Assessment of Small Mechanical Wastewater Treatment Plants: Relative Life Cycle Environmental Impacts of Construction and Operations

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Abstract

Many slow growing and shrinking rural communities struggle with aging or inadequate wastewater treatment plants (WWTPs), and face challenges in constructing and operating such facilities. Although existing literature has provided insight into the environmental sustainability of large facilities, including both the construction and operational phases, these studies have not examined small, rural facilities treating less than 7,000 m^3/d (1.8 MGD) of wastewater in adequate depth and breadth. In this study, a detailed inventory of the construction and operational data for 16 case studies of small WWTPs was developed to elucidate their environmental life cycle impacts. Conventional LCA framework was followed. The results show that the environmental impacts of both the construction and operational phases are considerable. Operational impacts are highly related to energy usage. Improving energy efficiency of a plant may reduce the environmental impacts related to operations. Construction impacts can vary considerably between facilities. Process-related factors (e.g., concrete and reinforcing steel used in basins) are typically sized using the design flow; thus much of the variability in construction impacts among plants stems from the non-process related infrastructure. Multiple regression analysis was used as an exploratory tool to identify which non-process related plant aspects contribute to the variable environmental impact of small WWTPs. These factors include aluminum, cast iron, and the capacity utilization ratio (defined as the ratio of average flow to design flow). Thus, industry practitioners should consider these factors when aiming to reduce the environmental impacts of a small WWTP related to construction. Scenario sensitivity analyses found that the environmental impact of construction became smaller with longer design life, and the end-of-life consideration does not heavily influence the environmental sustainability of a WWTP.

1. Introduction

Wastewater treatment plants (WWTP) are essential infrastructure systems in today's society, as these facilities treat raw wastewater to protect public health and the environment. According to the United States Department of Agriculture (USDA), 78% of the roughly 15,000 WWTPs in the US treat less than 3,785 m^3/d (1 million gallons per day) and serve small communities (USDA, 2020b). In most US states, including Nebraska, between 90-95% of the publicly owned WWTPs serve small communities (US EPA, 2016a). Additionally, 95% of non-metropolitan counties in the US experienced a growth rate of less than 10% in the last decade, emphasizing that many of these small communities are slowly growing or declining in population (USDA, 2020a).

Many of these slow growing and shrinking rural communities serving less than 10,000 people and with an average daily wastewater flow rate of less than 7,000 m^3/d (1.8 million gallons per day) currently struggle with aging or inadequate WWTPs and face challenges in constructing and operating these facilities (US EPA, 2020a; US EPA, 2016b). Although small WWTPs serve only 7% of the US population in total, roughly 80% of the WWTPs expected to be constructed will serve small communities (US EPA, 2016a). It is anticipated that these newly built WWTPs will ultimately serve 1.1 million people and have an estimated economic need of $5.5 billion (US EPA, 2016a).

Many small communities across the US report that meeting federal and local wastewater requirements are some of their most expensive infrastructure projects (ASCE, 2017). Loan programs are becoming increasingly available to small, slow growing communities that often times have fewer financing options when it comes to wastewater infrastructure upgrades and replacements (US EPA, 2020a; Pearson, 2007). For example, the USDA recently announced their intentions to help rural communities facing challenges related to wastewater infrastructure (USDA, 2020b). The Environmental Protection Agency (EPA) has also stated that their goal is to ensure long-term economic and environmental sustainability in rural communities (USDA, 2020b). Both agencies have committed to making rural systems a funding priority in the future, realizing the large scale, national impact such systems may have.

Existing loan programs, such as the Clean Water State Revolving Fund (CWSRF) and the Rural Utilities Service Water and Environmental Programs, aid small communities in constructing and operating wastewater treatment systems (USDA, 2020c). The current loan programs include general language encouraging sustainable design of small community infrastructure, but there is currently little guidance as to what key considerations may be to minimize the environmental impact from the construction of small community wastewater infrastructure.

Loan programs, although mainly intended to reduce economic impacts, may indirectly facilitate noticeable environmental impacts. The CWSRF requires a design planning period of at least 20 years, leading to the issue of overbuilding a WWTP's infrastructure (NDEE, 2019a) to meet the future needs of the oftentimes optimistic, anticipated population growth of a small community. Overbuilding refers to the idea that a plant may be built to handle a larger flow rate than currently experienced to allow for community growth. Although WWTPs in small towns are typically designed with multiple pumps, basins/tanks, and equipment per flow rate based design standards (GLUMRB, 2014), small communities that apply for loan programs may intentionally overbuild the WWTPs with the consideration that there will not be another funding opportunity available for upgrades and improvements for another 20 years (NYSDEC, 2014). Therefore, it is imperative that municipalities aim to meet the fluctuating demand for wastewater treatment more closely, realizing the potential environmental impacts of an overbuilt facility (Amores et al., 2013).

Life cycle assessment (LCA) can be used to directly measure the potential life cycle environmental impacts of various products and technologies (Kamali et al., 2019; Li et al., 2020). It is widely assumed that WWTPs have only positive impacts on the environment, as the main purpose of a WWTP is to treat raw wastewater to protect public health and the environment. However, the construction and operation of WWTPs of all sizes can create negative environmental impacts at a local, regional, and global level (Seifert et al., 2019).

Although existing literature has provided some insight into the environmental sustainability profiles of large wastewater treatment facilities (Morera et al., 2017; Corominas et al., 2013), these studies have not explicitly examined small facilities in adequate depth and breadth, particularly including both the construction and operation stages. As highlighted by Morera et al. (2020) and Nguyen et al. (2020), both of which found the construction phase to be an important contributor to the overall environmental impact of large WWTPs, the existing literature lacks studies using detailed construction inventory data. With the inevitable upgrades and replacements needed for wastewater infrastructure, and the necessity to ensure reduced public and environmental health risks, it is increasingly important to avoid shifting the environmental burden from operational aspects to infrastructure development in order to have a more holistically sustainable system (Nelson, 2005).

Studies that included the construction stage in their system boundaries generally found that the contribution of construction is higher than 5% of the total environmental impact (Corominas et al., 2013), with some studies (specifically those analyzing conventional activated sludge systems) finding the construction to account for up to 43% of the total environmental impact (Ortiz et al., 2007). Mo et al. (2018) found that the construction and operation phases of small drinking water facilities present high volumetric energy intensities and carbon footprints because of their lack of economies to scale, which suggests that small WWTPs will present similar results. Devi and Palaniappan (2017) found that the construction impacts become more significant as the energy efficiency of WWTP operations increase, which is important to note as many WWTPs are improving their energy efficiency to reduce operational costs (Thompson et al., 2020; Hanna et al., 2018). Similarly, Emmerson et al. (1995) used limited system boundaries and a limited construction and operational data inventory set (much of which was obtained from literature) to conduct an LCA of three WWTPs treating less than 200 m^3/d, and found the construction stage was important for facilities with lower operating costs. These findings suggest that the environmental impacts associated with construction may be an important portion of the overall environmental impact of small WWTPs, where the initial construction can be a large share of the total life cycle environmental impact relative to operations (Morera et al. 2017; Corominas et al., 2013; Li et al., 2010; Emmerson et al., 1995).

Based on current literature, construction impacts merit consideration. The significance of this research is highlighted by the use of multiple regression analysis (MRA) as an exploratory tool to identify non-process related factors independent of flow that can offer practitioners areas for potential environmental impact reduction. Suggestions and guidance as to what aspects of a small WWTP merit greater focus in the design and construction phase to reduce environmental impacts, realizing that many aspects of conventional WWTP designs are often constrained by standard design guidelines, will be provided to practicing engineers to bridge the gap between theory and practice.

This research is among the few studies focused on small WWTPs treating less than 7,000 m^3/d in slow growing communities, as most LCA studies related to WWTPs analyze large plants. The sample size of 16, to the best of our knowledge, is the first study to include this many case studies based on detailed construction and operational inventories. The detailed and site-specific inventories enhance the published literature by reducing the number of assumptions made related to the site-specific inventories of WWTPs and increases the validity of the contribution of construction to the overall environmental impacts of small WWTPs. The exploratory use of MRA has not yet been used to understand the relationship between inventory and flow rate, with the goal of identifying key factors that may offer potential reduction of environmental impacts related to the construction of small WWTPs. The objective of this research is to provide industry practitioners with initial guidance towards what may constitute a more or less sustainable WWTP in a slow growing and/or shrinking community from an environmental perspective. Although operations (e.g., water and energy savings) is generally the current focal point of environmental sustainability in the wastewater sector, construction of WWTPs may also present notable environmental impact reduction potential. It is of the upmost importance to gain a comprehensive understanding of the environmental impacts related to small WWTPs to encourage sustainable development of small community infrastructure. Thus, the authors are motivated to answer two key research questions: (1) Is the construction phase an important contributor to the total environmental impact of a small WWTP? (2) Which inventory inputs can be identified by MRA to potentially present the greatest opportunities to modify WWTP designs to reduce environmental impacts without straying from common design guidelines and practices? Ultimately, this research will utilize case studies to discuss environmental impacts of small WWTPs, and to highlight where a design engineer, community leader, regulator, or other stakeholder could modify construction practices to reduce overall WWTP environmental impacts.

2. Methodology

Conventional LCA framework was followed in this study. Each of the four LCA phases were completed (goal and scope, life cycle inventory, life cycle impact assessment, and interpretation). The interpretation phase included a MRA and a sensitivity scenario analysis.

2.1 Goal and scope

The goal of this study is to quantify the environmental impacts regarding the construction and operation phases of 16 small mechanical WWTP case studies from a life cycle perspective (Moussavi, 2019). More detailed methods, as well as additional case study data, are provided in Moussavi (2019). The product system analyzed in this study includes four types of small mechanical WWTPs most commonly employed in small, rural communities (US EPA, 2000a): 1) extended aeration (EA), 2) extended aeration – package (EA-P), 3) oxidation ditch (OD), 4) sequence batch reactor (SBR). These technologies are considered mechanical technologies, as they use mechanical components (e.g., pumps, blowers, etc.) to treat wastewater. These technologies are all biological aeration processes and are relatively similar in terms of the overall wastewater treatment process.

As shown in Figure 1, the primary treatment, tertiary treatment, and auxiliary functions (e.g., buildings, sidewalks, aluminum safety railings) highlighted in red, blue, and green respectively, are similar for all three types of plants, and only the secondary treatment process varies among technology, although all of the secondary treatment processes are modifications of the activated sludge process. These slight variations in the secondary treatment show the high degree of similarity among many parts of a small WWTP's infrastructure and operations. It was assumed that the four technologies studied are similar in terms of operations, consistent with what Hanna et al. (2018) found when looking at the energy intensity of small mechanical WWTPs. Hanna et al. (2018) used energy data collected from 83 and 71 small WWTPs in Nebraska and Pennsylvania, respectively, to benchmark the energy intensity of small WWTPs similar to the facilities studied in this research. Nebraska and Pennsylvania WWTPs were found to be similar in terms of energy intensity, suggesting that the construction impacts are likely similar as well. This further suggests that small Nebraska systems represent a wide range of systems based on similar design guidelines. Hanna et al. (2018) also found factors such as capacity utilization ratio (CUR, defined as the ratio of average flow to design flow) and climate-controlled floor area to be some of the significant factors influencing the energy intensity of small plants, rather than the specific technology employed at the plant. Although the impacts may vary slightly among technologies, the sample size of 16 plants is small, and site-specific factors dominate variability between plants; thus, environmental impacts in this study are not compared based on the secondary treatment technology (i.e., EA, EA-P, OD, and SBR).

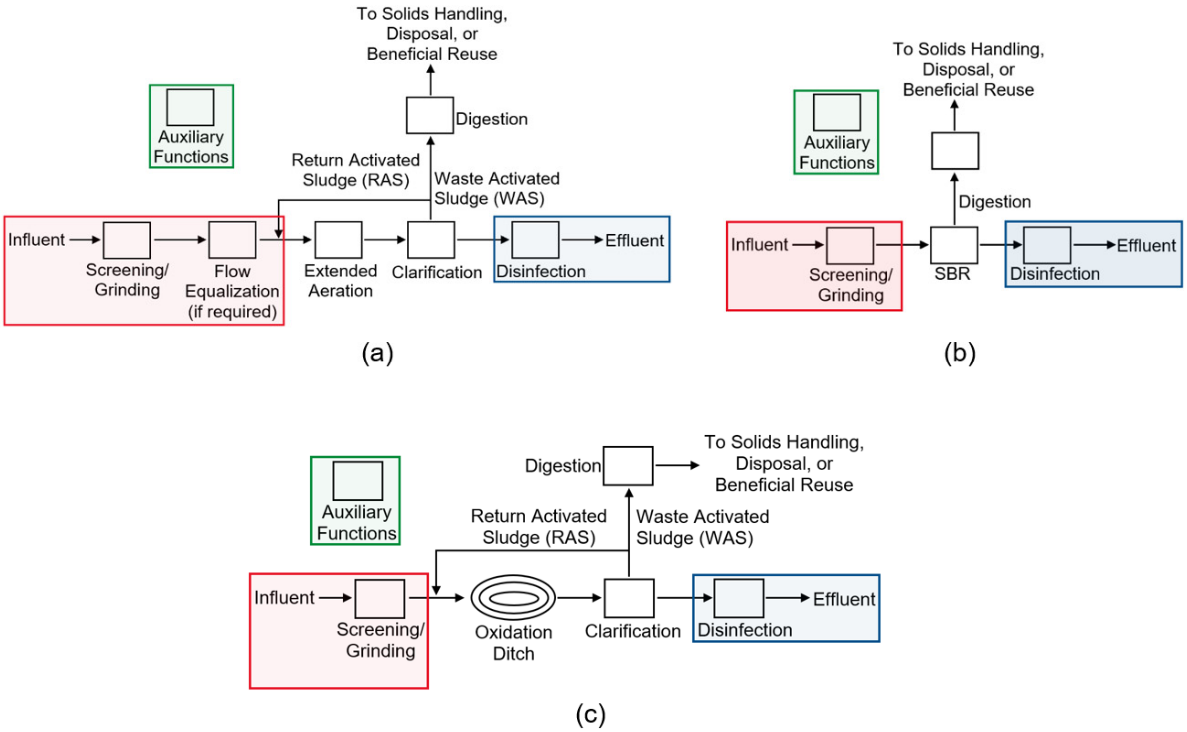

Figure 1. General process flow diagram of the mechanical WWTP technologies studied (a) extended aeration plant (b) sequence batch reactor (c) oxidation ditch, highlighting the various secondary treatment processes. Common treatment processes among the plants are highlighted in red (primary treatment), blue (tertiary treatment), and green (auxiliary functions). Modified figure from US EPA, 2000a.

The function of the product system is to treat raw municipal wastewater in order to meet regulatory agencies' requirements to ensure safety for humans and the environment. Therefore, the functional unit utilized in this study is one cubic meter of treated wastewater, consistent with relevant literature (Corominas et al., 2020, 2013; Morera et al., 2017). System boundaries were chosen to account for both the construction and operational phases of the mechanical WWTPs. The distinction between the construction phase and the operational phase was determined to be an important part of this research. The construction phase comprises of the civil works and equipment processes, and the operational phase comprises of the energy use, water emissions from the treated effluent, air emissions from the biological treatment process, and soil emissions from biosolids land application. The WWTP operational life was assumed to be 20 years based on common US design standards (GLUMRB, 2014). WWTPs can be demolished at the end of useful life, or the facilities may be retrofitted for continued operations. Due to the lack of data availability surrounding the demolition of WWTPs, the end-of-life phase was only considered as a possible scenario in a sensitivity analysis.

2.2 Life cycle inventory

A list of the specific communities analyzed in this study and their respective plant type, recorded population (United States Census Bureau, 2010), and flow rates (US EPA, 2019) are presented in Supplemental Information (SI) Table S1. Each community was assigned a unique letter, based on the relative amount of construction impact associated with the plant, as a means of identification. These 16 plants were chosen as case studies because of their reasonable representativeness of small systems and the availability of the utility and construction data (Moussavi, 2019). This study focuses on WWTPs serving communities less than 3,000 people, since this size range is representative of slow growing and shrinking rural communities in the US. The utility data for the chosen plants were readily available based on a previous study conducted by Hanna et al. (2018). The utility data was collected for a minimum of 12 months, but oftentimes up to three years. The plants also completed the construction process during one or two stages, allowing for complete construction plans to be accessible. A majority of the plants were built between 1975 and 2012, and only three of the plants were built earlier than 1975. The more recent build dates allowed easier access to and readability of construction plans and documents.

Inventory data used in this research was comprised of foreground data and background data, based on a similar study conducted by Morera et al. (2017). Foreground data refers to the data that can be measured at point of use. Foreground data collected includes energy usage, water and soil characteristics, air emissions from the biological treatment process, and construction inventories. Energy usage was collected from utility bills provided by the communities. Water and soil characteristics were obtained from the Nebraska Department of Environment and Energy (NDEE) and the US EPA's Enforcement and Compliance History Online (ECHO) databases (NDEE, 2019b; US EPA, 2019). Sludge data quality was compared with literature values and was deemed accurate as collected (Metcalf and Eddy, 2014). Sludge production rates were estimated using a linear regression of sludge land application rates versus average effluent flow rate. Air emissions from the biological wastewater treatment process are rarely included in WWTP LCA studies (Morera et al., 2017), and such emissions are not recorded by the NDEE. Consequently, air emissions associated with the biological treatment process were assumed to be a release of methane (CH_4), nitrous oxide (N_2O), and ammonia (NH_3) into the atmosphere based on literature estimates (Foley et al., 2010). Construction inventories were collected from engineering design documents, as well as from literature (Devi and Palaniappan, 2017). Transportation distance of construction materials was assumed to be 40 kilometers (km) based on typical values used in literature (Morera et al., 2017).

Background data refers to data that is measured and stored within the Ecoinvent database, as well as data that was used to create and refine foreground resources. Background data was collected using the Ecoinvent Database v3.3. This background data was used when data was not able to be collected on-site, or when the processes were too complicated to model using only directly collected data. Ecoinvent data was specifically used for background processes such as the US electricity grid mix, processes required to produce building materials and equipment, and transportation inputs and outputs. The dataset chosen for each input and output in the LCA model was based on user judgment, as well as literature (Morera et al., 2017).

All collected data inventory were aggregated and organized, with the appropriate conversions to a mass basis normalized by the flow over 20 years made. A complete list of this data inventory, as entered into SimaPro, is provided in SI Table S2. Figure 2 represents the total inventory data set within the selected system boundary for the specified product system, with each input's and output's respective units.

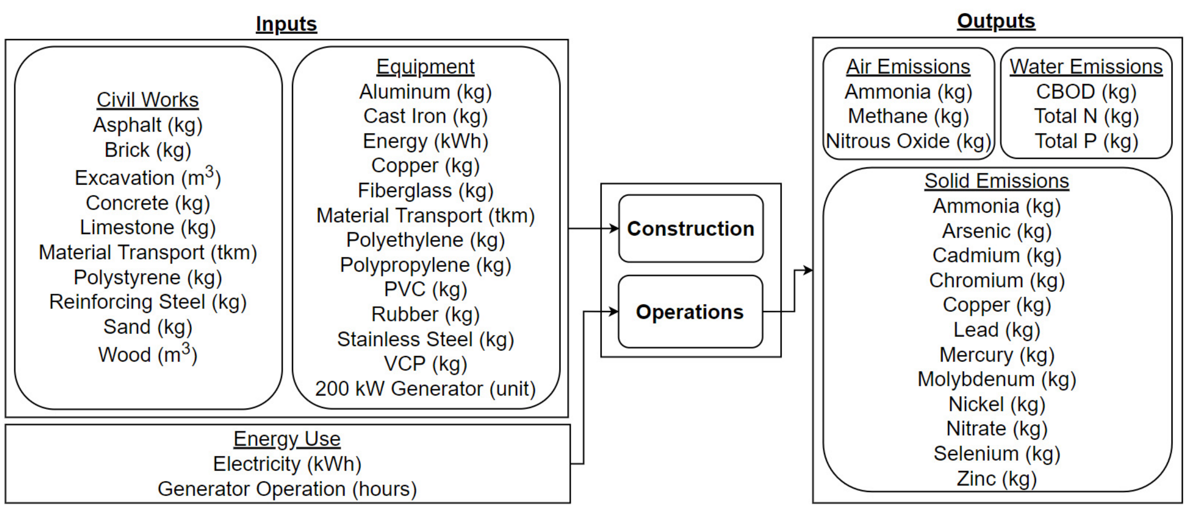

Figure 2. Product system data inputs and outputs

2.3 Life cycle impact assessment

SimaPro v8.4, compliant with the International Organization for Standards (ISO) 14040 series (ISO, 2006), was used to conduct the life cycle impact assessment (LCIA). The environmental impacts of each inventory item were calculated based on the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) impact assessment method v2.1 (Bare et al., 2003). TRACI was chosen for the current study due to its ability to represent regional and global environmental impacts, as well as its specificity to US systems and processes. The specific impact categories analyzed in this study include ozone depletion, global warming, smog, acidification, fossil fuel depletion, eutrophication, ecotoxicity, carcinogens, non-carcinogens, and respiratory effects. Those impact categories are further normalized based on a US factor to evaluate different categories on the same basis (Ryberg et al., 2014).

2.4 Scenario sensitivity and uncertainty analyses

ISO Standards state that results obtained during the LCIA phase should reflect results of any sensitivity analyses performed (ISO, 2006). The results of an LCA may be highly sensitive to specific variables. Scenario sensitivity analyses can specifically test the study's system boundaries and assumptions. A scenario sensitivity analysis varies a single variable in a model to see how changing that variable may affect the LCIA results. While this is not a strict mathematical model of sensitivity, this method can clearly illustrate the significance of certain variables to an impact category. In the case of LCA, this is often a path taken to further communicate the results (Guo and Murphy 2012; Bjorklund et al., 2002).

Analyses were performed to examine the sensitivity of the results based on two scenarios: (1) plant design life and (2) end-of-life for reinforced concrete. For (1), the environmental sustainability profile of each case study was developed for plant design lives of 10, 20, 30, 40, 50, and 60 years. These design lives were chosen based on the reported system lifespans of the case studies. This analysis aims to present the environmental impacts associated with the best and worst case build dates. For (2), two scenarios were analyzed: 100% waste of reinforced concrete and 100% recycling of reinforced concrete. This analysis provides insight as to which end-of-life process may have a more environmentally sustainable footprint. Uncertainty analysis was performed by considering the variability of the case studies. The uncertainty values for the environmental impacts for each impact category were obtained by calculating the minimum, mean, and maximum values of the data, similar to Morera et al. (2017). Error bars were developed to show the relative variability among the results for a specified impact category. A larger error bar in a given impact category corresponds to a more variable data set (Molinos-Senante et al., 2014). Uncertainty of the background data is not considered.

2.5 Multiple regression analysis

MRA can be used as an exploratory tool to further investigate possible factors driving the variability in LCA construction impacts (e.g., Lin et al., 2018). It is important to note that MRA, as used in this study, is not intended to be a predictive model due to the limited dataset. Rather, it was used as a means of identifying possible parameters that may influence the variability in the construction impact.

The dependent variable was calculated by multiplying the normalized environmental impact from the construction of each plant for each impact category by the respective impact category's TRACI normalization factor, and multiplying that product by the respective plant average flow rate to get a net environmental impact. This was done to put the impact on the same non-normalized scale as the raw input data (e.g., mass of cast iron). The variables identified as drivers to the variability in environmental impact of construction (i.e., the independent variables) were plant design flow, plant average flow, cast iron, and aluminum. These independent variables were chosen via a stepwise method based on each variable's F statistic and significance, using a significance level of 0.05. Other studies (Ruiz-Rosa et al., 2016; Fraas and Munley, 1984) found average flow rate and CUR to be important for overall WWTP cost modeling.

3. Results and discussion

3.1 Average environmental sustainability profile of 16 case studies

This study intends to show the potential environmental impacts of both the construction and operations of small WWTPs. The individual LCA results of each of the 16 case studies (see SI Table S3) were first averaged together to create a general environmental sustainability profile of a small WWTP in Nebraska. Because there is great variability among the LCA results of each case study, this average profile serves as a baseline to visualize the amount of variability seen among the cases studied. To compare impact categories on the same basis, the normalized and characterized average environmental profile of the 16 case studies are presented in Figure 3a and Figure 3b, respectively. The unit for the normalized environmental impact is "(environmental impact per 1 m^3 of treated wastewater)/(environmental impact per US citizen per year)" for a specific impact category based on the normalization factors provided by the Updated US and Canadian Normalization Factors for TRACI 2.1 (Ryberg et al., 2014). The unit for the relative environmental impact is the "process contribution as a percentage of the total impact" of a specific impact category. In Figure 3a the error bars to illustrate the variability in the LCI inputs, and consequently the LCA results, among the 16 plants.

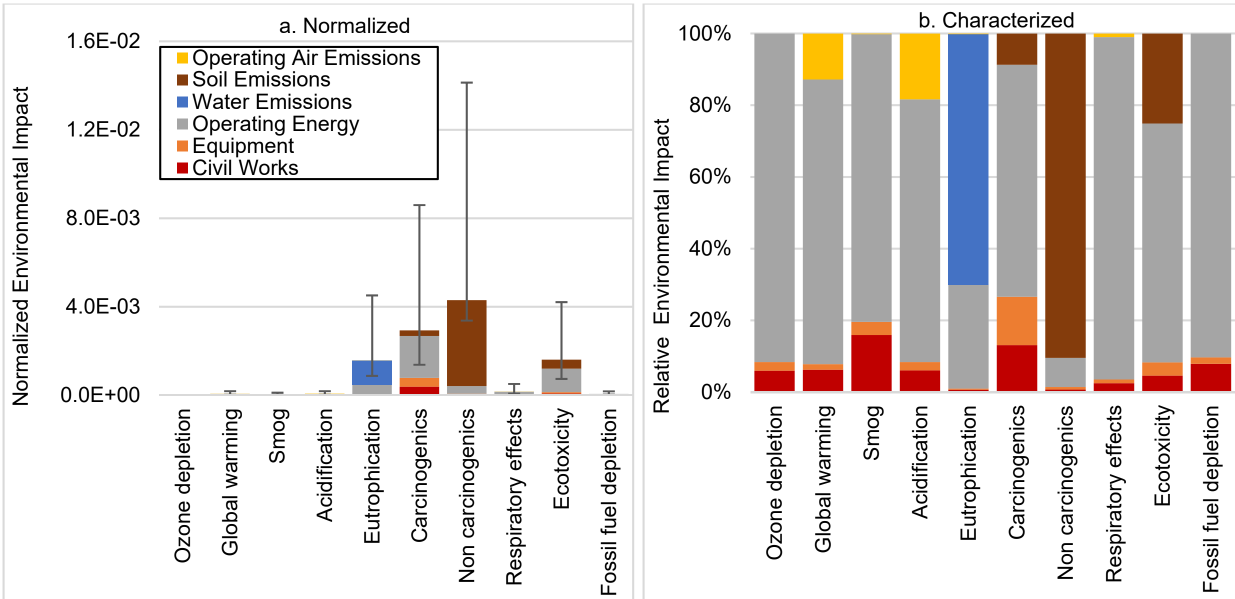

Figure 3. Average normalized (a) and relative (b) total environmental impact over 20 years of the 16 case studies with error bars placed on (a) showing the variability in LCI inputs

According to the LCA Handbook, the cutoff criteria for a process to have a considerable contribution to an impact category is at least 5% (Zampori et al., 2016). When considering the contribution of operating energy to the average environmental burden, the contribution is greater than 50% for all but two impact categories. For each impact category affected, almost all of the environmental burden associated with the operating energy process is due to the electricity usage (e.g., mechanical processes and machinery used for operations). Although the operating energy process is the dominating contributor to the environmental impact for most impact categories, it should be noted that if the electric grid moves towards renewable resources, the relative contribution of the operating energy may decrease for some impact categories (Polruang et al., 2018). Figure 3b also shows that the contribution of the construction process (civil works and equipment) to the overall burden for all but two impact categories (noncarcinogen and ecotoxicity) is greater than 5%, with respiratory effects at 4%. A relatively large amount of environmental impact associated with construction is due to reinforced concrete production and cast iron piping production for many of the impact categories. Operating air emissions contribute marginally to the overall environmental impact of a small WWTP in most impact categories except global warming and acidification. Operating air emissions contribute noticeably to these impact categories due to aeration processes during secondary wastewater treatment. It should be noted that the high contribution of soil emissions to the non-carcinogen impact category is likely an overestimation of metal toxic impacts, as current TRACI methods conduct characterization assuming the total metal concentration in the environment is bioavailable and toxic (Ryberg et al., 2014).

The impacts of both construction and operations are relevant for the small WWTPs illustrated in Figure 3, even when accounting for the variability among the individual plant LCIs. The findings presented in Figure 3 are consistent with relevant literature, which has found that construction may account for between 5% - 43% of the total environmental impact of a WWTP depending on technology and size (Corominas et al., 2013; Ortiz et al., 2007). For the impact categories of eutrophication, carcinogens, non-carcinogens, and ecotoxicity, there are large error bars, as shown in Figure 3a. This implies that there is a high variability among the LCI input data used to develop the average environmental sustainability profile of the 16 case studies. This variability can be attributed to site-specific factors such as operational efficiency and construction resources.

3.2 Influence of energy efficiency on the environmental impact of a WWTP

The operating energy is the dominating process contributing to the overall environmental impact of a facility in most impact categories. The energy efficiency of a plant can be evaluated by comparing its energy impact to a regression estimate of its energy intensity (i.e., plant average annual electricity usage divided by plant average annual flow rate) based on similar Nebraska

WWTPs (Hanna et al., 2018). The Hanna et al. (2018) model predicts the expected energy intensity of a small WWTP based on factors such as climate-controlled floor area, CUR, and average flow rates. If a facility is operating efficiently, the actual energy intensity will be similar to or smaller when compared to the regression value for similar plants. In cases where the actual energy intensity exceeds the regression estimated energy intensity, there are likely operational inefficiencies (e.g., lack of automation or inadequate screening) associated with that plant.

The carcinogen impact category was an impact category of focus due to the high relative contribution of construction to this category, as well as the association of this impact category with human health. Figure 4 shows the relationship between the actual and estimated energy intensities, and the carcinogen impact of operating energy, implying that more efficient plants create less environmental impact from operating energy. Similar relationships were observed for all other TRACI midpoint impact categories. This is intuitive, as a less efficient plant will use more energy to treat less flow than what it was designed to treat.

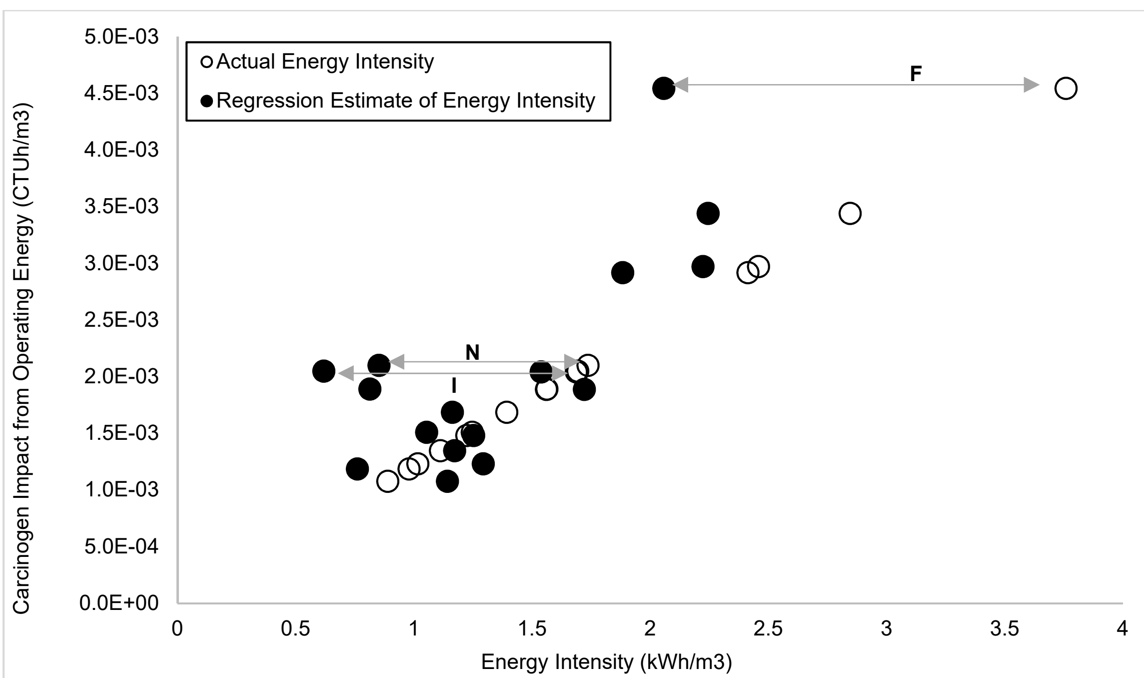

Figure 4. Carcinogen impact from operating energy vs. the actual and regression estimated energy intensities of each plant, highlighting Plants F, N, and I

When comparing the actual energy intensity to the regression estimate of energy intensity, it can be seen that most regression estimated energy intensities are to the left of the actual energy intensity for each plant, since a majority of the plants in this case study are less energy efficient than the regression average of Nebraska plants. This is, in part, because many of the case studies chosen for this research were previously involved in a technical assistance project that prioritized the inclusion of plants with a high potential for energy efficiency improvements (Thompson et al., 2020; Hanna et al., 2018).

The operating inefficiency can be highlighted by Plants F, N, and I, where there is a large horizontal distance between the actual energy intensity and the regression estimate of energy intensity. Plant F experiences inflow and infiltration (I&I) issues, oil and grease buildup from local cafes, and over 30-year-old basins. Plant N has significant I&I problems, variable flows due to a nearby egg processing facility, 25-year-old pumping equipment, operator overturn, damaged water lines due to freezing, non-programmable thermostats, and fluorescent lighting. In discussion with the facility operator and on-site electrical measurements of unit operations, it was discovered that Plant I has inadequate screening, leading to tumbleweeds clogging the mechanical aerators and mixers, causing a larger motor load, resulting in faster burnout and higher energy use.

3.3 Identification of key parameters influencing the variability in construction impact

Although operating energy is most often the largest contributor to the overall environmental profile of a facility, construction is also a notable contributor exhibiting significant variability for a given impact category as shown in Figure 3a, consistent with literature (Nguyen et al., 2020). Nguyen et al. (2020) found that the construction phase impact was largely due to the large amount of concrete and reinforced steel used for plant construction.

While this finding is consistent with this study's findings, the amount of concrete and reinforcing steel used in a WWTP's infrastructure is heavily dependent on design flow and follows strict design guidelines. Therefore, to answer the second research question raised in Section 1, MRA was used as an exploratory tool to further investigate which inventory inputs, beyond those that scale with design flow, drive the variability in LCA impacts related to the construction phase in order to provide recommendations for non-process related environmental impact reductions. A significance level, α, of 0.05 was used for this exploratory analysis. As mentioned previously, the carcinogen impact category was focused on in this study due to its implications, although the results presented are fairly representative of the remaining impact categories.

The independent variables identified by MRA as drivers to the variability in environmental impact of construction include plant design flow, plant average flow, cast iron, and aluminum. Plant design flow and plant average flow are related via the CUR. Although concrete and reinforcing steel, in addition to aluminum and cast iron, make up a large portion of the construction inventory for each plant (See SI Figure S1), concrete and reinforcing steel were not identified by the MRA to be drivers to the variability in the environmental impact from construction. This is again because resources such as cast iron and aluminum may vary based on factors beyond design flow (e.g., plant layout and user/safety preferences), whereas resources such as concrete and reinforcing steel are used mainly in infrastructure that scales in size based on design flow standards (e.g., basins). Therefore, construction impacts related to cast iron and aluminum may be directly reduced through construction practices such as implementing alternative plant layouts, whereas construction impacts related to concrete and reinforcing steel may be indirectly reduced by using a design flow rate closer to the average operational flow rate. Cast iron and aluminum will be discussed further in the subsequent sections.

These construction related factors may be among the best to consider if a design engineer or stakeholder is looking for areas to directly reduce the environmental impacts related to construction of a small WWTP, although factors beyond these (e.g., CUR) also merit consideration. The results shown in Table 1 represent the MRA results for the carcinogen impact category. However, similar trends were observed among the 10 TRACI impact categories (see SI Table S4) with the exception of aluminum, which was not as prevalent in some of the impact categories. The amount of aluminum at each plant varied highly, with some plants having minimal use. These key factors are discussed in more detail in the subsequent sections.

Table 1. Multiple regression analysis results for the construction impact to the carcinogen impact category

Regression Term	Coefficient	P-value
Intercept	-1.50E-02	1.58E-01
Plant Design Flow	4.38E-01	4.03E-06
Plant Average Flowrate	-4.88E-01	1.37E-04
Cast Iron	4.43E-06	2.98E-07
Aluminum	4.85E-06	4.58E-03
Adjusted R Square	0.99	
F - Test	6.01E-12	

3.3.1 Influence of CUR on construction and operational impacts

The CUR of a plant refers to the plant average flow divided by the plant design flow, both factors identified in the MRA in Section 3.3. These factors define how overbuilt a plant may be in terms of construction relative to the operational flow it treats (Corominas et al., 2020). As highlighted by the negative coefficient for plant average flow rate in Table 1, it is expected that as the plant average flow increases, the construction impact to carcinogens may decrease. As the plant average flow increases (i.e., the CUR increases), the plant begins to treat a flow rate closer to the design flow, resulting in more efficient operations and better use of the infrastructure built to accommodate the design flow.

Often in engineering, for a growing or large facility, it is expected that there is a trade-off of better energy efficiency (i.e., lower operating energy impacts) with more upfront infrastructure investment (i.e., higher construction impacts) (Devi and Palaniappan, 2017). However, this idea may not hold true for a small and potentially shrinking community, where a low CUR (i.e., the plant is treating less flow than it was designed to treat) may override the impact of additional infrastructure investment. Many small plants have not been constructed to include automation such as dissolved oxygen monitoring or aeration output control (e.g., variable frequency drives, timers) due to the perceived high capital cost of including such automation (Thompson et al., 2020). This leads to operational equipment (e.g., blowers and pumps) being selected for the basis of the design flow rate, resulting in potentially less efficient operations when the facility is experiencing flows lower than the design flow rate. A small plant with a low CUR may be less energy efficient in its operations due to operational overdesign (e.g., overaerating), which may heavily influence the operational impact of a plant without necessarily affecting the construction impact.

Figure 5 shows the relationship between the normalized carcinogen impact from construction and the normalized carcinogen impact from operating energy. Each CUR is noted next to the letter representing each plant on the symbol representing the mechanical treatment process. Figure 5 illustrates that a high construction impact, as represented by the construction carcinogen impact, weakly correlates to a high operating energy impact, consistent with the previously mentioned hypothesis for small communities. Many of these facilities were designed assuming an increasing population and flow but experienced declining flows due to losses of local industrial flows and stagnant or declining populations. Some plants, such as Plant D, might be expected to have a much higher operating energy impact due to its extremely low CUR. Plant

D's location to the lower left in Figure 5 is likely a result of an exceptional degree of plant automation. As most non-metropolitan regions of the US are declining or slow growing in terms of population (see SI Figure S2), Figure 5 emphasizes that, unless there is a compelling reason to anticipate a high wastewater flow rate growth, overdesigning a WWTP's infrastructure in a small, non-metropolitan community should be discouraged as it is a poor use of natural resources.

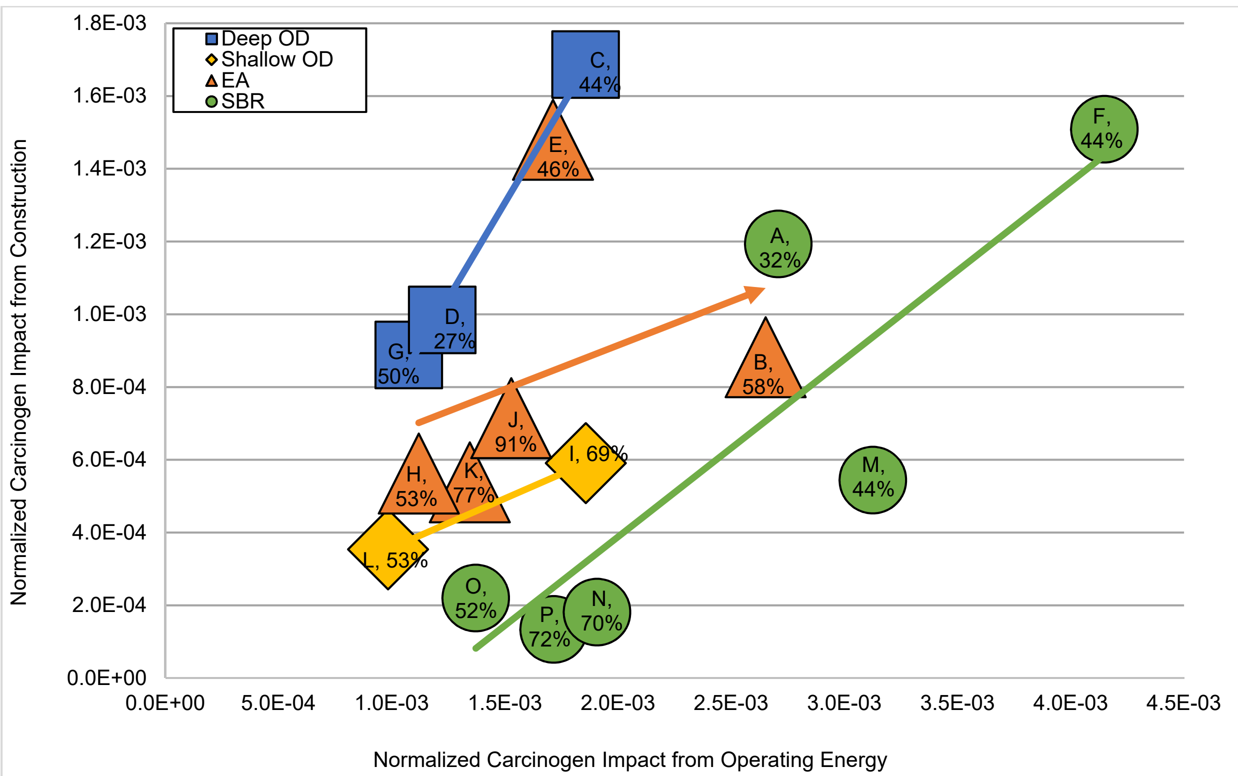

Figure 5. Normalized carcinogen impact from the construction process for each plant vs. normalized carcinogen impact from operating energy for each plant, categorized by plant technology, with plant identification and respective CUR placed inside shape.

The complex relationship depicted in Figure 5 can be most clearly seen when isolating deep ODs. The intended operational benefit of a deep OD basin versus a shallow and wide basin, according to conversations with consulting engineers, is the more efficient oxygen transfer in the deep basins as well as the ability to have a smaller construction footprint for an OD. However, for deep ODs, as the operating energy impact increases, the construction impact increases, and except for Plant D, the CUR decreases with the increasing impacts. Figure 5 shows that in cases like the ODs, certain factors (e.g., the increased construction impact associated with the additional infrastructure required to build the deep basins) may override the intended operational benefit, as there are no clear energy usage benefits observed in this data for the deep ODs, as intended by design engineers. This is highlighted by the decreasing CUR from Plant G to Plant C where, even as the construction impact increased, the decreasing CUR likely led to less efficient operations. Therefore, as WWTPs become more energy efficient, the environmental impact from operating energy decreases and construction impacts become relatively more important. Additionally, there is a 27% - 75% decrease in environmental impact from the construction phase, depending on the impact category, between the plant with the lowest CUR and the highest CUR (See SI Table S5). This further emphasizes the influence that idle, underused infrastructure may have on small plants' environmental impact related to construction.

As stated in Section 2.1, the intention of this research is not to compare plant technologies against each other. There is a high degree of similarity in small mechanical WWTP infrastructure and operations, and although the impacts may vary slightly among technologies, the sample size is too small to see any significant differences between the secondary treatment technologies studied.

3.3.2 Additional factors driving the variability in construction impacts

Additional factors beyond the CUR identified in the MRA as drivers to the variability in construction impacts include cast iron and aluminum. Cast iron is mainly used as a piping material in older WWTPs. The amount of cast iron piping at a plant, depending on plant layout and land topography, may contribute between 4% and 61% to the total carcinogen construction impact (see SI Table S6 for values for each of the case studies). Additionally, cast iron piping is an older piping material associated with high environmental impacts. Newer WWTPs are moving towards PVC piping in lieu of cast iron piping (US EPA, 2000b). Therefore, older WWTPs may have a higher construction impact due to cast iron piping compared to newer WWTPS. Aluminum varies from plant to plant depending on user/safety preferences. Aluminum may contribute between 1% and 18% to the total carcinogen construction impact (See SI Table S6).

The factors identified as primary contributors to construction impact variability are non-process related, whereas process-related factors such as reinforcing steel and concrete related to basin sizing, which are designed to treat a specified design flow, did not appear to have as much variability associated with them. The amount of non-process related materials (e.g., cast iron and aluminum) used in a plant's infrastructure directly influences the environmental impacts related to construction. Process-related factors may be more standardized across plants and scale with size due to design standards, which are largely based on flow rate (GLUMRB, 2014). Larger facilities may have inherently more construction impacts on an absolute number basis, regardless of the variability in non-process related resources, to meet design requirements. When normalized by flow, the construction impacts of small facilities may account for a relatively higher portion of the total impacts when compared to large facilities. This trend is also observed for cost of WWTPs. Friedler and Pistany (2006) found that as WWTPs get smaller, construction costs become a larger portion of the total cost, consistent with observations of the limited data set collected in the current study.

3.4 Scenario sensitivity analyses

Two analyses of different scenarios were conducted. The scenarios analyzed included various design lives and the end-of-life scenarios.

3.4.1 Influence of design life on construction impacts

The original study utilized a plant design life of 20 years, consistent with the 10 State Standards for design of a WWTP (GLUMRB, 2014). It is assumed that flow rate and operational impacts are constant over time. Some construction renovations have been completed at certain WWTPs over the years, however this analysis assumes a worst-case scenario build date. Plant design lives of 10 to 60 years were chosen as scenarios to examine the influence of design life to the relative environmental impacts for the case studies as shown in Figure 6.

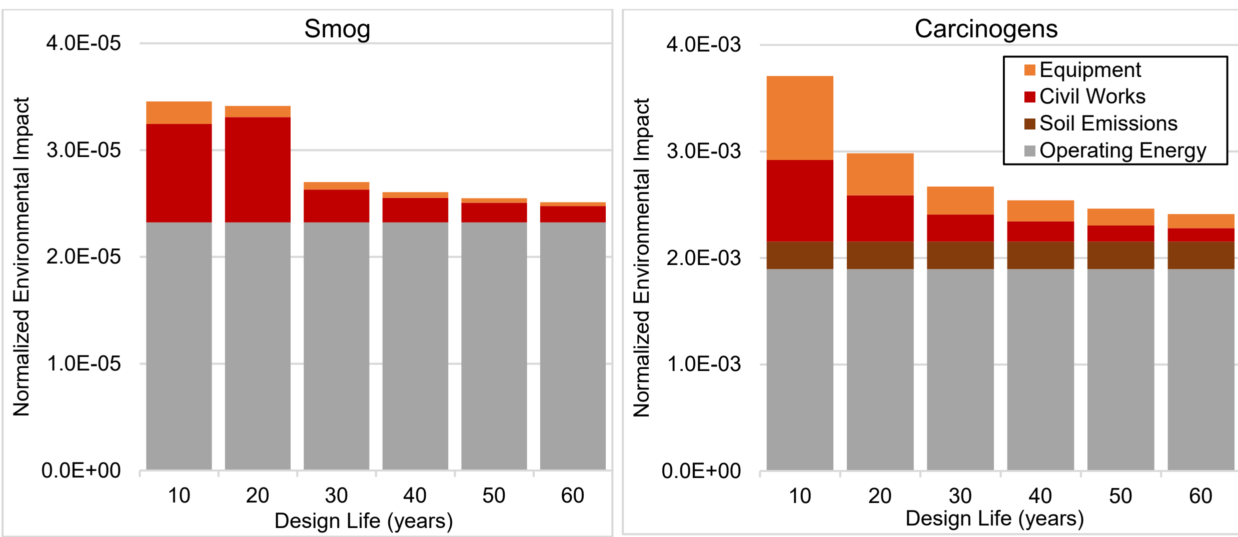

Figure 6. Average normalized environmental impact from construction for the 16 case studies for six design life scenarios for impact categories where there is a noticeable influence of design life on the impact of construction

As shown in Figure 6, the impact of construction to the impact categories of both smog and carcinogens decreases with an increased design life scenario, or as the construction impact is normalized over a longer time period. This is consistent for all impact categories. All other processes (operating energy, water emissions, soil emissions, and operating air emissions) have a constant normalized environmental impact regardless of the design life due to the assumed constant annual operations.

3.4.2 Influence of end-of-life consideration on the environmental impact of a small WWTP

The original LCA did not account for the end-of-life phase (e.g., demolition of a WWTP) due to the infrequent demolition of small WWTPs and consequentially, a lack of data available on this phase. However, the end-of-life phase may be an important consideration in LCA studies of small WWTPs due to the environmental impacts embedded within end-of-life processes, as the chosen process may decrease the overall environmental impact to one category at the cost of another (Morera et al., 2017). To illustrate the relative impact of end-of-life, Figure 7 provides the potential environmental impacts associated with one of two end-of-life processes: 1) 100% recycling of reinforced concrete 2) 100% wasting of reinforced concrete for final disposal at a WWTP. Reinforced concrete was evaluated because it is a large and essential portion of a WWTP's built infrastructure. A transport distance of 40 km, consistent with the original LCA conducted, was assumed for both end-of-life scenarios.

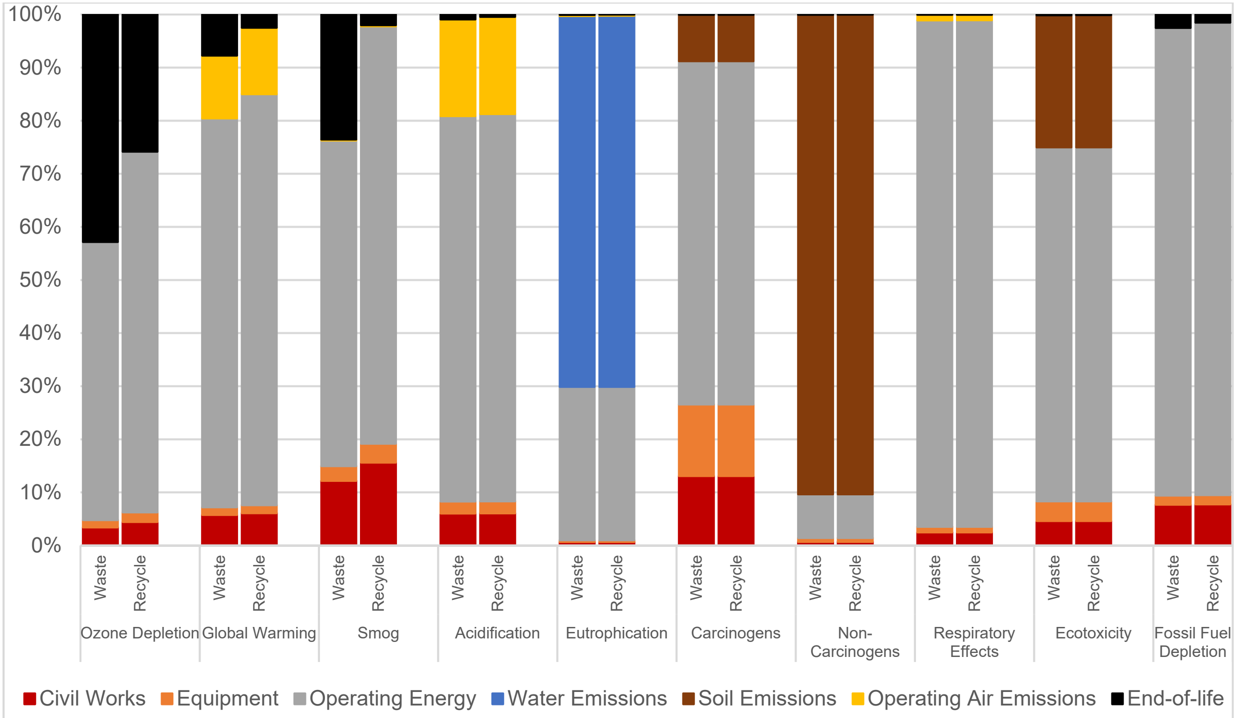

Figure 7. Average relative environmental impacts for the 16 case studies comparing two end-of-life scenarios for the average amount of reinforced concrete used at a plant for each impact category

As shown in Figure 7, the environmental impacts associated with either end-of-life scenario are relatively small compared to the total life cycle impacts for most impact categories. However, in the case of ozone depletion and smog, there is a noticeable relative impact based on the end-of-life scenario implemented. For ozone depletion, Figure 7 shows that wasting reinforced concrete during the end-of-life phase can account for 43% of the total environmental impact of a plant, whereas recycling may only account for 26% of the total. Similarly, for smog, Figure 7 shows that wasting reinforced concrete can account for 24% of the total environmental impact, whereas recycling reinforced concrete only accounts for 2% of the total impact. Both the waste treatment and recycling processes are energy, resource, and waste intensive processes, and can therefore contribute a notable environmental impact to the life cycle profile of a small WWTP. The wasting process releases substantial air emissions (e.g., greenhouse gases) due to the energy consumed by the machinery used to demolish the construction waste. The diesel associated with transporting the waste to the final destination, the deposition of inert material at a landfill, and the particulate matter emitted into the atmosphere are also contributing inputs to the wasting process. The recycling process also requires energy for the machinery and fuel for transportation. In addition, the recycling process emits particulate matter. However, literature suggests that the largest advantage of the recycling process is the avoided impacts associated with wasting for final disposal (e.g., landfilling, quarrying, and transportation) (Marinković et al., 2013). Although Figure 7 shows the recycling process to have lower potential environmental impacts compared to the wasting process, recycling is not always a viable option for small, rural facilities. Due to this minimal difference between the two process options, it is recommended that a small community implement the most feasible process.

3.5 Limitations and future work

Reliable LCA is important for helping industry practitioners make informed suggestions and to develop decision-making guidelines. The foreground data inventory used in this study is considered to be reasonably reliable, although it holds some limitations. Areas of data limitation include operating air emissions, sludge production rates, electricity usage, study sample size, and end-of-life inventory. Operating air emissions are seldom included in WWTP LCA studies (Morera et al., 2017), and both operating air emissions and sludge production rates are rarely documented through the NDEE or other databases. Moreover, the communities did not maintain air emissions records, and most communities did not maintain sludge production rate records. Thus, operating air emissions were largely estimated based on literature values (Foley et al., 2010), and sludge production rates were estimated using a simple linear regression model based on the few data points available through the NDEE. Although the environmental impacts due to air emissions and soil emissions were relatively small for most impact categories, with the exception of non-carcinogens for soil emissions, more thorough, site-specific studies are recommended to monitor and record air emissions resulting from the biological wastewater treatment process, as well as more precise sludge production rates for small community WWTPs.

The study represented each case study's electricity usage by using an average rate based on one to three years' worth of actual plant electricity usage. Electricity usage and the associated environmental impacts may vary year to year. However, even with such variability, the ultimate result of the research is not expected to change, and electricity is likely to remain the largest relative impact for a majority of the impact categories.

The sample size of 16 is not large, and site-specific factors dominate much of the variability between plants. But given the extensive work to compile the detailed construction and operational data, this is the first study of its kind to use as many as 16 case studies. It is recommended that future studies use as much site-specific data as possible. Lastly, there is limited data availability regarding the end-of-life phase for small WWTPs. Therefore, this phase was limited to a sensitivity scenario analysis. Future work may consider a detailed end-of-life phase of small WWTPs in their system boundaries to highlight potential environmental offsets due to demolition and disposal.

4. Conclusions

WWTPs are vital civil infrastructure systems. As small, rural communities struggling with aging or inadequate WWTPs upgrade and renovate their WWTPs, it is especially important that the long-term environmental sustainability is taken into consideration. The goal of this study was to use case studies to discuss the environmental impacts related to both the construction and operation of small WWTPs. A detailed data inventory was collected and analyzed using LCA methodology and MRA to identify factors that influence the variability in impacts among the case studies.

The implications this study has for small communities seeking wastewater infrastructure loans includes initial guidance on how to make potential sustainability improvements. Both the operational and construction impacts are important stages contributing to the life cycle environmental impacts of a small WWTP. When considering the contribution of operating energy to the overall average environmental burden of each impact category, the contribution of this process is over 50% for most impact categories. Environmental impacts from operating energy are influenced by energy efficiency. Many operational inefficiencies can be attributed to issues within the plant such as lack of automation. When considering the contribution of construction to the overall average environmental burden of each impact category, the contribution of this process is over 5% for most impact categories. Environmental impacts from construction are highly variable from plant to plant.

As WWTPs become more energy efficient, the environmental impact from operating energy decreases and construction impacts become relatively more important. The variability in construction impacts is largely driven by key factors unrelated to flow and identified by MRA, including CUR, cast iron, and aluminum. These are areas that a practicing engineer may consider when balancing environmental tradeoffs related to construction. Strategies that may directly reduce construction related environmental impacts include minimizing the use of these non-process related materials such as cast iron and aluminum, through alternative plant site layouts and site selection or limited usage for appurtenances like railings and grating, respectively. Additionally, building a plant to operate closer to current flow rates (i.e., increasing CUR) will reduce construction related environmental impacts by indirectly reducing the contribution of process related factors such as concrete and reinforcing steel to the overall environmental impact.

Lastly, different scenarios may influence the life cycle environmental impacts of a small WWTP. Environmental impacts from construction, regardless of impact category, decrease with increased design life under the assumption of constant operations. End-of-life consideration does not heavily influence the environmental sustainability of a WWTP.

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