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Environmental Impacts of Overdesign in Small Community Water Resource Recovery Facilities

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ENVIRONMENTAL IMPACTS OF OVERDESIGN IN SMALL COMMUNITY WATER RESOURCE RECOVERY FACILITIES

By

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ENVIRONMENTAL IMPACTS OF OVERDESIGN IN SMALL COMMUNITY WATER RESOURCE RECOVERY FACILITIES

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Although water resource recovery facilities (WRRFs) reduce environmental impacts related to water quality, their construction and operation result in negative environmental impacts in other categories. Past research into Nebraska WRRFs investigated variables determining energy intensity, opportunities and barriers for energy efficiency improvements, and environmental impacts of the construction and operation phase. This leads to the research question of what design practices can be considered to reduce the environmental impacts.

The Life Cycle Assessment (LCA) methodology was used to evaluate and compare the inventory and environmental impacts of nine small WRRFs, most of which are serving slow growing or declining populations. Inventory data was collected from the facilities' engineering design plans and utility bills and simplified to 21 lines of general representative inventory. The SimaPro v8 program used to convert inventory to environmental impact, and the Ecoinvent database was used for background data. The outputs were categorized by ten process elements to address the multi-functional nature of WRRFs and by the ten TRACI characterization factors.

The biological reactor and the conveyance elements were identified as high impact process elements. Whereas the biological reactor had low impact variability, the conveyance had high variability. Three opportunities for impact mitigation were

identified. The first suggested practice is to avoid significant overdesign by planning for no lower than a 75% capacity utilization. Planning for a lower design average flow rate was shown to mitigate lifetime electricity usage and secondary process concrete, and consequently Carcinogenic and Global Warming environmental impacts. Other suggested practices were focused on the conveyance process element, namely, to reduce ductile iron piping since it was found to contribute 93% of the carcinogenic impact in the conveyance element. The suggested practices were to minimize non-process facility area and to use polyvinyl chloride pipe instead of ductile iron pipe where possible.

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LIST OF ABBREVIATIONS

ASCE	American Society of Civil Engineers
CO_2	Carbon dioxide
CTU	Comparative toxicity units
CWNS	Clean Watersheds Needs Survey
CWSRF	Clean Water State Revolving Fund
EA	Extended aeration
ECHO	Enforcement and Compliance History Online
EPA	Environmental Protection Agency
EPD	Environmental product declaration
GWP	Global warming potentials
ISO	International Organization for Standards
km	Kilometers
kW	Kilowatt
kWh	Kilowatt hours
LEED	Leadership in Energy and Environmental Design
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life Cycle Impact Assessment
MGD	Million gallons per day
N_{eq}	Nitrogen equivalent
NDEE	Nebraska Department of Environment and Energy
O_3	Ozone

OD	Oxidation ditch
ODP	Ozone depletion potentials
P3	Partners in Pollution Prevention
$PM_{2.5}$	Particulate matter with diameters 2.5 micrometers or less
SBR	Sequence batch reactor
TRACI	Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts
UNL	University of Nebraska-Lincoln
U.S.	United States
USDA	U.S. Department of Agriculture
VFD	Variable frequency drive
WRRF	Water resource recovery facility

Chapter 1: Introduction

1.1 Introduction

In the global effort to minimize environmental impact, sustainability improvement opportunities are being investigated in all sectors, including municipal infrastructure. Water resource recovery facilities (WRRFs) are a critical infrastructure for local, regional, and national sustainability in water resources. However, although WRRFs reduce environmental impacts related to water quality, their construction and operation result in negative environmental impacts in other categories. The Life Cycle Assessment (LCA) methodology is an effective tool in comparing the environmental impacts of products and processes and has commonly been applied to evaluate WRRFs in environmental performance.

Although there have been many WRRF LCA studies, few have been done on small WRRFs. The LCA method should be used to investigate small systems because they make up 80% of centralized wastewater treatment systems in the United States with an estimated 614 more to be built between 2012-2032 (US EPA, 2012). Besides the fact that they constitute the majority of WRRFs, another important reason to investigate small systems is because WRRFs experience economies of scale in both energy usage (Hanna et al., 2017) and material inventory (Doka, 2003). For these reasons, design differences in small WRRF should be investigated to identify which practices lead to reduced inventory and associated environmental impact. This effort should include the construction phase, as it was found to contribute a significant portion of the impact profile in several studies (Morera et al., 2017; Ortiz et al., 2007; Renou et al., 2008).

Although more than 95% of non-metro counties in the country experienced slow growing or declining populations between 2010-2019 (USDA, 2020a), many small communities were designed for increasing populations. No studies were found that examined the material and environmental costs of overdesigning small WRRFs. This is one potential area for inventory and environmental impact mitigation. Other opportunities may be identified from a comparative LCA case studies of small WRRFs.

1.2 Objectives

The objective of this thesis is to identify design practices that reduce material inventory and environmental impact in small WRRFs serving communities with slow growing or declining populations. The goal is for these general suggested practices to be considered by design engineers on a case-by-case basis. By using the LCA methodology, the following questions should be answered: (1) which impact categories in WRRF construction and operation are most relevant in national environmental efforts, and (2) which process elements have the highest impacts and which have the highest impact variability. Using this information from a comparative LCA analysis, the general design practices that result in a reduced environmental impact profile can be identified, and the environmental impact mitigations from applying them can be quantified.

The rule-of-thumb reduction opportunities identified in this study should meet two criteria. First, the practices should have minimal economic trade-offs. Although the 10 impact categories are national and global environmental issues, they are not immediately noticeable to the stakeholders at a local level (besides the Eutrophication impact to an extent). If there were an economic trade-off to design a more sustainable facility, the design practice would likely not be implemented. The environmental impact reduction is desirable at the regional, national, and global levels, while the material inventory reduction is more important to the local stakeholders because of the implied construction cost reductions. For this reason, the results should be presented as material inventory reductions (easily translated to monetary cost) as well as environmental impact.

Second, the practices should contain minimal trade-offs between the ten TRACI environmental impact categories. In an LCA analysis, if there is a trade-off in impact categories it is up to the stakeholder to use value judgements to decide which categories are more important than others. Since the goal of this study is to provide rule-of-thumb practices to reduce environmental impact, requiring stakeholder involvement in value judgements should be avoided to the extent possible.

1.3 Thesis Organization

The thesis is organized into five chapters. Chapter 2 provides the relevant background information to the study. The chapter discusses the classifications of WRRFs, descriptions of WRRF process elements, incentives and efforts toward small community wastewater infrastructure, and past WRRF LCA research. Chapter 3 provides the methods and tools used to collect inventory data and convert the inventory to environmental impact. Chapter 4 is written as a stand-alone summary of the whole thesis in the format of a publishable paper. The results of the study are discussed here. Chapter 5 summarizes the conclusions of the study and provides areas for future research. The appendices include (1) a step-by-step methodology used including screenshots of the Excel spreadsheets, (2) the data sources and assumptions used in inventory collection, (3) the actual data used in the analysis, (4) information on the nine facilities used in the study, and (5) supplemental information to the results in Chapter 4.

Chapter 2: Literature Review

2.1 Introduction

Existing literature relevant to life cycle impacts of water resource recovery facilities (WRRFs) was reviewed and summarized in this chapter to provide a background and justification for the study. The chapter includes discussions on the following topics in order: WRRF classifications, WRRF process elements, incentives to minimize WRRF environmental impact, WRRF economies of scale, WRRF overdesign, the Life Cycle Assessment (LCA) method and tools, past WRRF LCA studies, and past research on small Nebraska WRRFs.

2.2 Wastewater Treatment Classifications

This section discusses the types of wastewater treatment methods from the broadest classification down to the focus of this thesis. The classifications in order are (1) decentralized and centralized systems, (2) large and small systems, (3) lagoons and mechanical systems, and (4) common types of mechanical systems. This discussion does not include the different types of lagoons. Some types of mechanical plants such as biological trickling filters and sequencing batch reactors are also excluded from this thesis.

Centralized and Decentralized Systems

Wastewater systems are classified as either decentralized or centralized systems. Decentralized systems are very small structures that treat sewage near the source where it is generated. These systems are used by one out of four households in the United States

(US EPA, 2016). They can be either individual septic systems, or small community cluster systems.

Centralized systems are public sewer systems that treat a community’s wastewater at a single location. The sewage is collected from homes, businesses, and industries and conveyed to the facility for treatment. After treatment, the water is either reused or discharged to a receiving water body. By the year 2000, centralized systems served approximately 208 million people which was 75% of the U.S. population (US EPA, 2016). The American Society of Civil Engineer’s (ASCE) infrastructure report card states that as populations in the south and west continue to grow, more rural households will make the switch from septic systems to centralized systems (ASCE, 2020). The report card estimated that there were 14,748 centralized wastewater treatment facilities in 2017 and estimates that 56 million more users will be connected to centralized systems by 2037.

Small Systems

The US EPA defines small WRRFs as systems that serve communities with populations of 10,000 or fewer and an average daily wastewater flow rate of less than 1 million gallons (US EPA, 2016). These communities often lack the technical, financial, and managerial capacity to efficiently construct and operate wastewater treatment systems. The Clean Watersheds Needs Survey (CWNS) is a report to congress on the financial needs for water infrastructure construction and repair. According to the report, there were 11,571 small systems in 2012 and an estimated 614 more projected to be built between 2012-2032 (US EPA, 2012). These centralized small systems make up 80% of centralized wastewater systems in the United States and are projected to serve 10% (28.9

million people) of the population. In 4 states (Nebraska, Kansas, Iowa, Montana), small systems constitute more than 95% of the number of WRRFs. Small systems also constitute a majority of WRRFs in other countries such as Switzerland where 71% (690 facilities) of treatment systems compiled for a LCI study served populations of less than 10,000 (Doka, 2003).

Mechanical Systems and Lagoon Systems

Centralized systems can be either a mechanical treatment facility or a lagoon. Lagoons are a popular method for wastewater treatment in small communities due to their simple construction and operation. They are large ponds designed to receive and hold wastewater to be treated by natural processes. Some lagoon systems use additional aeration for more efficient treatment and less land use.

A mechanical system is a constructed facility which uses mechanical equipment to artificially speed up natural treatment processes. These systems require a smaller area of land relative to lagoon systems. There are many types of mechanical WRRFs and there are many design decisions to be made even within the same types. This variety in construction design decisions can lead to high variability in material inventory between facilities.

Common Process Configurations for Small Mechanical WRRF

The activated sludge process is a conventional process used in wastewater treatment. The basic components of an activated sludge WRRF are (1) a biological reactor that suspends and aerates the microorganisms responsible for treatment; (2) a sedimentation tank, often referred to as a clarifier, to separate liquid and solids; and (3) a recycle system that returns the removed solids from the sedimentation tank back to the biological reactor. In a wastewater treatment facility, the process is typically combined with other physical and chemical processes upstream and downstream.

A variety of process configurations have been developed from the activated sludge process. Three common modifications of the conventional activated sludge (CAS) process are the Extended Aeration (EA) process, the Oxidation Ditch (OD), and the Sequencing Batch Reactor (SBR) configuration. The focus of this thesis is narrowed to the EA and OD type configurations because of their prevalence in rural communities. In a benchmarking study of small Nebraska WRRFs, a list of 110 WRRFs was compiled. Of the 110 facilities, 28 were CAS systems, 30 were OD systems, 22 were EA systems, and 16 were SBR systems (Hanna et al., 2017).

Extended Aeration

In the EA configuration, air for biological treatment and mixing can be supplied by diffuse aeration or mechanical aeration. The diffused air typically comes from blowers in a nearby building and channeled through discs or perforated pipes at the bottom of the basin. The solids residence time (SRT) is longer than the SRT for a CAS system, giving this configuration its name “extended aeration.” The EA modification requires a SRT of 20-40 days whereas a CAS system has a SRT of 5-15 days.

EA facilities are typically manufactured in sizes that treat 0.002-0.1 MGD (US EPA, 2000). Advantages of the EA configuration include minimal operator involvement (2-3 hours a day), good handling of organic loading and flow fluctuations, easy installation, little to no odor, and low sludge yield. The major disadvantage is that it requires more energy for the longer aeration period (US EPA, 2000).

Oxidation Ditch

The OD is a complete-mix reactor in a ring, oval, or horseshoe shaped basin designed to operate as an extended aeration system. The aeration and circulation of the mixed liquor is provided by mounted mechanical aerators, typically brush rotors or jet aerators. OD facilities are typically manufactured in sizes that treat 0.01-0.5 MGD (US EPA, 2000). The advantages of the OD configuration are the moderate energy requirements, effective operation in most weather conditions, high quality effluent, and low sludge yield.

Summary of WRRF Classifications

Figure 2.1 summarizes the types of WRRFs from the broadest classification down to the focus of this thesis. Only the more common systems are discussed in this section and used in the study. Specific types of lagoons, sequencing batch reactors, and biological trickling filters were excluded.

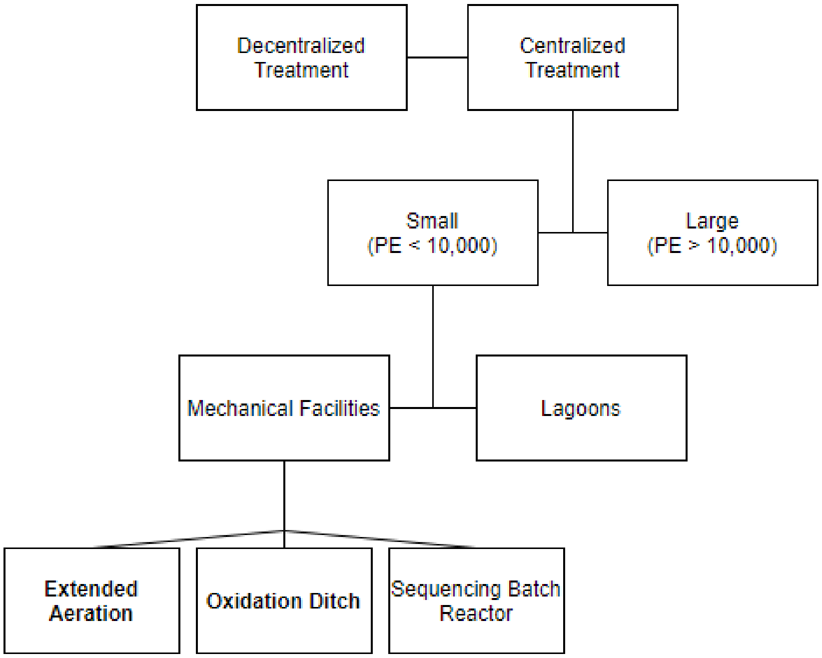


Figure 2.1: WRRF Classifications of Interest

2.3 Process Elements of OD and EA Type Plants

Although the activated sludge modifications differ in the design of the biological reactor, they have similar processes upstream and downstream from the biological reactor. This section discusses the functions and conventional design options of the common wastewater treatment processes. This information is taken from the 10 State Standards (Health Research Inc., 2014) and various EPA Wastewater Technology Fact Sheets. The design factors are important to discuss here to show that the suggested design practices in Section 4 Results do not break any guidelines; rather, they are design practices not discussed in detail in the guidelines.

Lift Stations

The wastewater treatment process is most efficient when gravity flow is used for conveyance between processes. For this to happen, the wastewater at the headworks must be at the highest elevation in the facility. This is achieved with an on-site lift station. The key elements of a lift station are the wet well, pumps, motors, piping and valves, equipment controls, and a ventilation system. The lift station design guidelines are discussed in Section 40 of the 10 State Standards (Health Research Inc., 2014).

Pump stations are either dry-pit or submersible. In dry-pit pump stations, the pumps and valves are housed in a pump room adjacent to the wet well. This allows for easy access if maintenance is needed on the equipment. Submersible pump stations have the pumps submerged in the wet well. The valves and flow meters are located on the dry surface for access. The advantage of a submersible pump station is the cheaper and easier construction because they do not require large above ground structures. The most common types of pumps for lift stations are centrifugal pumps (typically used for raw wastewater, primary and secondary sludge, and effluent). The 10 State Standards require pump stations to house multiple pumps. If there are only two pumps, they must have equal capacity (Health Research Inc., 2014).

Preliminary Treatment

The purpose of preliminary treatment is to remove grit, trash, and large debris at the headworks. If these are not removed, they will interfere with the treatment and damage the mechanical equipment. Preliminary treatment design options and guidelines are discussed in Section 60 of the 10 state standards (Health Research Inc., 2014).

Coarse screens are used to remove large solids, rags, and debris and have openings of 0.25 inches or larger. Fine screens remove smaller material with opening sizes between 0.06 to 0.25 inches. Manual bar screens require an operator to remove the debris caught by the screen, while mechanical screens are a self-cleaning equipment that dump the debris into a dumpster. Comminutors and grinders are installed in wastewater flow channels to grind and shred materials up to 0.75 inches in size. WRRFs serving larger populations may use grit removal equipment which are more expensive than screens and grinders. There are many types of grit removers, including aerated grit chambers, vortex-type chambers, detritus tanks, and hydro-cyclones. Selection of preliminary treatment equipment is based on grit size, detention time, and head loss.

Biological Reactors

The design of activated sludge biological reactors is discussed in Section 92 of the 10 State Standards (Health Research Inc., 2014). The reactor volume is designed based on the solids retention time, food to microorganism (F/M) ratio, and mixed liquor suspended solids (MLSS) levels. Liquid depths should be at least 10 feet and no more than 30 feet. Basin depths should not exceed 5.5 feet. Having multiple units capable of independent operation is preferable.

Clarifiers

Section 70 of the 10 State Standards state that facilities with design average flows over 100,000 gallons per day (gpd) (0.1 MGD) must have a sedimentation basin, also known as a clarifier (Health Research Inc., 2014). WRRFs will include at least one final clarifier anyway if they are activated sludge type systems. Larger facilities typically include primary clarifiers placed before the biological reactor to remove some of the total suspended solids (TSS) and biological oxygen demand (BOD). Both large and small activated sludge systems typically include final clarifiers which are placed after the biological reactor to separate the liquid from the solids. The solids that settle to the bottom are either sent back to the biological reactors as return activated sludge (RAS) or sent to a sludge digestion basin as waste activated sludge (WAS). Important clarifier design factors or inlet-outlet length, side water depth, surface overflow rate, and peak solids loading rate.

Tertiary Treatment

Disinfection is the last process in the liquid treatment train before discharging to a receiving water body. Different disinfection methods and design guidelines are discussed in Section 100 of the 10 State Standards (Health Research Inc., 2014). The proper disinfection process is selected based on flow rates, wastewater pH, effluent standards, and processes upstream of disinfection. Chlorination and UV disinfection are the most common methods of tertiary treatment.

Sludge Processing and Handling

Section 80 of the 10 State Standards discusses the processing, storage, and disposal of sludge from wastewater treatment. Sludge processing units are required at all mechanical WRRFs to process the sludge into a suitable form for safe disposal. Minimum considerations listed by the 10 State Standards include local land use, system energy requirements, cost effectiveness, equipment complexity and staffing, effects of heavy metals, sludge digestion requirements for pathogen reduction, return sludge requirements, sludge storage, ultimate disposal, and back up techniques (Health Research Inc., 2014).

Small systems typically use aerobic instead of anaerobic sludge digestion for cheaper and easier operation. The basin volume designs are based on population equivalents and provided in the 10 State Standards in Section 85.31 (Health Research Inc., 2014).

2.4 Incentives to Minimize WRRF Environmental Impact

The U.S. EPA’s Sustainable Infrastructure Program encourages utilities to find efficiencies that reduce overall infrastructure costs. This is mostly focused on water and energy savings. However, this program also encourages other strategies such as asset management, timing of equipment replacement, and sustainable pricing structures (U.S. EPA, 2008).

There are several federal programs created to help finance projects related to water infrastructure specifically. One example is the USDA’s Revolving Funds for Financing Water and Wastewater Projects which is governed by Section 306 of the Consolidated Farm and Rural Development Act. This program was created to help small rural communities extend and improve their water and wastewater infrastructure. The program encourages good practices that both save money and improve the natural environment (USDA, 2020b).

Another example is the Clean Water State Revolving Fund (CWSRF). The CWSRF was created under Title VI of the Clean Water Act (CWA) to provide below-market financing to construction of publicly owned wastewater treatment works in communities with populations of 10,000 or fewer. The larger goal of this financial assistance is to encourage sustainable infrastructure, as stated in the program’s long term goals to “Protect and enhance Nebraska’s water resources, the environment, and human health” and to “Encourage the incorporation of green infrastructure concepts and energy recovery, production, and conservation in CWSRF funded projects” (NDEE, 2020). Like the Sustainable Infrastructure Program, this is mostly focused on operational energy or water savings measures. However, a case could be made that green infrastructure would consider the total environmental impact of the construction as well as operation.

The building and construction industry constitutes 60% of resource consumption, 35% of energy consumption, and 35% of greenhouse gas emissions globally (Sobek, 2014). Opportunities to reduce environmental impacts of construction are typically identified in the early planning and design phases (Brophy & Lewis, 2012). The Leadership in Energy and Environmental Design (LEED) program is the most widely used green building rating system in the world and encourages green building design. Although this rating system is for building design rather than WRRF design, the objectives and approach could be applied to achieve more sustainable WRRF construction. For example, in the Materials and Resources section of LEED certification requirements, Option 4 assigns points to a project if its design is shown to reduce at least three life cycle assessment (LCA) environmental impact categories by at least 5% compared to baseline designs (Kestner et al., 2010). Even more points are assigned if a 10% reduction can be shown.

2.5 Economies of Scale in Infrastructure

Large metropolitan cities are often imagined to be most responsible for global negative environmental impacts. Although this is true in absolute terms, some studies suggest that smaller population communities contribute more impact on a per capita basis. For example, in one study, villages (population <5,000) were shown to have 11% higher CO_2 emissions per capita than metropolises (Gill & Moeller, 2018). Other studies suggest that smaller cities also use more material infrastructure per person. A city’s electrical lines, road area, water lines, and number of gas stations were all found to scale with approximately the same exponent value of 0.85 (Bettencourt et al., 2007; Kühnert et al., 2006). In other words, a city only needs 85% more material infrastructure in supply networks for every 100% increase in population size, indicating a systematic economy of scale.

This infrastructure economy of scale also applies to WRRFs. In a WRRF LCI analysis, Class 5 WRRFs (PE = 30-2,000) were shown to use more infrastructure per m^3 of treated wastewater than Class 1 WRRFs (PE > 100,000) (Doka, 2003). In a WRRF energy benchmarking study, facilities that treat higher flow rates were shown to have less energy usage per unit flow (Hanna et al., 2017). This is likely due to the fact that facilities serving larger communities have the financial capability for properly sized equipment and sophisticated controls that allow for variable power to accommodate for varying flow rates. A smaller facility will likely use equipment large enough to handle its highest flows with no variable frequency. For these reasons, rural infrastructure should not be neglected in the effort to reduce national and global emissions.

2.6 Overdesign of Small WRRFs

Many of these non-metro communities served by small systems are experiencing slow population growth or declining populations. According to USDA county population data, 28% and 67% of the 1,967 non-metro counties in the country experienced slow growing (<10% growth) and declining populations (<0% growth), respectively, between 2010-2019 (USDA, 2020a). Within this decade, the U.S. rural population declined by 0.1 million (Cromartie et al., 2020).

Despite having slow growing or declining populations, these communities often design their WRRFs for increasing populations. This facility overdesign is generally considered good practice because of the higher safety factor. Another reason for overdesigning is the "build it and they will come" mentality that assumes the population is more likely to increase if the infrastructure was designed to handle the growth. This practice of overdesigning results in more material inventory and consequently higher construction costs and environmental impact.

The degree of overdesign can be summarized by the capacity utilization (CU), which is the ratio of the recorded daily average flow rate to the design average daily flow rate. A facility is classified as overdesigned if its CU is under 100%. Figure 4.2 shows the CU of small Nebraska WRRFs (Hanna et al., 2017), illustrating that overdesign is common. The data in Figure 4.1 are based on three-year averages of flow rates reported to the state regulatory agency, which in some cases may be based on as little as a single annual measurement. Out of 96 facilities, 12 are under-designed and 84 are overdesigned.

In the figure, the facilities are also classified by their average wastewater generation per capita. Section 11.243 of the Ten State Standards suggests a design average flow rate based on 100 gallons per capita per day (GPCD) (Health Research Inc., 2014). The average wastewater generation rate of the 96 facilities was 110 GPCD with a standard deviation of 55 GPCD. The figure shows that of the 12 facilities above 100% CU, 8 of them have per capita wastewater generation rates higher than one standard deviation of the average. This suggests that the high CU facilities are not under-designed due to unexpected spikes in population growth, rather they are due to other reasons such as significant inflow and infiltration or a high industrial load. Even in these high CU cases, the flows are likely still lower than the design daily peak flow which is typically around 300-500% of the design daily average flow for small facilities (Qasim, 2017).

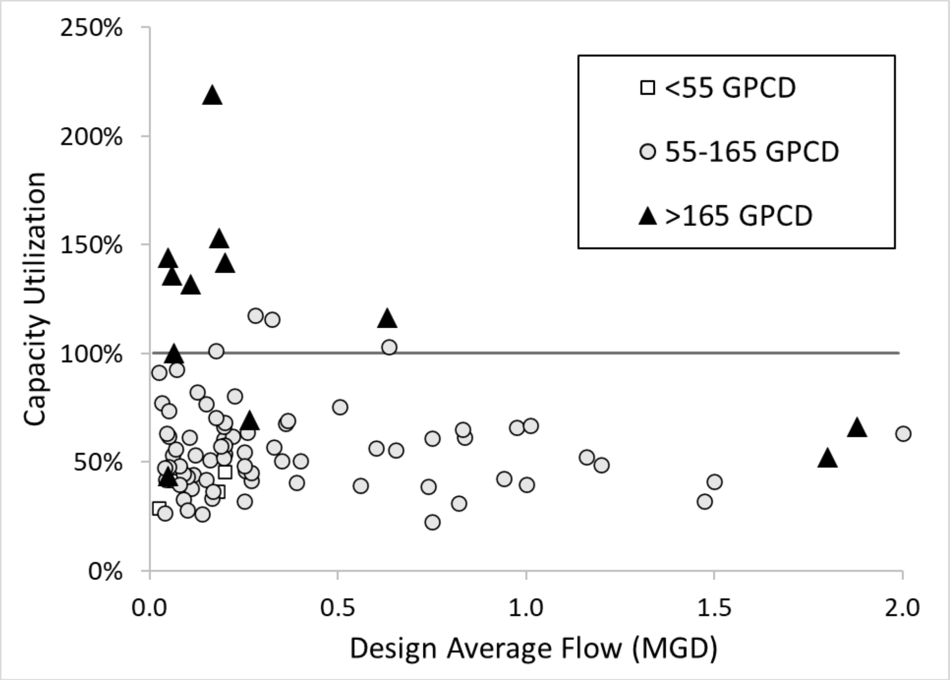


Figure 2.2: Capacity Utilization of Small Nebraska WRRFs Classified by Per Capita Wastewater Generation

2.7 LCA Methodology

Increased awareness of sustainability has created much interest in quantifiable metrics to evaluate and address environmental impacts. The Life Cycle Assessment (LCA) is a popular method developed for this purpose. LCA investigates environmental impacts from "cradle-to-grave", meaning from raw material acquisition, production, and on to end-of-life disposal or recycling.

For a valid comparison between LCA or LCI studies, the assumptions and context of each study must be consistent. The International Standards Organization (ISO) provides requirements and recommendations for LCA assumptions to ensure consistency and transparency (ISO, 2006). The ISO 14040 contains the principles and framework for conducting an LCA study while the ISO 14044 details the requirements and guidelines. The ISO outlines four main phases in conducting LCA studies:

1 Goal and Scope Definition: The functional unit, system boundaries, and level of detail depends on the subject and intended use of the study. The depth and the breadth of the study can vary greatly depending on the goal.

2 Inventory Analysis Phase: The life cycle inventory (LCI) analysis phase involves the collection of input/output data of the system. In some cases, the goals of an LCA study can be achieved with the LCI alone. These are referred to as LCI studies.

3 Impact Assessment Phase: The life cycle impact assessment (LCIA) is used to assess the LCI results in terms of environmental significance.

4 Interpretation: The interpretation phase summarizes and discusses the results of the LCI and LCIA. Any conclusions or recommendations for decision-making are included in this phase. The conclusions of the full LCA can be included in a more comprehensive decision process that includes economic and social trade-offs as well.

2.8 LCA Tools

To perform an LCA study, three tools are required. First, a database is required for background data on the production of the inventory foreground data collected in the LCI phase. Second, a set of characterization factors must be selected as the output for the results. These are also known as impact categories. Third, an LCA program must be used to convert the collected LCI data to the selected impact categories.

Database

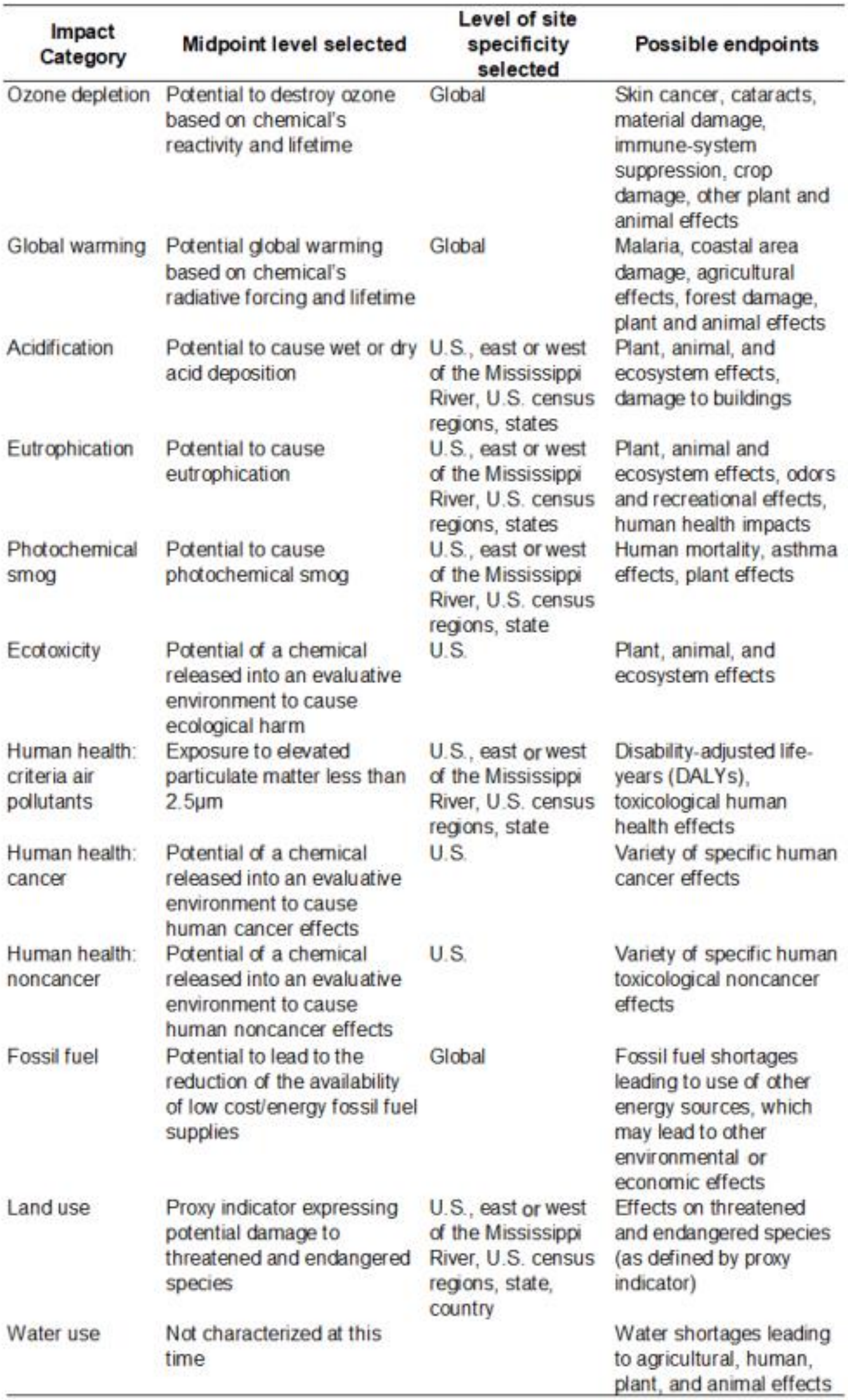
Foreground LCI data is typically compiled from measurements, detailed design documents, or vendor-supplied information, while background data is typically provided by an LCI database. Many databases have been developed due to the release of sustainability standards such as ISO 14040. Some commonly used databases include Ecoinvent, UVEK LCI Data, LCA Commons, and Environmental Footprint. The selection of the database for an LCA study is important because the differences in these databases may result in variable LCA results (Takano et al., 2014).

One study evaluated LCA databases using six decisive features, namely scope, completeness, transparency, comprehensiveness, update, and license (Martínez-Rocamora et al., 2016). Using these factors, the study compared 11 LCA databases and concluded that GaBi Database and Ecoinvent are the top scoring LCA databases, while ELSC is considered the best database that is free.

Characterization Factors

The U.S. EPA’s Tools for Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) provides a set of characterization factors most relevant to the United States. The categories are Ozone Depletion, Global Warming, Smog, Acidification, Eutrophication, Carcinogens, Non-Carcinogens, and Respiratory Affecting Pollutants. These were the impact categories that were recognized as most valuable to minimize based on various programs and regulations within EPA. Land Use and Water Use are recent additions but have not yet been updated in many of the LCA software packages. The mid-points, site specificity, and potential end-points of the ten TRACI impact categories are summarized in Table 2.1 (Bare, 2011).

Table 2.1: Summary of TRACI 2.0 Impact Categories



Impact Category	Midpoint level selected	Level of site specificity selected	Possible endpoints
Ozone depletion	Potential to destroy ozone based on chemical's reactivity and lifetime	Global	Skin cancer, cataracts, material damage, immune-system suppression, crop damage, other plant and animal effects
Global warming	Potential global warming based on chemical's radiative forcing and lifetime	Global	Malaria, coastal area damage, agricultural effects, forest damage, plant and animal effects
Acidification	Potential to cause wet or dry acid deposition	U.S., east or west of the Mississippi River, U.S. census regions, states	Plant, animal, and ecosystem effects, damage to buildings
Eutrophication	Potential to cause eutrophication	U.S., east or west of the Mississippi River, U.S. census regions, states	Plant, animal and ecosystem effects, odors and recreational effects, human health impacts
Photochemical smog	Potential to cause photochemical smog	U.S., east or west of the Mississippi River, U.S. census regions, state	Human mortality, asthma effects, plant effects
Ecotoxicity	Potential of a chemical released into an evaluative environment to cause ecological harm	U.S.	Plant, animal, and ecosystem effects
Human health: criteria air pollutants	Exposure to elevated particulate matter less than 2.5µm	U.S., east or west of the Mississippi River, U.S. census regions, state	Disability-adjusted life-years (DALYs), toxicological human health effects
Human health: cancer	Potential of a chemical released into an evaluative environment to cause human cancer effects	U.S.	Variety of specific human cancer effects
Human health: noncancer	Potential of a chemical released into an evaluative environment to cause human noncancer effects	U.S.	Variety of specific human toxicological noncancer effects
Fossil fuel	Potential to lead to the reduction of the availability of low cost/energy fossil fuel supplies	Global	Fossil fuel shortages leading to use of other energy sources, which may lead to other environmental or economic effects
Land use	Proxy indicator expressing potential damage to threatened and endangered species	U.S., east or west of the Mississippi River, U.S. census regions, state, country	Effects on threatened and endangered species (as defined by proxy indicator)
Water use	Not characterized at this time		Water shortages leading to agricultural, human, plant, and animal effects

LCA Software Packages

The third tool required to perform an LCA is a program that converts the foreground data (collected in the LCI phase) to the selected set of impact category outputs using the background data from a selected database. One paper comparing LCA software considered 15 performance factors and concluded that the four best packages were the Boustead Model, TEAM, PEMS 3.0 and SimaPro (Rice et al., 1997). In a review of 45 LCA studies on WRRF (Corominas et al., 2013), 19 studies used CML, 7 used EDIP 97, 3 used Eco-indicator 99, 2 used Impact 2002+, 2 used eco-points 97, 1 used EPS, and 1 used ReCiPe. The remaining studies either stopped at the inventory assessment or did not indicate the method selected for impact assessment. Only 4 of the 45 studies (Hospido et al., 2012; Muñoz et al., 2008; Ortiz et al., 2007; Renou et al., 2008) used multiple LCIA tools to investigate how they would influence the LCA results.

2.9 LCA Studies Applied to WRRF

There is a growing interest in using LCA to evaluate the broader environmental impacts in WRRF construction and operation. The technique has been applied to wastewater treatment technologies since the 1990s with more than 45 studies published in peer-reviewed journals between 1990 and 2013 (Corominas et al., 2013).

WRRF LCA studies are conducted for a variety of objectives. Some studies are conducted to characterize environmental impacts of specific case studies (Bravo & Ferrer, 2011; Clauson-Kaas et al., 2001; Hospido et al., 2004). Other studies evaluate control strategies for nitrogen removal or other biological nutrient removal configurations (Clauson-Kaas et al., 2004; Foley et al., 2010; Vidal et al., 2002). One of the most common WRRF LCA study objectives is to compare different technologies and configurations to determine the alternative with the best environmental performance (Garfí et al., 2017; Mels et al., 1999). Although there are many LCA studies comparing different WRRF technologies and configurations, no studies were found that compared WRRFs of the same with the same processes but with different construction/design decisions.

WRRF LCA Studies Highlighting Construction Phase Impacts

LCA studies applied to wastewater treatment technologies often assume that the construction phase impacts are insignificant and exclude these impacts from their scope. This is likely due to the fact that construction inventory data collection a tedious and labor-intensive process (Morera et al., 2020). Reviews of WRRF LCA studies found that less than half of the studies include construction phase impacts (Corominas et al., 2013; Gallego-Schmid & Tarpani, 2019; Nguyen et al., 2020a). However, several studies that included the construction phase concluded that it was significant in the overall WRRF environmental impact profile (Morera et al., 2017; Ortiz et al., 2007; Renou et al., 2008). A phase is considered non-negligible if it contributes more than 5% of the impact category (Zampori et al., 2016).

One recent study used a comprehensive methodology to account for construction inventory and compared construction phase impacts with the operation phase (Morera et al., 2017). In this study the inventory was obtained from a detailed construction budget and the as-built design documents, then grouped into a simplified list of representative inventories. Beside the detailed data collection, another advantage of this study was that it classified the facility into five different process elements. Using an operational life span of 20 years, the study showed that contribution of construction phase impacts to the overall facility impact non-negligible. Based on these results, another study was conducted to investigate the construction phase impacts (Nguyen et al., 2020b). This study found that concrete and reinforcing steel were inventories significantly contributing to environmental impact, constituting up to 90% of the construction phase impacts in some categories (Nguyen et al., 2020b).

Whereas the studies mentioned above were performed on large WRRFs (14.5 and 120 MGD), a similar comparative study by Moussavi et al. (2021) was conducted for small mechanical WRRFs (0.08 – 1.80 MGD). The study analyzed 12 facilities using detailed inventory accounting from design plans and construction budgets and concluded that the average construction phase impact is significant in 7 of the 10 impact categories. The construction phase was responsible for 11% in Ecotoxicity, 8% in Ozone Depletion, 9% in Global Warming, 10% in Fossil Fuel Depletion, 10% in Acidification, 15% in Non-Carcinogens, 20% in Smog, and 29% in Carcinogens (Moussavi et al., 2021). Further, the paper identified cast iron, aluminum, and capacity utilization as important factors contributing to environmental impact. Whereas concrete and reinforcing steel are strongly correlated with flow rate, these inventories are not, and therefore opportunities to reduce these inventories are likely.

All the studies mentioned above investigated the construction phase contribution and concluded that construction phase impacts are significant. However, these studies did not investigate different design practices to reduce material inventory and environmental impact.

2.10 Past Research on Small Nebraska WRRFs

A Nebraska WRRF energy benchmarking study was conducted to identify which variables were significant in energy efficiency (Hanna et al., 2017). The significant variables determining the energy usage and efficiency of a facility were the average flow, capacity utilization, climate-controlled floor area, use of sludge digestion, and use of dewatering technology. A major conclusion of this study was discussed in Section 2.5, namely, that there is an economy of scale in energy usage. As facilities get larger, the energy usage per unit of water treated generally decreases. Another conclusion of the study was discussed in Section 2.6, namely, that there may be trade-offs associated with overdesign.

The conclusions of the paper by Hanna et al. (2017) led another study to investigate energy efficiency improvement opportunities for small WWTP (Thompson, 2018). Although several effective ways to improve energy efficiency were identified, the study acknowledged that there were many social and financial barriers preventing these improvements to be implemented. It is worth investigating opportunities for resource reduction that come with little to no inhibiting financial costs, and that can be identified in the planning and design stage.

A study by Moussavi et al. (2019) applied the LCA methodology to assess the environmental impacts of small WWTP operation *and* construction. This LCA study compared the significance of the construction phase, the emissions from the operational phase, and the energy usage from the operational phase, and concluded that the construction phase was significant. One important conclusion of the study was discussed in Section 2.9, namely that there are some inventories that are significant in environmental impact but do not correlate strongly with flow rate. The methodology used in this study to account for inventory and environmental impact was rigorous and should be imitated for future LCA studies on small WRRFs.

2.11 Summary of Literature Review

There are several federal programs created to help finance projects related to water infrastructure specifically such as the USDA's Revolving Funds for Water and Wastewater Projects and the CWSRF. These programs encourage sustainable design and operation practices in order to both alleviate expenses and improve the natural environment. A large focus is given to wastewater systems serving small communities because of their limited financial, technical, and managerial capabilities.

Small systems currently constitute 80% of the WRRFs in the United States, and 614 more are projected to be built between 2012 and 2032. Compared to larger WRRFs, small systems typically have higher energy usages per unit flow (Hanna et al., 2017) and material inventory per unit flow (Doka, 2003) because of economies of scale. The EA and OD type processes are especially of interest because of their prevalence in rural areas.

LCA is a method used to evaluate and compare the environmental impacts of different products/processes. LCA is increasingly being applied to WRRFs to identify best process types and operations. The WRRF LCA studies that include the construction phase conclude that it is significant (Morera et al., 2017; Renou et al., 2008; Moussavi et al., 2019). One study suggests that a reduction in concrete, reinforcing steel, and other inventories would result in significant WRRF impact reductions (Nguyen et al., 2020b).

However, not many studies suggest design practices that reduce these material inventories. Comparing WRRFs with the same processes and configurations but with differences in design decisions would be a useful approach for identifying the design decisions that result in less material inventory and environmental impact.

Chapter 3: Methods

3.1 Introduction

This chapter discusses the methods and sources used to collect inventory data and convert them to environmental impact. First, the selection criteria for the facilities in the dataset is discussed. Then, the Life Cycle Assessment (LCA) standards are outlined along with their application to this project. The Goal and Scope subsection discusses the objectives of the study, functional unit, and system boundaries. The Life Cycle Inventory (LCI) subsection discusses the sources and organization of the input data, the breakdown of the WRRF by 10 process elements, and a list of which material inventories are included in each process element. The Life Cycle Impact Assessment (LCIA) subsection discusses the selection of a database, characterization factor set, and program.

3.2 Selection of Case Studies

The small Nebraska WRRFs in this study were selected based on three criteria. The first criterion was to represent a range of one order of magnitude in design flow (0.1 – 1.0 MGD). The facilities selected have average design flow rates ranging from 0.08 to 1.8 MGD. The second criterion was availability of construction data. The design drawings for 8 of the selected facilities have already been obtained for use in a past study and were available to be used in this study. These drawings were either obtained directly from the local consultants or from the NDEE public records (NDEE, 2020b). The third criterion was contemporaneity. The selected facilities must have been constructed or modified after 2000. Modifications are additions or expansions resulting in more than one construction phase. An example of an addition would be the construction of a UV disinfection channel. An example of an expansion would be the construction of an additional treatment basin to handle higher flow rates. If a facility has had an addition or expansion, the most recent phase's design year and design average flow rate were used.

Based on these criteria, nine WRRFs were selected for the study. The plant type, 2019 population (U.S. Census Bureau, 2020), average flow rate (US EPA, 2020), original and modification construction year, design year, design population, and design average flow rate (engineering reports in NDEE public records) are summarized in Table 3.1. Five of the facilities are Oxidation Ditch (OD) plants, and four are Extended Aeration (EA). Plants A-E are OD type plants in order of increasing flow. Plants F-I are EA type plants, listed in order of increasing flow. More information on these facilities including the names of the communities is provided in Appendix C.

Table 3.1: Summary of WRRFs in Study

Facility	Facility Type	2019 Pop.	Design Pop	Avg Flow (MGD)	Design Avg Flow (MGD)	Constr/ Mod Years	Design Year
A	OD	890	944	0.11	0.16	1969 2017	2040
B	OD	540	743	0.15	0.168	1986 2013	2030
C	OD	1,585	2,300	0.11	0.255	1973 2011	2031
D	OD	2,371	7,370	0.23	0.82	1975 2005	2025
E	OD	4,547	19,000	0.91	1.9	1995 2012	2032
F	EA	450	710	0.04	0.078	1989 2008	2028*
G	EA	977	1,500	0.06	0.15	1992 2005	2025
H	EA	1,960	2,750	0.18	0.33	1964 2012	2032*
I	EA	3,448	4,013	0.39	0.504	1987 2010	2030

Facility Types: Oxidation Ditch (OD), Extended Aeration (EA)
* assumed design year

3.3 LCA Framework

The ISO 14040 and 14044 standards discussed in Section 2.7 were used in this study to ensure a valid comparison between the LCA and LCI results of the 9 facilities. The standards outline the four main phases of an LCA study. The first phase is defining the goal and the scope of the research. Defining the functional unit and system boundaries are both important aspects in this phase to ensure valid comparisons between products or processes. The second phase is the life cycle inventory analysis. During this phase, an inventory of the system's input/output data is collected. The data collection should focus on the data necessary to meet the goals defined in the first phase. The third phase is the impact assessment phase which translates the inventory data to environmental impact. This phase allows the user to understand the environmental significance of the LCI results. The fourth and final phase is the interpretation phase. In this phase, the results of the LCI and the LCIA are summarized, and the conclusions or recommendations are discussed in accordance with the goal and scope. The first three phases are discussed in depth in this chapter, and the fourth phase will be discussed in Section 4 Results.

3.3.1 LCA Project Goals and Scope

The first phase of an LCA study defines the goal and the scope of the analysis. The objectives and goals were discussed in detail in Chapter 1. The scope subsection discusses the functional unit and system boundaries.

Functional Unit

The functional unit is an important aspect of LCA that varies depending on the goal of the study. In a study by Emmerson et al. (1995), three different wastewater treatment technologies were compared. No functional unit was required to normalize the impacts of each treatment type because the selected facilities had comparable flow rates (about 200 m^3/day). In a study by Morera et al. (2017), an LCA was performed using a detailed inventory of one large WRRF to compare construction phase impacts to operation impacts. The functional unit was 1 m^3 of treated wastewater over 20 years. However, this was not required for normalization because the impacts were being compared within one facility, not between different facilities. A study by Moussavi et al. (2019) compared the environmental impact profile of small WRRFs with a range of flow rates. To compare the results between plants, the average treated flow throughout the facility's useful life was used as a functional unit. The lifetime average treated flow was estimated based on three-year averages of flow rates reported to the state regulatory agency, which in some cases may be based on as little as a single annual measurement. Using this functional unit, the impacts were normalized and comparable.

For this study, the disadvantage of using lifetime average flow as a functional unit would be the overestimation of construction phase impacts for plants that have been overdesigned. Instead, since this thesis has a large focus on comparing the construction phase, the functional unit selected was 1 MGD of *design* average flow rate. The advantage of using the design average flow rate is that it is more reflective for comparisons since construction material inventories are based on the engineering design, not on operation. An even more accurate functional unit in comparing construction impacts would be the design *peak* flow rate since the peak flow rate is the parameter used in determining basin and pipe sizes. However, since the peaking factors are expected be similar between plants, the difference between using design average flow and design peak flow is expected to be small. The design average flow rate is a more intuitive functional unit to the target audience of design engineers, operators, and regulators. For the facilities that have expanded in size, the later construction phases of the expansions were included. In these cases, the functional unit was the most recently updated design average flow rate.

System Boundaries

The system boundary includes two phases: construction and electricity usage. In the construction phase, the foreground data collected includes civil works and equipment. The associated background data includes raw material acquisition and production energy. The material inventory collection and conversion to impact will be discussed further in Section 3.3.2.

Water, soil, and air emissions are relatively small contributors to most environmental impact categories (Moussavi, 2019) and also difficult to account for because of the high uncertainty in the data. For these reasons, they are excluded from this analysis which simplifies the operation phase to only include 20-year electricity usage. The mean design life for the facilities in this study was 20 years (range = 17-23).

End of Life

Some WRRF LCA studies such as Emmerson et al. (1995) include a theoretical end-of-life in the system boundaries. This is an important consideration in studies that compare construction phase impacts to operational phase impacts because different practices may result in a higher construction phase impact. In this thesis, the facilities are all still in operation, therefore no end-of-life construction budgets are available. If the end-of-life construction impacts were to be included, they would have to be estimated based on literature. Since this thesis is a comparative study of construction phase impacts, the effects of theoretical end-of-life impacts applied to all facilities would likely cancel out. For example, if multipliers from literature were used to estimate impacts from concrete transport and recycling, they would be applied to all 9 facilities. This would raise the absolute impact but may have little effect on the relative impact between plants. Furthermore, the end-of-life is relatively small compared to other phases in all impact categories except for Ozone Depletion (Moussavi, 2019). For these reasons, the end-of-life demolition and recycling are not included in the system boundaries for the LCI and LCIA.

3.3.2 Life Cycle Inventory

The second phase of an LCA analysis is the life-cycle inventory (LCI) data collection. During this phase, an inventory of the system's input/output data is collected. The facilities' annual electricity usages between 2016-2019 were based on utility bills obtained either from the community's records or from the utility provider. The mean design life for the facilities in this study was 20 years (range = 17-23). To estimate the lifetime electricity usage in the operation phase, the mean design life was multiplied by the average annual electricity usage of each facility.

The material inventory data were collected from engineering design plans and construction budgets obtained for each facility. The data were simplified by reducing all inventory to twenty lines of general inventory. For example, although there are different mixtures and water contents of concrete, all concrete was represented by one general concrete mixture type. The twenty lines of general construction inventory were the same inventory lines used in a past study with similar objectives (Moussavi, 2019), namely excavation, reinforcing steel, concrete, rock/limestone, sand, brick, wood, asphalt, cast iron, stainless steel, aluminum, copper, rubber, fiber glass, VCP, polyethylene, polypropylene, polyvinyl chloride, polystyrene insulation, and material transport. This list was based on a similar study which included 30 lines of inventory (Morera et al., 2017). Equipment such as motors and blowers were broken down into cast iron, steel, aluminum, copper, and rubber estimated by their nameplate power draw in a model created from various environmental product declarations (EPD). These models are provided in Appendix A.

Of the 20 lines of representative inventory, two were estimated based on multipliers found in literature rather than directly from the design plans, namely reinforcing steel and material transport. An accurate accounting of reinforcing steel would be complicated and labor-intensive. Instead, the amount of reinforcing steel was estimated using a multiplier of 77.6 kg of reinforcing steel per m^3 of concrete (Foley et al., 2010). An average distance of 40 km for material transport was used, consistent with two past WRRF LCA studies (Morera et al., 2017 ; Moussavi et al., 2019).

Breakdown by Process Element

One challenge in conducting comparative WRRF LCA studies is the multifunctional nature of WRRFs. To address this challenge, past studies broke down the LCI and LCIA system boundaries by the different process elements of the WRRF. One recent example of this is the study by Morera et al. (2017) which broke down the inventory and impacts into 5 “units”, namely Pumping & Pre-Treatment, Primary Treatment, Secondary Treatment, Sludge Line & Deposition, and Other.

It is important to include as many of the process elements in the scope as possible. Small-to-medium WRRFs considering only secondary treatment may neglect up to 40% in some impacts. Simply excluding “urbanization” as an element may neglect up to 40% in some impacts (Morera et al., 2020). The urbanization element included buildings and landscape material such as sidewalks and fences. For a more detailed construction phase comparison, this thesis compares WRRFs by 10 different process elements, namely the lift station, preliminary treatment, biological reactor, clarifier, sludge digester, post-digestion sludge handling, disinfection, conveyance, buildings, and other. The advantage of this breakdown compared to an aggregate analysis is a narrower search for solutions for impact reduction (Xue et al., 2019)

Since this is a comparative study, the level of detail in data collection must be consistent between all facilities. The inventories included in the scope of this study are summarized in Table 3.2, broken down by the ten process elements. Inventories were excluded from the analysis if they were seemingly insignificant or difficult to account for. For example, replaceable supplies such as UV bulbs, sealants, and nylon hoses were excluded because their contribution was expected to be insignificant and difficult to account for. The in-building potable water piping was excluded because the data were not available in the design plans. The clarifier skimmer/scraper assembly could not be accounted for because different WRRFs used different types and none of the design plans included the dimensions or materials for them.

Table 3.2: Construction Phase Material Inventory by Process Element

Element	Inventory Included	Inventory Not Included
Lift Station	wet wells, dry wells, influent pumps, suction and discharge piping within lift station	ladders, pump shafts, pump shaft covers
Preliminary	manual bar screens, vertical screens, parshall flumes, grit removers, degritting basins, piping to and from degritters within building	Access hatches, ladders, stop gates
Biological	basins, piping within basins, air blowers, blower silencers, RAS pumps, diffusers, gates, weirs	Access hatches, stop gates
Clarifier	basins, piping within basins, weirs, baffles	skimmer assembly, scraper assembly, flex hoses, nylon tubes
Tertiary	UV basins, UV concrete channels, UV steel channels, piping within channels	UV bulbs and rack
Sludge Digestion	basins, piping within basins, air blowers, WAS pumps, diffusers	
Sludge Handling	Thickening basins, belt presses, storage pads, lagoons, influent structures, sludge loadout stands, piping within basins & lagoons	
Conveyance	piping between elements, splitter boxes, selector tanks, manholes	pipe supports, thrust blocks, casing, bitumen sealing, fittings with < 2" dia.
Buildings	foundation, brick walls, CMU walls, insulation, floors, roof trusses and frames, roof insulation, flexicore slabs, roof asphalt covers	HVAC, storm drain gutters and downspouts, louvers, vents, seams, fascias, sill plates, volume dampers, windows, doors, overhead doors
Other	potable water lines, hydrants, pavement and driveway, aluminum handrails, aluminum grating, walkways	water piping inside buildings, expansion joints, nuts and bolts, saddle clamps, pipe supports, support beams, support frames, wall brackets, floor brackets, sealant, control panels, control monitors, adapters

3.4.3 Life Cycle Impact Assessment

The next step in the LCA assessment is to convert the material inventories from the LCI phase to environmental impacts. This requires three models/tools. First, a database is needed to account for all the background processes that go into the production of one unit of the foreground inventory data collected. Second, a set of environmental impact categories is needed to be used as the output metrics. Third, an LCA software must be used to convert the foreground inventory data to the output environmental impact categories using the background data from the database.

Database

In a study comparing 11 LCA databases, Ecoinvent and GaBi Database were concluded to be the two most complete LCA databases, while ELSC was considered the best free database (Martínez-Rocamora et al., 2016). Two past studies with similar objectives also used Ecoinvent as the database (Morera et al, 2017 ; Moussavi et al, 2019). For these reasons, Ecoinvent was the database selected for this study. The global market database in Ecoinvent was used for 19 of the 20 general inventory lines. The European market database was used for the material transport inventory line because the global market database was unavailable.

Impact Categories

This research uses the ten impact categories outlined by the U.S. EPA's Tools for Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) tool (Bare, 2011). TRACI was chosen because of its comprehensiveness and applicability to the United States. The ten TRACI impact categories are Acidification (ACI), Carcinogens (CAR), Ecotoxicity (ET), Eutrophication (EU), Fossil Fuel Depletion (FD), Global Warming Potential (GW), Non-Carcinogens (NC), Ozone Depletion (OD), Respiratory Effects (RE), and Smog (SM).

LCA Software

SimaPro v8 was the program selected for this research because of its transparency, robustness, compliance with ISO 14040, and inclusion of the Ecoinvent database and TRACI impact category output (PRe, 2019). SimaPro was used to determine the amount of environmental impact resulting from the production of one unit of inventory. For example, the amount of each impact category emitted from production of 1 m^3 of concrete was obtained. These unit multipliers were obtained for all 20 general inventory lines and provided in Appendix A. The actual conversion of inventory to impact category was done on Microsoft Excel using these multipliers obtained from SimaPro.

Summary

A visual summary of the methodology used to convert inventory to environmental impact categories is shown in Figure 3.1. First, the data was collected and reduced to 20 lines of representative inventory. SimaPro v8 provided the unit multipliers that were used to convert inventory to impact. SimaPro v8 uses the Ecoinvent database to perform this analysis. The set of characterization factors chosen for the output was the TRACI 2.0 set of impact categories. The unit multipliers were then multiplied by the collected inventory data in Microsoft Excel.

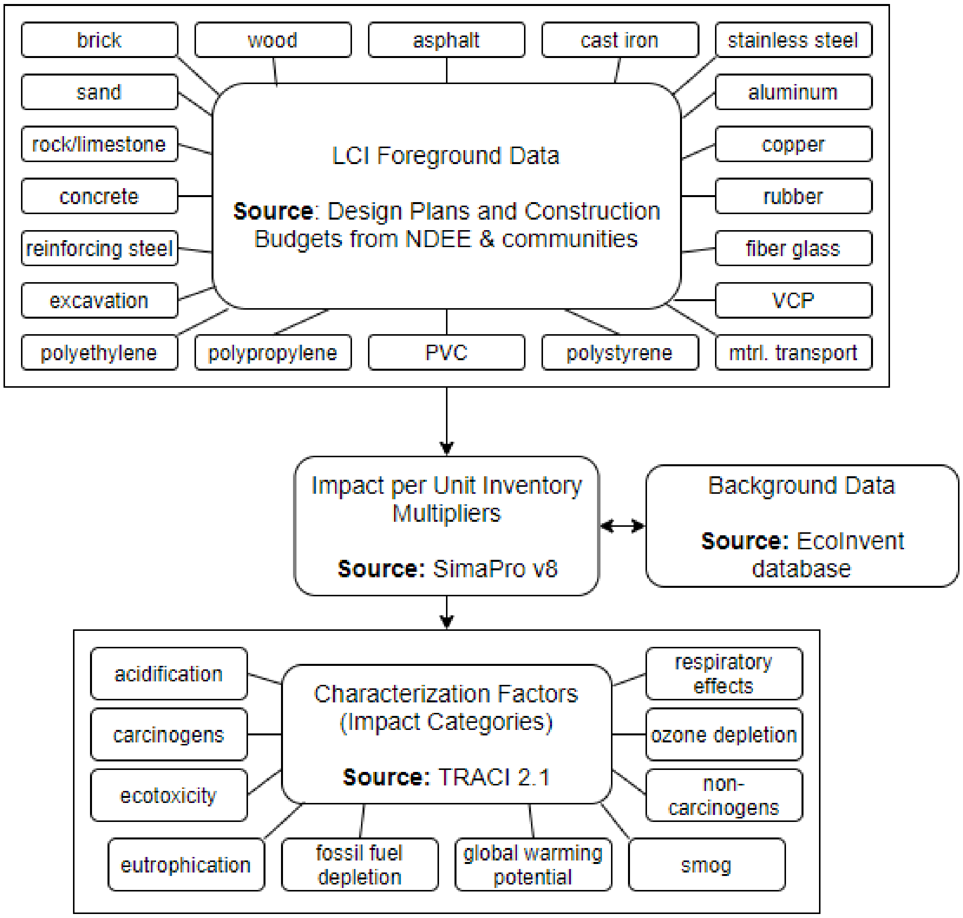


Figure 3.1: LCI conversion to LCA methodology summary

Chapter 4: Results and Discussion

4.1 Introduction

In the global effort to minimize environmental impacts, sustainability improvement opportunities are being investigated in many areas (US EPA, 2020a; US EPA, 2020b) including municipal infrastructure. Water resource recovery facilities (WRRFs) are a critical infrastructure for local, regional, and national sustainability in water resources. However, although WRRFs reduce environmental impacts related to water quality, their construction and operation also results in environmental impacts. The Life Cycle Assessment (LCA) methodology is an effective tool for comparing the environmental impacts of products and processes and has commonly been applied to evaluate the environmental performance of WRRFs. Applying LCA to investigate small systems serving communities with slow growing or declining populations is merited because these systems constitute a majority of wastewater systems in the United States (US EPA, 2012; USDA, 2020a).

Small WRRFs are defined as systems serving communities with populations of less than 10,000 and an average daily flow of less than 1 million gallons (US EPA, 2016). According to the Clean Watersheds Needs Survey (CWNS), small systems make up 80% of centralized wastewater treatment systems in the United States. In four states (Nebraska, Kansas, Iowa, Montana), small systems constitute more than 95%. There are currently 11,571 small systems in the country and an estimated 614 more to be built between 2012-2032 (US EPA, 2012). Small systems also constitute a majority of the systems in other countries such as Switzerland where 690 out of 967 facilities serve a population equivalent (PE) of less than 10,000 (Doka, 2003).

Besides the fact that they constitute the majority of WRRFs, an important reason to investigate small systems is the economy of scale in infrastructure. Facilities that treat lower flow rates were shown to use more energy per unit flow in the United States (Hanna et al., 2017) and Australia (de Haas & Dancey, 2015). One likely reason is that these smaller facilities size their aeration equipment to treat the high flows projected 20 years into the future. Unlike larger facilities, small facilities often lack the financial and technical capability for controls that allow varying power output to accommodate the current flow rate (Thompson et al., 2020). Additionally, Class 5 (PE = 30-2,000) WRRFs were shown to use more infrastructure per m^3 of treated wastewater than Class 1 (PE > 100,000) WRRFs in a LCI analysis using WRRFs in Switzerland (Doka, 2003).

Many of these non-metro communities served by small systems are experiencing slow growing or declining populations, often resulting in overdesigned systems. According to USDA county population data, 28% of U.S. non-metro counties have grown less than 10% between 2010-2019 while 67% experienced a decline in population (USDA, 2020a). Despite this, many communities often design their WRRFs for increasing populations which is generally considered good practice because of the higher safety factor. Another reason for overdesigning is the “build it and they will come” mentality that assumes the population is more likely to increase if the infrastructure is designed to handle the growth (KDHE, 1999). This practice of overdesigning results in more material inventory and consequently higher construction costs and environmental impact.

The degree of overdesign can be summarized by the capacity utilization (CU), which is the ratio of the recorded daily average flow rate to the design average daily flow rate. A facility can be classified as overdesigned in this study if its projected CU at design year based on current population trends is under 100%. Figure 4.2 shows the current CU of small Nebraska WRRFs based on data from Hanna et al. (2017), illustrating that overdesign may be common.

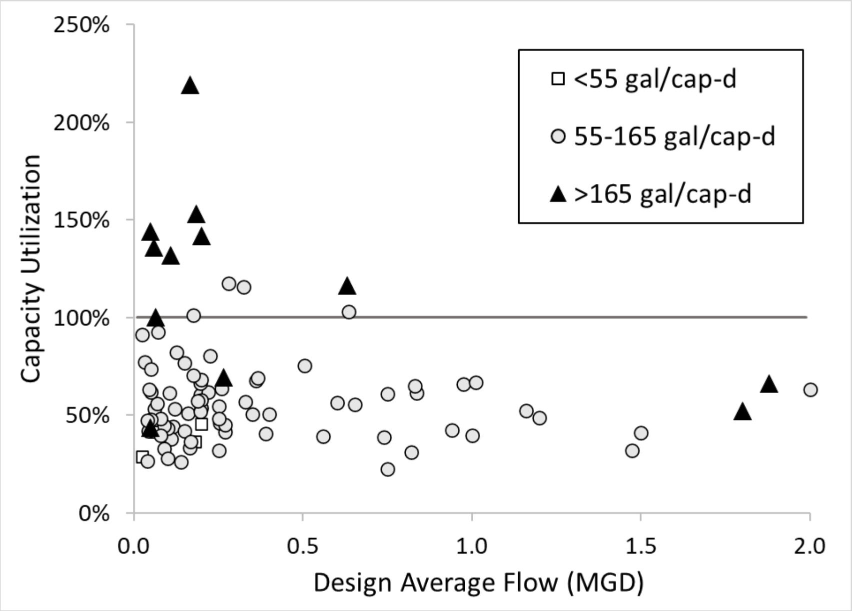


Figure 4.1: Capacity Utilization of Small Nebraska WRRFs Classified by Per Capita Wastewater Generation. Recorded average flows based on three-year averages reported to the Nebraska Department of Environment and Energy (US EPA, 2020). Design flows and wastewater generation rates taken from (Hanna et al., 2018).

Out of 96 facilities, 12 are over 100% CU and 84 are under 100% CU. Of the 12 facilities exceeding CU, eight have wastewater generation rates higher than one standard deviation from the average (> 165 gallons per capita day (GPCD)). This suggests that the high CU facilities are not under-designed due to unexpected spikes in population growth. Rather, they are due to other reasons such as significant inflow and infiltration (I&I) or a high industrial load. Rather than overdesigning to accommodate for I&I, addressing the problem at its source by improving collection systems may be a better solution.

Even in these high CU cases, the flows are likely still lower than the design hydraulic daily peak flows which are typically around 300-500% of the design daily average flow for small facilities (Qasim, 2017). Further, many facilities have two basins for redundancy, each designed to handle the plant’s entire flow on its own. Therefore, there is an implicit overdesign that adds an extra safety factor to prevent exceeding capacity.

In assessing the environmental impact of WRRFs, both the construction phase and the operation phase should be considered. In several reviews of WRRF LCA studies, the construction phase was considered in less than half: 22 out of 45 studies (Corominas et al., 2013), 22% of studies (Nguyen et al., 2020a), and 14 out of 43 studies (Gallego-Schmid & Tarpani, 2019). However, several studies that included the construction phase concluded that it contributed a significant portion of the impact profile (Morera et al., 2017; Moussavi et al., 2021; Ortiz et al., 2007; Renou et al., 2008). Further, the construction phase will likely become more significant in relative impact if the electricity grid transitions from fossil fuels to renewable energies.

Construction inventories that correlate strongly with flow rate include concrete and reinforcing steel (Morera et al., 2020) which have also been identified as major contributing inventories in several construction phase impact categories (Nguyen et al., 2020b). Factors contributing to environmental impact but not strongly correlated with flow rate include capacity utilization, aluminum, and iron (Moussavi et al., 2021), therefore there is potential for reducing them independent of flow-based design standards. Further research is needed to identify any design practices that reduce a WRRF’s environmental impact by focusing on these factors.

The focus of this study is narrowed to the Extended Aeration (EA) and Oxidation Ditch (OD) configurations because of their prevalence in small communities. Of the 110 WRRFs studied in a benchmarking study, 28 were conventional activated sludge, 30 were OD, 22 were EA, 16 were sequencing batch reactor, and 14 were other (Hanna et al., 2017). The EA and OD facilities have similar configurations with the main difference being the biological reactor. EA facilities have a basin aerated by diffusers while OD facilities have a racetrack shape where wastewater is circulated and aerated by rotors. Because of their similarities, these configurations are analyzed as one category rather than comparing them to each other. Figure 4.2 shows a typical basic process flow diagram for EA and OD WRRFs.

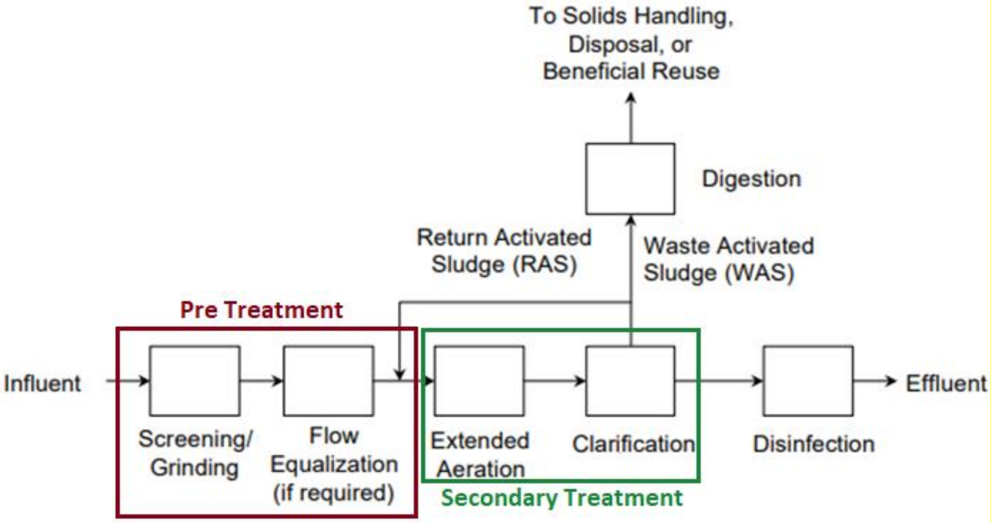


Figure 4.2: Typical EA Activated Sludge Configuration (US EPA, 2000). The OD configuration is the same general layout but with a different biological reactor.

This study aims to identify practical design recommendations for small WRRFs that reduce environmental impact based on nine case studies, specifically by investigating opportunities to reduce concrete, reinforcing steel, iron piping, and overdesign. The objective is to achieve this using a comparative LCA framework to identify the facilities with low normalized impact and identify the reasons for the low impact. Then, based on trends seen among the nine case studies, the study aims to provide a theoretical quantification of potential impact mitigations if the suggested design practices were applied. The novelties of this study include (i) its focus on small facilities serving slow growing or declining populations, (ii) its large sample size of nine case studies, (iii) a detailed construction inventory based on engineering design plans and budgets, (iv) a finer breakdown of the treatment process into 10 elements, and (v) a discussion of actual design practices that reduce environmental impacts rather than simply identifying significant factors.

4.2 Methodology

The LCA method was used to evaluate and compare the environmental impacts of nine small WRRFs which are roughly representative of small WRRFs in the northern U.S. The study includes both the construction phase using detailed inventory data from design plans and budgets and the operation phase from utility bills. Based on the analysis results, design approaches that reduce environmental impact from iron piping and overdesign were identified and quantified. Then, design engineers and operators were consulted to identify the limitations or disadvantages in the application of these suggested practices.

Selection of Case Studies

The small WRRFs in this study were selected based on the following criteria: (i) they should represent a range of at least one order of magnitude in design flow (0.08 - 1.8 MGD), (ii) they should have been constructed or modified after 2001 to still be operating within a 20-year design life, (iii) they should be an extended aeration or oxidation ditch process, and (iv) they should have readily accessible detailed operational data and construction data. Table 4.1 summarizes the facility types, populations (U.S. Census Bureau), flow rates (US EPA, 2020), design parameters, construction year, and most recent modification year (NDEE, 2020b) of the nine facilities in the study. For the cases where the design life was not provided, a typical 20-year design life was assumed.

Table 4.1: Summary of Nine Facilities' Characteristics and Design Parameters

Facility	Facility Type	2019 Pop.	Design Pop	Avg Flow (MGD)	Design Avg Flow (MGD)	Constr/ Mod Years	Design Year
A	OD	890	944	0.11	0.16	1969 2017	2040
B	OD	540	743	0.15	0.168	1986 2013	2030
C	OD	1,585	2,300	0.11	0.255	1973 2011	2031
D	OD	2,371	7,370	0.23	0.82	1975 2005	2025
E	OD	4,547	19,000	0.91	1.9	1995 2012	2032
F	EA	450	710	0.04	0.078	1989 2008	2028*
G	EA	977	1,500	0.06	0.15	1992 2005	2025
H	EA	1,960	2,750	0.18	0.33	1964 2012	2032*
I	EA	3,448	4,013	0.39	0.504	1987 2010	2030

Facility Types: Oxidation Ditch (OD), Extended Aeration (EA)
* assumed design year

LCA Framework

The ISO 14040/14044 standards were used to ensure a valid comparison between the LCI/LCA results of the nine facilities (ISO, 2006). The four phases outlined in the ISO standards are: goal and scope definition, inventory analysis, impact assessment, and interpretation.

Goal and Scope Definition

The goal of this study was to identify design recommendations for small EA/OD WRRFs that reduce environmental impact from iron piping and overdesign, and then to quantify the associated potential impact mitigations. The functional unit used was 1 MGD (3,785.4 m^3/day) in design average wastewater flow. If a facility underwent modifications, the most recent design average flow was used. Although using the actual average flow rate as a functional unit is useful to compare operational phase impacts, the material inventories from civil works and equipment are based on design flow rather than actual operational flow. Additionally, because many of these systems do not include controls on their aeration equipment for varying output depending on actual flow rates, the design flow may be an appropriate functional unit for the operational phase as well.

The system boundary included two phases: construction and operation. In the construction phase, the foreground data collected included civil works and equipment. The associated background data included raw material acquisition and production energy. Water, soil, and air emissions from operation were excluded from the analysis for two reasons. First, many of these facilities only record water and soil emission data annually and do not record air emissions at all. If these were to be accounted for, they would have to be extrapolated based on annual data points or estimated using multipliers from literature which would result in high uncertainty. Second, this study focuses on optimizing construction and operation decisions to reduce inventory while keeping the function the same, therefore these changes are expected to have little effect on the water, soil, and air emissions. For these reasons, the operation phase was simplified to only include 20-year electricity usage.

End-of-life scenarios for WRRFs include abandoning the infrastructure in place, retrofitting to extend life, and demolishing to a landfill with or without recycling some components. The end-of-life impacts are excluded from this analysis. The study focuses on reducing inventory in the construction phase which already implies less impact for the end-of-life no matter which scenario is chosen. Further, the facilities in this study are still in operation, therefore no end-of-life procedures or budgets were available.

Inventory Analysis

The electricity usage in the operation phase was estimated based on utility bills obtained either from the community's records or from the utility provider. The mean design life for the facilities in this study was 20 years (range = 17-23) based on design documents. To estimate the lifetime electricity usage in the operation phase, the mean design life was multiplied by the average annual electricity usage of each facility based on the utility bills of recent years.

The material inventory data were collected from the facilities' engineering design plans and construction budgets, obtained from the Nebraska Department of Environment and Energy's public records search (NDEE, 2020b). The data were simplified by reducing all inventory to twenty lines of general representative inventory. For example, although there are different mixtures and water contents of concrete, all concrete was represented by one general type. The twenty lines of general inventory were the same as a past study with similar objectives (Moussavi et al., 2021), namely excavation, reinforcing steel, concrete, rock/limestone, sand, brick, wood, asphalt, cast iron, stainless steel, aluminum, copper, rubber, fiber glass, VCP, polyethylene, polypropylene, polyvinyl chloride, polystyrene insulation, and material transport.

An accurate accounting of reinforcing steel would be complicated and labor-intensive. Instead, the amount of reinforcing steel was estimated using a multiplier of 77.6 kg of reinforcing steel per m^3 of concrete (Foley et al., 2010). For material transport, an average distance of 40 km was assumed, consistent with two past WRRF LCA studies (Morera et al., 2017 ; Moussavi et al., 2021). Equipment such as pumps and motors were broken down into cast iron, steel, aluminum, copper, and rubber, estimated by their nameplate power draw based on various environmental product declarations (EPD).

To address the multi-functional nature of WRRFs, past studies divided the LCI/LCIA into five process elements (Morera et al., 2017; Nguyen et al., 2020b). The novelty introduced in this study is the division of the LCI into ten process elements: lift station, pre-treatment, biological reactor, clarifier, disinfection, sludge digestion, post-digestion sludge handling, conveyance, buildings, and other auxiliary inventories. The "conveyance" element included manholes, piping, fittings, and valves between processes starting from the headworks to the effluent manhole. The "other auxiliary" element included pavement, fences, aluminum stairs and walkways, and potable water piping. This finer breakdown allowed for a narrower examination of how some facilities are doing better than others in normalized impact. This was especially true for the "conveyance" element which many past studies simply grouped into other major process elements even though it is highly variable between facilities. Further, not all facilities include all process elements, therefore finer breakdowns allow for fairer comparisons.

Impact Assessment

An LCA database is needed to account for all the background processes that go into the production of one unit of foreground inventory data. The Ecoinvent database was selected for this study because of its high score in an evaluation of databases based on scope, transparency, comprehensiveness, and update recency (Martínez-Rocamora et al., 2016) and because it was used in two past studies with similar methodologies (Morera et al., 2017; Moussavi et al., 2021). SimaPro v8 was the LCA program used to convert inventory to impact, selected for its robustness, compliance with ISO 14040, and inclusion of the Ecoinvent database. The impacts from the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) were used as the output metrics because of their relevance to the United States' environmental regulations (Bare, 2011). Figure 4.3 summarizes the sources and methodology used to obtain and calculate the LCA.

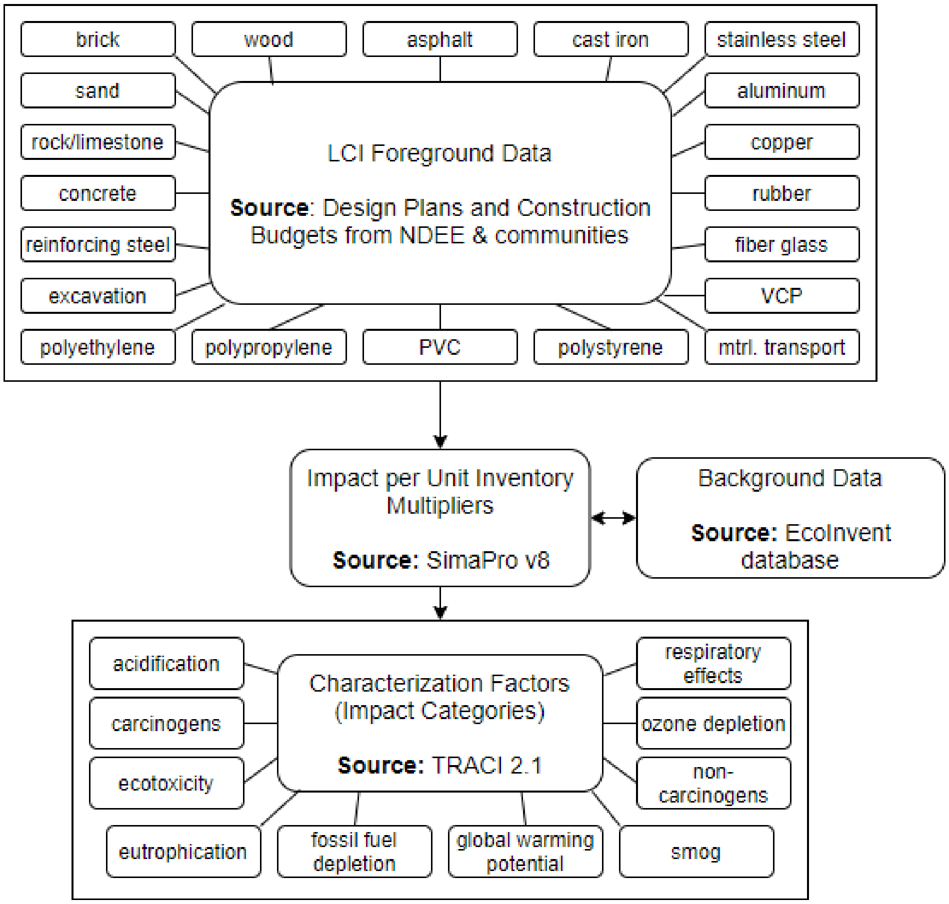


Figure 4.3 Schematic of Data Analysis Sources and Programs

The environmental impacts of the facilities were then analyzed by process element to determine which element had high impact and high impact variability measured by the coefficient of variation (CV). Based on this, three suggested practices were identified and quantified using the following procedures.

To show conveyance impact savings associated with optimizing layout, the relationship between a facility's total piping length was plotted against its non-process area, both normalized by design average flow. Non-process area is defined as the area that is not occupied by a biological reactor, clarifier, or sludge digestion basin. Both the total area and non-process areas were measured by aerial measurements from Google Earth and provided in the Supplementary Information (SI) Appendix.

To show conveyance impact savings associated with using PVC instead of DIP, the inventory spreadsheets of each facility was adjusted to have some pipe lengths be PVC instead of DIP. A conservative approach was taken that did not include adjusting the fittings. Only pipe lengths where PVC application is possible were adjusted. Pipe lengths that were not adjusted include (i) raw influent piping due their large diameters and connection to the sewer, (ii) air piping due to pressure requirements, (iii) sludge piping due to difficulties that may arise with the sludge pumps, and (iv) any length of pipe with a parallel pathway within 5 ft of a structure or basin due to PVCs low external load.

To quantify the amount of savings associated with addressing overdesign, two models were used. First, a model that estimates annual electricity usage (Hanna et al., 2017) was used to determine the percent decrease in electricity usage from increasing the capacity utilization variable to an appropriate level. Then, the nine facilities in this study were used to determine the relationship between secondary process construction inventory to the design average flow. This relationship was used to estimate inventories at other flow rates by interpolation.

4.3 Results

A reduction in resource inventory will result in reductions in all environmental impact categories. However, for simplicity, only two categories were selected as representative impacts to present the results: Carcinogenic impact and Global Warming impact. The average TRACI impacts of the nine WRRFs normalized by annual national emissions (Ryberg et al., 2014) are illustrated in Figure 4.4. The Carcinogenic impact in comparative toxic units (CTU) was selected as a representative impact because it was the dominant category at 1.02×10^{-4} (CTU/MGD)/(CTU/year). Although the Global Warming category was only the 7th most impactful category after normalization, it was also selected as a representative impact because of the prevalence of climate change in the global conversation in sustainability. For example, almost all WRRF LCA studies include climate change as a factor (Corominas et al., 2013), and one study had climate change as the only impact factor (Ortiz et al., 2007). The impact profile shows that the construction phase contributed an average of 32% (range = 15-42%) and 10% (range = 4-14%) of the overall impact in the Carcinogenic and Global Warming categories, respectively.

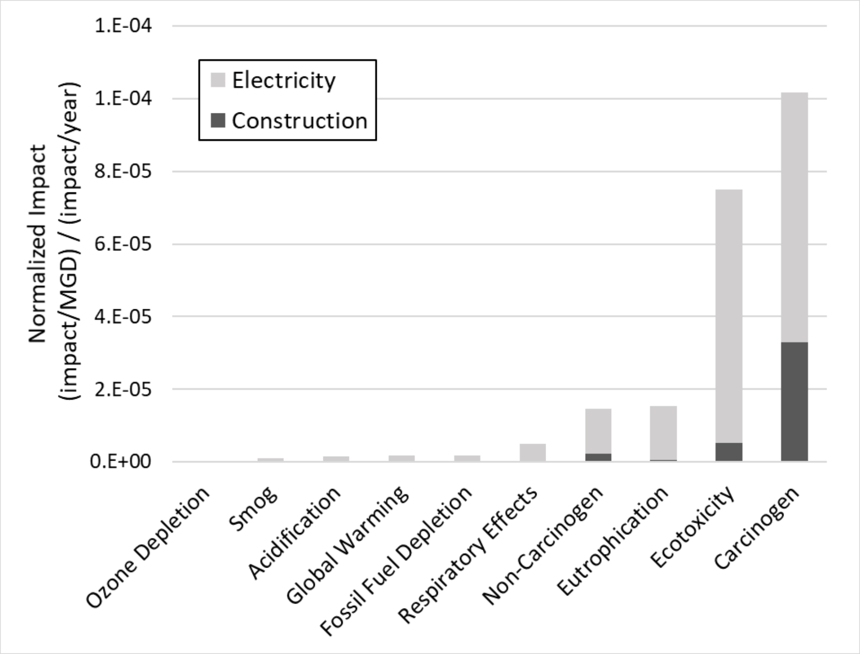


Figure 4.4 Average Impact Profiles of 9 WRRFs Normalized by Annual National Emissions

4.3.1 Construction Phase Impacts

Figure 4.5 summarizes the construction phase impacts of the nine facilities in the sample broken down by the ten process elements. The black bar represents the 50th percentile, and the top and bottom of the gray box represent the 75th and 25th percentile, respectively. The UV disinfection and post-digestion sludge handling columns contain less than nine data points because not all facilities included these processes in their treatment. In the Carcinogenic category, the conveyance and biological reactor elements contributed the highest average impacts at 0.15 and 0.13 CTU/MGD [3.96E-05 and 3.43E-05 CTU/(m^3/d)], respectively. The biological reactor impact had low variability among facilities (CV = 21%), while the conveyance element had high variability (CV = 73%) which was expected due to the variations in layouts seen across facilities. In the Global Warming category, the biological reactor stood out as the highest impact contributing element at an average impact of 394,372 $kgCO_2eq/MGD$ [104 $kgCO_2eq/(m^3/d)$] with a 17% coefficient of variation among facilities.

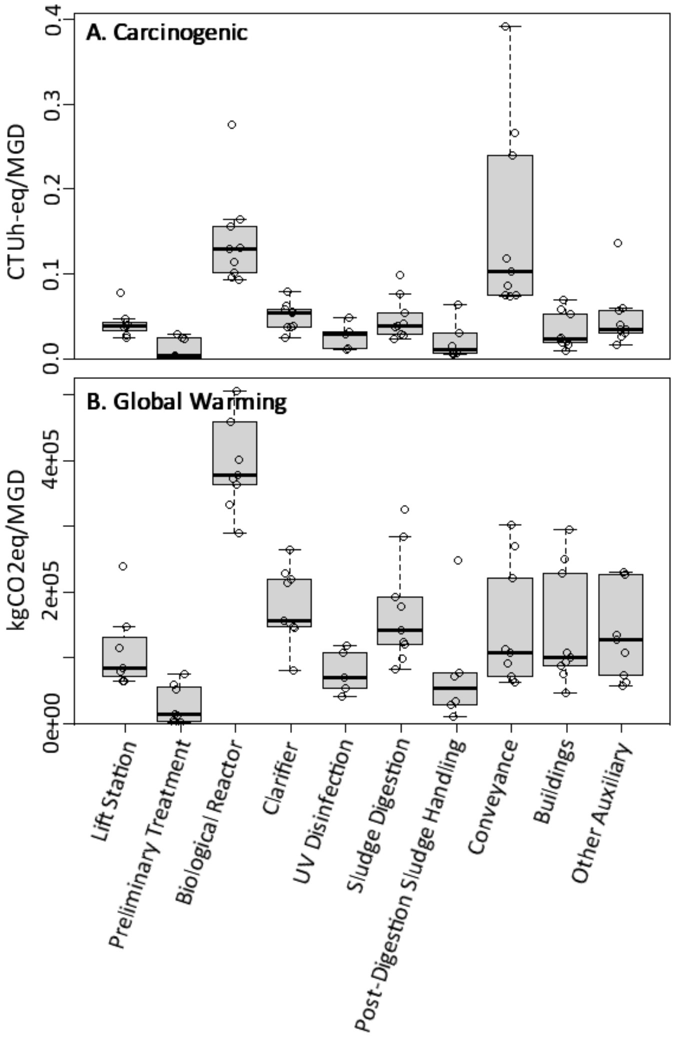


Figure 4.5: Construction Phase Impacts for A. Carcinogens and B. Global Warming for each process element.

In the Carcinogenic category, reinforcing steel was the inventory most responsible for the biological reactor impact (65% average contribution), and ductile iron piping was most responsible for conveyance (93% average contribution). In the Global Warming category, concrete was the inventory most responsible for the biological reactor impact at an average contribution of 48%. These results suggest that opportunities for significant construction phase impact mitigations will most likely be found in the biological reactor and conveyance elements, and more specifically in reducing concrete, reinforcing steel, and ductile iron piping in these process elements.

4.3.2 Conveyance LCI and LCA Mitigation Opportunities

The conveyance element was the highest contributor to the Carcinogen impact mostly due to the ductile iron piping. Conveyance also had high impact variability between plants. The plants with the lowest conveyance construction impact were examined to determine the reason for the low impact. From this, two impact reduction opportunities were identified: (1) minimize facility non-process area, and (2) use polyvinyl chloride (PVC) pipe instead of ductile iron pipe (DIP) where possible.

Based on the nine facilities in the study, Figure 4.6 shows the relationships of conveyance piping length to non-process facility area and associated Carcinogenic impact to non-process facility area, normalized by average design flow. Although there are only nine data points, the plots suggest that lower non-process area is correlated with less total pipe length ($R^2 = 0.87$) and consequently less Carcinogenic impact ($R^2 = 0.71$).

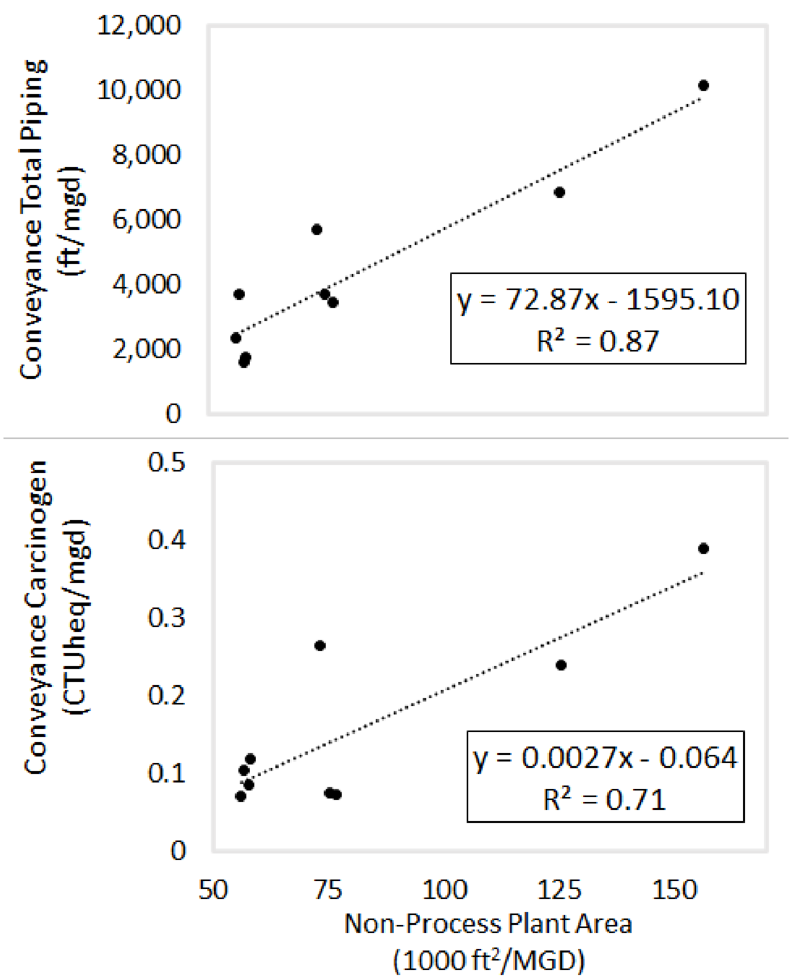


Figure 4.6: Conveyance Pipe Length and Associated Carcinogenic Impact vs Non-Process Area

One suggested practice is to minimize the facility's non-process area to the extent possible. This can be done by placing the process basins closer together, requiring less piping. Of the 9 case studies, Plant C had the highest non-process area, and consequently the highest normalized piping length and associated Carcinogen impact. Plant C's normalized Carcinogen impact associated with piping was more than 533% of Plant A's which had the lowest normalized non-process area. Although there are many reasons for the variabilities in normalized non-process area, this suggests that optimizing the facility layout is possible and worth considering in design to reduce inventory and impact.

Several advantages and disadvantages of this practice were identified from discussions with small WRRF operators and design engineers. One advantage is that the saved unused land area can be used in future process additions or facility expansions. Depending on the topography of the area, another potential advantage would be the improved hydraulics due to shorter distances between processes. One potential disadvantage is that if the basins are too close to each other, future maintenance and construction that requires large vehicles on-site will be more difficult. This is especially true for future construction that involves adding buried pipe.

With DIP identified as the largest contributor to construction phase carcinogenic impact, the second suggested practice was to use PVC pipe instead of DIP where possible. The production of PVC has been shown to have significantly lower impact than DIP (Hajibabaei et al., 2018; Vahidi et al., 2015) However, this finding is only true for lower diameter pipes because as PVC pipe diameter increases, the pipe thickness increases significantly. For example, PVC production becomes higher impact than DIP in the Global Warming impact category at diameters larger than 30 inches (72 cm) (Du et al., 2013).

In a discussion with local wastewater engineers, it was learned that PVC piping application in small WRRF is typically limited to 4 to 12 inch (10.16 – 30.48 cm) diameter pipes; the design standards for PVC pipe within this diameter range are outlined in the AWWA C900 document (AWWA C905-10, 1998). Figure 4.7 compares the environmental impacts of DIP and schedule 80 PVC pipe production from 4 to 14 inch (10.16 – 35.56 cm) diameters. In this range, PVC pipe production has higher impact than DIP in only 2 out of 10 impact categories. In the Acidification category, PVC impact is higher than DIP at diameters larger than 6 inches (15.24 cm). In the Fossil Fuel Depletion category, PVC is higher than DIP for the full diameter range.

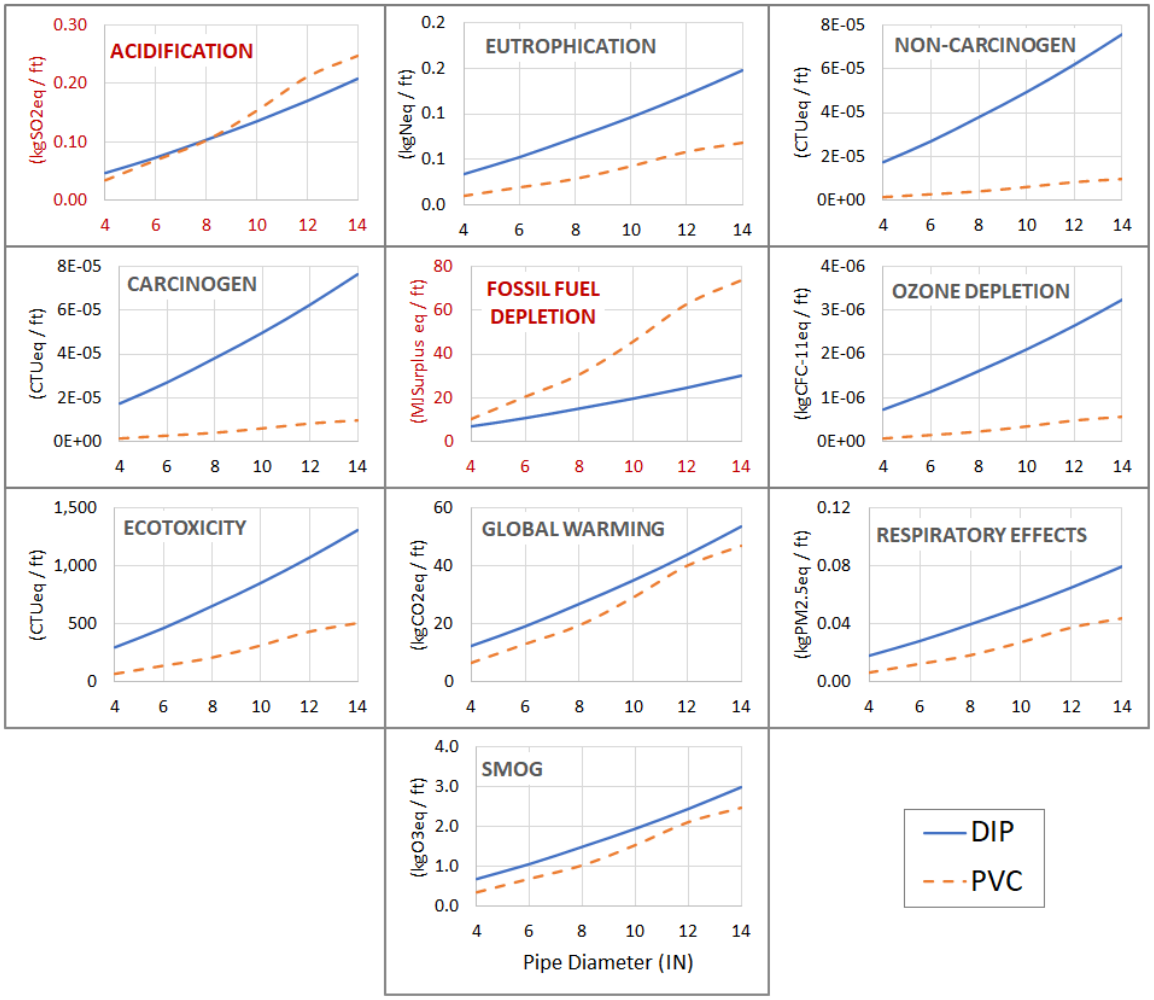


Figure 4.7: PVC vs DIP TRACI Impact Comparison for Pipe Diameters of 4-14 in.

In discussions with small WRRF operators and design engineers, the advantages (besides less environmental impact) and limitations of PVC pipe compared to DIP pipe were identified. Advantages of PVC include its lighter weight, ease of installation due to easy cutting, lower cost, corrosion resistance, tuberculation resistance, and smooth surface without additional lining or coating (AWWA, 2020). Due to its corrosion resistance, PVC may also have a higher effective service life than DIP (Burn et al., 2006).

Further, the higher smoothness of PVC compared to DIP may reduce energy use in pumping operations due to less friction loss.

The limitations of PVC compared to DIP include (1) the pipe must be either indoors or buried because PVC degrades when exposed to sunlight over long periods of time, (2) minimum bury depths depending on soil class, and (3) the pipe should run at least 5 ft away from structures because of its low external load strength. More information on the design limitations and guidelines for PVC application are provided in the AWWA M23 manual (AWWA, 2020).

With these design limitations considered, one case study (Plant C) was investigated to see how much environmental impact would have been avoided if PVC were used instead of DIP where possible. Relative to the full WRRF impact profile that includes both construction and operation, the suggested practice showed a potential 4.3% reduction in the Carcinogenic impact and no significant changes (less than 1%) in the other impact categories.

4.3.3 LCI and LCA Mitigation Opportunities from Addressing Overdesign

Unlike the conveyance process element which had high impact variability between facilities, the secondary process basins (biological reactors and clarifiers) had a low degree of variability in Figure 4.5. The biological reactors among the 9 facilities showed a 21% and 17% coefficient of variation in the Carcinogenic and Global Warming impact categories, respectively, while the clarifiers showed 36% and 30%. This is likely because these secondary process basins are designed based on flow rates and closely follow technical design standards and structural requirements. For this reason, it is difficult to identify impact reduction opportunities from different design recommendations. Instead, impact reduction opportunities can be achieved in the planning stage where the design average flow itself is decided. Using the inventory of the nine facilities in the sample, a clear relationship was seen between the secondary process concrete and excavation with the design average flow, shown in Figure 4.8.

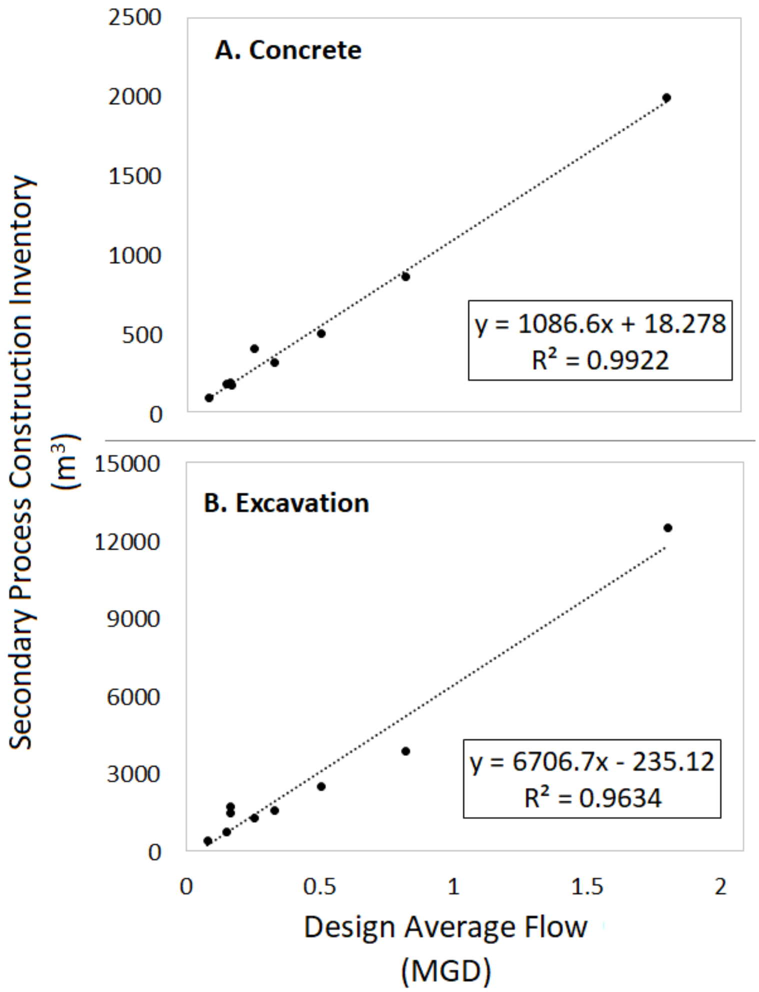


Figure 4.8: Secondary Reactor LCI for A. Concrete and B. Excavation vs Design Average Flow

Changing the units and adjusting the y-intercept in the figure above allowed for a comparison with a recent study that also investigated the relationship between secondary process basin LCI and design flow (Morera et al., 2020). The referenced study found a slope of 1,100 kg per m^3 of treated wastewater per day, while this study found a slope of 707 kg per m^3 of treated wastewater per day. Both studies show a strong relationship between construction inventory and design average flow. The differences in the slopes of the equations are assumed to be due to the different size range of the facilities between the studies. In the study by Morera et al. (2020), the relationship was based on four facilities with flow rates between 0.40-5.5 MGD, whereas in this study, the relationship was based on nine facilities with flow rates between 0.08-1.8 MGD.

Environmental Impact Reduction from Less Overdesign

In one recent study analyzing 16 small WRRFs, the extent of overdesign was identified as a factor contributing to higher environmental impact, suggesting that it is worth investigating the potential benefits from reducing the degree of overdesign. Using the equations from Figure 4.8, the amount of concrete could be estimated for the facilities if they were designed with a flow rate closer to their recorded average flow rates. Using the regression model from a Nebraska WRRF energy benchmarking study (Hanna et al., 2017), the potential percent electricity usage mitigation from correcting for overdesign and more appropriately sized equipment could be estimated and applied to the nine WRRFs in the study. Addressing overdesign may be one of the few ways to reduce small facility electricity usage because many of these communities face financial barriers in implementing variable frequency drives and controls (Thompson et al., 2020).

Based on these two models, Figure 4.9 summarizes the percent mitigations in 20-year electricity usage and secondary process concrete LCI if the facilities had been designed to operate at 75% capacity utilization (CU) assuming the current population is reflective of the end-of-life population. The CU of 75% was chosen arbitrarily as a reasonable operating condition that still allows for some population growth. It should be noted that the average flow capacity is different than the hydraulic capacity which is based on peak flows. Therefore a 100% average flow capacity does not mean the basins are completely full. The gray x-axis represents the facilities' current CU, while the black x-axis shows the percent reduction in design flow associated with an increase from the current CU to 75%. For example, Plant E is currently operating at a CU of 51% and its population has only grown 2% in the past 10 years. If Plant E had been designed to currently operate at a 75% CU, that would mean a 32.6% reduction in design average flow and would result in 10.0% and 33.2% mitigations in 20-year electricity usage and secondary process concrete as compared to the existing plant conditions, respectively. Generally, for every percent decrease in design average flow rate toward a 75% CU, a 0.4% and 1.1% decrease in lifetime electricity usage and secondary process concrete can be achieved, respectively.

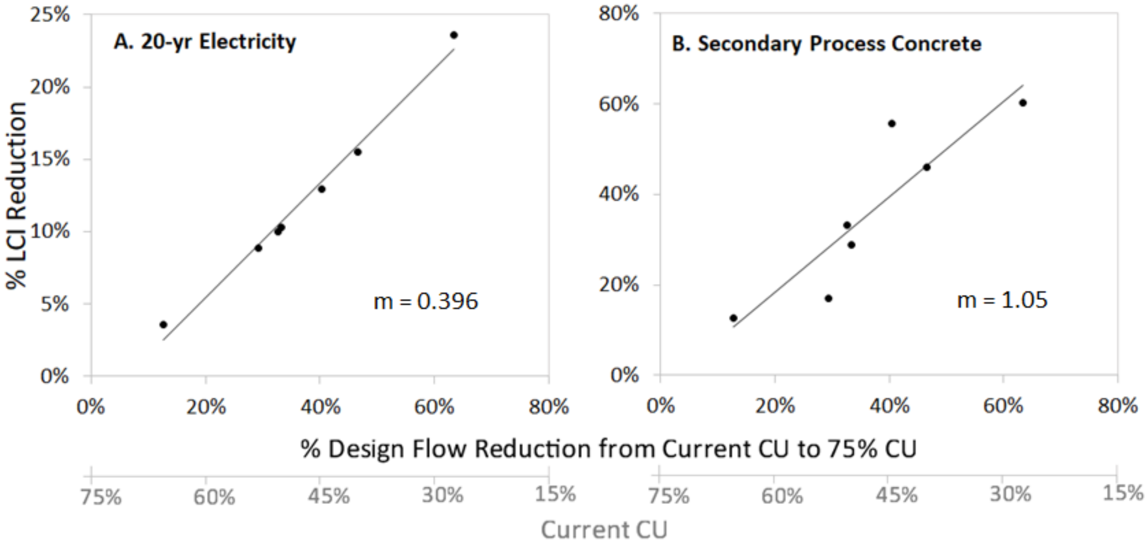


Figure 4.9: Percent LCI Mitigations from Overdesign Correction to 75% Capacity Utilization

The potential LCI mitigations were also calculated for excavation and reinforcing steel, provided in the Supplementary Information (SI) Appendix. Using the potential LCI mitigations in these four inventories (concrete, reinforcing steel, excavation, 20-year electricity usage), the potential LCA mitigations were calculated for the Carcinogenic and Global Warming impact categories and summarized in Figure 4.10. For example, Plant E is currently operating at a 51% CU (gray x-axis) and experiencing a very slow population growth. If the design average flow rate had been decreased by 32.6% (black x-axis) so that the facility would be operating at 75% CU, savings of 9.8% and 10.6% would have been achieved in the Carcinogenic and Global Warming impact categories, respectively. Generally, for every percent decrease in design average flow rate toward a 75% CU, a 0.31% and 0.35% mitigation can be achieved in the Carcinogenic and Global Warming impacts, respectively. In summary, sizing facilities for a slower population growth which reflects actual population trends results in a reduction in inventory, and consequently a reduction in life cycle environmental impacts. The material inventory mitigations also imply cost reductions which is a more immediate deciding factor for the communities.

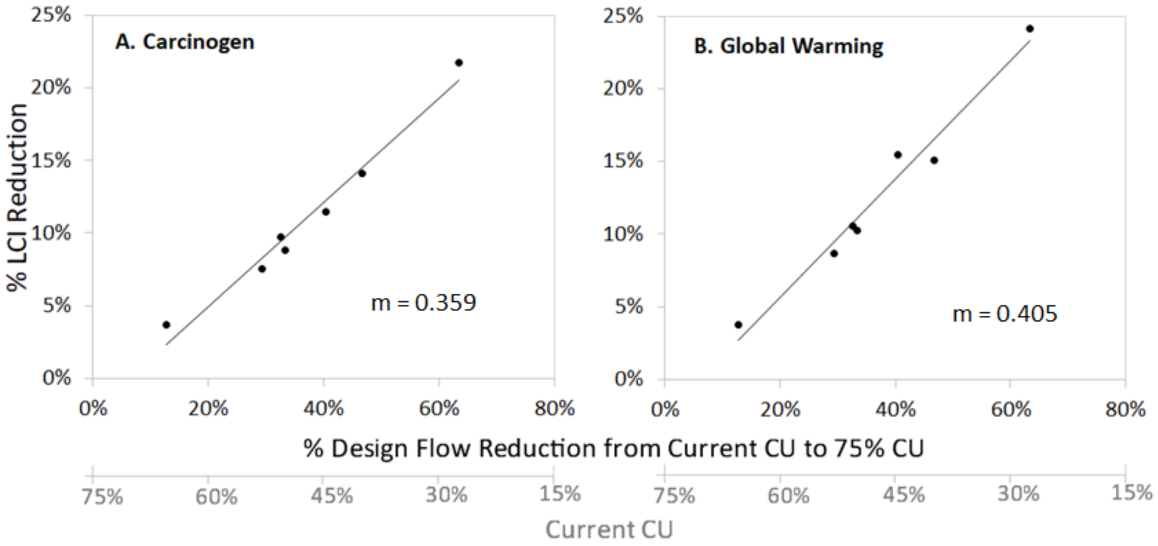


Figure 4.10: Percent LCA Mitigations from Overdesign Correction to 75% Capacity Utilization

Limitations

There are several limitations in the methodology of this study that limit its application to specific types of WRRFs. There is high uncertainty associated with using the model by (Hanna et al., 2018) to estimate electricity usage associated with overdesign. There is also uncertainty with the relationship used to estimate the construction materials associated with overdesign. The graph only included nine case studies which, although is more than past case studies investigating a similar question, does not achieve statistical significance. Further, the WRRFs in the set only represent the basic extended aeration and oxidation ditch configurations. The benefits from the suggested practices are expected to apply to all process types, but the amounts of impact mitigation may be different. The facilities also were all from Nebraska and therefore can only represent WRRFs in northern United States or other regions with similar climates. The quantified benefits of the suggested practices may exist for regions with other climates but by different amounts.

This study did not include air, soil, and water emissions which may be significant contributors to some impact categories such as eutrophication or non-carcinogenic human health pollutants. Limitations in the construction phase accounting include (i) all inventory was reduced to 20 lines of general representative inventory, (ii) multipliers from literature were used to estimate reinforcing steel and material transport distances, (iii) seemingly insignificant supplies were excluded from the analysis as well as inventories where data was unavailable, and (iv) in determining the degree of overdesign, the actual average flow rates were based on annual recorded flows for the past 2-4 years and assumed to be representative over the facility’s life.

4.4 Conclusions

This study explored potential design decision recommendations to reduce environmental impact in the construction and operation of WRRFs. Although these results were based on nine case studies, the general suggested practices are anticipated to be relevant and applicable in the design of future small extended aeration or oxidation ditch type WRRFs serving slow growing or declining populations in similar climates. The suggested practices may not be applicable in every case, but merit consideration by the design engineers.

The two impact categories of interest in this study were the Carcinogenic impact and Global Warming categories. The Carcinogenic category was selected because it was the dominant TRACI impact after normalizing by national annual emissions. The Global Warming category was selected because of its prevalence in WRRF LCA studies and the global conversation on sustainability overall. In these categories, the biological reactor and the conveyance were the highest contributing process elements. Opportunities for significant construction phase impact mitigations can be achieved in reducing concrete, reinforcing steel, and ductile iron piping in these process elements.

Optimizing layout and minimizing facility area generally reduces required piping and associated environmental impact. Non-process area is correlated with less total pipe length ($R^2 = 0.87$) and consequently less Carcinogenic impact (CTU) ($R^2 = 0.71$). The most spread-out facility was Plant C which had a normalized Carcinogen impact associated with piping more than five times higher than Plant A which had the lowest normalized non-process area.

Production of PVC results in less environmental impact than DIP in all impact categories except for Acidification and Fossil Fuel Depletion. In one case study, using PVC instead of DIP would result in a potential 4.3% reduction in the WRRF's life cycle Carcinogenic impact (including both construction and electricity usage) and no significant changes (less than 1%) in the other impact categories.

Avoiding significant overdesign by designing for a lower average flow can lead to mitigations in lifetime electricity usage, secondary process concrete, and the associated environmental impacts. The construction inventory reduction would result from smaller basins requiring less concrete and reinforcing steel. The electricity usage reduction would be due to both using smaller equipment requiring less power, and higher efficiency operations due to being appropriately sized. On average, this practice was estimated to mitigate 0.34% of lifetime electricity usage and 0.99% of secondary process concrete for every percent reduction in design average flow toward a 75% capacity utilization based on the nine case studies. Relatedly, a 0.31% and 0.35% mitigation in the Carcinogenic and Global Warming impacts could be achieved for every percent reduction in design average flow toward a 75% capacity utilization.

Chapter 5: Conclusions and Recommendations

5.1 Introduction

The objectives of this study were to identify practical design decisions for small WRRFs that reduce environmental impact based on nine case studies, specifically by investigating opportunities to reduce concrete, reinforcing steel, iron piping, and overdesign. By using the LCA methodology, the following questions were investigated: (i) which impact categories in WRRF construction and operation are most relevant nationally, (ii) which process elements within a WRRF have the highest impacts and which have the highest impact variability, (iii) what design practices can be applied to reduce inventory and environmental impact in these process elements of interest, and (iv) how much environmental impact can potentially be reduced from the application of these suggested practices.

5.2 Findings

Although these results were based on nine case studies, the general suggested practices are anticipated to be relevant and applicable in the design of future small EA or OD type WRRFs serving slow growing or declining populations. The suggested practices may not be applicable in every case, but merit consideration by the design engineers. The major conclusions of the study are listed below:

1. The two impact categories of interest in this study were the Carcinogenic impact and Global Warming categories. The Carcinogenic category was selected because it was the dominant TRACI impact after normalizing by national annual emissions. The Global Warming category was selected because of its prevalence in WRRF LCA studies and the global conversation on sustainability overall. In these categories, the biological reactor

and the conveyance were the highest contributing process elements. The biological reactor emits an average of 0.13 CTU/MGD in Carcinogenic impact and 394,372 kgCO2eq/MGD in Global Warming impact. Opportunities for significant construction phase impact mitigations can be achieved in reducing concrete, reinforcing steel, and ductile iron piping in these process elements.

2. Optimizing layout and minimizing facility area generally reduces required piping and associated environmental impact. Non-process area is correlated with less total pipe length ($R^2 = 0.87$) and consequently less Carcinogenic impact (CTU) ($R^2 = 0.71$). The most spread-out facility was Plant C which had a normalized Carcinogen impact associated with piping more than five times higher than Plant A which had the lowest normalized non-process area.

3. Production of PVC results in less environmental impact than DIP in all impact categories except for Acidification and Fossil Fuel Depletion. In one case study, using PVC instead of DIP would result in a potential 4.3% reduction in the WRRF's life cycle Carcinogenic impact (including both construction and electricity usage) and no significant changes (less than 1%) in the other impact categories.

4. Avoiding significant overdesign by designing for a lower average flow can lead to mitigations in lifetime electricity usage, secondary process concrete, and the associated environmental impacts. The construction inventory reduction would result from smaller basins requiring less concrete and reinforcing steel. The electricity usage reduction would be due to both using smaller equipment requiring less power, and higher efficiency operations due to being appropriately sized. On average, this practice was estimated to

mitigate 0.396% of lifetime electricity usage and 1.05% of secondary process concrete for every percent reduction in design average flow toward a 75% capacity utilization based on the nine case studies. Relatedly, a 0.359% and 0.405% mitigation in the Carcinogenic and Global Warming impacts could be achieved for every percent reduction in design average flow toward a 75% capacity utilization.

5.3 Recommendations for Future Research

Future research should be conducted to further develop an understanding of WRRF environmental impacts using this comparative LCA framework. The same methodology used in this thesis can be used to quantify the potential environmental impact mitigations from applying these suggested practices to SBR type plants instead of EA/OD type plants. The same can also be done for a higher flow range sample set, for example 1 to 4 MGD plants that would likely be Conventional Activated Sludge (CAS) systems instead of EA/OD.

The data assumptions and limitations of this study can be addressed in future studies using lower sample sizes that allow for a more comprehensive and detailed data collection. This may include a detailed tracking of effluent quality, gas emissions, and sludge output. Further, the breakdown into 10 process elements in this study was only done for the construction phase. A future study could use meters to specifically measure the electricity usage of each process element so that this breakdown could be done for the operation phase as well. It is also worth investigating the effects of designing and construction the facility in stages, starting out with a smaller facility and only expanding if the population experiences unexpected growth. This research could also consider using other technologies for the expansions such as membrane bioreactors which have a small footprint but require being covered or indoors.

Another project worth researching is an investigation of the life cycle environmental impacts associated with retrofitting a facility for biological nutrient removal. This could be done as a comparative LCA study comparing the before and after scenarios of a biological nutrient removal retrofit. The retrofit construction phase is speculated to be negligible. The operation phase is speculated to result in decreased impacts associated with electricity usage, and also a decreased Eutrophication impact from removing nutrients in the effluent. However, the operational changes may also require more chemical inputs, increase nitrous oxide emissions from the wastewater, and result in more sludge production. It is worth comparing these before and after scenarios for a comprehensive evaluation of the nutrient removal configurations.

Finally, the comparative LCA framework used in this study could be expanded to a larger scope, comparing small communities' collection systems instead of their WRRFs. This is especially important given the conclusion that PVC pipe production results in less environmental impact than DIP. A future study could investigate collection systems constructed using DIP, PVC, and HDPE pipe, and include an economic analysis as well as an environmental impact analysis. These comparisons should be broken down by phases including the pipe production, transportation, installation, and operation. The operation phase would compare the pump power draws required for different pipe materials with different friction coefficients correlated with head loss. It is also worth investigating opportunities to reduce I&I to answer the question of whether it is more feasible to address I&I in the collection system or to simply overdesign the WRRFs to handle the added flow.

Chapter 6: References

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Appendices

Appendix A

The spreadsheets used in the material inventory accounting and conversion to environmental impact are discussed in depth in this section. The assumptions, organization, and data processing methods used for in these steps are provided with examples of screenshots used for Plant E.

Material Inventory Data Collection Spreadsheet: construction, piping, equipment

The inventory data was simplified to 20 lines of general inventory, namely excavation, reinforcing steel, concrete, rock/limestone, sand, brick, wood, asphalt, cast iron, stainless steel, aluminum, copper, rubber, fiber glass, VCP, polyethylene, polypropylene, polyvinyl chloride, polystyrene insulation, and material transport. A separate Excel spreadsheet was created for each facility in the dataset.

Each data collection spreadsheet was subdivided into 3 tabs, namely Civil Works, Piping, and Equipment. The Civil Works tab was for data collection and conversions of the buildings, basins, walkways, and excavation. Figure A1 shows an example of the spreadsheet used to organize and convert the data into appropriate units. The columns with blue headers are where the user inputs the raw amount of material inventory used. The columns with red headers are the inventory outputs, converted into the appropriate units to be used in the SimaPro v8 program.

Table A1. Facility Inventory Collection and Conversions Example – Civil Works

Process Element	Material	Volume (ft^3)	Other Quantity	Other Unit	Notes	Excavation (m^3)	Concrete (m^3)	Reinf. Steel (kg)	Crushed Rock (kg)	Sand (kg)	Grout/Limestone (kg)	Aluminum (kg)	Brick (kg)	Wood (m3)	polystyrene (kg)	asphalt (kg)	Steel (kg)	Cast Iron (kg)
Lift Station	concrete	3,045.10			doesn't inc		86.23	6689.58										
Lift Station	excavation	24,642.30				697.79												
Lift Station	crushed rock	1,056.30							47913.77									
Lift Station	grout	618.7									47986.37							
Preliminary	concrete	118			pre-screen		3.35	259.67										
Preliminary	concrete	687			in-building		19.45	1509.22										
Preliminary	excavation	285.60			channel ar	8.09												
Biological	excavation	300,781			OD1 and O	8517.14												
Biological	concrete	51,111			OD1 and O		1447.31	112283.20										
Biological	crushed rock	28,751			OD1 and O				1304127.22									
Clarifier	excavation	56,297			new clarifi	1594.15												
Clarifier	concrete	7,470.80			new clarifi		211.55	16412.10										
Clarifier	crushed rock	3,217.00			new clarifi				145923.12									
Clarifier			34.7	ft^3	steel - wei												7659.68	
Clarifier	excavation	86,205			old clarifie	2441.06												
Clarifier	concrete	12,059			old clarifie		341.48	26491.83										
Clarifier	crushed rock	4,926.10			old clarifie				223447.90									
Clarifier			60	ft^3	steel - wei												13244.4	
Sludge Digestion	concrete	30,614.20			basins		866.90											
Sludge Digestion	concrete	86.00			sump pit		2.44	188.93										
Sludge Digestion	excavation	85,972.90			basins	2434.48												
Conveyance	excavation	111.5			MH1	3.16												
Conveyance	concrete	62.9			MH1		1.78	138.18										
Conveyance			0.2618	ft^3	cast iron -													54.09
Conveyance	excavation	407.3			splitter bo	11.53												
Conveyance	concrete	136.9			splitter bo		3.88	300.75										
Conveyance	grout	13.4			splitter bo						1039.30							
Conveyance	excavation	815			splitter bo	23.07												
Conveyance	concrete	273.8			splitter bo		7.75	601.49										
Conveyance	grout	27			splitter bo						2078.61							
Conveyance	concrete	331			MH10		9.37	727.15										
Conveyance	excavation	760.3			MH10	21.53												
Conveyance			0.2618	ft^3	cast iron - MH1													54.09

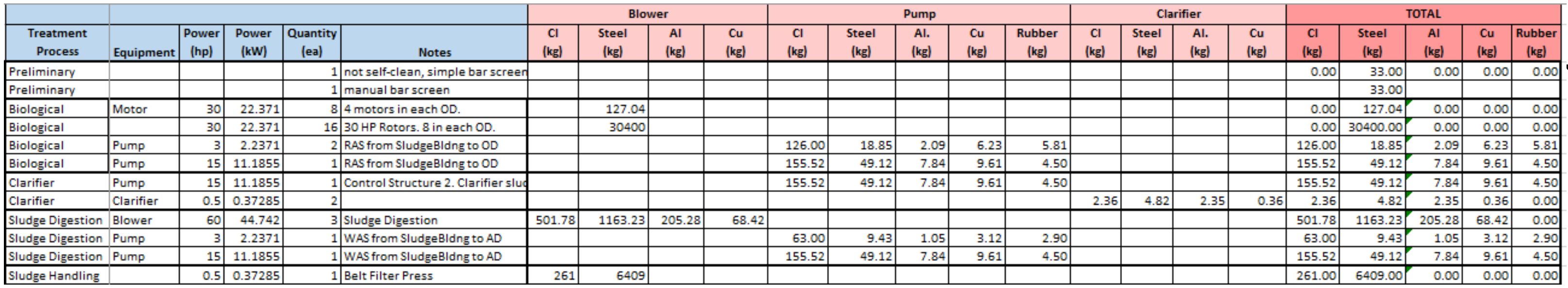
The Piping tab was used for data collection and conversions of the pipelines, fittings, and valves. Figure A2 shows an example of the spreadsheet used to organize and convert the inventory data. The columns with blue headers are the user input columns where diameters and lengths are entered. The spreadsheet converts them into material weights in kilograms of DIP, VCP, PVC, or PE. The sources and assumptions for pipe material weights by diameter are provided in Appendix B.

Table A2. Facility Inventory Collection and Conversions Example– Piping

Treatment Process	Material	Dia. (in)	Component	Quantity (ft or ea)	Notes	90s (kg)	45s (kg)	22.5s (kg)	tees (kg)	wye (kg)	flex coup (kg)	reducer (kg)	check (kg)	gate (kg)	plug (kg)	butterfly (kg)	telescope (kg)	DIP (kg)	VCP (kg)	copper (kg)	PVC (kg)	total iron (kg)
Lift Station	DIP	8	pipe	2	suction													27.31				1123.39
Lift Station	CIP	8	gate valve	2	suction									265.00								
Lift Station	CIP	8	check valve	1	suction								116.00									
Lift Station	CIP	8	90 bend	3	suction	190.51																
Lift Station	CIP		reducer	1	14x8" reducer							129.27										
Lift Station	DIP	8	pipe	15	discharge													204.80				
Lift Station	CIP	8	90 bend	3	discharge	190.51																
Biological	DIP	16	pipe	60.5	influent													1923.71				9082.83
Biological	CIP	16	90 bend	3	influent	687.19																
Biological	CIP	16	gate valve	3	knife gate valv									1585.50								
Biological	CIP	4	gate valve	2	slide gates, sc									97.00								
Biological	DIP	6	pipe	48	RAS influent													465.93				
Biological	CIP	6	90 bend	4	RAS influent	145.15																
Biological	DIP	16	pipe	117	effluent													3720.23				
Biological	CIP	16	90 bend	2	effluent	458.13																
Sludge Digestio	DIP	10	pipe	409.6	air													7283.02				10403.72
Sludge Digestio	CIP	10	butterfly valve	4	air											97.60						
Sludge Digestio	CIP	10	90 bend	12	air	1170.27																
Sludge Digestio	PVC	4	pipe	296	diffusers													1852.83				
Sludge Handlin	DIP	6	pipe	26.3	to belt filter pr													255.29				291.58
Sludge Handlin	CIP	6	90 bend	1	to belt filter pr	36.29																
Conveyance	DIP	24	pipe	30	Screen to Split													1556.73				
Conveyance	CIP	24	butterfly valve	2	Splitter 1											358.00						
Conveyance	DIP	16	pipe	129.6	Splitter1 to MI													4120.87				
Conveyance	CIP	16	90 bend	3	Splitter1 to MI	687.19																
Conveyance	CIP	16	Tee	2	Splitter1 to MI				521.63													
Conveyance	CIP	16	gate valve	3	MH1 to OD1									1585.50								
Conveyance	DIP	16	pipe	48	MH1 to OD1													1526.25				
Conveyance	CIP	16	90 bend	3	MH1 to OD1	687.19																
Conveyance	CIP	16	Tee	2	MH1 to OD1				521.63													
Conveyance	DIP	16	pipe	43.2	Splitter1 to OI													1373.62				
Conveyance	DIP	16	pipe	88.2	OD2 to Splitte													2804.48				

The Equipment tab organizes the equipment list and nameplate data, then converts them to the appropriate materials and units. Figure A3 shows an example of the spreadsheet used to perform this. The columns with blue headers are where the user inputs the equipment type, power draw, and quantity. The columns with red headers are the spreadsheet outputs converted to material weights in kilograms of stainless steel, cast iron, aluminum, copper, and/or rubber. These conversions were made based on Environmental Product Declaration models provided in Appendix B.

Table A3. Facility Inventory Collection and Unit Conversions – Equipment



						Blower				Pump					Clarifier				TOTAL				
Treatment Process	Equipment	Power (hp)	Power (kW)	Quantity (ea)	Notes	Cl (kg)	Steel (kg)	Al (kg)	Cu (kg)	Cl (kg)	Steel (kg)	Al. (kg)	Cu (kg)	Rubber (kg)	Cl (kg)	Steel (kg)	Al. (kg)	Cu (kg)	Cl (kg)	Steel (kg)	Al (kg)	Cu (kg)	Rubber (kg)
Preliminary				1	not self-clean, simple bar screen														0.00	33.00	0.00	0.00	0.00
Preliminary				1	manual bar screen															33.00			
Biological	Motor	30	22.371	8	4 motors in each OD.		127.04												0.00	127.04	0.00	0.00	0.00
Biological		30	22.371	16	30 HP Rotors. 8 in each OD.		30400												0.00	30400.00	0.00	0.00	0.00
Biological	Pump	3	2.2371	2	RAS from SludgeBldng to OD					126.00	18.85	2.09	6.23	5.81					126.00	18.85	2.09	6.23	5.81
Biological	Pump	15	11.1855	1	RAS from SludgeBldng to OD					155.52	49.12	7.84	9.61	4.50					155.52	49.12	7.84	9.61	4.50
Clarifier	Pump	15	11.1855	1	Control Structure 2. Clarifier sluc					155.52	49.12	7.84	9.61	4.50					155.52	49.12	7.84	9.61	4.50
Clarifier	Clarifier	0.5	0.37285	2											2.36	4.82	2.35	0.36	2.36	4.82	2.35	0.36	0.00
Sludge Digestion	Blower	60	44.742	3	Sludge Digestion	501.78	1163.23	205.28	68.42										501.78	1163.23	205.28	68.42	0.00
Sludge Digestion	Pump	3	2.2371	1	WAS from SludgeBldng to AD					63.00	9.43	1.05	3.12	2.90					63.00	9.43	1.05	3.12	2.90
Sludge Digestion	Pump	15	11.1855	1	WAS from SludgeBldng to AD					155.52	49.12	7.84	9.61	4.50					155.52	49.12	7.84	9.61	4.50
Sludge Handling		0.5	0.37285	1	Belt Filter Press	261	6409												261.00	6409.00	0.00	0.00	0.00

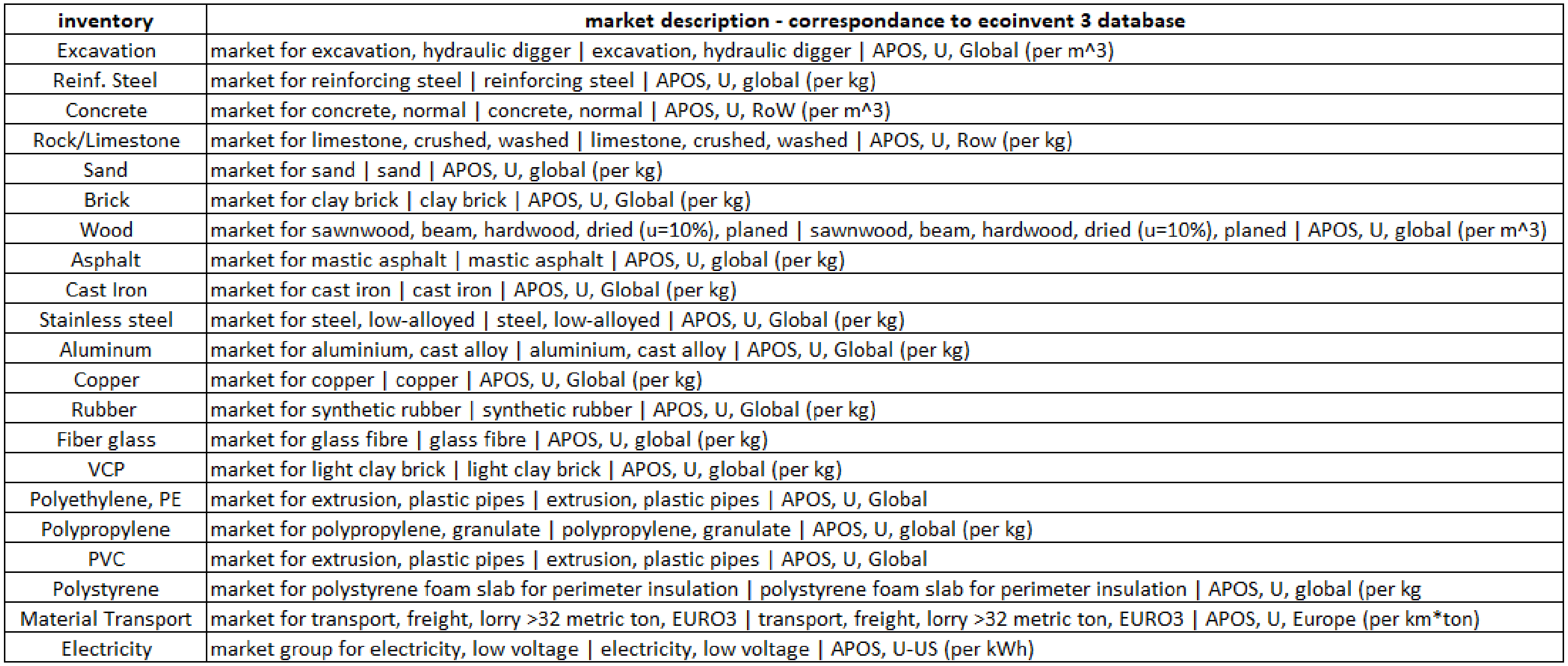
Inventory to Impact Conversion

SimaPro v8 was used to determine the TRACI environmental impact per unit of inventory. These values were compiled into a Microsoft Excel spreadsheet where they were used as multipliers for the data analysis. The multipliers and inventory market descriptions are provided in Tables A4 and A5, respectively.

Table A4. Multipliers Used to Convert Inventory to Environmental Impact

Inventory	Unit	Acidification (kgSO2eq)	Carcinogenics (CTU)	Ecotoxicity (CTU)	Eutrophication (kgNeq)	Fossil Fuel Depletion (Mjsurplus)	Global Warming (kgCO2eq)	Non Carcinogenics (CTU)	Ozone Depletion (kgCFC-11eq)	Respiratory Effects (kgPM2.5eq)	Smog (kgO3eq)
Excavation	per m^3	0.005	2.59E-08	1.089	0.001	1.123	0.538	4.34E-08	1.25E-07	7.20E-04	0.151
Reinf. Steel	per kg	0.009	1.21E-06	40.115	0.010	1.346	2.319	1.44E-06	1.45E-07	3.41E-03	0.129
Concrete	per m^3	0.709	6.33E-06	799.044	0.281	171.561	223.529	3.62E-05	1.82E-05	1.07E-01	14.227
Rock/Limestone	per kg	0.000	2.43E-10	0.026	0.000	0.011	0.006	1.08E-09	1.18E-09	2.60E-05	0.002
Sand	per kg	0.000	7.79E-10	0.084	0.000	0.021	0.012	3.35E-09	2.26E-09	1.21E-05	0.002
Brick	per kg	0.001	1.28E-08	1.388	0.000	0.461	0.316	5.03E-08	3.64E-08	1.55E-04	0.021
Wood	per m^3	0.896	1.02E-05	1014.034	0.403	191.197	133.693	6.61E-05	2.02E-05	3.14E-01	20.341
Asphalt	per kg	0.002	9.97E-09	1.140	0.001	0.761	0.270	5.90E-08	8.43E-08	2.51E-04	0.019
Cast Iron	per kg	0.008	2.79E-06	48.107	0.005	1.096	1.965	2.78E-06	1.18E-07	2.91E-03	0.109
Stainless steel	per kg	0.008	2.03E-06	75.761	0.013	1.090	1.789	2.99E-06	1.12E-07	3.35E-03	0.111
Aluminum	per kg	0.039	1.34E-06	104.336	0.022	5.083	6.269	3.48E-06	8.91E-07	6.87E-03	0.432
Copper	per kg	0.344	5.57E-06	3310.539	0.617	13.712	8.154	1.55E-04	3.68E-06	4.15E-02	1.254
Rubber	per kg	0.013	1.38E-07	18.614	0.008	10.242	2.694	7.05E-07	7.21E-07	2.50E-03	0.148
Fiber glass	per kg	0.016	1.67E-07	19.211	0.007	3.528	2.495	1.32E-06	2.23E-07	2.64E-03	0.235
VCP	per kg	0.001	1.30E-08	1.194	0.000	0.342	0.162	4.71E-08	2.62E-08	9.74E-05	0.013
Polyethylene, PE	per kg	0.002	3.15E-08	3.373	0.002	0.329	0.446	1.15E-07	3.00E-08	5.92E-04	0.025
Polypropylene	per kg	0.007	5.56E-08	3.535	0.001	10.220	2.053	4.68E-08	1.90E-08	5.36E-04	0.094
PVC	per kg	0.028	1.08E-06	57.973	0.008	8.419	5.346	1.14E-06	6.34E-08	5.00E-03	0.284
Polystyrene	per kg	0.016	1.65E-07	14.795	0.005	13.363	4.507	3.68E-07	1.51E-07	1.88E-03	0.193
Material Transport	per km*ton	0.001	2.46E-09	0.504	0.000	0.209	0.091	2.21E-08	2.34E-08	7.54E-05	0.016
Electricity	per kWh	0.002	6.37E-08	13.663	0.006	0.497	0.695	2.33E-07	5.80E-08	2.11E-03	0.019

Table A5. Inventory Market Descriptions – Correspondence to Ecoinvent database



inventory	market description - correspondance to ecoinvent 3 database
Excavation	market for excavation, hydraulic digger | excavation, hydraulic digger | APOS, U, Global (per m^3)
Reinf. Steel	market for reinforcing steel | reinforcing steel | APOS, U, global (per kg)
Concrete	market for concrete, normal | concrete, normal | APOS, U, RoW (per m^3)
Rock/Limestone	market for limestone, crushed, washed | limestone, crushed, washed | APOS, U, Row (per kg)
Sand	market for sand | sand | APOS, U, global (per kg)
Brick	market for clay brick | clay brick | APOS, U, Global (per kg)
Wood	market for sawnwood, beam, hardwood, dried (u=10%), planed | sawnwood, beam, hardwood, dried (u=10%), planed | APOS, U, global (per m^3)
Asphalt	market for mastic asphalt | mastic asphalt | APOS, U, global (per kg)
Cast Iron	market for cast iron | cast iron | APOS, U, Global (per kg)
Stainless steel	market for steel, low-alloyed | steel, low-alloyed | APOS, U, Global (per kg)
Aluminum	market for aluminium, cast alloy | aluminium, cast alloy | APOS, U, Global (per kg)
Copper	market for copper | copper | APOS, U, Global (per kg)
Rubber	market for synthetic rubber | synthetic rubber | APOS, U, Global (per kg)
Fiber glass	market for glass fibre | glass fibre | APOS, U, global (per kg)
VCP	market for light clay brick | light clay brick | APOS, U, global (per kg)
Polyethylene, PE	market for extrusion, plastic pipes | extrusion, plastic pipes | APOS, U, Global
Polypropylene	market for polypropylene, granulate | polypropylene, granulate | APOS, U, global (per kg)
PVC	market for extrusion, plastic pipes | extrusion, plastic pipes | APOS, U, Global
Polystyrene	market for polystyrene foam slab for perimeter insulation | polystyrene foam slab for perimeter insulation | APOS, U, global (per kg
Material Transport	market for transport, freight, lorry >32 metric ton, EURO3 | transport, freight, lorry >32 metric ton, EURO3 | APOS, U, Europe (per km*ton)
Electricity	market group for electricity, low voltage | electricity, low voltage | APOS, U-US (per kWh)

Appendix B

Sources and assumptions used in the material inventory data collection are provided in this section. These are presented in order of process element.

Lift Station / Preliminary Treatment

Parshall Flumes

Parshall Flume density = 2.25 lbs/ft^2 = 1 kg/ft^2
https://www.openchannelflow.com/flumes/aluminum-parshall-flumes

Parshall Flume dimensions:
https://www.openchannelflow.com/flumes/parshall-flumes/parshall-dimensional-drawings

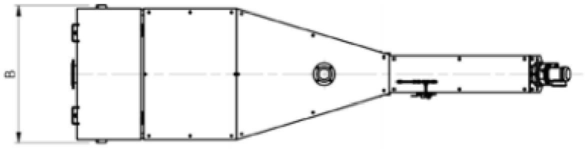
6” Parshall Flume = **25.6 kg aluminum**
9” Parshall Flume = **30.5 kg aluminum**

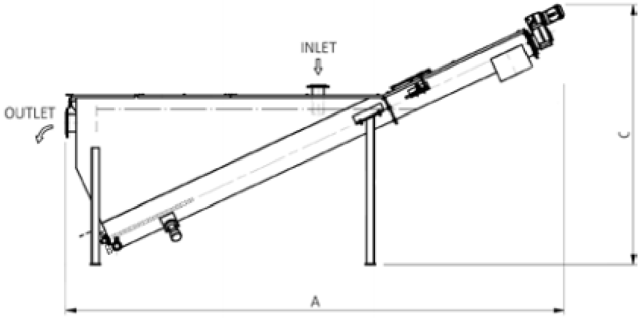
Bar Screens

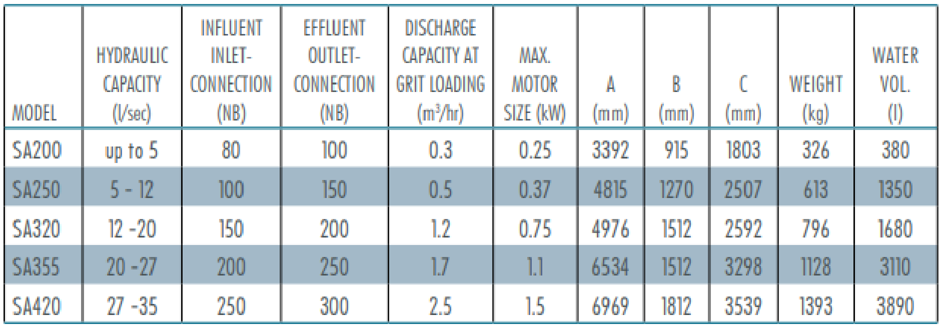
- Estimate 1
  - Screen width = 2 ft
  - Bar length = 3 ft
  - Spacing = 3 cm = 0.098 t
  - Bar width = 2.5 cm = 0.082 ft
  - 11 bars per screen, assume circular cross-section
  - (11) * (pi*(0.082/2)^2) * 3 = 0.174 ft^3
  - Assume 304 stainless steel, density = 221 kg/ft^3
  - =38 kg
- Estimate 2
  - Steel bars = 3/8” x 1+1/2”
  - = 0.004 ft^2 cross section
  - Assume 3 ft wide and 11 bars per screen
  - = 0.132 ft^3
  - Assume 304 stainless steel, density = 221 kg/ft^3
  - =29 kg
- Average: **33 kg** (same value as past study)

- Vertical bar screens: assume same as manual bar screen except with encasement and a 1 hp motor
  - [(2 ft) * (3 ft) * 2] + [(1 ft) * (3 ft) * 2] * (0.4/12) = 0.6 ft^3
  - 220 kg/ft3
  - Case = 132 kg
  - Total screen = **170 kg**
  - Include a **0.5 hp motor** – estimate as a clarifier motor

Grit Classifiers







MODEL	HYDRAULIC CAPACITY (l/sec)	INFLUENT INLET-CONNECTION (NB)	EFFLUENT OUTLET-CONNECTION (NB)	DISCHARGE CAPACITY AT GRIT LOADING (m^3/hr)	MAX. MOTOR SIZE (kW)	A (mm)	B (mm)	C (mm)	WEIGHT (kg)	WATER VOL. (l)
SA200	up to 5	80	100	0.3	0.25	3392	915	1803	326	380
SA250	5 - 12	100	150	0.5	0.37	4815	1270	2507	613	1350
SA320	12 -20	150	200	1.2	0.75	4976	1512	2592	796	1680
SA355	20 -27	200	250	1.7	1.1	6534	1512	3298	1128	3110
SA420	27 -35	250	300	2.5	1.5	6969	1812	3539	1393	3890

https://www.spirac.com/products/sandsep%C2%AE

Gothenburg:

L = 13.175 ft (4,015 mm)
Interpolating from SandSep Grit Classifier dimensions:

$$y = y1 + \frac{y2 - y1}{x2 - x1}(x - x1)$$

$$W = 326 + \frac{613 - 326}{4815 - 3392} * (4015 - 3392) = \mathbf{451.7}\ \boldsymbol{kg\ stainless\ steel}$$

+ 1x 0.25 hp motor

Albion

L = 12.5 ft (3,810 mm)
Interpolating from SandSep Grit Classifier dimensions:

$$y = y1 + \frac{y2 - y1}{x2 - x1}(x - x1)$$

$$W = 326 + \frac{613 - 326}{4815 - 3392} * (3810 - 3392) = \mathbf{410.3}\ \boldsymbol{kg\ stainless\ steel}$$

+ 1 x 0.25 hp motor

Bennet:

L = 10.4 ft (3169.92 mm)
extrapolating from SandSep Grit Classifier dimensions:

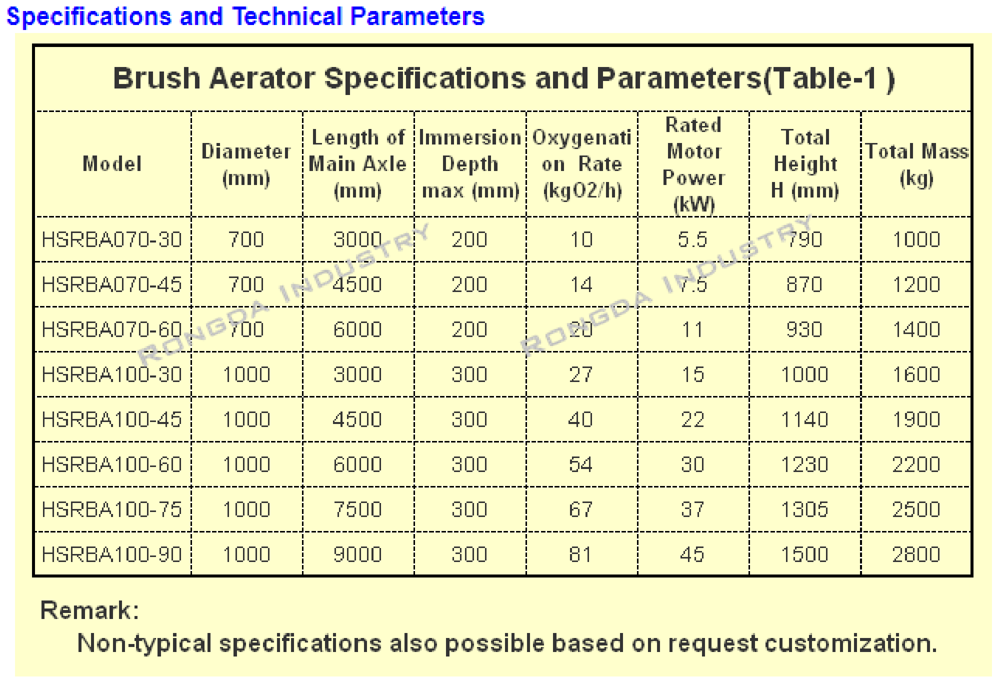
$$y = y1 + \frac{y2 - y1}{x2 - x1}(x - x1)$$

$$W = 326 + \frac{613 - 326}{4815 - 3392} * (3169.92 - 3392) = \mathbf{281.2}\ \boldsymbol{kg\ stainless\ steel}$$

+ 1 x 0.25 hp motor

Biological Reactor

Oxidation Ditch Rotors



Specifications and Technical Parameters

Brush Aerator Specifications and Parameters(Table-1)

Model	Diameter (mm)	Length of Main Axle (mm)	Immersion Depth max (mm)	Oxygenation Rate (kgO2/h)	Rated Motor Power (kW)	Total Height H (mm)	Total Mass (kg)
HSRBA070-30	700	3000	200	10	5.5	790	1000
HSRBA070-45	700	4500	200	14	7.5	870	1200
HSRBA070-60	700	6000	200	20	11	930	1400
HSRBA100-30	1000	3000	300	27	15	1000	1600
HSRBA100-45	1000	4500	300	40	22	1140	1900
HSRBA100-60	1000	6000	300	54	30	1230	2200
HSRBA100-75	1000	7500	300	67	37	1305	2500
HSRBA100-90	1000	9000	300	81	45	1500	2800

Remark:
Non-typical specifications also possible based on request customization.

http://www.disk-aerator.com/product/HSRBA-Rotor-Brush-Aerator.html

Albion:

- Main Axle Length = 2800 mm
- Rotor Diameter = 1300 mm
- Mass = **1,600 kg** steel per rotor

Aurora:

- OD channel width = 16 ft.
- Assume Main Axle Length = 4,500 mm
- Assume Diameter = 1,000 mm
- Mass = **1,900 kg** steel per rotor

Bassett:

- Main Axle Length = 1830 mm
- Rotor Diameter = 700 mm
- Mass = **610 kg** steel per rotor

Clarifier

<u>Weirs and Baffles – Fiberglass Density</u>

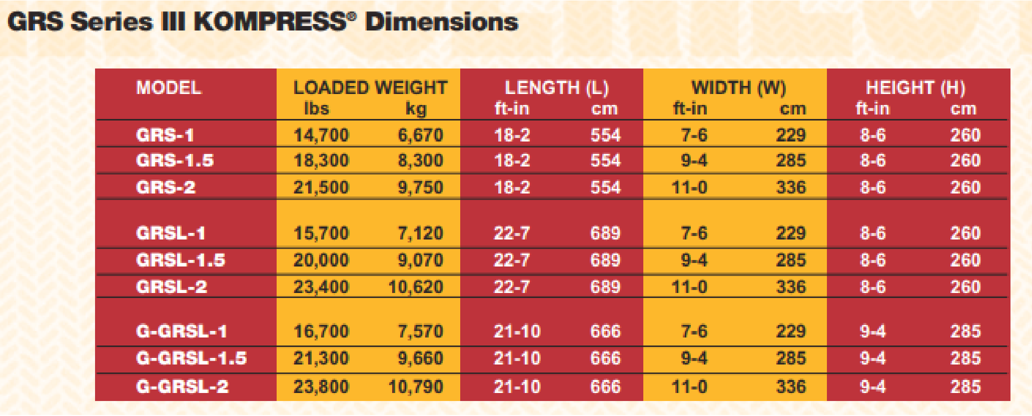
80-100 lbs/ft^3 = 36.3-45.3 kg/ft^3
average = **40.8 kg/ft^3**
http://www.fiberglass-afi.com/fiberglass-properties.htm

UV Disinfection

- Trojan3000PTP Steel channel
  - 7 ft long
  - 0.4 (2/5) inch thick
  - 220 kg/ft^3 stainless steel 304
  - **355 kg steel** (similar to past study which used 339 kg)

Post Digestion Sludge Handling

Sludge Dewatering Equipment:



GRS Series III KOMPRESS® Dimensions

MODEL	LOADED WEIGHT		LENGTH (L)		WIDTH (W)		HEIGHT (H)	
	lbs	kg	ft-in	cm	ft-in	cm	ft-in	cm
GRS-1	14,700	6,670	18-2	554	7-6	229	8-6	260
GRS-1.5	18,300	8,300	18-2	554	9-4	285	8-6	260
GRS-2	21,500	9,750	18-2	554	11-0	336	8-6	260
GRSL-1	15,700	7,120	22-7	689	7-6	229	8-6	260
GRSL-1.5	20,000	9,070	22-7	689	9-4	285	8-6	260
GRSL-2	23,400	10,620	22-7	689	11-0	336	8-6	260
G-GRSL-1	16,700	7,570	21-10	666	7-6	229	9-4	285
G-GRSL-1.5	21,300	9,660	21-10	666	9-4	285	9-4	285
G-GRSL-2	23,800	10,790	21-10	666	11-0	336	9-4	285

https://www.komline.com/wp-content/uploads/KompressSpread.pdf

Aurora:

L = 242 in
w = 158 in
H = 84 in

m = **6,409 kg steel**
assume all steel (frame, drum, rollers, feed box, support bars)

Conveyance

Butterfly Valves

- Assume 200 PSI, DIP, Extended Neck
- Valves may be either Lug style or Wafer style. The average of the Wafer Style and Lug Style weights were used.
- Product Weights from NIBCO valve catalog C-BFV-1119
- http://nibco.com/Valves/Butterfly-Valves/Ductile-Iron-Butterfly-Valves/

Check Valves

- Assume Class 150
- Product weights from NIBCO valve catalog
- https://nibco.com/resources/ProductSubmittalDocs/F93831BI.pdf

Other Fittings and Valves

- Taken from past WRRF LCA studies (Moussavi et al., 2021 ; Thompson et al., 2018)

DIP Pipe Unit Weights

- Plain end pipe, 350 psi
- https://american-usa.com/products/ductile-iron-pipe-and-fittings/restrained-joint-pipe/flanged-joint-pipe/weights

PVC Pipe Unit Weights

- ASTM D1785 – Schedule 80
- https://www.engineeringtoolbox.com/pvc-cpvc-pipes-dimensions-d_795.html

Table B1. Pipe Weight per Unit Length by Diameter

Piping Unit Weights (kg/ft)				
Diameter	**DIP**	**PVC**	**PE**	**VCP**
1	0.0	0.19	0.12	
1.5	0.0	0.30	0.19	
2	0.0	0.43	0.29	
2.5	0	0.66	0.46	
3	0.0	0.88	0.64	
4	6.3	1.25	1.40	4.5
5	0.0		2.38	
6	9.7	2.46	2.93	9.1
8	13.7	3.65	5.79	13.6
10	17.8	5.44	8.84	20.4
12	22.3	7.48	11.28	27.2
14	27.3	8.75	14.32	
15	0.0		18.29	40.8
16	31.8	11.54		
18	36.6	16.286		63.5
20	41.5			
24	51.9			108.8
30	70.0			173.7
36	95.4			192.7
42	124.3			287.1
48	157.2			
54	200.4			

Table B2. DI Fitting Weights by Diameter

Dia.	**11.25 bend**	**22.5 bend**	**45 bend**	**90 bend**	**Tee**	**Cross**	**Wye**	**Blind Flange**	**Flex Couple.**
1			*0.11*	*0.18*	0.18				0.7
1.5			*0.18*	*0.41*	0.41				1
2			*0.37*	*0.73*	0.50				1.1
3	*13*	*13*	*13*	*18*	*18*	*29*	*27*		1.9
4	16	16	16	23	29	39	36	6	3
6	25	25	25	36	48	59	57	11	3.9
8	41	41	39	64	75	93	98	18	10.7
10	61	59	59	98	129	156	147	27	15
12	91	91	91	147	184	222	225	36	15.9
14	102	102	100	175	206	249	302	50	16.8
15									
16	129	129	127	229	261	313	401	66	24
18	152	152	150	286	315	374	488	79	25
20	197	197	193	367	401	479	630	102	
24	293	290	286	562	626	739	950	149	
30	519	517	508	955	975	1134	1871	319	
36	816	812	796	1490	1436	1644	2862	559	
42	1216	1209	1179	2207	2025	2295	4159	558	
48	1674	1662	1622	3080	2676	3463	5488	752	

[1] values in red italic text were interpolated or extrapolated

Table B3. DI Reducer Fittings Weights by Diameter

dia.	90 reduc	tee red	cross red	wye reduc
4" x 3"				
4" x 2"				
6" x 5"				
6" X 4"	32	45	52	52
6" x 3"				
6" x 2"				
8" x 6"		68	79	86
8" x 5"				
8" x 4"	45	66	75	82
10" x 8"	98	109	127	134
10" x 6"	82	104	116	122
12" x 10"	147	172	197	206
12" x 8"	129	152	168	191
12" x 6"	107	145	156	179
14" x 12"	168	202	243	281
14" x 10"	147	188	218	263
14" x 8"	129	181	202	247
18" x 14"	243	297	340	442
18" x 12"	170	252	347	422
18" x 10"	211	240	265	401
4" x 2"x 2"	211			

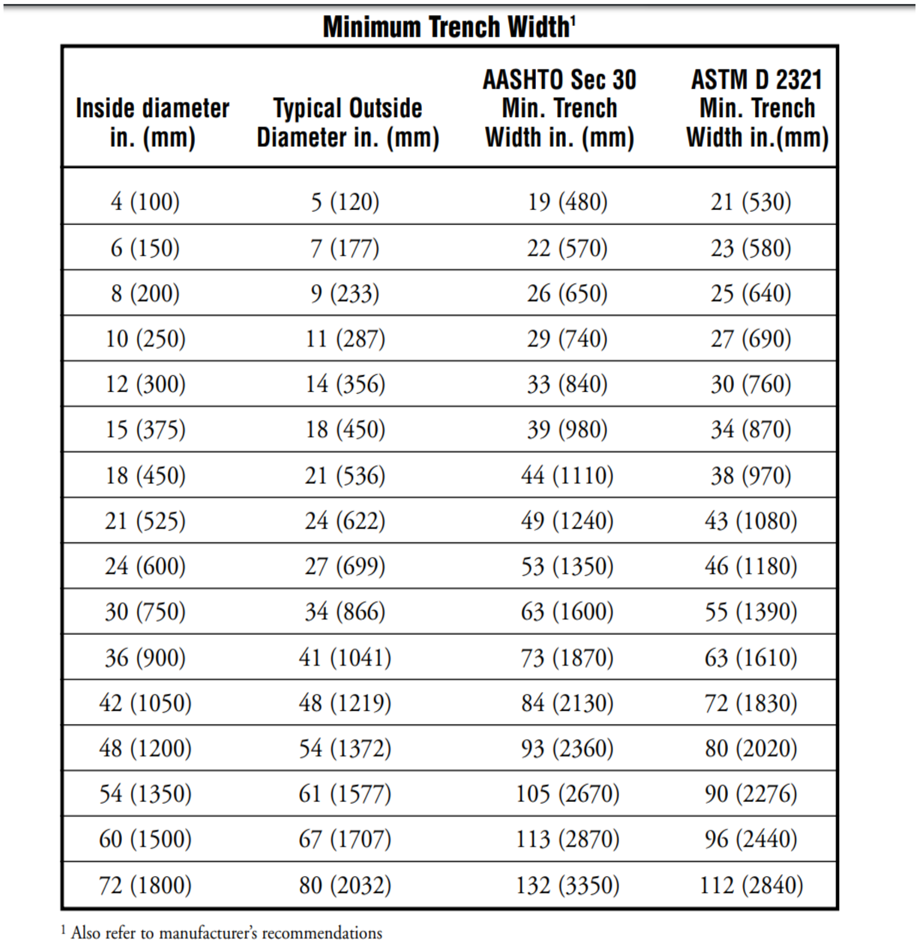
Table B4. DI Valve Weights by Diameter

dia.	check	gate	plug	butterfly	telescope	ball
1		5.8				2.27
1.5						5.91
2	11	19.5		2.85	16	7.73
3	21	33	25	3.95	20	19.09
4	37	48.5	30	5.9	33	29.09
5	45	57	50	8.15		NA
6	66	80	50	9.55	53	57.27
8	116	132.5	78	14.05	90	90
10	193	190	113	24.4	170	134.55
12	299	311.5	177	36.35	224	216.82
14		414	252	64	284	
15					370	
16		528.5	327	90		
18		727	454	119		
24		1446	1266	179		

Table B5. PVC Fitting Weights by Diameter

dia	90 bend	tee
1	0.054	0.073
1.5	0.113	0.150
2	0.172	0.231
3	0.467	0.649
4	0.785	1.007
5	1.624	2.082
6	2.050	2.722
8	4.010	5.357
10	7.144	11.000
12	11.766	17.209

Table B6. Pipe Installation – Minimum Trench Widths obtained from Plastic Pipe at https://plasticpipe.org/pdf/chapter-6_installation_construction.pdf



Minimum Trench Width[1]

Inside diameter in. (mm)	Typical Outside Diameter in. (mm)	AASHTO Sec 30 Min. Trench Width in. (mm)	ASTM D 2321 Min. Trench Width in.(mm)
4 (100)	5 (120)	19 (480)	21 (530)
6 (150)	7 (177)	22 (570)	23 (580)
8 (200)	9 (233)	26 (650)	25 (640)
10 (250)	11 (287)	29 (740)	27 (690)
12 (300)	14 (356)	33 (840)	30 (760)
15 (375)	18 (450)	39 (980)	34 (870)
18 (450)	21 (536)	44 (1110)	38 (970)
21 (525)	24 (622)	49 (1240)	43 (1080)
24 (600)	27 (699)	53 (1350)	46 (1180)
30 (750)	34 (866)	63 (1600)	55 (1390)
36 (900)	41 (1041)	73 (1870)	63 (1610)
42 (1050)	48 (1219)	84 (2130)	72 (1830)
48 (1200)	54 (1372)	93 (2360)	80 (2020)
54 (1350)	61 (1577)	105 (2670)	90 (2276)
60 (1500)	67 (1707)	113 (2870)	96 (2440)
72 (1800)	80 (2032)	132 (3350)	112 (2840)

[1] Also refer to manufacturer's recommendations

Buildings

Asphalt Roll: 1.1 lb/ft^2 = **0.499 kg/ft^2**
https://www.engineeringtoolbox.com/roofing-materials-weight-d_1498.html

Asphalt Shingles: 2.7 lb/ft^2 = **1.225 kg/ft^2**
https://www.engineeringtoolbox.com/roofing-materials-weight-d_1498.html

Foam extruded polystyrene 2"
Density of Polystyrene = **1.44 kg/ft^3**
http://commercial.owenscorning.com/uploadedFiles/foam/products/Commercial%20Property%20Directory%20of%20Physical%20Properties.pdf

Polystyrene board 2”
0.105 lbs/inch*ft^2 = 1.26 lbs/ft^3 = **0.57 kg/ft^3**
https://roofonline.com/weight-of-roofing-materials

1” fiberglass batt insulation
0.04 lbs/ft^2
5 ½ “ fiberglass batt insulation
0.22 lbs/ft^2 = **0.1 kg-fiberglass/ft^2**
http://dom.dacha-dom.ru/uteplitel/weight.pdf

Flexicore Roof Slabs

- Width = 1.7 ft
- Area = .757 ft^2/unit

CMU Block Dimensions

- 8” CMU – Double Corner
  - L = 15.625 in = 1.3 ft
  - W = 7.625 in = 0.635 ft
  - A = 1.3 * 0.635 = 0.8274 ft^2
  - Ahollow = (5.125 in)*(12.3125 in) = 63.10 in^2 = 0.4382 ft^2
  - Asolid = (0.8274 – 0.4382) = 0.3892 ft^2
  - Unit Area = (0.3892 ft^2)/(1.3 ft) = **0.2994 ft^2/ft**

- 6” CMU – Double Corner
  - L = 15.625 in = 1.3 ft
  - W = 5.625 in = 0.46875 ft
  - A = 0.609375 ft^2
  - Ahollow = (11.875)*(3.25) = 43.046875 in^2 = 0.2989 ft^2
  - Asolid = 0.609375 – 0.2989 = 0.310475 ft^2
  - Unit Area = (0.310475)/(1.3 ft) = **0.2388 ft^2/ft**

- 4” CMU – Double Corner
  - L = 15.625 in = 1.3 ft
  - W = 3.625 in = 0.3021 ft
  - A = 0.39271 ft^2
  - Ahollow = (1.625 in)*(12.3125) = 20 in^2 = 0.138943 ft^2
  - Asolid = 0.39271 – 0.138943 = 0.253767 ft^2
  - Unit Area = 0.253767/1.3 = **0.1952 ft^2/ft**

Other Auxiliary Inventory

Aluminum Handrails

- 3.5 ft vertical pipe every 5-ft horizontal length
- 1.5-in Schedule 40 aluminum = 0.94 lbs/ft = 0.4264 kg/ft
- One vertical pipe = 3.5 * 0.4264 = 1.492
- Vertical pipe every 5-ft horizontal = 0.2984 kg/ft
- Horizontal pipe = 2 * 0.4264 = 0.8528
- Total = 0.8528 + 0.2984 = **1.15 kg/ft**
- Assumed pipe fittings in the lengths of pipe
- https://www.industrialmetalsupply.com/6061-aluminum-pipe/alp15024ns

Aluminum Grating

- Bearing Bar Size: 1x1/8”
- 1.8 lbs/ft^2 = **0.816 kg/ft^2**
- Past study used 1.14 kg/ft^2
- http://www.gratingpacific.com/load_tables/algrip_safety/aluminum_bar_grating_load_table.pdf

Chain Link Fence

- 2 - 1/4" -11-1/2 gauge GAW Chain Link
- H = 72” = 6 ft high
- 2.4 lbs/ft = **1.09 kg/ft**
- https://www.yourfencestore.com/cl/clgal.htm

Fire Hydrant

- Assume 4.5”
- 1.6 ft lower barrel length
- 2 way
- Assume all ductile iron (even though valves are steel)
- 380 lbs = **172.4 kg**
  http://catalog.muellercompany.com/viewdocument.ashx?t=d&i=813

Yard Hydrant

- Assume 3 ft bury depth
- Cast Iron
- **8.6 kg**
  https://www.woodfordmfg.com/woodford/Woodford%20Brochure%20Pages/Woodford%20Yard%20Hydrants%206%20Page.pdf

Asphalt Pavement

- 145 lbs per cubic foot http://www.asphaltpavement.org/index.php?option=com_content&view=article&id=144&Itemid=227#:~:text=Using%20the%20previous%20example%20and,%2Fft)%20%3D%205%2C752%20cu.

Appendix C

Table C1. General Facility Information

Facility	Town Name	ISS	Facility Type	2019 Pop.	Avg Flow (MGD)	Design Pop.	Design Avg Flow (MGD)
A	Randolph	57815	OD	890	0.11	944	0.16
B	Bassett	57647	OD	540	0.15	743	0.168
C	Albion	57877	OD	1,585	0.11	2,300	0.255
D	Hickman	31730	OD	2,371	0.23	7,370	0.82
E	Aurora	62816	OD	4,547	0.91	19,000	1.9
F	Coleridge	62886	EA	450	0.04	710	0.078
G	Bennet	57899	EA	977	0.06	1,500	0.15
H	Syracuse	37593	EA	1,960	0.18	2,750	0.33
I	Gothenburg	8613	EA	3,448	0.39	4,013	0.504

Table C2. Facility Design, Construction, and Modification Years

Facility	Constr./ Mod. Years	Design Year	Design Life	Additions/Expansions
A	1969, 2008, 2017	2040	23	add 2 rotors (2008), general improvements (2017)
B	1986, 2013	2030	17	general improvements (2013)
C	1973, 2011	2031	20	general improvements and modifications (2011)
D	1975, 1998, 2005	2025	20	new aerobic digesters (1998) new oxidation ditch (2005)
E	1995, 2012	2032	20	new process train (2012)
F	1989, 2008	2028*	20*	UV disinfection (2008)
G	1992, 2005	2025	20	switch from lagoon to EA (2005)
H	1964, 1980, 2012	2032*	20*	switch from lagoon to EA (1980), UV disinfection (2012)
I	1987, 1999, 2010	2030	20	UV disinfection (1999), new process train (2010)

* assumed design year and life based on average of other facilities in study

Table C3. Community Populations Between 2010-2019

Plant	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2010-2019 %**
A	941	936	927	918	911	913	914	906	895	890	-5%
B	617	599	577	580	584	570	566	570	541	540	-12%
C	1667	1638	1644	1633	1625	1604	1612	1610	1599	1585	-5%
D	1670	1738	1797	1846	1975	2079	2141	2214	2292	2371	42%
E	4485	4448	4430	4462	4452	4462	4467	4483	4524	4547	1%
F	471	468	465	460	454	454	461	453	447	450	-4%
G	730	765	798	818	843	851	864	892	954	977	34%
H	1942	1939	1937	1936	1951	1966	1981	1966	1971	1960	1%
I	3592	3589	3547	3545	3543	3528	3508	3482	3473	3448	-4%

Appendix D

General Figures

Table D1. Annual United States Emissions from (Ryberg et al., 2014) Used to Normalize Impacts in Figure 4.X.

Impact	**National Annual Emission (impact/yr)**
Acidification (kgSO2eq)	2.80E+10
Carcinogenic (CTU)	1.57E+04
Ecotoxicity (CTU)	3.32E+12
Eutrophication (kgNeq)	6.60E+09
Fossil Fuel Depletion (MJ-Surplus)	5.30E+12
Global Warming (kgCO2eq)	7.40E+12
Non-Carcinogenic (CTU)	3.21E+05
Ozone Depletion (kgCFC-11eq)	4.90E+07
Respiratory Effects (kgPM2.5eq)	7.40E+09
Smog (kgO3eq)	4.20E+11

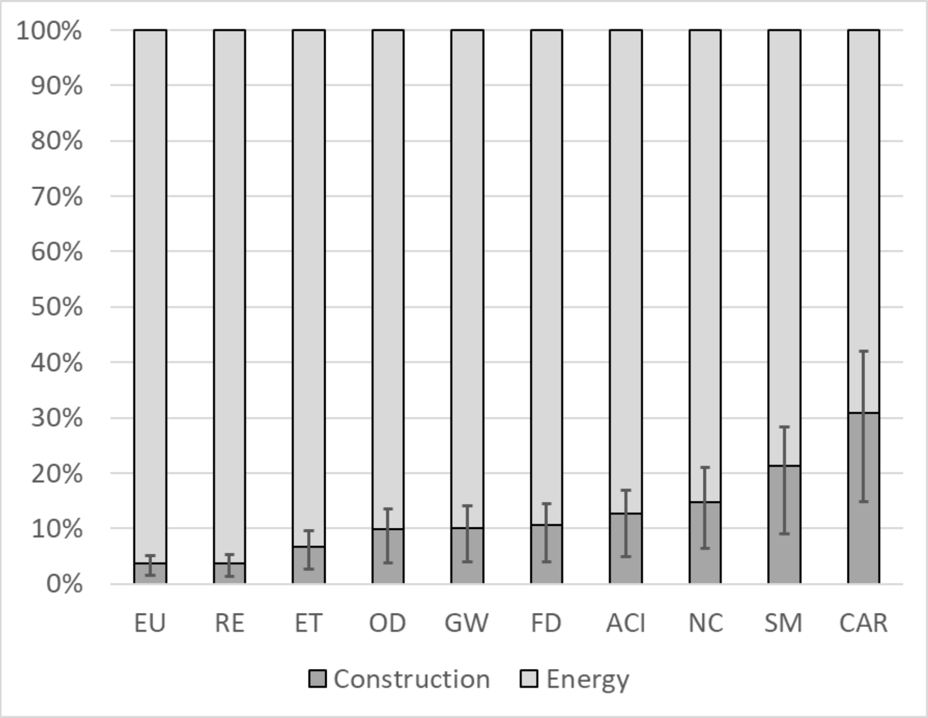


Figure D1. Relative Construction to Electricity Impact Profiles. Supplement to Figure 4.4

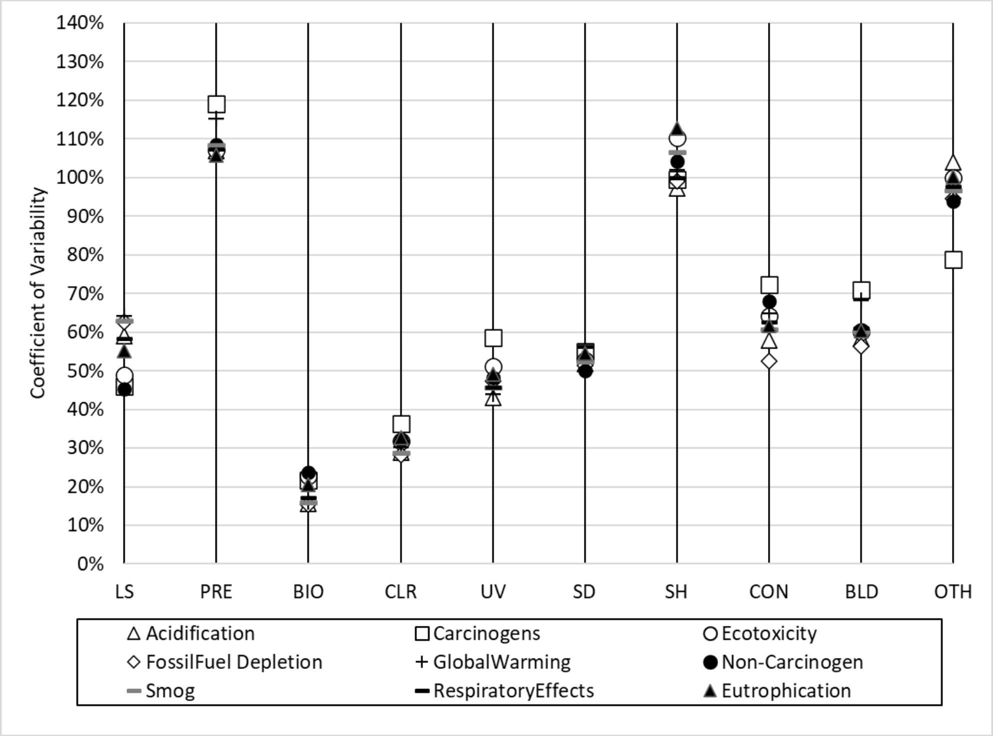


Figure D10. Process Element Impact Coefficients of Variation

Supplemental Information for Suggested Practice 1

Measure the distance or area of a geometric shape on the ground

Perimeter: 878.23 Feet

Area: 28,962.29 Square Feet

☑ Mouse Navigation

Figure D11. Randolph Aerial View

Measure the distance or area of a geometric shape on the ground

Perimeter: 590.00 Feet

Area: 22,092.57 Square Feet

☑ Mouse Navigation

Figure D12. Basset Aerial View

Measure the distance or area of a geometric shape on the ground

Perimeter: 909.98 Feet

Area: 47,495.97 Square Feet

☑ Mouse Navigation

Figure D13. Albion Aerial View

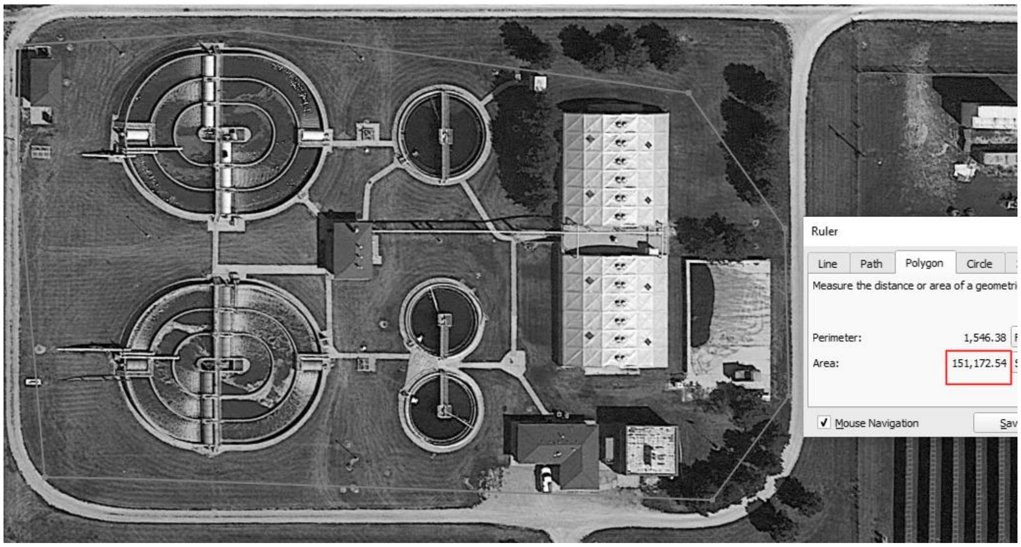
Measure the distance or area of a geometric shape on the ground

Perimeter: 1,188.42 Feet

Area: 56,974.43 Square Feet

☑ Mouse Navigation

Figure D14. Hickman Aerial View



Measure the distance or area of a geometri

Perimeter: 1,546.38

Area: 151,172.54

☑ Mouse Navigation

Figure D15. Aurora Aerial View

Measure the distance or area of a geometric shape on the ground

Perimeter: 427.82 Feet

Area: 11,147.29 Square Feet

☑ Mouse Navigation

Figure D16. Coleridge Aerial View

Measure the distance or area of a geometric shape on the ground

Perimeter: 487.11 Feet

Area: 14,048.44 Square Feet

☑ Mouse Navigation

Figure D17. Bennet Aerial View

Measure the distance or area of a geomet

Perimeter: 626.97

Area: 22,563.14

Figure D18. Syracuse Aerial View

Measure the distance or area of a geometric shape on the ground

Perimeter: 1,180.96 Feet

Area: 56,824.13 Square Feet

☑ Mouse Navigation

Figure D19. Gothenburg Aerial View

Table D2. Facility Total Piping Lengths and Areas

Plant	Avg Des Q (mgd)	Total Pipe Length (ft)	Total Area (ft^2)	Process Area (ft^2)	Non-Process Area (ft^2)
A	0.165	388.5	28,960	19,720	9240
B	0.168	575.8	22,095	9,206	12889
C	0.255	2584.5	47,500	7,613	39887
D	0.82	1306.5	56,970	9,575	47395
E	1.9	3307.9	151,170	41,050	110120
F	0.078	533.5	11,150	1,355	9795
G	0.15	557.2	14,050	2,780	11270
H	0.33	1228.5	22,560	3,830	18730
I	0.504	2886.4	45,540	8,600	36940

Table D3. Normalized Facility Total Piping Lengths, Areas, and Carcinogenic Impact. Supplement to Figure 4.6

Plant	**Avg Des Q (MGD)**	**Total Pipe Length (ft/MGD)**	**Total Area (ft^2/MGD)**	**Non-Process Area (1000 ft^2/MGD)**	**CAR (CTUeq/MGD)**
A	0.165	2,355	175515	56	0.07
B	0.168	3,427	131518	77	0.07
C	0.255	10,135	186275	156	0.39
D	0.82	1,593	69476	58	0.09
E	1.9	1,741	79563	58	0.12
F	0.078	6,839	142949	126	0.24
G	0.15	3,715	93667	75	0.07
H	0.33	3,723	68364	57	0.10
I	0.504	5,727	90357	73	0.27

Supplemental Information for Suggested Practice 2

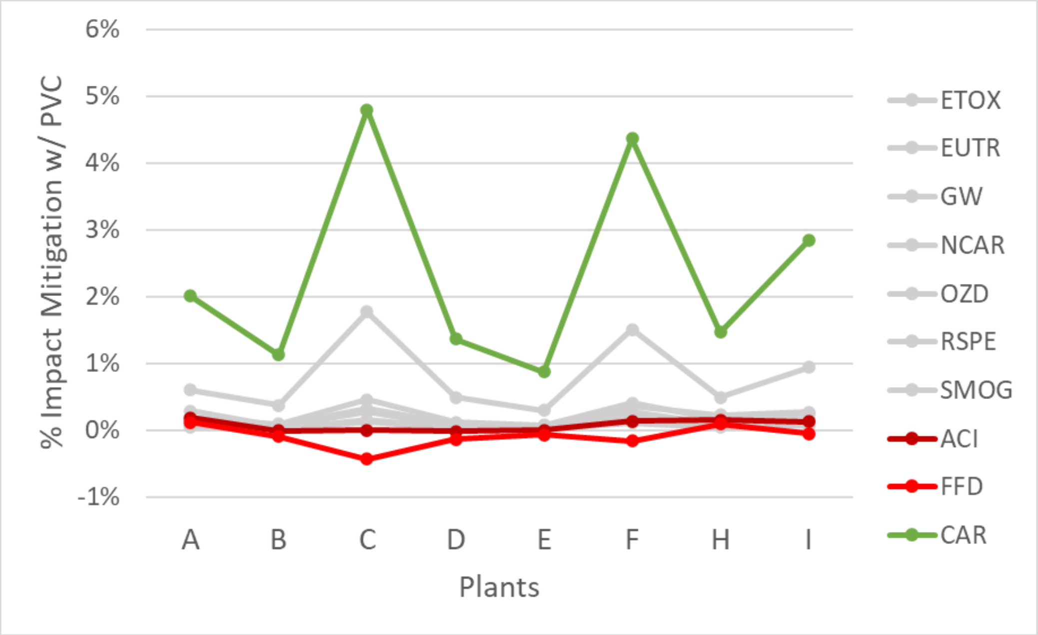


Figure D20. Impact Mitigations from Theoretical Replacement of DIP with PVC. Carcinogenic (green) is the most significant impact category reduced from the change. A small trade-off is seen in the Acidification (dark red) and Fossil Fuel Depletion (red) impact categories.

Supplemental Information for Suggested Practice 3

Table D4. Original Capacity Utilizations and Inventories

						Biological			Clarifier		
Plant	avg flow (MGD)	des avg flow (MGD)	CUR	Hanna 20-yr Electricity (kWh)	Actual 20-yr Electricity (kWh)	Concrete (m^3)	Excavation (m^3)	Reinforcing Steel (kg)	Concrete (m^3)	Excavation (m^3)	Reinforcing Steel (kg)
A	0.108	0.165	65%	2,497,621	5,142,085	159	1580	12331	41	189	3202
C	0.114	0.255	45%	6,433,977	5,333,000	278	777	21554	136	558	10544
D	0.225	0.82	27%	7,996,748	6,925,333	719	2988	55767	150	912	11668
E	0.91	1.8	51%	30,629,468	24,540,172	1447	8517	112283	553	4035	42904
F	0.04	0.08	50%	1,957,929	1,648,145	66	309	5141	41	133	3174
G	0.06	0.15	40%	4,377,128	3,097,333	149	646	11541	46	147	3593
H	0.175	0.33	53%	5,518,958	4,915,949	214	1159	16608	113	482	8797

Table D5. Corrected Capacity Utilizations and Associated Inventory Amounts

				Biological			Clarifier		
CUR	des avg flow (MGD)	Hanna 20-yr Electricity (kWh)	Theor. 20-yr Electricity (kWh)	Concrete (m^3)	Excavation (m^3)	Reinforcing Steel (kg)	Concrete (m^3)	Excavation (m^3)	Reinforcing Steel (kg)
75%	0.144	2,408,141	4,957,865	124	645	9613	51	289	3944
75%	0.152	5,600,939	4,642,511	130	680	10110	53	305	4122
75%	0.300	6,107,729	5,289,408	249	1343	19295	96	601	7413
75%	1.213	27,557,074	22,078,585	979	5431	75983	357	2432	27720
75%	0.053	1,756,323	1,478,437	51	239	3986	25	107	1928
75%	0.080	3,698,494	2,617,120	73	358	5641	33	160	2521
75%	0.233	5,029,365	4,479,850	195	1044	15158	76	468	5931

Table D6. LCI Mitigation Amounts and Percentages from Correcting Capacity Utilization to 75%

	LCI				LCI %			
des avg flow (MGD)	Theor. 20-yr Electricity (kWh)	SP Concrete (m^3)	SP Excavation (m^3)	SP Reinforcing Steel (kg)	Theor. 20-yr Electricity (kWh)	SP Concrete (m^3)	SP Excavation (m^3)	SP Reinforcing Steel (kg)
12.7%	184,220	25	836	1,975	3.6%	12.7%	47.2%	12.7%
40.4%	690,489	230	350	17,867	12.9%	55.7%	26.2%	55.7%
63.4%	1,635,925	525	1,955	40,726	23.6%	60.4%	50.1%	60.4%
32.6%	2,461,587	664	4,689	51,483	10.03%	33.2%	37.4%	33.2%
33.3%	169,707	31	96	2,401	10.3%	28.9%	21.8%	28.9%
46.7%	480,214	90	275	6,972	15.5%	46.1%	34.6%	46.1%
29.3%	436,100	56	129	4,317	8.9%	17.0%	7.9%	17.0%

Table D7. LCA Mitigation Amounts in Construction and Operation Phase

	CAR (CTU)		GW (kgCO2eq)	
Plant	**Civil Works**	**Electric**	**Civil Works**	**Electric**
A	0.0026	0.012	10,719	128,002
C	0.0231	0.044	93,091	479,775
D	0.0527	0.104	212,823	1,136,695
E	0.0666	0.157	270,226	1,710,392
F	0.0031	0.011	12,536	117,918
G	0.0090	0.031	36,401	333,668
H	0.0056	0.028	22,516	303,017