						
Chlorination	1.1E-4	1.0E-4	1.0E-4	9.0E-5	9.0E-5	9.0E-5	9.0E-5	6.7E-5	6.7E-5
Dechlorination	4.3E-5	4.3E-5	4.3E-5	4.3E-5	4.3E-5	4.3E-5	4.3E-5	5.1E-5	5.1E-5
Reverse osmosis								1.7E-3	1.6E-3
Denitrification, attached growth						4.5E-4		5.3E-5	
Denitrification, suspended growth			4.8E-4						
Nitrification, suspended growth			5.5E-4						
Ultrafiltration								6.7E-4	
Chemical phosphorus removal			2.5E-4	1.3E-5	1.3E-5	1.3E-5	6.4E-6	1.3E-5	6.3E-6
Membrane filter							8.3E-4		8.3E-4
Centrifuge	8.6E-5	7.3E-5	1.3E-4	7.4E-5	7.4E-5	7.4E-5	7.2E-5	7.4E-5	7.1E-5
Sludge hauling and landfill	1.7E-3	1.5E-3	2.6E-3	1.5E-3	1.5E-3	1.5E-3	1.4E-3	1.5E-3	1.4E-3
Anaerobic digester	1.4E-4	1.2E-4	1.7E-4	1.2E-4	1.2E-4	1.2E-4	1.2E-4	1.2E-4	1.1E-4
Fermentation				3.1E-6	3.1E-6	3.1E-6		3.1E-6	3.1E-6
Gravity thickener	2.6E-6	2.5E-6	2.9E-6	2.5E-6	2.5E-6	2.5E-6	2.5E-6	2.5E-6	2.5E-6
Effluent release	0.06	6.5E-3	0.01	3.3E-3	3.3E-3	2.2E-3	3.0E-3	5.9E-4	8.5E-4
Underground injection of brine								1.1E-3	1.1E-3
Total	0.07	9.8E-3	0.02	6.8E-3	6.9E-3	6.1E-3	6.8E-3	7.5E-3	7.5E-3

Table J-2. Cumulative Energy Demand Results by Detailed Unit Process (MJ/m^3 Wastewater Treated)

Process	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Screening and grit removal	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Primary clarifier	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Activated sludge	2.0	-	2.1	-	-	-	-	-	-
Secondary clarifier	0.02	0.02	0.02	0.02	0.02	0.02		0.02	-
Biological nutrient removal-3-stage	-	6.1	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	7.2	-	5.0	-	-
Biological nutrient removal-5-stage	-	-	-	6.5	-	6.5	-	6.5	5.6
Filtration	-	-	-	0.09	0.09	0.09	-	9.2E-3	-
Tertiary clarification, denitrification	-	-	0.02	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	0.01	-	-	-	-	-	-
Chlorination	0.35	0.33	0.33	0.29	0.29	0.29	0.29	0.23	0.23
Dechlorination	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.20	0.20
Reverse osmosis	-	-	-	-	-	-	-	6.9	6.5
Denitrification, attached growth	-	-	-	-	-	2.7	-	0.30	-
Denitrification, suspended growth	-	-	3.8	-	-	-	-	-	-
Nitrification, suspended growth	-	-	2.3	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	2.8	-
Chemical phosphorus removal	-	-	0.79	0.04	0.04	0.04	0.02	0.04	0.02
Membrane filter	-	-	-	-	-	-	3.4	-	3.4
Centrifuge	0.39	0.33	0.57	0.33	0.33	0.33	0.33	0.33	0.32
Sludge hauling and landfill	0.51	0.44	0.88	0.45	0.45	0.45	0.43	0.45	0.43
Anaerobic digester	1.8	1.6	2.5	1.8	1.6	1.6	1.6	1.6	1.5
Fermentation	-	-	-	0.01	0.01	0.01	-	0.01	0.01
Gravity thickener	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Effluent release	-	-	-	-	-	-	-	-	-
Underground injection of brine	-	-	-	-	-	-	-	4.7	4.7
Total	5.4	9.1	14	9.7	10	12	11	24	23

Table J-3. Global Warming Potential Results by Detailed Unit Process (kg CO_2 eq/m^3 Wastewater Treated)

Process	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Screening and grit removal	2.7E-3	2.7E-3	2.7E-3	2.7E-3	2.7E-3	2.7E-3	2.7E-3	2.7E-3	2.7E-3
Primary clarifier	1.0E-3	1.0E-3	1.1E-3	1.0E-3	1.0E-3	1.0E-3	1.0E-3	1.0E-3	1.0E-3
Activated sludge	0.14	-	0.21	-	-	-	-	-	-
Secondary clarifier	1.6E-3	1.5E-3	1.6E-3	1.5E-3	1.5E-3	1.5E-3		1.5E-3	-
Biological nutrient removal-3-stage	-	0.49	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	0.68	-	0.66	-	-
Biological nutrient removal-5-stage	-	-	-	0.75	-	0.75	-	0.75	0.69
Filtration	-	-	-	4.5E-3	4.5E-3	4.5E-3	-	4.8E-4	-
Tertiary clarification, denitrification	-	-	1.4E-3	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	1.2E-3	-	-	-	-	-	-
Chlorination	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01
Dechlorination	9.4E-3	9.4E-3	9.4E-3	9.4E-3	9.4E-3	9.4E-3	9.4E-3	0.01	0.01
Reverse osmosis	-	-	-	-	-	-	-	0.39	0.36
Denitrification, attached growth	-	-	-	-	-	0.12	-	0.01	-
Denitrification, suspended growth	-	-	0.14	-	-	-	-	-	-
Nitrification, suspended growth	-	-	0.13	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	0.15	-
Chemical phosphorus removal	-	-	0.04	2.1E-3	2.1E-3	2.1E-3	1.0E-3	2.1E-3	1.0E-3
Membrane filter	-	-	-	-	-	-	0.19		0.19
Centrifuge	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02
Sludge hauling and landfill	0.07	0.06	0.09	0.06	0.06	0.06	0.06	0.06	0.05
Anaerobic digester	0.19	0.16	0.23	0.16	0.16	0.16	0.15	0.16	0.15
Fermentation	-	-	-	7.4E-4	7.4E-4	7.4E-4	-	7.4E-4	7.4E-4
Gravity thickener	6.5E-4	6.1E-4	7.2E-4	6.1E-4	6.1E-4	6.1E-4	6.1E-4	6.1E-4	6.0E-4
Effluent release	0.07	0.02	0.02	0.01	0.01	6.8E-3	7.0E-3	1.5E-3	3.9E-3
Underground injection of brine	-	-	-	-	-	-	-	0.26	0.26
Total	0.52	0.77	0.92	1.0	0.96	1.1	1.1	1.8	1.8

Table J-4. Acidification Potential Results by Detailed Unit Process (kg SO_2 eq/m^3 Wastewater Treated)

Process	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Screening and grit removal	2.1E-4	2.1E-4	2.1E-4	2.1E-4	2.1E-4	2.1E-4	2.1E-4	2.1E-4	2.1E-4
Primary clarifier	5.7E-5	5.7E-5	5.9E-5	5.7E-5	5.7E-5	5.7E-5	5.7E-5	5.7E-5	5.7E-5
Activated sludge	9.0E-3	-	9.2E-3	-	-	-	-	-	-
Secondary clarifier	8.6E-5	7.8E-5	8.8E-5	8.1E-5	8.2E-5	8.2E-5	-	8.2E-5	-
Biological nutrient removal-3-stage	-	0.03	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	0.03	-	0.02	-	-
Biological nutrient removal-5-stage	-	-	-	0.03	-	0.03	-	0.03	0.02
Filtration	-	-	-	3.5E-4	3.5E-4	3.5E-4	-	3.7E-5	-
Tertiary clarification, denitrification	-	-	6.9E-5	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	5.8E-5	-	-	-	-	-	-
Chlorination	6.5E-4	6.4E-4	6.4E-4	6.3E-4	6.3E-4	6.3E-4	6.3E-4	5.9E-4	5.9E-4
Dechlorination	6.0E-4	6.0E-4	6.0E-4	6.0E-4	6.0E-4	6.0E-4	6.0E-4	5.9E-4	5.9E-4
Reverse osmosis	-	-	-	-	-	-	-	0.03	0.03
Denitrification, attached growth	-	-	-	-	-	7.9E-3	-	9.2E-4	-
Denitrification, suspended growth	-	-	8.0E-3	-	-	-	-	-	-
Nitrification, suspended growth	-	-	9.8E-3	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	0.01	-
Chemical phosphorus removal	-	-	7.5E-4	3.8E-5	3.8E-5	3.8E-5	1.9E-5	3.8E-5	1.9E-5
Membrane filter	-	-	-	-	-	-	0.01	-	0.01
Centrifuge	1.1E-3	9.5E-4	1.6E-3	9.6E-4	9.6E-4	9.6E-4	9.4E-4	9.6E-4	9.2E-4
Sludge hauling and landfill	-	-	-	-9.6E-4	-9.7E-4	-9.7E-4	-9.8E-4	-9.7E-4	-9.3E-4
Anaerobic digester	2.4E-3	2.1E-3	3.0E-3	2.2E-3	2.0E-3	2.0E-3	2.0E-3	2.0E-3	2.0E-3
Fermentation	-	-	-	5.6E-5	5.6E-5	5.6E-5	-	5.6E-5	5.5E-5
Gravity thickener	4.7E-5	4.5E-5	5.2E-5	4.5E-5	4.5E-5	4.5E-5	4.4E-5	4.5E-5	4.4E-5
Effluent release	-	-	-	-	-	-	-	-	-
Underground injection of brine	-	-	-	-	-	-	-	0.02	0.02
Total	0.01	0.03	0.03	0.03	0.04	0.04	0.04	0.09	0.09

Table J-5. Fossil Depletion Results by Detailed Unit Process (kg oil eq/m^3 Wastewater Treated)

Process	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Screening and grit removal	1.1E-3	1.1E-3	1.1E-3	1.1E-3	1.1E-3	1.1E-3	1.1E-3	1.1E-3	1.1E-3
Primary clarifier	3.1E-4	3.0E-4	3.1E-4	3.0E-4	3.0E-4	3.0E-4	3.0E-4	3.0E-4	3.0E-4
Activated sludge	0.05	-	0.05	-	-	-	-	-	-
Secondary clarifier	4.6E-4	4.2E-4	4.7E-4	4.4E-4	4.4E-4	4.4E-4	-	4.4E-4	-
Biological nutrient removal-3-stage	-	0.14	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	0.16		0.11	-	-
Biological nutrient removal-5-stage	-	-	-	0.15		0.15	-	0.15	0.12
Filtration	-	-	-	1.9E-3	1.9E-3	1.9E-3	-	2.1E-4	-
Tertiary clarification, denitrification	-	-	3.8E-4	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	3.2E-4	-	-	-	-	-	-
Chlorination	6.0E-3	5.7E-3	5.7E-3	5.2E-3	5.2E-3	5.2E-3	5.2E-3	4.2E-3	4.3E-3
Dechlorination	3.6E-3	3.6E-3	3.6E-3	3.6E-3	3.6E-3	3.6E-3	3.6E-3	4.1E-3	4.1E-3
Reverse osmosis	-	-	-	-	-	-	-	0.15	0.14
Denitrification, attached growth	-	-	-	-	-	0.06	-	6.7E-3	-
Denitrification, suspended growth	-	-	0.09	-	-	-	-	-	-
Nitrification, suspended growth	-	-	0.05	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	0.06	-
Chemical phosphorus removal	-	-	0.01	6.3E-4	6.3E-4	6.3E-4	3.2E-4	6.3E-4	3.2E-4
Membrane filter	-	-	-	-	-	-	0.08	-	0.08
Centrifuge	8.8E-3	7.5E-3	0.01	7.6E-3	7.5E-3	7.5E-3	7.4E-3	7.5E-3	7.2E-3
Sludge hauling and landfill	0.01	9.2E-3	0.02	9.6E-3	9.5E-3	9.5E-3	9.1E-3	9.5E-3	9.0E-3
Anaerobic digester	0.04	0.04	0.06	0.04	0.04	0.04	0.04	0.04	0.03
Fermentation	-	-	-	2.8E-4	2.8E-4	2.8E-4	-	2.8E-4	2.8E-4
Gravity thickener	2.4E-4	2.3E-4	2.7E-4	2.3E-4	2.3E-4	2.3E-4	2.3E-4	2.3E-4	2.2E-4
Effluent release	-	-	-	-	-	-	-	-	-
Underground injection of brine	-	-	-	-	-	-	-	0.10	0.10
Total	0.12	0.20	0.30	0.22	0.23	0.28	0.25	0.54	0.51

Table J-6. Smog Formation Potential Results by Detailed Unit Process (kg O_3 eq/m^3 Wastewater Treated)

Process	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Screening and grit removal	1.6E-3	1.6E-3	1.6E-3	1.6E-3	1.6E-3	1.6E-3	1.6E-3	1.6E-3	1.6E-3
Primary clarifier	4.5E-4	4.5E-4	4.6E-4	4.5E-4	4.5E-4	4.5E-4	4.5E-4	4.5E-4	4.5E-4
Activated sludge	0.07	-	0.07	-	-	-	-	-	-
Secondary clarifier	6.8E-4	6.2E-4	7.0E-4	6.5E-4	6.5E-4	6.5E-4	-	6.5E-4	-
Biological nutrient removal-3-stage	-	0.21	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	0.25	-	0.17	-	-
Biological nutrient removal-5-stage	-	-	-	0.22	-	0.22	-	0.22	0.19
Filtration	-	-	-	2.7E-3	2.7E-3	2.7E-3	-	2.9E-4	-
Tertiary clarification, denitrification	-	-	5.5E-4	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	4.7E-4	-	-	-	-	-	-
Chlorination	5.1E-3	5.0E-3	5.0E-3	4.9E-3	4.9E-3	4.9E-3	4.9E-3	4.6E-3	4.6E-3
Dechlorination	5.0E-3	5.0E-3	5.0E-3	5.0E-3	5.0E-3	5.0E-3	5.0E-3	5.3E-3	5.3E-3
Reverse osmosis	-	-	-	-	-	-	-	0.22	0.21
Denitrification, attached growth	-	-	-	-	-	0.06	-	7.1E-3	-
Denitrification, suspended growth	-	-	0.06	-	-	-	-	-	-
Nitrification, suspended growth	-	-	0.08	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	0.08	-
Chemical phosphorus removal	-	-	3.0E-3	1.5E-4	1.5E-4	1.5E-4	7.6E-5	1.5E-4	7.5E-5
Membrane filter	-	-	-	-	-	-	0.11	-	0.11
Centrifuge	8.6E-3	7.3E-3	0.01	7.4E-3	7.4E-3	7.4E-3	7.2E-3	7.4E-3	7.1E-3
Sludge hauling and landfill	-	-	-7.1E-3	-5.9E-3	-5.9E-3	-5.9E-3	-6.0E-3	-5.9E-3	-5.7E-3
Anaerobic digester	0.05	0.04	0.05	0.04	0.04	0.04	0.04	0.04	0.04
Fermentation	-	-	-	4.3E-4	4.3E-4	4.3E-4	-	4.3E-4	4.3E-4
Gravity thickener	3.7E-4	3.5E-4	4.0E-4	3.5E-4	3.5E-4	3.5E-4	3.4E-4	3.5E-4	3.4E-4
Effluent release	-	-	-	-	-	-	-	-	-
Underground injection of brine	-	-	-	-	-	4.3E-4	-	0.16	0.16
Total	0.14	0.27	0.29	0.28	0.30	0.34	0.33	0.75	0.72

Table J-7. Human Health- Particulate Matter Formation Potential Results by Detailed Unit Process (kg PM2.5 eq/m^3 Wastewater Treated)

Process	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Screening and grit removal	2.4E-5	2.4E-5	2.4E-5	2.4E-5	2.4E-5	2.4E-5	2.4E-5	2.4E-5	2.4E-5
Primary clarifier	6.5E-6	6.5E-6	6.6E-6	6.5E-6	6.5E-6	6.5E-6	6.5E-6	6.5E-6	6.4E-6
Activated sludge	1.0E-3	-	1.0E-3	-	-	-	-	-	-
Secondary clarifier	9.8E-6	8.9E-6	1.0E-5	9.2E-6	9.3E-6	9.3E-6	-	9.3E-6	-
Biological nutrient removal-3-stage	-	3.0E-3	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	3.6E-3	-	2.5E-3	-	-
Biological nutrient removal-5-stage	-	-	-	3.2E-3	-	3.2E-3	-	3.2E-3	2.7E-3
Filtration	-	-	-	3.9E-5	3.9E-5	3.9E-5	-	4.1E-6	-
Tertiary clarification, denitrification	-	-	7.9E-6	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	6.6E-6	-	-	-	-	-	-
Chlorination	7.2E-5	7.1E-5	7.1E-5	7.0E-5	7.0E-5	7.0E-5	7.0E-5	6.6E-5	6.6E-5
Dechlorination	7.0E-5	7.0E-5	7.0E-5	7.0E-5	7.0E-5	7.0E-5	7.0E-5	7.1E-5	7.1E-5
Reverse osmosis	-	-	-	-	-	-	-	3.2E-3	3.1E-3
Denitrification, attached growth	-	-	-	-	-	8.8E-4	-	1.0E-4	-
Denitrification, suspended growth	-	-	8.9E-4	-	-	-	-	-	-
Nitrification, suspended growth	-	-	1.1E-3	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	1.2E-3	-
Chemical phosphorus removal	-	-	6.6E-5	3.3E-6	3.3E-6	3.3E-6	1.7E-6	3.3E-6	1.7E-6
Membrane filter	-	-	-	-	-	-	1.6E-3	-	1.6E-3
Centrifuge	1.3E-4	1.1E-4	1.8E-4	1.1E-4	1.1E-4	1.1E-4	1.1E-4	1.1E-4	1.0E-4
Sludge hauling and landfill	-	-	-1.5E-4	-1.1E-4	-1.1E-4	-1.1E-4	-1.1E-4	-1.1E-4	-1.1E-4
Anaerobic digester	1.8E-4	1.6E-4	2.3E-4	1.7E-4	1.6E-4	1.6E-4	1.6E-4	1.6E-4	1.5E-4
Fermentation	-	-	-	6.2E-6	6.2E-6	6.2E-6	-	6.2E-6	6.2E-6
Gravity thickener	5.3E-6	5.0E-6	5.8E-6	5.0E-6	5.0E-6	5.0E-6	5.0E-6	5.0E-6	4.9E-6
Effluent release	-	-	-	-	-	-	-	-	-
Underground injection of brine	-	-	-	-	-	-	-	2.3E-3	2.3E-3
Total	1.5E-3	3.4E-3	3.5E-3	3.6E-3	3.9E-3	4.5E-3	4.4E-3	0.01	0.01

Table J-8. Ozone Depletion Potential Results by Detailed Unit Process (kg CFC-11 eq/m^3 Wastewater Treated)

Process	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Screening and grit removal	1.8E-9	1.8E-9	1.8E-9	1.8E-9	1.8E-9	1.8E-9	1.8E-9	1.8E-9	1.8E-9
Primary clarifier	5.0E-10	5.0E-10	5.1E-10	5.0E-10	5.0E-10	5.0E-10	5.0E-10	5.0E-10	5.0E-10
Activated sludge	6.1E-7	-	3.9E-7	-	-	-	-	-	-
Secondary clarifier	7.6E-10	6.9E-10	7.8E-10	7.1E-10	7.2E-10	7.2E-10	-	7.2E-10	-
Biological nutrient removal-3-stage	-	2.6E-6	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	2.7E-6	-	6.4E-6	-	-
Biological nutrient removal-5-stage	-	-	-	6.6E-6	-	6.6E-6	-	6.6E-6	6.5E-6
Filtration	-	-	-	3.0E-9	3.0E-9	3.0E-9	-	3.2E-10	-
Tertiary clarification, denitrification	-	-	6.1E-10	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	5.1E-10	-	-	-	-	-	-
Chlorination	2.6E-8	2.5E-8	2.5E-8	2.1E-8	2.1E-8	2.1E-8	2.1E-8	1.5E-8	1.5E-8
Dechlorination	6.0E-9	6.0E-9	6.0E-9	6.0E-9	6.0E-9	6.0E-9	6.0E-9	6.7E-9	6.7E-9
Reverse osmosis	-	-	-	-	-	-	-	2.7E-7	2.5E-7
Denitrification, attached growth	-	-	-	-	-	7.4E-8	-	8.5E-9	-
Denitrification, suspended growth	-	-	8.2E-8	-	-	-	-	-	-
Nitrification, suspended growth	-	-	8.6E-8	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	1.1E-7	-
Chemical phosphorus removal	-	-	1.5E-8	7.7E-10	7.7E-10	7.7E-10	3.9E-10	7.7E-10	3.8E-10
Membrane filter	-	-	-	-	-	-	1.3E-7	-	1.3E-7
Centrifuge	1.1E-8	9.1E-9	1.5E-8	9.2E-9	9.1E-9	9.1E-9	9.0E-9	9.1E-9	8.8E-9
Sludge hauling and landfill	4.9E-9	4.4E-9	1.2E-8	4.9E-9	4.8E-9	4.8E-9	4.4E-9	4.8E-9	4.6E-9
Anaerobic digester	5.9E-7	4.9E-7	6.5E-7	4.7E-7	4.7E-7	4.7E-7	4.8E-7	4.7E-7	4.5E-7
Fermentation				4.8E-10	4.8E-10	4.8E-10	-	4.8E-10	4.8E-10
Gravity thickener	4.1E-10	3.9E-10	4.5E-10	3.9E-10	3.9E-10	3.9E-10	3.9E-10	3.9E-10	3.8E-10
Effluent release	2.6E-6	6.9E-7	6.7E-7	5.2E-7	5.2E-7	2.5E-7	2.6E-7	5.5E-8	1.4E-7
Underground injection of brine	-	-	-	-	-	-	-	1.8E-7	1.8E-7
Total	3.9E-6	3.8E-6	2.0E-6	7.6E-6	3.7E-6	7.4E-6	7.3E-6	7.7E-6	7.7E-6

Table J-9. Water Depletion Results by Detailed Unit Process (m^3 H_2O/m^3 Wastewater Treated)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	8.2E-6	8.1E-6	8.2E-6	8.2E-6	8.2E-6	8.2E-6	8.1E-6	8.2E-6	8.1E-6
Primary clarifier	5.9E-6	5.8E-6	6.0E-6	5.8E-6	5.8E-6	5.8E-6	5.8E-6	5.8E-6	5.8E-6
Activated sludge	3.6E-4	-	3.8E-4	-	-	-	-	-	-
Secondary clarifier	9.4E-6	9.1E-6	9.5E-6	9.2E-6	9.2E-6	9.2E-6	-	9.2E-6	-
Biological nutrient removal-3-stage	-	1.1E-3	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	1.3E-3	-	8.7E-4	-	-
Biological nutrient removal-5-stage	-	-	-	1.2E-3	-	1.2E-3	-	1.2E-3	9.7E-4
Filtration	-	-	-	1.6E-5	1.6E-5	1.6E-5	-	1.7E-6	-
Tertiary clarification, denitrification	-	-	8.7E-6	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	8.3E-6	-	-	-	-	-	-
Chlorination	1.7E-4	1.6E-4	1.6E-4	1.3E-4	1.3E-4	1.3E-4	1.3E-4	9.0E-5	9.1E-5
Dechlorination	3.7E-5	3.7E-5	3.7E-5	3.7E-5	3.7E-5	3.7E-5	3.7E-5	4.9E-5	4.9E-5
Reverse osmosis	-	-	-	-	-	-	-	1.7E-3	1.6E-3
Denitrification, attached growth	-	-	-	-	-	3.5E-4	-	4.0E-5	-
Denitrification, suspended growth	-	-	4.1E-4	-	-	-	-	-	-
Nitrification, suspended growth	-	-	4.1E-4	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	1.4E-3	-
Chemical phosphorus removal	-	-	2.4E-3	1.2E-4	1.2E-4	1.2E-4	6.0E-5	1.2E-4	6.0E-5
Membrane filter	-	-	-	-	-	-	6.7E-4	-	6.7E-4
Centrifuge	6.3E-5	5.3E-5	9.1E-5	5.4E-5	5.4E-5	5.4E-5	5.3E-5	5.4E-5	5.1E-5
Sludge hauling and landfill	9.0E-5	7.8E-5	1.5E-4	8.0E-5	8.0E-5	8.0E-5	7.7E-5	8.0E-5	7.6E-5
Anaerobic digester	5.7E-5	5.1E-5	7.4E-5	5.5E-5	5.1E-5	5.1E-5	5.0E-5	5.1E-5	4.8E-5
Fermentation	-	-	-	2.6E-6	2.6E-6	2.6E-6	-	2.6E-6	2.6E-6
Gravity thickener	2.4E-6	2.3E-6	2.7E-6	2.3E-6	2.3E-6	2.3E-6	2.3E-6	2.3E-6	2.2E-6
Effluent release	-	-	-	-	-	-	-	-	-
Underground injection of brine	-	-	-	-	-	-	-	0.18	0.17
Total	8.0E-4	1.5E-3	4.1E-3	1.7E-3	1.8E-3	2.0E-3	2.0E-3	0.19	0.17

Table J-10. Human Health-Cancer Results by Detailed Unit Process (CTU$_h$/m^3 Wastewater Treated)

Process	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Screening and grit removal	1.1E-11	1.1E-11	1.1E-11	1.1E-11	1.1E-11	1.1E-11	1.1E-11	1.1E-11	1.1E-11
Primary clarifier	5.0E-12	4.9E-12	5.1E-12	4.9E-12	4.9E-12	4.9E-12	4.9E-12	4.9E-12	4.9E-12
Activated sludge	4.8E-10	-	5.0E-10	-	-	-	-	-	-
Secondary clarifier	7.5E-12	7.1E-12	7.6E-12	7.2E-12	7.2E-12	7.2E-12	-	7.2E-12	-
Biological nutrient removal-3-stage	-	1.4E-9	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	1.7E-9	-	1.2E-9	-	-
Biological nutrient removal-5-stage	-	-	-	1.5E-9	-	1.5E-9	-	1.5E-9	1.3E-9
Filtration	-	-	-	1.9E-11	1.9E-11	1.9E-11	-	2.0E-12	-
Tertiary clarification, denitrification	-	-	6.6E-12	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	6.0E-12	-	-	-	-	-	-
Chlorination	1.9E-10	1.4E-10	1.4E-10	1.2E-10	1.2E-10	1.2E-10	1.2E-10	8.4E-11	8.5E-11
Dechlorination	5.4E-11	5.4E-11	5.4E-11	5.4E-11	5.4E-11	5.4E-11	5.4E-11	7.3E-11	7.4E-11
Reverse osmosis	-	-	-	-	-	-	-	1.7E-9	1.6E-9
Denitrification, attached growth	-	-	-	-	-	4.8E-10	-	5.6E-11	-
Denitrification, suspended growth	-	-	5.6E-10	-	-	-	-	-	-
Nitrification, suspended growth	-	-	5.6E-10	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	7.6E-10	-
Chemical phosphorus removal	-	-	4.9E-9	2.4E-10	2.4E-10	2.4E-10	1.2E-10	2.4E-10	1.2E-10
Membrane filter	-	-	-	-	-	-	8.1E-10	-	8.1E-10
Centrifuge	8.8E-11	7.5E-11	1.3E-10	7.6E-11	7.6E-11	7.6E-11	7.4E-11	7.6E-11	7.3E-11
Sludge hauling and landfill	2.6E-10	2.3E-10	3.8E-10	2.4E-10	2.5E-10	2.4E-10	2.7E-10	2.8E-10	2.8E-10
Anaerobic digester	9.0E-11	8.1E-11	1.2E-10	8.7E-11	8.1E-11	8.1E-11	7.9E-11	8.1E-11	7.6E-11
Fermentation	-	-	-	3.1E-12	3.1E-12	3.1E-12	-	3.1E-12	3.1E-12
Gravity thickener	2.7E-12	2.6E-12	3.0E-12	2.6E-12	2.6E-12	2.6E-12	2.6E-12	2.6E-12	2.5E-12
Effluent release	3.1E-9	3.1E-9	2.5E-9	2.1E-9	1.5E-9	2.4E-9	1.0E-9	4.0E-10	1.7E-10
Underground injection of brine	-	-	-	-	-	-	-	1.1E-9	1.1E-9
Total	4.3E-9	5.1E-9	9.9E-9	4.5E-9	4.1E-9	5.2E-9	3.7E-9	6.4E-9	5.7E-9

Table J-11. Human Health-NonCancer Results by Detailed Unit Process (CTU_h/m^3 Wastewater Treated)

Process	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Screening and grit removal	1.1E-10	1.1E-10	1.1E-10	1.1E-10	1.1E-10	1.1E-10	1.1E-10	1.1E-10	1.1E-10
Primary clarifier	6.1E-11	6.0E-11	6.1E-11	6.0E-11	6.0E-11	6.0E-11	6.0E-11	6.0E-11	6.0E-11
Activated sludge	4.8E-9	-	4.9E-9	-	-	-	-	-	-
Secondary clarifier	9.3E-11	8.9E-11	9.4E-11	9.1E-11	9.1E-11	9.1E-11	-	9.1E-11	-
Biological nutrient removal-3-stage	-	1.4E-8	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	1.7E-8	-	1.2E-8	-	-
Biological nutrient removal-5-stage	-	-	-	1.5E-8	-	1.5E-8	-	1.5E-8	1.3E-8
Filtration	-	-	-	1.8E-10	1.8E-10	1.8E-10	-	2.0E-11	-
Tertiary clarification, denitrification	-	-	8.4E-11	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	7.8E-11	-	-	-	-	-	-
Chlorination	2.0E-9	1.6E-9	1.6E-9	1.3E-9	1.3E-9	1.3E-9	1.3E-9	9.2E-10	9.3E-10
Dechlorination	9.6E-10	9.6E-10	9.6E-10	9.6E-10	9.6E-10	9.6E-10	9.6E-10	1.6E-9	1.6E-9
Reverse osmosis	-	-	-	-	-	-	-	1.6E-8	1.5E-8
Denitrification, attached growth	-	-	-	-	-	4.5E-9	-	5.3E-10	-
Denitrification, suspended growth	-	-	5.1E-9	-	-	-	-	-	-
Nitrification, suspended growth	-	-	5.4E-9	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	1.1E-8	-
Chemical phosphorus removal	-	-	1.2E-8	5.8E-10	5.8E-10	5.8E-10	3.0E-10	5.8E-10	2.9E-10
Membrane filter	-	-	-	-	-	-	8.0E-9	-	8.0E-9
Centrifuge	9.3E-10	7.9E-10	1.3E-9	8.0E-10	8.0E-10	8.0E-10	7.8E-10	8.0E-10	7.7E-10
Sludge hauling and landfill	4.5E-9	4.2E-9	5.8E-9	4.9E-9	5.3E-9	4.9E-9	6.3E-9	6.6E-9	6.7E-9
Anaerobic digester	2.1E-9	1.9E-9	2.9E-9	2.1E-9	1.9E-9	1.9E-9	1.8E-9	1.9E-9	1.8E-9
Fermentation	-	-	-	3.2E-11	3.2E-11	3.2E-11	-	3.2E-11	3.2E-11
Gravity thickener	2.9E-11	2.7E-11	3.2E-11	2.7E-11	2.7E-11	2.7E-11	2.7E-11	2.7E-11	2.6E-11
Effluent release	1.0E-7	1.0E-7	1.0E-7	7.6E-8	6.2E-8	7.6E-8	1.9E-8	1.1E-8	2.1E-9
Underground injection of brine	-	-	-	-	-	-	-	1.1E-8	1.1E-8
Total	1.2E-7	1.3E-7	1.4E-7	1.0E-7	9.0E-8	1.1E-7	5.0E-8	7.7E-8	6.1E-8

Table J-12. Ecotoxicity Results by Detailed Unit Process (CTU_e/m^3 Wastewater Treated)

Process	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Screening and grit removal	0.59	0.58	0.59	0.59	0.59	0.59	0.58	0.59	0.58
Primary clarifier	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Activated sludge	25	-	26	-	-	-	-	-	-
Secondary clarifier	0.29	0.27	0.29	0.28	0.28	0.28	-	0.28	-
Biological nutrient removal-3-stage	-	74	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	88	-	61	-	-
Biological nutrient removal-5-stage	-	-	-	80	-	80	-	80	68
Filtration	-	-	-	1.0	1.0	1.0	-	0.11	-
Tertiary clarification, denitrification	-	-	0.24	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	0.21	-	-	-	-	-	-
Chlorination	5.2	4.9	4.9	4.3	4.3	4.3	4.3	3.2	3.2
Dechlorination	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.5	2.6
Reverse osmosis	-	-	-	-	-	-	-	83	78
Denitrification, attached growth	-	-	-	-	-	23	-	2.7	-
Denitrification, suspended growth	-	-	25	-	-	-	-	-	-
Nitrification, suspended growth	-	-	28	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	34	-
Chemical phosphorus removal	-	-	14	0.68	0.68	0.68	0.35	0.68	0.34
Membrane filter	-	-	-	-	-	-	42	-	42
Centrifuge	3.5	3.0	5.1	3.0	3.0	3.0	3.0	3.0	2.9
Sludge hauling and landfill	11	11	12	14	14	14	17	18	18
Anaerobic digester	7.3	6.4	9.7	7.0	6.4	6.4	6.2	6.4	6.0
Fermentation	-	-	-	0.16	0.16	0.16	-	0.16	0.16
Gravity thickener	0.14	0.13	0.15	0.13	0.13	0.13	0.13	0.13	0.13
Effluent release	2.8E+2	2.8E+2	2.8E+2	1.6E+2	1.6E+2	1.6E+2	72	25	6.0
Underground injection of brine	-	-	-	-	-	-	-	57	57
Total	3.4E+2	3.9E+2	4.1E+2	2.7E+2	2.8E+2	2.9E+2	2.1E+2	3.2E+2	2.9E+2

United States
Environmental Protection
Agency

Errata to:

Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants

Prepared for:

U.S. Environmental Protection Agency
Standards and Health Protection Division
Office of Water, Office of Science and Technology
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EPA 832-R-21-006ES

ERRATA

ERG identified an error in Appendix F of the Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants (EPA 832-R-21-006), dated August 2021. Equation F-3, the equation used to calculate nitrous oxide (N2O) emissions from wastewater treatment processes, included an incorrect molecular weight conversion factor of N to N2O of 44/14. The correct conversation factor is 44/28.

This error only affects N2O emission from biological treatment. The corrected emissions are half as much as those presented in the report, as shown in Table 1 below. Emissions of N2O only affect the global warming potential (GWP) impact category but are reflected in all related charts and discussion (Figures 6-5, 8-1 and 9-3 and Tables 8-1 and 8-3). Figure 1 compares the GWP impact of treatment systems before and after correction of the N2O conversion factor (Figure 6-5 in the report).

Table 1. Comparison of N_2O Emissions from Biological Treatment

System Configuration Level	N_2O Emitted by Process (kg N_2O/yr)	
	Original Estimate[a]	Corrected Estimate
1	6.6E+02	3.3E+02
2-1	2.9E+03	1.5E+03
2-2	3.9E+02	1.9E+02
3-1	7.8E+03	3.9E+03
3-2	3.0E+03	1.5E+03
4-1	8.2E+03	4.1E+03
4-2	7.7E+03	3.9E+03
5-1	7.8E+03	3.9E+03
5-2	7.7E+03	3.9E+03

a – Estimates included in Table F-2 of *Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants (*EPA 832-R-21-006.

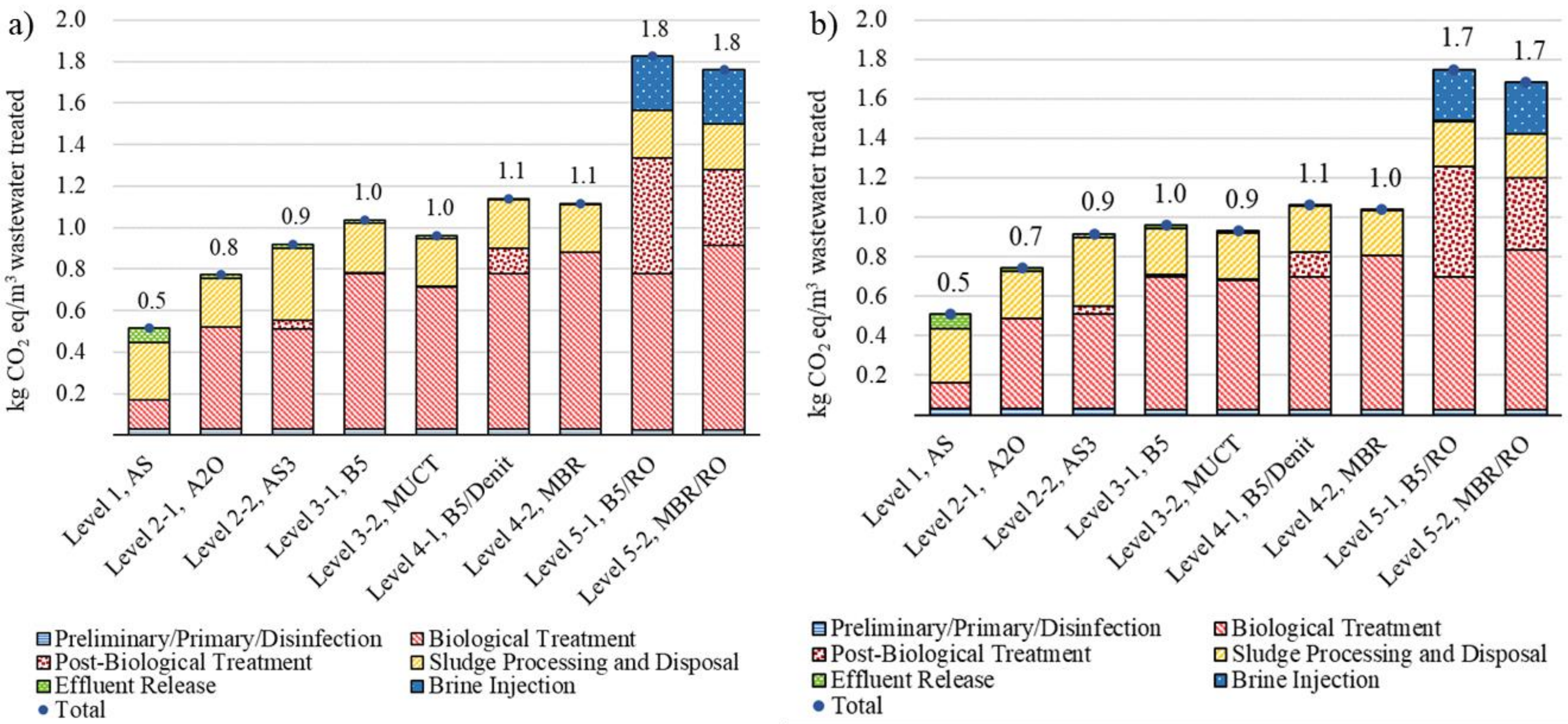

Figure 1. Comparison of Global Warming Potential Impact prior to (panel a) and following (panel b) correction of the N_2O conversion factor.

Because the error affected the calculation of biological treatment emissions, which are included for all systems, it has a limited effect on the comparative results between systems. Correction of the error alters the height of the biological treatment bars of each system. Prior to correction of the error, N2O emissions from biological treatment contributed between 0.8% and 15% of total GWP emissions.

- The largest contribution of N_2O to GWP is observed for treatment levels 3-1, 4-1, and 4-2 (14-15%). Using the updated conversion factor the contribution of N_2O to GWP drops to between 7 and 8%.
- More moderate contributions are observed for treatment levels 2-1, 3-2, 5-1 and 5-2 (6-8%). Using the updated conversion factor the contribution of N_2O to GWP drops to between 3 and 4%.
- The smallest contribution of N_2O to GWP is observed for treatment levels 1 and 2-2 (0.8-3%). Using the updated conversion factor the contribution of N_2O to GWP drops to between 0.4 and 1.3%.