Contribution of the construction phase to environmental impacts of the wastewater treatment plant

Thi Kieu Loan Nguyen[a], Huu Hao Ngo[a,*], Wenshan Guo[a], Soon Woong Chang[b], Dinh Duc Nguyen[b,c], Tien Vinh Nguyen[a], Duc Long Nghiem[a]

[a]*Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, NWS 2007, Australia*
[b]*Department of Environmental Energy Engineering, Kyonggi University, 442-760, Republic of Korea*
[c]*Institution of Research and Development, Duy Tan University, Da Nang, Vietnam*

*Corresponding author: Email: ngohuuhao121@gmail.com

Abstract

This study aims to investigate the environmental issues regarding the construction phase of the wastewater treatment plant (WWTP) and explore the roles of different materials through their environmental impacts. Detailed inventories of the two WWTPs were conducted by involving materials and transportation for civil works undertaken. EPD 2018 and ReCiPe life cycle impact assessment methods were employed to measure all the impact categories. Five treatment processes - (1) pumping, (2) primary treatment, (3) secondary treatment, (4) sludge line, and (5) building landscape - were considered for the assessment. It was found that concrete and reinforcing steel played similarly vital roles in most of the EPD 2018 impacts. The significant score of reinforcing steel was found on human cancer toxicity, which contributed more than 90% of the impacts. The contribution of diesel on ozone formation was 5% higher than that of reinforcing steel. Glassfiber was responsible for 70% of the burdens on ozone depletion, showing much higher than the total share of concrete and reinforcing steel. Primary treatment units only contributed 9.5% of the construction impacts in the Girona WWTP but up to 43.8% in Mill Creek WWTP mainly because of the proportion of consumed materials. In short, the comprehensive data inventories were necessary when evaluating the total environmental impacts of the WWTP.

Keywords: Life cycle assessment, environmental impacts, wastewater treatment plant

1. Introduction

The purpose of a wastewater treatment plant (WWTP) is to remove contaminants from the effluent before they are released to receiving water bodies. Besides generating dischargeable effluent, WWTPs also cause problems during their operational lifetimes, such as global warming and climate change (Nguyen et al., 2019). Life Cycle Assessment (LCA) is one of the most trusted methodologies for measuring the impacts of a WWTP throughout its life cycle and assessing its performance (Gallego-Schmid et al., 2019). Evaluation is generally conducted by analyzing the emissions from an individual relevant process or the whole system. LCA can assess the environmental sustainability of a process by measuring the impacts on different categories (Corominas et al., 2020).

LCA has been conducted to analyze the environmental performance of WWTPs since the 1990s, and it has resulted in many papers (Nguyen et al., 2020). Most studies focus on the operation phase, which is deemed to make the most significant contribution to the state of the natural environment. The construction and demolition phases are commonly ignored in many papers as their proportion is assumed to be negligible compared with the operation stage (Sabeen et al., 2018). The consumption of chemical and other related energy during the treatment process resulting in a considerable amount and various types of emissions and wastes (Nguyen et al., 2020). Compared to the operation process, construction generally occurs in a short time. Other reasons explaining the exclusion of the construction stage from the research are the limited information and time-consuming costs associated with building the data inventories (Morera et al., 2020). Moreover, published LCA studies lack transparency in data provided (Gallego-Schmid et al., 2019), which leads to limitations in choosing the research boundary and minimize the results.

According to some recent reviews, Gallego- Schmid et al. (2019) indicated that 32% of the LCA studies in developing countries include construction, while another study reported that only 22% of the LCA papers review the construction process (Nguyen et al., 2020). The relative contributions between construction and operation need more evidence (Morera et al., 2020). According to Emmerson et al. (1995), the construction stage contributes less than 5% of the overall potential impacts. Meanwhile, some other research highlights the significant role of construction on some impact categories (Morera et al., 2017, Resende et al., 2019), which are described in detail below in this study. The differences between studies might come from the availability and quality of the inventory data. There are different methods to build up the inventory data for each case. Previous analyses have primarily fallen short in considering the formation of the individual treatment unit. As a system, to improve the accuracy of the WWTP assessment, all the relevant activities need to be included. Despite the differences in technology, data inventories, and assessment methodology, more LCA studies are needed for better and comparable assessments.

Only a limited number of existing studies identify the contribution of construction works and analyze the proportion of each unit process to the total environmental impacts wielded by WWTP. Assessing the stage contribution at the unit process is necessary to explore the biggest contributors to mitigation strategies (Xue et al., 2019). Moreover, the construction stage has a greater influence when a broad range of construction materials list is provided (Morera et al., 2017). Previous studies have problems in calculating the burdens of building materials. Most previous papers concerning materials focused only on Global Warming Potential (GWP), while other environmental impacts are ignored (Jeong et al., 2019). This paper examines in more detail the construction activities of different units in WWTPs, such as pumping, primary treatment, secondary treatment, sludge treatment, and other processes (building and exterior landscaping). To bridge the gaps in our knowledge, LCA in our study considers the materials component of each unit process and analyses their impacts on various environmental indicators.

This study aims to present a complete report on the influence of various parts of the WWTP to the environment. LCA is conducted to: (1) classify and quantify the materials used in the construction phase; (2) carry out an analysis on the significant impacts categories; (3) explain the role of some primary elements. The scope of the research focuses on the construction phase solely. Most studies have an interest in comparing the proportion of construction with operational aspects (Xue et al., 2019, Morera et al., 2020). However, this study is to understand the impacts of each unit in various categories and to explore the differences by analyzing the amount of related material. As specific Environmental Product Declaration (EDP) is not available for all the devices, equipment was excluded. Moreover, this research only considers the core units without the inclusion of the collection sewer system.

2. Materials and methods

2.1. Life cycle assessment

LCA is a comprehensive procedure for analyzing the potential environmental impacts of a product or a process. An LCA study is typically carried out in four steps, namely: (1) goal and scope definition, (2) life cycle inventory analysis (LCI), (3) life cycle impact assessment (LCIA), and (4) life cycle improvement analysis and interpretation (LCAI) (ISO, 2006).

2.1.1. Goal and scope

The goal of this study is to analyze the impacts of different units during the construction phase for two WWTPs. The chosen case studies are Girona, located in Catalonia, Spain, and Mill Creek in Cincinnati, Ohio, United States. There are various functional units depending on the objective of the research. The functional unit of this study is 1 m^3 of influent wastewater.

System boundaries comprise the input and output flow of materials and energy resources for the construction phase. It is essential to mention here that the operation and demolition phases are not considered as part of this research. In this study, all the material input for infrastructure site and earthworks are comprised, which include the building components (wall, insulation, foundations, etc.) and treatment components. Production of materials, their transportation from the factory to the WWTP sites, and consumption to build the infrastructure systems are covered.

2.1.2. LCI

The LCI includes all the materials required to build the infrastructure and all the resources for material production (ISO, 2006). The data for the target systems and raw materials were obtained from published reports in the literature (Morera et al., 2017, Arden et al., 2019, Xue et al., 2019). More details about the plant configuration at the Girona WWTP are documented in the work of Morera et al. (2017), while the Mill Creek plant is part of the research by Arden et al. (2019). Inventory data on systems construction referred to the functional unit are shown in Table 1 for Girona WWTP and Table 2 for Mill Creek WWTP. The full material list for two WWTPs are gathered and provided in the supporting documents.

Table 1. Summary of inventory for Girona WWTP, values are referred to 1 m^3 of influent

Material/Process	Unit	Total
Inputs		
Diesel	MJ	2.96E-02
Transport	tkm	1.61E-02
Reinforcing steel	kg	4.92E-03
Other steel	kg	1.61E-04
Cast iron	kg	2.68E-05
Aluminium	kg	1.96E-06
Wire copper	kg	1.34E-09
Elastomeric rubber	kg	2.68E-05
Polyester reinforced with glass fiber	kg	1.15E-03
PVC	kg	3.49E-05
Wood	m3	1.55E-07
Concrete	m^3	5.33E-05
Brick	kg	6.42E-04
Other concrete	kg	2.36E-03
Roofing tile	kg	7.48E-05
Plastering	kg	5.11E-09
Synthetic oil	kg	6.61E-06
Mastic asphalt	kg	3.74E-06
Gravel	kg	1.03E-02
Adhesive	kg	5.00E-07
Cement + mortar	kg	1.45E-03

Paper	kg	2.10E-09
Windows	kg	3.16E-06
Paint	kg	1.29E-07
Butyl	kg	2.01E-09
Crushed rocks	kg	2.99E-03
Resin	kg	3.29E-06
Bitumen	kg	3.87E-06
Water	kg	9.44E-04
Rock wool	kg	2.10E-06
Output		
Material deposition	ton	3.23E-04

Table 2. Inventory for Mill Creek WWTP, values are referred to 1 m^3 of influent

Material	unit	Total
Inputs		
Concrete	m3	2.54E-05
Reinforcing Steel	kg	2.59E-03
Electrical steel	kg	2.27E-05
Stainless 18/8 coil	kg	3.84E-06
Other steel	kg	4.89E-06
HDPE	kg	2.96E-05
Cast Iron	kg	5.78E-05
Aluminum	kg	1.36E-06
Copper	kg	3.99E-06
Output		
Earthworks	kg	3.40E-02

2.1.3. Impacts assessment

The potential environmental impacts have been calculated through the use of LCIA characterization factors related to the subset of impact categories from ReCiPe 2016 and EPD 2018 (PRe', 2019). SimaPro 9 ® was conducted for the assessment (PRe-sustainability, 2018). Both mandatory and optional LCIA elements were considered in this analysis. Necessary elements include a selection of impact categories and category indicators, classification of inventory data, and characterization of the inventory within the impact categories. Optional elements consist of normalization of category indicators where the results refer to information, grouping impact categories, weighting results across impact categories, and data quality analysis (ISO, 2006).

a. EPD (2018)

This method was developed from EPD 2008, EPD 2013, and used to create the Environmental Product Declarations (EPDs) (PRe', 2019). In the EPD, the volume of materials and energy used to manufacture a product is declared. Therefore, this method provides documented and comparable information about the impact of a single product during its whole life cycle. EPD 2018 helps to provide a reliable source of data on the environmental burdens of a product and compare it to choose better materials. By using EPD 2018, eight impact categories are reported. Especially, eutrophication, global warming, ozone depletion, and abiotic resource depletion are taken from the CML-IA baseline method, while acidification adapted from CML-IA nonbaseline method. Water scarcity and photochemical oxidation are based on the AWARE method and ReCiPe 2008, respectively (PRe', 2019). The EPD method is only applicable to the European context.

b. ReCiPe 2016

This method is an updated and extended version of ReCiPe 2008, which involved midpoint and endpoint impact categories (PRe', 2019). ReCiPe was known as the method with the broadest set of impact categories. A key benefit of ReCiPe 2016 is its ability to provide global characterization factors while maintaining a number of indicators to implement at the national and international levels. At the midpoint level, 18 impact categories were quantified to observe the relative importance of emissions or extraction. All of these indicators are multiplied by damage factors to analyze the damage pathways to the endpoint area. The endpoint categories were calculated and comprised of human health, ecosystems, and resource scarcity (PRe', 2019), to reflect the potential effect. Water consumption on human health, terrestrial ecosystems, and freshwater ecosystems are newly added to focus on the water footprint. The advantage of the ReCiPe method is that single scores analyses help to compare damage categories easily.

2.2. Procedure to obtain the construction inventory

Detailed inventories for the construction phase include three steps: firstly, gathering and classifying the material list; secondly, searching for an equivalent element in the Ecoinvent database; and thirdly, calculating the material inventories. By applying these steps, all the resources used to manufacture and transport the materials are included. After being normalized to the functional unit, the amounts of all materials are presented in the list. Ecoinvent database provides information about raw materials and energy required to produce each element.

Five WWTP units are considered in this case study: (1) pumping, (2) primary treatment, (3) secondary treatment, (4) sludge line, and (5) others.

2.3. Wastewater treatment plants description

All the information on these two plants configuration is based on the 2016 reports (Commission, 2016, Institute, 2016), as presented in Table 3. These WWTPs function by removing nutrients in an advanced way, but they differ from each other regarding treatment capacity and technology.

Table 3. Characteristic of the case studies WWTPs

WWTP Location	Design PE	Design flow ($m^3.d^{-1}$)	Design treatment	Influent BOD (mg/l)	Effluent BOD-TN-TP (mg/l)	Removal efficiencies BOD-TN-TP (%)
Girona Spain	206,250	55,000	BNP	167.46	10 – 7.94 – 0.74	94 – 77.6 – 86.2
Mill Creek United	850,000	454,200	B/TSS	218.75	2.17 – 0.54 – 0.10	99.2 – NR – NR

States

Design treatment (B: BOD removal; N: Nitrogen removal; P: Phosphorus removal; TSS: Total solid suspended removal). NR: not relevant. TN: total nitrogen. TP: total phosphorus.

3. Results

3.1. Environmental impact assessment for case studies

3.1.1. Girona WWTP

Fig.1 presents the results obtained from the LCA for the Girona WWTP on the eight impact categories. It shows the contribution of the different elements included in the infrastructure system. It can be seen from the results that eight factors responsible for substantial impacts on all categories. These components include six materials and two other elements. The materials are diesel, reinforcing steel, glass fiber reinforced plastic, and concrete. The two other elements are the inert waste from the earthworks and transportation activities. Concrete and reinforcing steel present similar significant roles in most of the impacts, and they range from about 17% to 47%. The most considerable percentages show the footprint of reinforcing steel on abiotic depletion elements similar to the impact of concrete on water scarcity. This is explained by the raw material and energy consumption in steel and concrete production. Glass fiber reinforced plastic accounts for more than 10% to 20% of all indicators. The highest percentage of diesel is 19% on photochemical oxidation. The share of inert waste and reinforcing steel on ozone layer depletion amounts to approximately 19%.

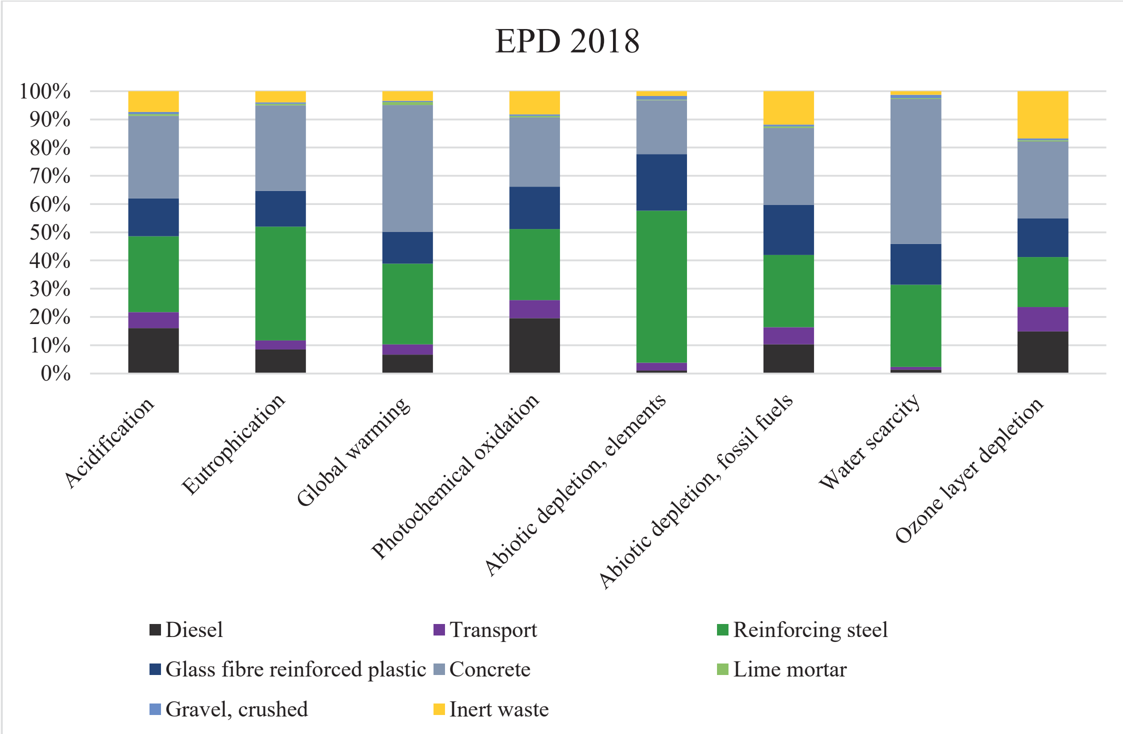

Fig.1. Life Cycle Impact Assessment (LCIA) using EPD 2018 indicators for Girona WWTP

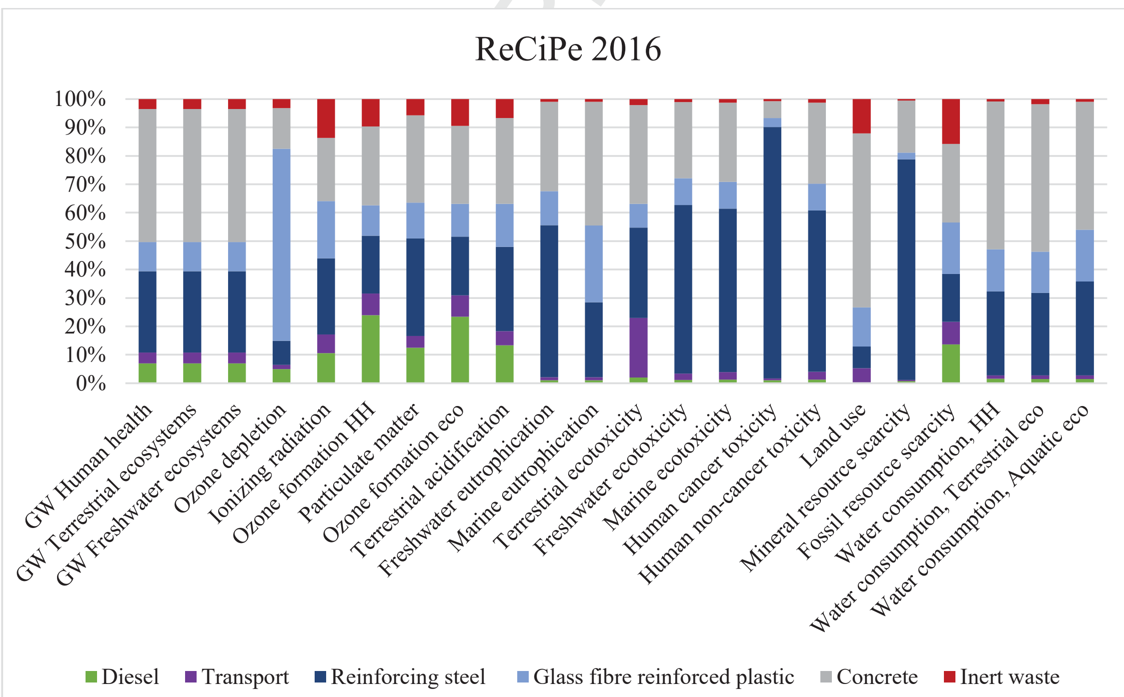

Fig. 2. LCIA using ReCiPe 2016 indicators

By using ReCiPe, the results are once again confirmed from Figure 2 that the largest contributor is reinforcing steel and concrete. The most significant impacts of reinforcing steel are responsible for 90% on human cancer toxicity and 80% on mineral resource scarcity. Glass fiber reinforced plastic and concrete reveal a significant influence on OD and land use, respectively. Diesel and inert waste do contribute to all impact indicators with a small score on most categories. The biggest share of diesel is evident for ozone formation concerning both human health and ecosystems. Meanwhile, the most considerable proportion of transportation contributes to terrestrial ecotoxicity, which accounts for more than 20% and is only behind concrete and reinforcing steel.

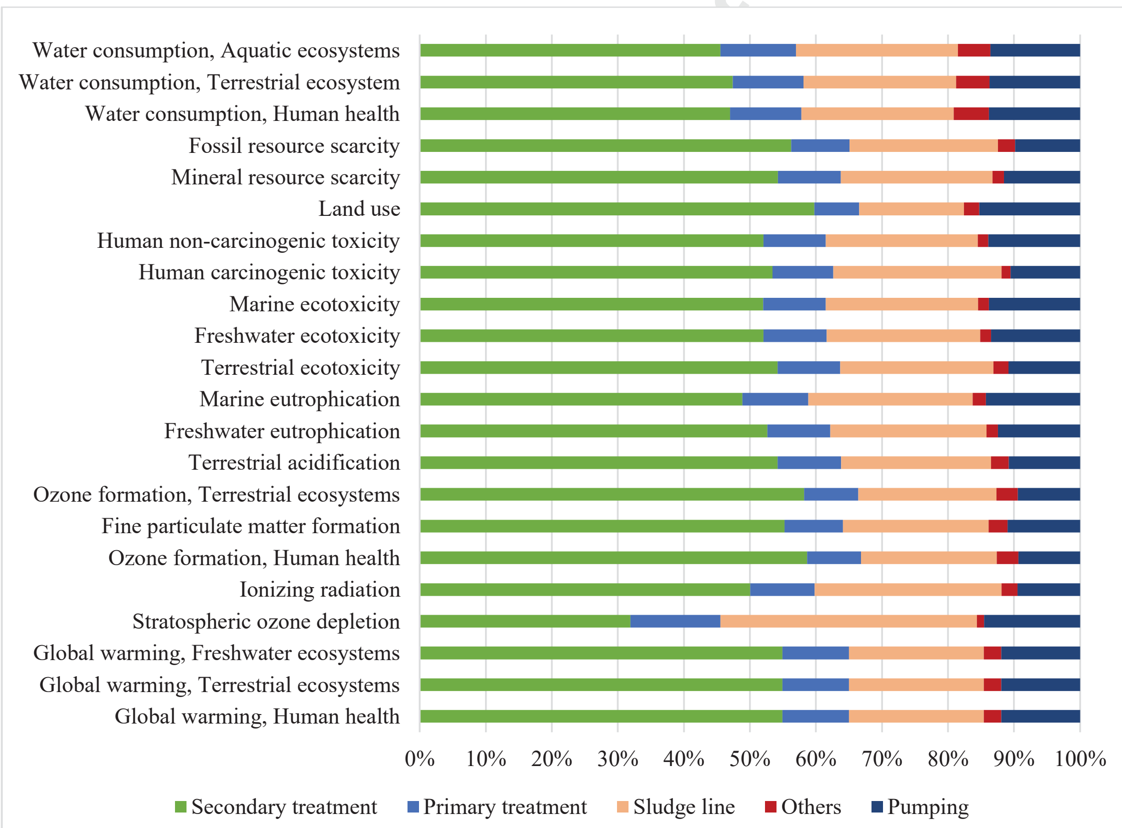

Fig. 3. LCIA using ReCiPe 2016 for a single unit in the construction of the Girona WWTP

SimaPro helps to analyze the burdens of each treatment unit in all categories by identifying the components and factors which generate a high proportion. For parameter analysis, all the treatment units are normalized and presented in Figure 3. Results show that the secondary treatment process dominated most of the impact categories, followed by the sludge line, pumping, and primary treatment. The secondary treatment process wields the most effect on land use and ozone formation. The hierarchy has a change in stratospheric ozone depletion, while the sludge line records the biggest influence of 40%.

3.1.2. Mill Creek WWTP

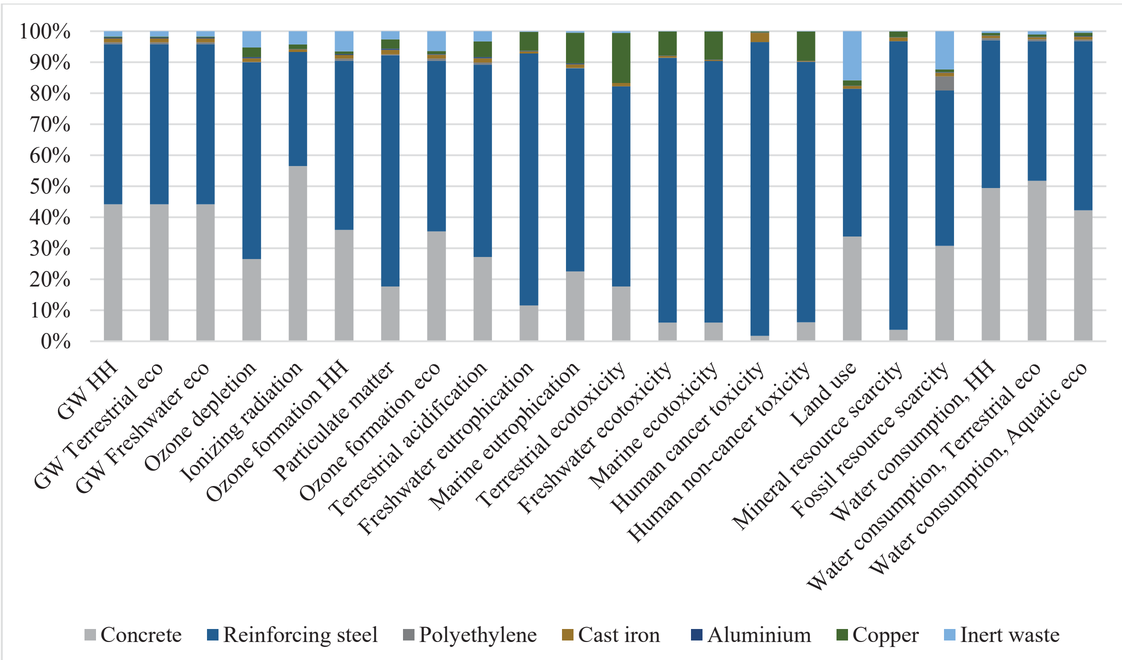

Figure 4. ReCiPe method for construction material in Mill Creek WWTP

As can be seen in Figure 4. the material list was classified into seven main groups, namely concrete, reinforcing steel, polyethylene, cast iron, aluminum, copper, and inert waste. Reinforcing steel also contributes significantly to most of the impacts, except for ionizing radiation, where the largest share is concrete. Inert waste plays a vital role in land use and fossil resource scarcity. Copper, which was barely mentioned previously, accounts for 17% of the burden on terrestrial ecotoxicity. The impact of polyethylene is quite small for all categories except for fossil resource scarcity, and it contributes 5% to the total.

The contribution of each treatment unit is expressed in Figure 5. Primary treatment scores more than 50% of 14 of the 22 impacts categories. The most significant burden of primary treatment can be found in land use, which reaches as much as 77%. Secondary treatment only has a substantial impact on ionizing radiation. While primary treatment and secondary treatment are the two major contributors, the influence of the sludge line is quite small for all indicators. The role of pumping is negligible in this case.

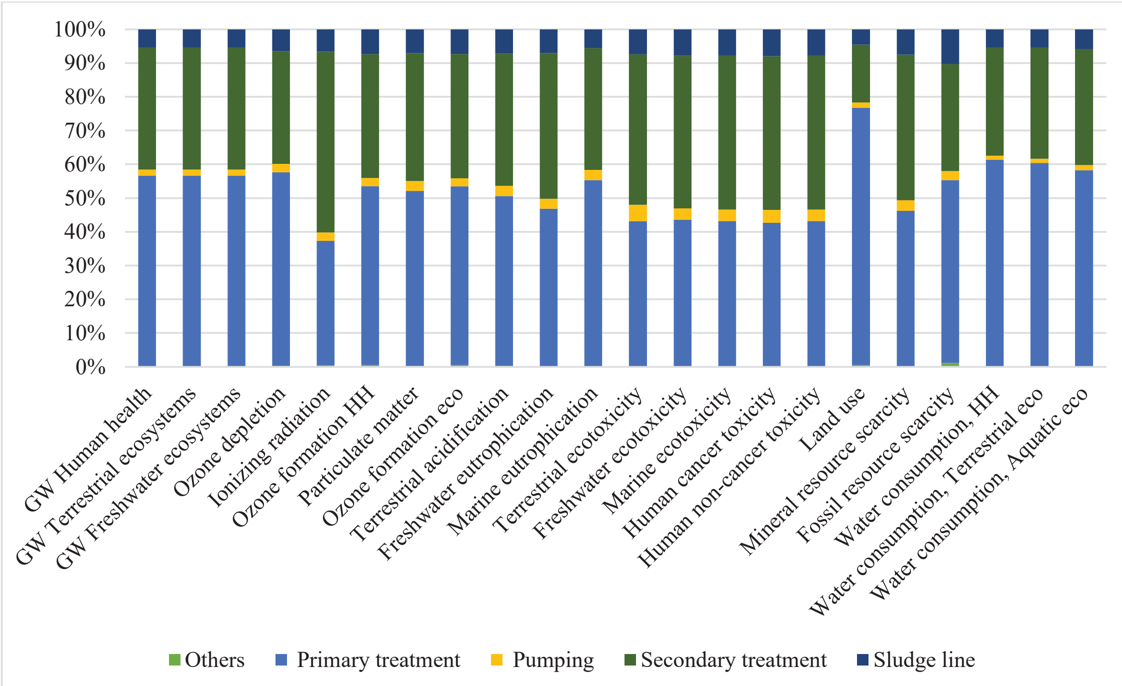

Figure 5. Contribution of the individual treatment unit

3.1.3. Weighting indicator results

Figure 6 shows the ReCiPe weighted results at the endpoint level, where impacts are examined at the end of the cause-effect chain, using the damage assessment on human health (HH), ecosystems, and resources. The default Hierarchist version of ReCiPe with average weighting factors is chosen to be multiplied and corresponds to each impact category. Weighted results are referred to as eco-indicator point (Pt), the annual environmental load per citizen. As shown in Figure 6, the damage category HH accounts for most of the total ecological burdens, 94% in Girona WWTP, and 95.4% in Mill Creek. Ecosystems score 4.5% and 5.8% in Mill Creek and Girona, respectively, while resources make only a negligible contribution.

In Girona WWTP, secondary treatment units contribute more than half of the total impact, accounting for 53%. Sludge line is the second-highest contributor with a share of 23.3%, followed by pumping and primary treatment, which account for 12.5% and 9.4%, respectively. Notably, in Mill Creek WWTP, the proportions of primary treatment and secondary treatment are similar, amounting to 43.8% and 44.9%, respectively. The total score for the sludge line and pumping is about 11%, where one third goes to the pumping contribution.

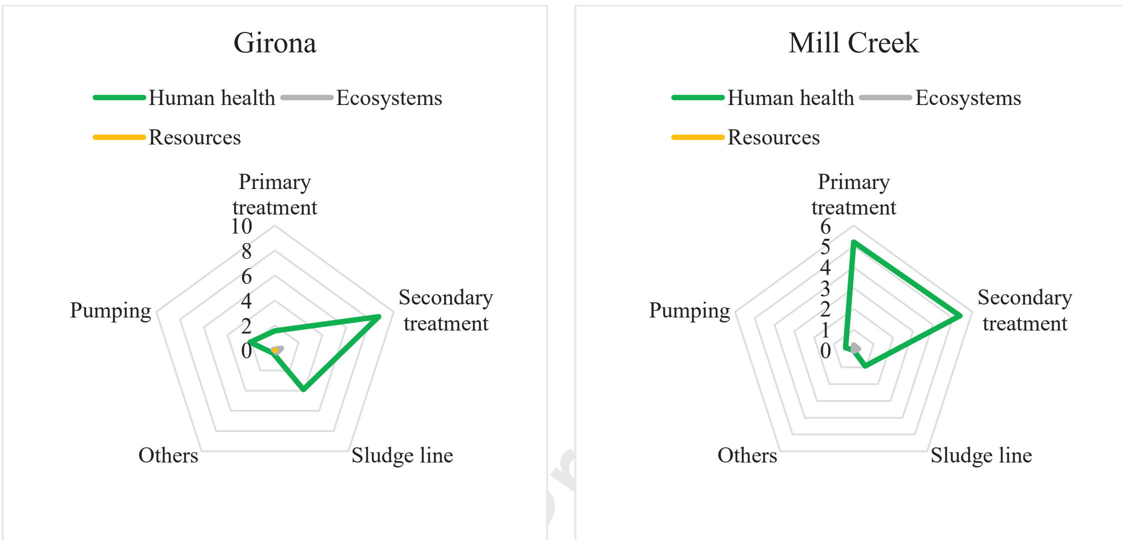

Figure 6. ReCiPe's weighted endpoint damage categories for case studies

3.2. Environmental burdens caused by construction reported in the literature

3.2.1. Construction of low-tech wastewater systems

In most studies done utilizing low-tech and low-energy processes, construction can be responsible for up to 80% of the impacts for some categories (Corominas et al., 2013, Resende et al., 2019). There are two main reasons for this outcome. Firstly, due to the low-tech, low-energy treatment process, the impacts of electricity, and the volume of emissions from the operation phase are quite small. Secondly, is that this system requires a large area, and therefore, a massive amount of materials is needed for construction. In total, there is an increase in construction impacts and a decline in operation burdens. Lutterbeck et al. (2017) reported that the development of the upflow anaerobic sludge blanket combined with an anaerobic filter (UASB/BF) contributes 36% to the total impacts of the system. The consumption of fiberglass material is the cause of the burden. Moreover, the production of the silicon wafer and copper wire makes the greatest contribution to the photoreactors' construction and the single total score for environmental impacts, accounting for 45% of the points (Pt). Regarding three endpoint categories, resource estimates for the most significant burdens being shared concerning the construction, while the operational matters mostly influence human health and ecosystems.

According to Garfi et al. (2017), the construction stage accounted for 25-35% of the total impact. Nevertheless, construction shares 60-65% of the burden on metal depletion potential. Based on prior studies, it was suggested that the longer the distance of materials transportation, the significantly higher would be the impacts of construction (Garfí et al., 2017). Resende et al. (2019) recently explored the contribution of some primary materials and found that although the amount of steel was much smaller than brick, its influence is still sizeable.

3.2.2. Construction of WWTP

Table. 4. Summary of LCA studies concerning the construction phase since 2015. (C: construction phase, O: operation phase, D: demolition phase)

Reference	Boundary	Phase included	Data inventory	Functional unit	Data source	LCIA method
(Risch et al., 2015)	Sewer system, WWTP	C, O, D	Provided	Collection and treatment of a wastewater load from 5200 PE/d	Ecoinvent	ReCiPe Midpoint and Endpoint V1.07
(Jeong et al., 2015)	Water supply, wastewater collection/ treatment, stormwater collection system	C, O, D	Not provided	1 m^3 of water distributed to point-of-use	NA	TRACI v2.1
(Hernández-Padilla et al., 2017)	WWTP	C, O	Provided	1 m^3 of treated wastewater	Literature	IW+, ReCiPe, Impact 2002+
(Garfí et al., 2017)	WWTP	C, O	Provided	1 m^3 of water	Ecoinvent	ReCiPe Midpoint

(Morera et al., 2017)	WWTP	C, O, D	Provided	1 m^3 of treated wastewater	Plant project budget	ReCiPe Midpoint
(Zepon Tarpani et al., 2018)	WWTP	C, O, D	Provided	1000 m^3 of wastewater	Ecoinvent, reports	ReCiPe 2008
(Rashidi et al., 2018)	WWTP	C, O	Not provided	100,000 m^3 d^{-1} for 20 years	Literature	Local methodology
(Awad et al., 2019)	WWTP	C, O	Provided	1 m^3 of treated wastewater	Ecoinvent	CML 2000
(Li et al., 2019)	WWTP	C, O	Not provided	1 m^3 of treated wastewater	NA	Traci 2.1
(Xue et al., 2019)	Urban water system	C, O, D	Provided	1 m^3 of treated and distributed water, and 1 m^3 of treated wastewater	Plant document, US database	Traci 2.0
(Morera et al., 2020)	WWTP	C	Provided	1 m^3 of treated wastewater	Construction budget, literature, Ecoinvent	ReCiPe Midpoint
(Lopes et al., 2020)	WWTP	C, O	Provided	1 m^3 of treated wastewater	WWTP project report	CML 2 baseline; Cumulative energy demand

Several LCA studies have shown an interest in the construction phase, and they are listed in Table 4. Regarding the construction phase of these studies, Award et al. (2019) asserted that it made the smallest contribution when compared to the operations phase. An exception here is freshwater aquatic ecotoxicity, which reached 42% due to cement and steel production. Jeong et al. (2015) discovered that infrastructure construction for wastewater collection and treatment share 27 % of the impact on carcinogenic effects, even more than the proportion of electricity consumption. The highest contribution of construction is documented in Risch et al. (2015), as only four among 18 impact categories are less than 5%. Especially, 81% of urban land occupation and 91% of terrestrial ecotoxicity are those reported for construction.

The results in the research by Morera et al. (2017) and Xue et al. (2019) have similarities. Morera et al. (2017) reported that for climate change (CC), ozone depletion (OD), and freshwater eutrophication (FE), the contribution of construction varies from 5 to 10% of the total impact. The percentage of human toxicity (HT) and fossil depletion (FD) are approximately 16%. Metal depletion (MD) has the largest share of 63%. Xue et al. (2019) contended that the construction stage (WTP combined WWTP) contributed less than 5% to most of the environmental impacts. MD shows the significant role played by construction, which accounts for 68%, followed by human health and ecotoxicity, of which the percentages are 13% and 7%, respectively.

Concerned about the impacts of different materials, Lopes et al. (2020) found that materials consumption in the construction stage has a significant impact potential due to the use of reinforcing steel, cement, and gravel. Reinforcing steel during concrete production is the main reason for the greatest impacts of construction on abiotic depletion, ozone layer depletion, all toxicity indicators, and acidification. Jeong et al. (2015) stated that when broadening the scope of construction materials, construction is expected to exert much more environmental impacts. In their research, steel and cast iron production contribute 16% to non-carcinogenic factors. Diesel fuel consumption is the main reason for the proportion of terrestrial and marine ecotoxicities in research by Risch et al. (2015). According to Morera et al. (2017), the concrete production process for secondary treatment and sludge line contributes the most to CC. Meanwhile, the reinforcing steel production process is focused on MD and HT. There is only a minimal contribution made by plastic production to HT and MD.

A very recent study has the same interest as ours. Morera et al. (2020) found secondary treatment is the unit with a significant share between 30 and 70% for most of the potential impacts. Concrete is the most important material as it represents 38% of CC, 25% of OC, and 25% of FD. The secondary treatment has a major proportion due to more than half of the amount of concrete is consumed here. The sludge line has a proportion smaller than 10%. Reinforcing steel makes the second-highest contribution, which represents 20 % of CC, 18% of FD, but a significant proportion of MD amounts to 64% share. Polystyrene consumption has a marked influence on OD.

After reviewing the results from existing studies, we found that the construction phase cannot be neglected when analyzing the total environmental impacts of a WWTP. The contribution of the construction phase should be calculated case by case and could not be estimated base on documented results. Table 4 shows there are different LCIA methods for environmental assessment, but only a small number of LCA studies. For this reason and the paucity of results, more studies are needed, and they should focus on the environmental impacts of the construction phase. From the life cycle perspective, the performance of the WWTP can be improved by maximizing the environmental benefits and minimizing the undesired impacts.

4. Discussion

4.1. Influence of materials to impact categories

Having better knowledge of what each type of material contributes to the environment will benefit in reducing impacts strategies. Some new materials, which have more physical advantages, are suggested as being able to substitute for traditional ones. However, regarding the raw material and energy consumption during the manufacturing processes, the more advantages they have, the more impacts they will make. For example, fiberglass material is widely used in construction because it is lightweight, compact, easy to handle, and has higher chemical resistance than concrete. The quantity of consumed concrete is 110 times higher than glass fiber. Still, the environmental burdens caused by concrete are only four times that of fiberglass, concerning global warming and water scarcity. The other impacts of concrete are approximately double fiberglass, as can be seen in Figure 1 and supporting documents for Girona WWTP.

During the construction phase, diesel is consumed in building machines and diesel-electric generators. The results in the study by Risch et al. (2015) indicated that diesel fuel consumption contributes the most to terrestrial and marine ecotoxicities, while our research observes the negligible impact of diesel on these indicators. It can be seen that mining and refining processes during diesel production increase the acidification rate and reduce the neutralizing capacity of the soil. However, these impacts contribute to acidification much more than on ecotoxicity. Our finding agrees with that of Morera et al. (2020). Although the amount of diesel after normalization to 1m^3 of influent is different, its proportions are similar, as presented in Figure 7. Explaining our results, what we can see is that during diesel production and consumption, CO, CO_2, N_2O, and CH_2O were generated and emitted. These gases are ozone precursors, which are highly toxic to human health, block oxygen uptake, and responsible for global warming. Therefore, diesel greatly influences ozone formation, human health, ecosystems, and photochemical oxidation.

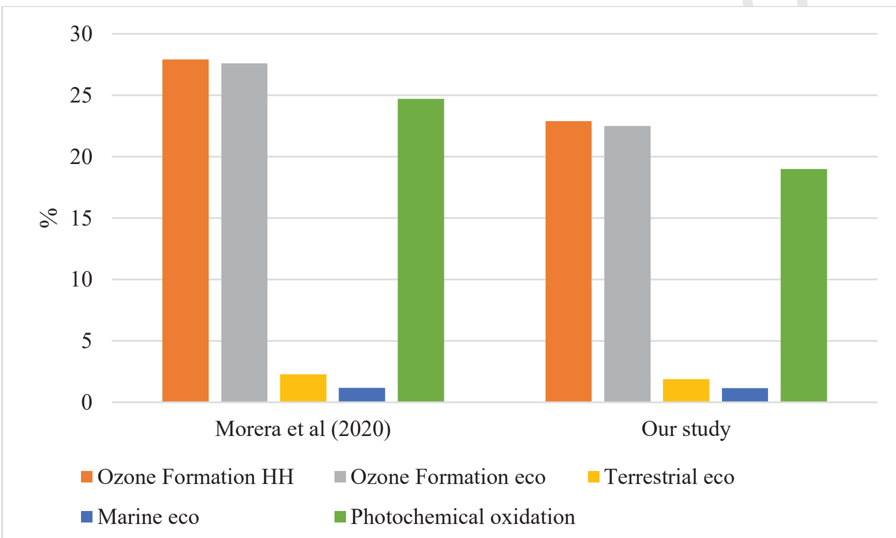

Figure 7. Diesel's impacts in our study and that by Morera et al. (2020). Ozone formation human health and ecotoxicity; marine ecotoxicity; and terrestrial ecotoxicity are analysed by ReCiPe, while EPD was conducted for photochemical oxidation.

4.2. Reinforcing steel, concrete, and their environmental impacts

Steel in general and concrete are two primary building materials. Concrete is accountable for less embodied energy and environmental impacts than other construction materials like glass, aluminum, and ceramic tiles. It is the most common material for foundations, structural walls, roofs, and floors because it has a long service life and durable. Due to the massive amounts of concrete consumed in the building industry, it is responsible for the majority of embodied energy. Reinforcing steel is used in reinforced concrete to strengthen the structure and hold the concrete in tension. As stated in the previous study, reinforcing steel has high impact potential as a consequence of the production process, which consists of mining and steel manufacture (Lopes et al., 2020). Vast quantities of concrete and reinforcing steel, as seen in Table 5, are consumed in the reviewed WWTPs.

Similar to other studies, our results show that reinforcing steel and concrete are the top two contributors to most of the impact categories with the exception of ozone depletion, where glass fiber is dominant. Global warming is a common reference standard for GHG emissions. Greater energy consumption will lead to higher GWP impacts. It can be observed from Figure 1 that concrete production has a higher GWP than that of steel. Toxicity potential, regarding ecotoxicity potential and human toxicity potential, is the negative effect on a living organism caused by pollutants or contaminants. Figure 1 and Figure 4 show that reinforcing steel has a higher impact on toxicity than concrete.

Table 5. Reinforcing steel and concrete used for construction per functional unit (FU)

WWTP/ References	Reinforcing steel (kg)	Concrete (m^3)	FU
LEscala/ (Morera et al., 2020)	0.074	0.0008	1m^3 influent
Granular activated carbon (Zepon Tarpani et al., 2018)	0.4150	0.0008	1000m^3 wastewater
Nanofiltration (Zepon Tarpani et al., 2018)	0.0901	0.0002	1000m^3 wastewater
Girona (our study)	0.00492	0.0000533	1m^3 influent
Mill Creek (our study)	0.00262	0.0000254	1m^3 influent

Due to large quantities of concrete and reinforcing steel and the significant contribution of these two materials, reducing them will lower the burdens. However, as they are two primary materials for building structures, it is difficult to limit their quantity. Therefore, other options to minimize their impacts should be considered, for instance, using sustainable alternative materials and recycling materials. As mentioned before, alternative material should be analyzed by LCA before being used, and more research is required on this topic. For the second option discussed above, material recycling is based on abiotic depletion (AD) and mineral resource scarcity (MRC). Concrete recycling has some advantages because it is hard to crush while recycling methods for metals are available. AD is the correlation between extractions of resources to its available stock of fossil fuels, minerals, and metals. Therefore, any attempt to recycle the metal materials could result in curtailing the abiotic depletion potential outcomes. Mineral resources are metals, minerals, and aggregates that are embedded in natural or anthropogenic stock. Mineral resource scarcity shows a promising reduction, which depends on the quantity of steel required. An effort to recycle steel more effectively will be beneficial for both impact categories.

4.3. The impact of individual treatment unit on the construction phase

Secondary treatment is responsible for the most substantial proportion of the total effects. As indicated in the study by Morera et al. (2020), secondary treatment units contribute between 30 and 60% depending on the size of WWTP and the impact categories. In this study, secondary treatment contributed 53% in the Girona WWTP and 45% in the Mill Creek WWTP. However, the share of primary treatment is significantly different when scoring only 9.5% in Girona but 43.8% in Mill Creek. These changes are due to expanding the size of primary treatment, which exhibited by the percentage of materials in the individual treatment unit (Table 6).

Table 6. Material usage in the primary and secondary treatment units.

Mill Creek		
Material	Primary treatment (%)	Secondary treatment (%)
Concrete	49.53	48.23
Reinforcing Steel	44.35	45.80
Electrical steel	0.19	67.68
Stainless 18/8 coil	3.04	22.04
Other steel	0.23	67.73
HDPE	27.78	0.00
Cast Iron	0.78	36.44
Aluminum	0.80	66.74
Copper	0.22	68.06
Earthworks	19.47	20.92
Girona		
Material deposition in a landfill	3.11	87.06
Diesel burned in mechanical machines	0.57	72.54
Transport	5.18	55.18
Reinforcing steel	8.60	55.15
Polyester reinforced with glass fiber	16.66	16.66
Concrete	11.53	56.50
Gravel	4.22	30.87

Table 6 presents the contributions of different materials to the construction process and their respective impact on the environment. The amount of materials is closely linked to the proportion of the effects; therefore, insufficient data inventories could lead to underestimating or not understanding the final numbers. Prior research attempted to create the material data inventories by using the concrete volume as a multiplier for other materials observed where high variations in outcomes were observed (Foley et al., 2010, Morera et al., 2020). Therefore, the material required for one unit cannot be representative of the entire WWTP.

This work highlights the critical role of building materials. The outcomes of this study still have limitations because some results may vary due to the sizes of WWTP or different treatment technologies. However, utilizing a practical approach, these outcomes do provide evidence for the potential impacts of building materials and promising reduction options. An interesting perspective on the future extension of this work would be to inspect how the results may be different when using alternative material and/or various sizes of treatment throughout the whole life cycle of a WWTP.

5. Conclusions

This study explored the relative contribution to environmental impacts generated from different treatment units by calculating the burdens of various materials used in two WWTPs. The life cycle assessment approach was applied using plant-specific data and the Ecoinvent database. The selective functional unit was 1 m^3 of influent wastewater. The key findings are as follows:

- Inclusion of the construction phase when analyzing the environmental impacts of the WWTP is essential.;
- In adition to concrete and reinforcing steel, diesel and glass fiber are also the major contributors to the impact of construction phase on the environment. The glass fiber led to ozone depletion, which resulted in 70% of the impact;
- Secondary treatment units contributed appropriately 50% of the environmental impacts during the construction phase.
- Increasing the size of the primary treatment could reduce the impacts of secondary treatment.

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