# Municipal Wastewater Sludge as a Sustainable Bioresource: Spatial Analysis Across Ontario

by

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## Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

## Statement of Contribution

I would like to acknowledge my co-authors, Dr. Nandita Basu and Dr. Ushnik Mukherjee, for their valuable contributions to the research described in this thesis. I also recognize the Ontario Clean Water Agency (OCWA) and all collaborators involved in the project, especially the late Aaron Law, whose guidance was instrumental in the early stages of this work.

# Abstract

Effective wastewater sludge management is critical for sustainable wastewater treatment, nutrient recovery, and environmental protection. However, Ontario lacks in data of sludge generation and nutrient content, particularly across diverse facility sizes and treatment processes. This study aims to fill that gap by estimating wastewater sludge generation, nitrogen and phosphorus content, and disposal practices across 548 municipal wastewater treatment plants (WWTPs) in Ontario. Using a combination of facility-level annual reports, the Wastewater Systems Effluent Regulations (WSER) database, Ontario Clean Water Agency (OCWA) records, and National Pollutant Release Inventory (NPRI) was developed treatment-specific coefficients from a subset of plants with complete data to extrapolate sludge generation, nitrogen and phosphorus mass for facilities lacking direct data.

For the year 2022, the most recent year with complete data, Ontario's WWTPs generated an estimated $356{,}265 \pm 35{,}859$ dry metric tons of sludge, with a per capita generation of 23.5 kg/person/year falling within the range reported in the literature (17.8–31.0 kg/person/ year). Nutrient content analysis revealed median concentrations of 29 kg/ metric tons of dry sludge for phosphorus and 42 kg / metric tons of dry sludge for nitrogen, resulting in an estimated $9{,}937 \pm 1{,}837$ metric tons of phosphorus and $15{,}302 \pm 9{,}044$ metric tons of nitrogen generation per year in wastewater sludge. Over 50% of the nutrients are concentrated in larger, anaerobic digester-equipped facilities, located primary in Southern Ontario. Incineration accounts for the end-use of 30% of the total sludge generated, resulting in the loss of their nutrients. In contrast, agricultural disposal, practiced by 140 facilities, allows for nutrient recovery from 26% of total sludge generated.

Spatial and process-level analysis revealed that plant size and stabilization method are predictors of disposal type. Large plants (defined with influent ($\geq 37{,}850$ m³/day), which are more likely to operate aerobic or anaerobic digesters, tend to adopt more sustainable disposal methods when conditions permit (e.g. during appropriate seasons). In contrast, small facilities (with influent ($\leq 3{,}785$ m³/day) often lack in advance stabilization and are more likely to rely on less sustainable practices such as landfill. Many of these facilities also lack consistent reporting, making it difficult to track sludge generated and disposal pathways.

By quantifying the generation of sludge and nutrient flows across Ontario, this study provides a baseline for evidence-based decision-making. The data can be used by municipalities and regulators to identify areas with high biosolids generation, data gaps, and to target specific regions for further

study or investment. These findings highlight the need for provincial-level data transparency and target strategies to promote nutrient circularity in municipal sludge management, particularly by addressing the data and resource gaps at smaller facilities. While this study provides a valuable province level overview, a key limitation is the reliance on extrapolation data or facilities lacking complete records, underscoring the need for improved, standardized reporting and new methodologies with more data in the future.

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# List of Abbreviations

WWTP Wastewater Treatment Plant

GHG Greenhouse Gas

PFAS Per- And Polyfluoroalkyl Substances

N Nitrogen

P Phosphorus

AD Anaerobic Digestion

SDG Sustainable Development Goals

BOD Biochemical Oxygen Demand

TSS Total Suspended Solids

CAS Conventional Activated Sludge

SBR Sequencing Batch Reactor

CHP Combined Heat and Power

OCWA Ontario Clean Water Agency

WSER Wastewater Systems Effluent Regulations

NPRI National Pollutant Release Inventory

ECCC Environment and Climate Change Canada

MECP Ontario Ministry of The Environment, Conservation and Parks

TS Total Solids

DS Dry Solid Factor

GC Generation Per Capita

# Chapter 1 - Introduction

## 1.1 Background and context

Municipal wastewater treatment is essential for protecting public health and environmental quality, but it generates large volumes of residual sludge that require careful management. In Ontario, regulatory frameworks such as the *Nutrient Management Act* (Ontario Ministry of the Environment, 2002) and supporting design guidelines (Pileggi et al., 2008) govern land application and disposal practices. While these policies have established a foundation for safe reuse, sludge management continues to present technical and financial challenges due to variable composition, handling difficulties, and emerging contaminants (O'Kelly, 2005; Okoffo et al., 2020; Oleszkiewicz & Mavinic, 2002).

Sludge, broadly defined as the solid, semi-solid, or liquid residue produced during the treatment of domestic sewage (Seiple et al., 2017) is generated at multiple stages and contains a complex mixture of water, organic matter, inorganic solids, and microbial biomass. The largest quantities are generated during primary, when settleable solids are removed through sedimentation, and secondary treatment, where microbial biomass from the degradation of organic matter and nutrients is separated from the treated effluent. In some processes, additional solids are formed during tertiary treatment through the addition of chemicals and physical processes in water purification. When this material is treated to meet regulatory standards for beneficial use or disposal—through stabilization, dewatering, or pathogen reduction—it is referred to as biosolids (Elgarahy et al., 2024). Although the distinction is straightforward, it has important implications: most data collection and reporting have focused on biosolids for compliance and end use, while the larger sludge stream remains poorly quantified (Seiple et al., 2017).

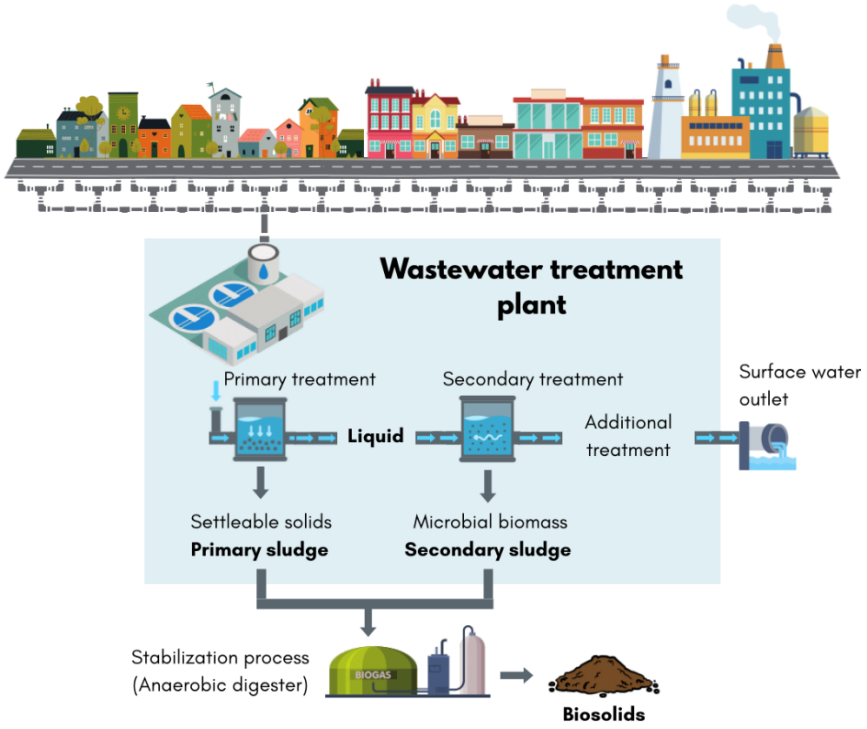



**Figure 1:** Municipal wastewater sludge generation process (designed in Canva).

Sewage sludge is also used as bioresource through the process of anaerobic digestion, which yields two products: biogas for renewable energy generation and biosolids with reduced volatile organic content suitable for beneficial reuse (Elalami et al., 2019; Khanh Nguyen et al., 2021). Biosolids can then be managed through land application as fertilizer or through energy recovery pathways (Chojnacka et al., 2023). Biosolids are nutrient-rich, particularly in nitrogen (N) and phosphorus (P), which are essential for agricultural productivity and global food security (Marchuk et al., 2023). They also contain potassium, micronutrients, and organic carbon, making them a valuable soil amendment (Fytili & Zabaniotou, 2008). Given concerns over phosphorus scarcity and the environmental costs of synthetic fertilizers, nutrient recovery from biosolids provides a sustainable, locally available alternative (Kahiluoto et al., 2015).

Because of their nutrient and energy potential, sludge management is increasingly framed within circular economy and sustainability agendas (Awasthi et al., 2022; Gherghel et al., 2019). Properly managed, they can contribute to several United Nations Sustainable Development Goals (SDGs), including clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), sustainable cities

and communities (SDG 11), responsible consumption and production (SDG 12), and climate action (SDG 13) (Bagheri et al., 2023).

However, a key barrier to achieving these benefits is the lack of spatially resolved data. Large facilities under stricter regulation often maintain detailed records, whereas smaller plants may lack systematic monitoring, leaving substantial gaps. This unevenness complicates efforts to estimate the quantity, nutrient composition, and treatment efficiency of sludge across a region, thereby limiting effective planning for reuse, infrastructure investment, and end-use allocation (Collivignarelli et al., 2019; Hudcová et al., 2019). Addressing this gap requires a big-data integration approach that compiles facility-level records, harmonizes multiple data sources, fills missing values, and applies spatial analysis to produce comprehensive estimates (Milbrandt et al., 2018).

Several international efforts demonstrate possible approaches. In the United States, Beecher et al. (2007, 2023) conducted national surveys and derived generation coefficients based on flow data to estimate biosolids production. Seiple et al. (2017) modeled sludge generation using influent characteristics such as $BOD_5$ and TSS combined with processes efficiencies for more than 15,000 facilities. In Europe, Eurostat developed country-specific coefficients based on flow or population equivalents, while in Australia, Okoffo et al. (2020) applied population-based linear models. Other studies have compiled detailed facility-level data without extrapolating to regional or national scales. For example, Jin et al. (2018) collected data on biosolids generation, treatment processes, and end uses from 136 Ontario facilities but did not estimate province-wide totals. Collectively, these studies highlight both the progress made and the limitations of current approaches, underscoring the need for comprehensive, integrated assessments to support sustainable management strategies.

## 1.2 Objectives

The overarching goal of this study is to improve understanding of sludge generation and management in Ontario through a data-driven, spatially resolved approach. Specifically, this work aims to:

1. Quantify sludge generation across wastewater treatment facilities by integrating multiple data sources and applying estimation methods to address missing or incomplete records.
2. Characterize regional variability in sludge production, nutrient content, and treatment processes to identify hotspots and assess opportunities for aggregation and resource recovery.

Recent advances in big data and decision-support frameworks offer a way to address this gap. By combining regulatory inventories, wastewater treatment facility databases, and spatial demographic datasets, it is now possible to generate more comprehensive, facility-level estimates of sludge production. Such approaches have been demonstrated in the United States to evaluate national-scale production, aggregation potential, and opportunities for waste-to-energy conversion (Seiple et al., 2017). In Ontario, applying similar methods can provide the evidence base needed to transition from disposal-oriented sludge management toward integrated resource recovery strategies. These include nutrient recycling, bioenergy generation, and greenhouse gas mitigation, aligning sludge management with broader sustainability objectives (Renfrew et al., 2024; Shen et al., 2015).

# Chapter 2 - Literature Review

This chapter provides the background necessary to contextualize the research presented in this thesis, addressing key aspects of wastewater treatment processes, sludge properties and management.

## 2.1 Wastewater treatment processes: sludge generation

The generation of sludge is a multi-stage process within WWTPs, where wastewater from residential, commercial, and industrial sources is treated to produce treated effluent and stabilized solids (Kumar et al., 2017). Primary treatment removes settleable solids by sedimentation, producing primary sludge (Riffat, 2012). Secondary treatment (e.g., activated sludge, trickling filters, biofilm reactors) converts dissolved organics into microbial biomass that is later separated as secondary sludge (Song et al., 2023). Following secondary treatment, many WWTPs apply tertiary treatment to meet stringent discharge regulation. These stages can include granular media filtration or membrane filtration, chemical phosphorus precipitation or nitrate polishing in denitrifying filters (Zagklis & Bampos, 2022) (Riffat, 2012). In some facilities, an additional quaternary treatment step is implemented, incorporating disinfection commonly though chlorination or ultraviolet irradiation, to inactivate pathogens, or advanced oxidation process such as ozonation to remove pharmaceuticals, and certain microplastics (Adeel et al., 2024). The treated liquid is then discharged to receiving water bodies, while the sludges generated undergo further treatment processing to stabilize this material where it reduces volume, eliminates odor, and removes pathogens such as bacteria and viruses, as well as other contaminants like toxic organic compounds. Once stabilized, these treated solids are referred to as sewage biosolids.(Elgarahy et al., 2024; Khanh Nguyen et al., 2021).

In contrast with WWTPs, lagoons provide low-energy treatment for small/rural systems via long retention in shallow basins; solids settle and partially digest. Sludge often accumulates as long-term storage and may not meet pathogen-reduction standards without further treatment, complicating inventory, and estimation. Lagoon systems vary in design and function, including anaerobic lagoons, primarily used for settling and partial digestion of solids; facultative lagoons, characterized by both aerobic and anaerobic layers; and aerated lagoons, where mechanical aeration promotes faster biological activity (Calabrò et al., 2024).

### 2.1.1 Wastewater sludge properties and characteristics

Wastewater sludge refers to the semi-solid by-products generated during the treatment of municipal or industrial wastewater. Its physical and chemical characteristics vary widely depending on the treatment stage, influent quality, and any chemical additives used during processing (Elgarahy et al., 2024). Key properties—such as moisture content, nutrient levels, pH, and pathogen presence—are critical for determining how sludge can be handled, treated, and reused.

The composition and behavior of wastewater sludge are influenced by factors including the origin of sewage, treatment technologies, and stabilization processes. These characteristics affect settling behavior, odor potential, pathogen risk, and suitability for downstream applications (Elgarahy et al., 2024; Singh & Agrawal, 2008).

### 2.1.2 Sludge storage, transportation, and application

Wastewater sludge can exist in either liquid or dewatered (dry) form, and its moisture content largely determines how it is stored, transported, and managed. Liquid sludge, which contains a high proportion of water, is generally handled near treatment facilities due to the cost and logistical challenges associated with transporting large volumes (US EPA, 2000). It may be temporarily stored in lagoons or tanks and, when stabilized, applied to land through spray or injection methods where permitted.

Dry sludge, with moisture content reduced to less than 10% (Le & Price, 2024), is easier to transport and can be stored for longer periods. It is often pelletized or granulated, improving usability for land application across larger areas or as a renewable energy feedstock.

Beyond moisture content, stabilization is a critical factor in determining whether sludge can be beneficially applied or must be managed as a waste product. Only when sludge has undergone sufficient treatment to reduce pathogens, odors, and vector attraction does it meet the regulatory standards to be classified as biosolids. This distinction introduces the next section, which examines the properties of biosolids and their role in nutrient recovery through land application.

### 2.1.3 Biosolids in agriculture: nutrient recovery and key properties

Biosolids, the stabilized form of wastewater sludge, are treated to meet regulatory standards for pathogen reduction, odor control, and handling safety (U.S. EPA, 2000). Their nutrient-rich composition, particularly in nitrogen (N) and phosphorus (P), makes them valuable for agricultural use, supporting soil fertility and reducing reliance on synthetic fertilizers (Buta et al., 2021; Elgarahy et al., 2024). Micronutrients further enhance their agronomic value, particularly in nutrient-depleted soils.

Physical properties, including moisture content, pH, volatile solids (VS), and specific gravity, directly influence application methods and performance. Liquid biosolids (94–97% moisture) may be applied through spraying or injection near treatment facilities, while dewatered or pelletized biosolids allow for wider transport and use (US EPA, 2000; Wang et al., 2008). Stabilization processes also affect pH—alkaline treatment raises it to inhibit pathogens, while anaerobic digestion maintains near-neutral levels for microbial activity (O'Kelly, 2005).

Regulatory frameworks ensure that land application is safe and environmentally sound. Ontario Regulation 267/03 establishes standards for biosolids application, including contaminant limits, stabilization requirements, and pathogen control (Ontario Ministry of the Environment, 2002). In the U.S., the EPA Part 503 Rule defines Class A biosolids as virtually pathogen-free and Class B as partially treated, with differing restrictions on application methods and site access (U.S. EPA, 2025).

Biosolids contribute to nutrient circularity by recycling essential elements back into agricultural soils and offsetting the use of synthetic fertilizers (Harder et al., 2021). This practice helps address the phosphorus paradox—where phosphorus is essential yet finite—while improving soil health and potentially reducing greenhouse gas emissions through avoided fertilizer production (Archer et al., 2020; Leinweber et al., 2018; Yu et al., 2021).

### 2.1.4 Energy generation and nutrient recovery from wastewater sludge

Among the available sludge management strategies—such as landfilling, incineration, composting, and land application—anaerobic digestion (AD) stands out as a key pathway that addresses multiple objectives: reducing sludge volume, stabilizing organic matter, producing renewable energy, and recovering nutrients (Kasinath et al., 2021). AD transforms sludge from a waste product into a

resource, aligning with circular economy principles by generating biogas for energy use and creating nutrient-rich digestate for agricultural application.

#### 2.1.4.1 Anaerobic digestion (AD)

Anaerobic digestion is a widely implemented technology for sludge stabilization and energy recovery. It operates under oxygen-free conditions, where microbial communities break down organic matter through four biochemical stages (Yuan & Zhu, 2016):

1. Hydrolysis: Complex organic compounds (e.g., proteins, carbohydrates, and fats) are broken down into simpler molecules like amino acids and sugars.
2. Acidogenesis: These products are converted by acidogenic bacteria into volatile fatty acids (VFAs), ammonia, and hydrogen.
3. Acetogenesis: VFAs are transformed into acetic acid, hydrogen, and carbon dioxide by acetogenic bacteria.
4. Methanogenesis: Methanogens produce methane and carbon dioxide from acetic acid, hydrogen, and carbon dioxide.

Over recent decades, AD capacity has expanded rapidly, with global installations growing at an average rate of 18.4% per year (World Biogas Association, 2024).

In addition to producing biogas, AD reduces pathogens and odors while lowering the overall mass of sludge requiring further treatment or disposal. This dual benefit—stabilization and energy recovery—makes it one of the most sustainable options for sludge management.

#### 2.1.4.2 Biogas production

Biogas produced through AD typically consists of 50–75% methane and 25–50% carbon dioxide, making it a valuable renewable energy resource suitable for electricity and heat generation or for upgrading to renewable natural gas (Khanh Nguyen et al., 2021). The quantity and quality of biogas generated depend heavily on temperature, pH, moisture content and the composition of the organic matter being digested (Volschan Junior et al., 2021).

To optimize yields, pretreatment methods—including thermal, chemical, and mechanical processes—are often applied to enhance sludge biodegradability (Atelge et al., 2020). Co-digestion with high-energy substrates, such as food waste, is another strategy to increase methane production, improve process stability, and integrate waste streams from multiple sources (Elalami et al., 2019).

#### 2.1.4.3 Biogas utilization

After purification, biogas can be used in combined heat and power (CHP) systems, enabling wastewater treatment plants (WWTPs) to generate electricity and thermal energy simultaneously (Volschan Junior et al., 2021). Facilities with sufficient influent volume—typically above 22,730 $m^3$/day—are more likely to achieve cost-effective energy recovery (Naik-Dhungel, 2010). Large-scale plants have reached impressive levels of energy self-sufficiency, including 100% in some U.S. facilities (662,000 $m^3$/day) and up to 96% in plants across England, Mexico, and the Czech Republic (Volschan Junior et al., 2021).

#### 2.1.4.4 Benefits of energy and nutrient recovery

Anaerobic digestion offers multiple environmental and economic benefits. It reduces greenhouse gas emissions, lowers operational costs, and supports energy independence for WWTPs (Awad et al., 2019; Gherghel et al., 2019). Beyond energy generation, AD produces a nutrient-rich digestate that can be applied as a biofertilizer, enhancing soil fertility and contributing to nutrient circularity (Khanh Nguyen et al., 2021).

Anaerobic co-digestion can dilute undesirable components present in sludge, such as heavy metals, pharmaceuticals, and pathogens, thereby improving the quality of the digestate and mitigate risk associated with land application (Karki et al., 2021; Mata-Alvarez et al., 2014). Studies have also shown that co-digestion can also improve digestate quality by diluting undesirable components such as heavy metals and pharmaceuticals, and studies suggest it may help reduce antibiotic resistance genes and bacteria (Zhang et al., 2018).

## 2.2 Sludge estimation

Sludge is generated at a WWTP during primary, secondary, and sometimes tertiary treatment stages, by the physical settling of solids and the biological growth of microorganisms. In primary treatment, sedimentation captures settleable organic and inorganic solids, producing primary sludge (Figure 2) (Metcalf & Eddy et al., 2013). During secondary treatment, microbial communities degrade organic matter, and the excess biomass produced is partially recycled as return activated sludge, and the rest sent for disposal as waste activated sludge (WAS). The total sludge generated by a WWTP is the sum of primary sludge and the waste activated sludge. The amount of sludge produced is thus a function of a range of factors, including the flow rate $Q_i$, the suspended solids concentration in the inflow $x_i$,

and the substrate availability in the influent $S_s$, as well as the efficiency of removal processes that vary widely across treatment systems. At the plant level, a total solids balance (Figure 2) can be used to estimate the sludge produced. However, this is impossible to achieve at the national scale, given the lack of availability of such plant-specific information.

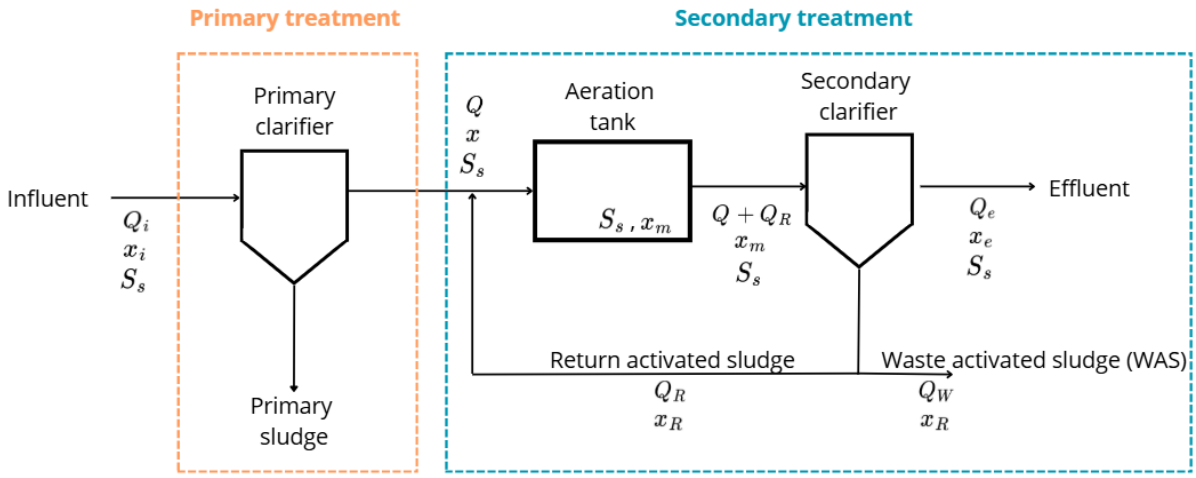



**Figure 2:** Simplified flow diagram of primary and secondary wastewater treatment process with sludge streams (designed on Canva, adapted from Metcalf & Eddy et al. (2013)).

Where:

$Q_i$ = influent flowrate ($m^3/s$)

$x_i$ = influent biomass concentration (mg/L)

$S_s$ = substrate concentration (mg/L)

$Q$ = secondary influent flowrate ($m^3/s$)

$x$ = biomass concentration after primary treatment (mg/L)

$x_m$ = mixed liquor (aeration tank) biomass concentration (mg/L)

$Q_R$ = return sludge flowrate ($m^3/s$)

$x_R$ = return activated sludge biomass concentration (mg/L)

$Q_W$ = waste activated sludge flowrate ($m^3/s$)

$Q_e$ = effluent flowrate ($m^3/s$)

$x_e$ = effluent biomass concentration (mg/L)

At the regional/national scale, sludge management has been extensively studied for larger WWTPs serving more than 10,000 people or designed for a capacity greater than 1 million gallons per day, and most data available is for these larger facilities (Krause & Bronstein, 2024). For example, biosolids generation rates were analyzed for 136 WWTPs across Ontario with design flows over 1,000 m³/day (Jin et al., 2018). National scale inventories that include both small and large WWTPs are much more challenging to develop, with significant uncertainties in the magnitudes.

One of the most widely used methods for estimating national scale biosolid generation rates is through survey of WWTP operators; however, these are also often limited to the larger facilities. The survey method was used by Beecher et al 2007 and 2023 and Rauch-Williams et al. (2018) to estimate biosolid generation rates across the US. Another indirect measurement-based approach was used by Krause & Bronstein (2024) who quantified sludge landfill data to extrapolate per capita sludge generation and estimate the fraction of sludge present in municipal waste, achieving a final national sludge generation.

A more mechanistic approach was developed by Seiple et al. (2017) linking sludge yield to influent flow and wastewater TSS and $BOD_5$ concentrations, with separate formulations to distinguish between primary and secondary sludge estimates. While they used site-specific inflow rates, national average concentrations for TSS and the 5-day biological oxygen demand at 20ºC was used due to a lack of such information. Literature-based factors such as solids removal efficiencies and biomass yield were also used in their model. It was interesting that their US scale model for 15,000 WWTPs produced quite similar estimates as the survey methods described earlier.

Simpler model coefficient-based approaches were also used for national scale estimates, using for example, a per capita biosolid generation rate developed by Okoffo et al. (2020), using survey data from 557 WWTPs in Australia. In Europe, Eurostat (2023), estimated country-specific coefficients based on population equivalent (the organic load generated per person per day) to calculate national sludge production for each country. For Ontario, the Ministry of the Environment, Conservation and Parks (MECP) provides a sludge generation rate coefficient linked to treatment and stabilization methods to estimate the mass generated per effluent flow (Pileggi et al., 2008).

Taken together, these studies demonstrate a diverse range of methodologies, including survey-based approaches, empirical relationships based on population or flow, process-based mass balance models, and indirect estimates derived from disposal records. Despite these advances, the limited direct reporting requires researchers to rely on alternative datasets and methodological strategies. A similar challenge arises in the estimation of sludge nutrient content, where direct measurement is uncommon, and extrapolations are often necessary.

### 2.2.1 Nutrient estimation

In addition to estimating sludge mass, growing attention has been given to quantifying the nutrient content, specifically nitrogen (N) and phosphorus (P), in sludge. Understanding these nutrient levels is essential for assessing their potential for land application, nutrient recovery, and integration into circular economy strategies. In the U.S., Beecher (2023) derived average nutrient concentration from the survey data to quantify N and P in biosolids. Rauch-Williams et al. (2018) used standard literature values for nutrient concentrations in combination with total sludge production to estimate nutrient quantity. In Ontario, Pollution Probe (2019) calculated average effluent phosphorus concentration using National Pollutant Release Inventory (NPRI) dataset and applied these values to facility flows to estimated phosphorus disposed of per year in sludge.

Overall, existing methods provide a useful approximation of nutrient content in sludge, primarily due to the lack of direct measurements across facilities. The next section explores the gaps and limitations in current estimation approaches for sludge generation and its nutrient content, and outlines the methodology adopted in this project.

## 2.3 Research gaps and project approach

These studies collectively illustrate a range of estimation strategies that differ in data granularity and methodological complexity. Recognizing the limitations of readily available data in Ontario, specifically the absence of detailed influent load characteristics to develop a mechanistic model like the one by Seiple et al. (2017) and the lack of comprehensive indirect sources (like quantity data related to sludge management, e.g. landfilling), we develop a parsimonious, data-informed approach to estimate sludge volume and nutrient content. It follows the logic of extrapolating from a subset data that is collected from exhaustive web-scouring and uses generation factors based on the effluent

and population served to estimate a province-wide generation, following the methodology used in Ontario before, as outlined in the MECP Design Guidelines for Sewage Works (Pileggi et al., 2008).

A key limitation of the MECP guidelines, however, is that their coefficients were calculated prior to 2008, meaning they may not reflect current wastewater characteristics or treatment efficiencies. Therefore, this study calculated new, updated coefficients from the plants for which data was collected during the web-scouring and applied them to a broader number of plants. This enables development of updated estimates of sludge generation factors that reflect the different types of treatment and stabilization processes across Ontario's WWTPs.

Building on insights from these studies, the following chapter presents the methodological framework developed to estimate sludge generation, nutrient content, and analyse disposal pathways across Ontario's WWTPs. This approach addresses current data gaps and supports more informed decision-making for sustainable sludge management in the province.

# Chapter 3 - Methodology

This study addresses key data gaps in wastewater sludge generation in Ontario through a structured, data-driven approach. The methodology focuses on estimating sludge generation (Section 3.1), analyzing current disposal pathways (Section 3.2), and quantifying nutrient content, specifically nitrogen and phosphorus, in biosolids across all WWTPs (Section 3.3).

The research is guided by the central hypothesis that municipal sludge generation and nutrient content can be accurately estimated on a province-wide scale by using updated, process-specific generation factors. This approach allows for a more nuanced estimation that accounts for the diversity of wastewater treatment processes, lagoon-systems, and stabilization methods, thereby providing a framework for informed decision-making in sustainable sludge management.

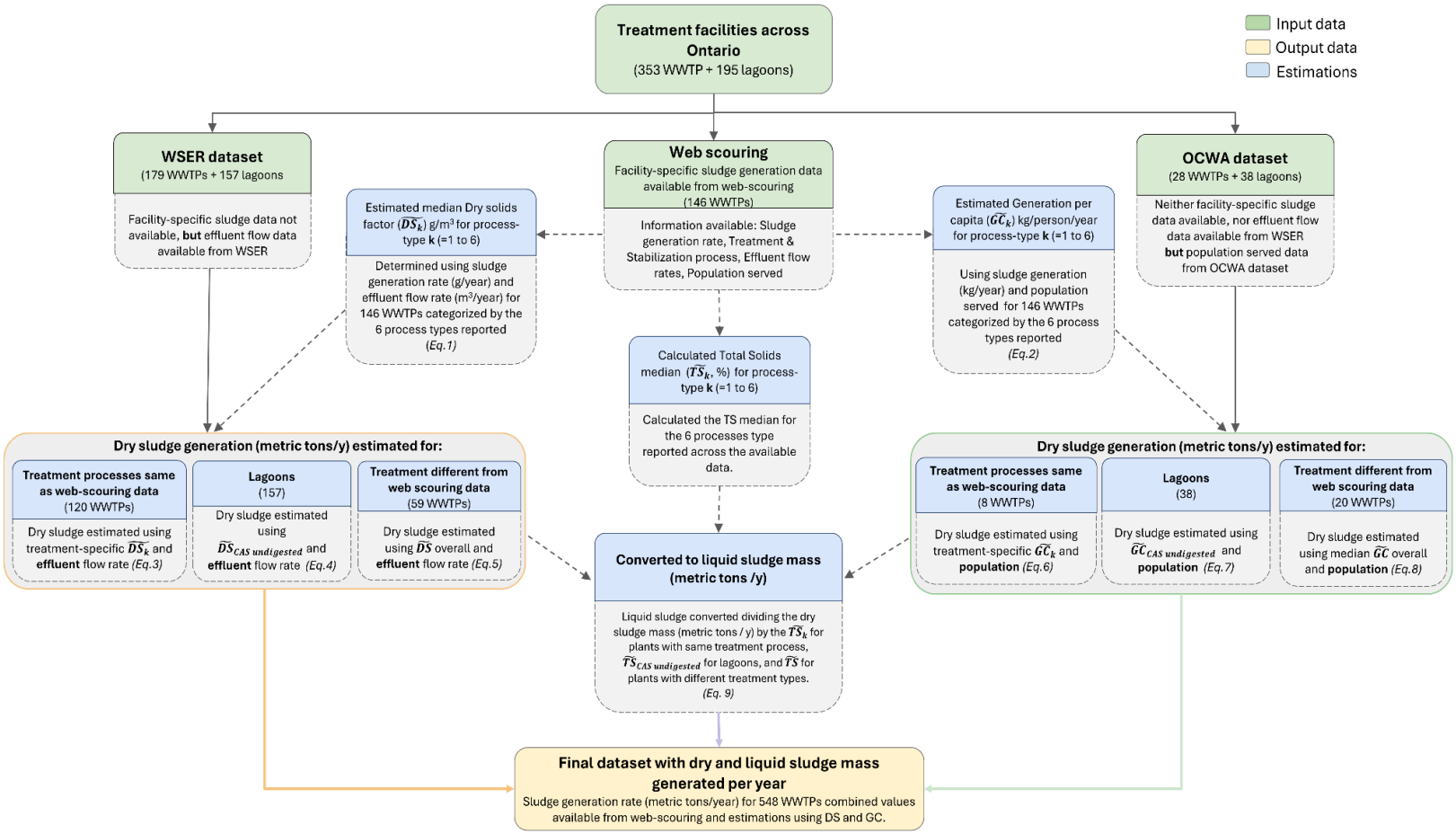



**Figure 3:** Methodological framework illustrating the processing steps, and estimation procedures used to calculate municipal sludge generation across Ontario

## 3.1 Estimation of the municipal sludge generation rates

### 3.1.1 Data Sources

To estimate municipal sludge generation rates across Ontario, data was compiled from multiple sources: (1) WWTP-specific annual reports available online, (2) Ontario Clean Water Agency (OCWA), and (3) Wastewater Systems Effluent Regulations (WSER) dataset developed by Environment and Climate Change Canada (ECCC). A list of the information collected from annual reports and a hyperlink to the dataset can be found in Appendix A.

According to Statistics Canada (2022), Ontario has 375 wastewater treatment plants (WWTPs) and 237 lagoon systems. Our initial integration of these datasets identified a total of 548 facilities across the province (353 WWTPs and 195 lagoon-systems). Of these, we were able to find sludge generation rates ($metric\ tons/y$) rates for 146 WWTPs, using annual reports that were available online for each one of them. Sludge generation rates were not available for the remaining 402 WWTPs, and this was estimated using other information on them that was available from the OCWA or the WSER datasets. Specifically, we estimated a set of treatment-process-specific coefficients from the 146 WWTPs with available generation rates and used these coefficients to estimate sludge generation. These coefficients were expressed in two units: grams per cubic meters (g/m3), representing the mass of sludge generated per volume of effluent, and kilograms per person per year (kg/person/y), representing the per capita sludge generation rate.

Of these 402 WWTPs, we found information on treatment process, effluent flow rate and geolocation for 336 WWTPs from the WSER database. For the remaining 66 facilities, we had data on treatment type and population from OCWA but did not have geolocation data from WSER. In the following sections, we describe the methods for estimating the sludge generation.

### 3.1.2 Estimation of wastewater sludge generation rates and coefficients from annual reports

Information was found on either liquid or dry biosolid generation rates for 146 WWTPs, with 125 WWTPs having data for 2022, while we found data on 17 WWTPs for 2021, and 4 WWTPs for 2020. For WWTPs with data available for more than one year, we calculated the year-to-year percent change in sludge generation rates for each plant and then averaged these changes across all plants

with multi-year data. This analysis showed that interannual was less than 1.3% indicating that sludge production rates were consistent over the observed period.

In all cases where both liquid and dry sludge were reported, total solids content (TS) values, which represent the proportion of solids in the liquid sludge, were also available. For the WWTPs reporting only one form of sludge, TS values were used to convert between dry and liquid sludge. Specifically, when only liquid sludge was reported, it was multiplied by TS value to estimate dry sludge; when only dry sludge was available, it was divided by the TS value to estimate liquid sludge. This TS values used for these conversions were derived from the reported data across all three years of available data (2020-2022).

The data was separated into categories based on the WWTP's treatment process to estimate a process-specific median TS values ($\widetilde{TS}_k$). Data from a total of 96 WWTP-years were available, where a WWTP-year represents one WWTP contributing data for a single year. For example, some plants reported for all three years, while others had one or two years of data.

The 96 WWTP-years were specific to six distinct treatment processes: extended aeration with digested sludge (50 WWTP-years), extended aeration with undigested sludge (11 WWTP-years), conventional activated sludge (CAS) with anaerobic digestion (19 WWTP-years), CAS with aerobic digestion (2 WWTP-years), CAS with undigested sludge (3 WWTP-years), and sequential batch reactors (SBR) with digested sludge (11 WWTP-years). Using these data points, a median was calculated for each of the six categories, and an overall median across all treatment processes (TS) was calculated for cases where the process was not specified. The results are presented in Table 1. Note that for WWTPs in Table 1 that have extended aeration with digested sludge or SBR with digested sludge as treatment and stabilization process, we do not have the information about the type of digestion process, i.e. whether it is an aerobic or anaerobic digestion process.

**Table 1:** Median total solids percentages by treatment and stabilization process with the number of datapoints

| **Treatment and stabilization processes** | Number of datapoints (WWTP-years) | $\widetilde{TS}_k$ (Q1 - Q3) (%) |
|---|---|---|
| Extended Aeration with Digested Sludge | 50 | 1.9 (1.4 - 2.5) |
| Extended Aeration with Undigested Sludge | 11 | 2.0 (1.5 - 3.0) |
| CAS with Anaerobic Digester | 19 | 2.6 (2.0 - 3.4) |
| CAS with Aerobic Digester | 2 | 1.6 (1.4 - 1.9) |
| CAS with Undigested Sludge | 3 | 3.9 (3.6 - 4.0) |
| SBR with Digested Sludge | 11 | 2.5 (1.6 - 3.3) |
| Overall | 96 | 2.1 (1.5 - 2.9) |

The median process specific TS values ($\widetilde{TS}_k$, %) were then used to estimate both liquid and dry sludge for all 146 WWTPs. Among these, 64 reported only liquid sludge, 23 reported only dry sludge, while 59 reported both. For the 64 plants with only liquid sludge, dry sludge was calculated by multiplying the reported liquid sludge mass by their corresponding median process specific TS values, resulting in dry sludge data for all 146 WWTPs.

Using this dry sludge dataset, two coefficients relating sludge generation with effluent flow and population were calculated to estimate sludge production for plants lacking reported data. The dry solids factor ($DS,\ g/m^3$), representing the mass of sludge (in grams, $g$) generated per unit volume of effluent flow ($m^3$), for each of the 146 WWTPs as shown on Equation 1:

$$DS_{i,k} = \frac{D_{i,k}}{Q_i} * 10^6 \qquad i = 1\ to\ 146 \quad (1)$$

Where $D_{i,k}$ is the reported dry sludge generation ($metric\ tons/y$) for WWTP $i$ and process type $k$, $Q_i$ represent the plant $i$ effluent flow volume ($m^3/y$) and $10^6$ converts metric tons to grams.

Because sludge generation is influenced by the treatment and stabilization processes, the dry solids factor is also expected to vary across treatment types (U.S. EPA, 1999, Pileggi et al., 2008). The process-specific dry solids factor for each of the six distinct treatment process types ($k$ = 1, 6) identified in the annual reports, was estimated using the median value calculated for each process, defined as $\widetilde{DS_k}$. An overall median dry solid factor across all 146 WWTPs ($\widetilde{DS}$), was further estimated, and it was used for cases where the treatment process did not match those found in the annual reports.

Also, the per capita sludge generation rate $GC_{i,k}$ ($kg/person/y$) was estimated for WWTP $i$ with treatment process $k$ from the 146 data, as shown on Equation 2:

$$GC_{i,k} = \frac{D_{i,k}}{P_i} * 10^3 \qquad i = 1\ to\ 146 \quad (2)$$

Where $D_{i,k}$ is the reported dry sludge generation ($metric\ tons/y$) for WWTP $i$ and process type $k$, $P_i$ is the population served by plant $i$, and $10^3$ converts metric tons to kilograms.

Similar to the dry solids factor, per capita generation values were grouped by treatment process types ($k$ = 1, 6) identified in the annual reports, and the median value for each treatment types was assigned as $\widetilde{GC_k}$. If a facility's treatment process did not match any of those identified in the annual reports, the overall median across all facilities ($\widetilde{GC}$) was applied.

### 3.1.3 Estimation of sludge generation rates for plants in WSER dataset

We found data on effluent flow, treatment and stabilization process and geolocation for 336 WWTPs from the WSER database. Of these, there were 120 WWTPs with treatment processes that matched the six categories we defined earlier in section 3.1.2 For these facilities, dry solids generation rates were estimated using the equation below with the process-specific $DS$ value ($\widetilde{DS_k}$):

$$D_{i,k} = Q_i * \widetilde{DS_k} * 10^{-6} \qquad i = 147\ to\ 266 \quad (3)$$

Where $10^{-6}$ is a conversion factor used to convert grams to metric tons.

The WSER dataset included other categories of treatment processes that were not included in our annual reports: namely lagoons (157 WWTPs) and advanced technologies, namely membrane

bioreactor, biological aerated filters (BAF), biological nutrient removal (BNR), rotating biological contactor (RBC), moving bed biofilm reactor (MBBR), integrated fixed-film activated sludge (IFAS) and oxidation ditch, with digested and undigested sludge (59 WWTPs). For lagoons, we assumed that the $DS$ factor would be the same as those of CAS with undigested sludge:

$$DB_{i,k} = Q_i * \widetilde{DS}_{CAS\ Undigested} * 10^{-6} \qquad i = 267\ to\ 423 \qquad (4)$$

For advanced technologies, we used the overall median ($\widetilde{DS}$):

$$DB_{i,k} = Q_i * \widetilde{DS} * 10^{-6} \qquad i = 424\ to\ 482 \qquad (5)$$

The number of WWTPs identified in each treatment and stabilization process category across the three datasets (annual reports, WSER, and OCWA) is summarized in Table 2 below.

**Table 2:** Number of plants in annual reports, WSER and OCWA dataset for each treatment and stabilization process category

| Treatment and stabilization processes | Reports | WSER | OCWA |
|---|---|---|---|
| Extended Aeration with Digested Sludge | 65 | 49 | 1 |
| Extended Aeration with Undigested Sludge | 14 | 16 | 3 |
| CAS with Anaerobic Digester | 42 | 22 | 1 |
| CAS with Aerobic Digester | 6 | 7 | - |
| CAS with Undigested Sludge | 6 | 9 | - |
| SBR with Digested Sludge | 13 | 17 | 3 |
| Lagoons | - | 157 | 38 |
| *Advanced technologies processes with Digested Sludge | - | 21 | 2 |
| *Advanced technologies processes with Undigested Sludge | - | 38 | 18 |
| Total | 146 | 336 | 66 |

*Membrane bioreactors, BAF, BNR, RBC, MBBR, IFAS and oxidation ditch.

### 3.1.4 Estimation of sludge generation rates for plants in OCWA dataset

For 66 WWTPs where effluent flow data were unavailable, but population served was reported in OCWA dataset, sludge generation was estimated using a per capita generation coefficient. For 8 WWTPs where the facility's treatment process matched one of the process categories identified from the annual reports, the corresponding process-specific coefficient ($\widetilde{GC_k}$) was used:

$$D_{i,k} = \widetilde{GC_k} * P_i * 10^{-3} \qquad i = 483 \; to \; 490 \qquad (6)$$

Where $10^{-6}$ is a conversion factor used to convert kg to metric tons.

For 38 lagoons with only population data available the generation per capita of CAS with undigested sludge was used:

$$D_{i,k} = \widetilde{GC}_{CAS\ Undigested} * P_i * 10^{-3} \qquad i = 491\ to\ 528 \qquad (7)$$

For the 20 WWTPs with advanced technology, the overall median ($\widetilde{GC}$) was applied:

$$D_{i,k} = \widetilde{GC} * P_i * 10^{-3} \qquad i = 529\ to\ 548 \qquad (8)$$

### 3.1.5 Converting dry mass to liquid mass

Sludge generation per year was initially estimated in terms of dry sludge mass ($D_{i,k}$, $metric\ tons/y$ ). To facilitate comparisons with liquid sludge handling and to support subsequent analyses of storage, transport, and treatment requirements, this amount was converted to liquid sludge mass ( $L_{i,k}$, $metric\ tons/y$), using Equation 9:

$$L_{i,k} = \frac{D_{i,k}}{\widetilde{TS}_k} \qquad i = 147\ to\ 548 \qquad (9)$$

The total solids values ($\widetilde{TS}_k$) were assigned according to the plant's treatment process, using the corresponding median process-specific TS value for WWTPs that matched a process category from the annual reports, $\widetilde{TS}_{CAS\ Undigested}$ for lagoons, and the overall median $TS$ values across all process ($\widetilde{TS}$) for advanced technology processes.

### 3.1.6 Sample calculation process

Appendix C provides a detailed sample calculation for dry and liquid sludge estimation for two WWTPs, one from the WSER dataset with effluent data available for it and one from the OCWA dataset with no effluent data but population served data available. The sample calculations highlight how the $\widetilde{DS}_k$ and $\widetilde{GC}_k$ factors are used in equations 3-5 and 6-8, respectively, and $\widetilde{TS}_k$ in Equation 9, to estimate dry and liquid sludge quantities under different scenarios.

### 3.2 Disposal methods in Ontario

Information on wastewater sludge disposal methods was obtained from the OCWA dataset. Of the 548 WWTPs included, 324 reported their disposal methods. The main strategies reported across the province include the use of lagoons, where sludge is stored long-term, with minimal treatment or removal; agriculture application, in which stabilized sludge are land-applied as a regulated nutrient source; and landfill disposal, often chosen due to limited on-site storage or treatment capacity. Some facilities rely on transportation, sending sludge to other locations for further treatment or disposal, while others use incineration to reduce volume and eliminate contaminants. In the dataset, some facilities reported the disposal using combined categories, such as "agriculture or landfill" and "agriculture or transported", this reflects how the information was recorded and it is not clear how much sludge was directed to each method or whether multiple strategies were applied simultaneously. A portion of facilities did not report disposal information and were categorized as unknown.

The distribution of WWTPs by disposal method is summarized in Table 3 below.

**Table 3:** Number of WWTPs by disposal method

| Sludge disposal method | Number of WWTPs |
|---|---|
| Agricultural | 140 |
| Agricultural or Landfill | 22 |
| Agricultural or Transported | 18 |
| Incineration | 16 |
| Landfill | 71 |
| Transported | 57 |
| Unknown | 224 |

This categorization was later used to examine the spatial distribution of disposal strategies and to analyze patterns in relation to plant size and digestion type.

## 3.3 Estimation of nutrient content in wastewater sludge

### 3.3.1 Data sources

There are three specific datasets we used to estimate the N and P concentration ( $metric\ tons$-P $/\ metric\ tons$ dry sludge) in sludge, as well as WWTP-specific total N and P mass ($metric\ tons/\ y$) in the biosolids. The National Pollutant Release Inventory (NPRI) organizes data under three categories: Releases, Disposals, and Transfers. “Releases" are direct emissions to the environment (air, water, or land), transfers refer to quantities sent off-site for recycling, treatment, or energy recovery, and “Disposals” cover landfill, land application, and other final containment options (Environment and Climate Change Canada, 2008). According to the NPRI’s biosolids reporting guidance (Government of Canada, 2002), biosolids, stabilized sludge, must be reported under the “Disposals” category when they are sent for land application, off-site for land treatment, incineration, landfill, storage or treatment prior to final disposal. For this reason, we used only the P “Disposals” data for the waste and wastewater systems sector, which best reflects the scenario we are working with.

This dataset provided total phosphorus mass in stabilized sludge for 30 facilities reporting under the “Disposals” category. For 88 other facilities, WWTP-specific annual reports provided information on solids phosphorus concentrations in influent and effluent streams, which we used to estimate phosphorus retained in solid sludge. Neither of these two datasets included nitrogen data. For this, we used the OCWA dataset, which reported nitrogen concentrations in wastewater sludge for 40 WWTPs. Estimation methods for the remaining WWTPs are described below.

### 3.3.2 Estimating nitrogen concentration and mass in wastewater sludge

The OCWA dataset provided N concentration data (${C_{N_i}}^{Liq}, g\ -N\ /\ m^3\ of\ liquid\ sludge$ ) for 40 WWTPs. For the remaining 508 facilities, where no measured N concentrations were available, we converted the available liquid-based concentration values to a dry weight basis ($C_{N_i}, g\ N/\ metric\ tons$ dry sludge), since our primary sludge quantity estimates were expressed in dry weight,

consistent with standard practice in the literature. The conversion was performed using the following equation:

$$C_{N_i} = \frac{C_{N_i}{}^{Liq}}{\widetilde{TS}_k * \rho} * 10^{-6} \quad (10)$$

Where $\widetilde{TS}_k$ is the overall median of total solid, $\rho$ represents the density of liquid sludge ( $g/m^3$), and $10^{-6}$ converts grams to metric tons. These values were used to calculated $N_{mass_i}$ as a product of $D_i$ and $C_{N_i}$ for the 40 WWTPs with reported data. Since the number of available data points was insufficient to calculate process-specific median, a single overall median nitrogen concentration ( $\tilde{C}_{\mathrm{N}}$) and its interquartile values (Q1 and Q3) were calculated across all 40 WWTPs. This $\tilde{C}_{\mathrm{N}}$ was then applied to the remaining 508 WWTPs, using their dry sludge mass ($D_i$), to calculate $N_{mass_i}$ using Equation 11.

$$N_{mass_i} = D_i * \tilde{C}_{\mathrm{N}} \qquad i = 41 \; to \; 548 \quad (11)$$

### 3.3.3 Phosphorus mass in wastewater sludge

We had information on phosphorus mass in stabilized sludge ( $P_{mass_i}$, $metric\ tons/y$) for 30 WWTPs from the NPRI dataset. We were able to derive phosphorus mass in sludge for 88 more WWTP based on influent and effluent data available from their annual reports. The P concentration ($metric\ tons$-P $/\ metric\ tons$ dry sludge) in sludge quantified from these two datasets was then used to estimate P mass in sludge in the remaining 430 plants.

For the 88 WWTPs that reported the phosphorus concentrations in their influent ($C_{P,influent_i}$, $g/m^3$) and effluent ($C_{P,effluent_i}$, $g/m^3$) streams, we used these concentrations in combination with influent ($Q_{influent_i}$, $m^3/day$) and effluent ($Q_{effluent_i}$, $m^3/day$) flow data available from their respective annual reports, to estimate the phosphorus mass in the influent ( $P_{influent_i}$, $metric\ tons/y$) and effluent ( $P_{effluent_i}$, $metric\ tons/y$) streams, as shown in Equations 12 and 13, respectively.

$$P_{influent_i} = C_{P,influent_i} * Q_{influent_i} * 365 * 10^{-6} \quad (12)$$

$$P_{effluent_i} = C_{P,effluent_i} * Q_{effluent_i} * 365 * 10^{-6} \quad (13)$$

Equations 13 and 14 estimate the annual phosphorus mass in the influent and effluent streams, respectively, using reported concentrations and flow rates. These values were converted to metric tons per year using $365 * 10^{-6}$, then used in mass balance (Equation 14) to estimate the phosphorus mass retained in sludge ( $P_{mass_i}$, $metric\ tons/y$), for each of 88 WWTPs. It should note that this mass balance does not account for returned sludge within the treatment process.

$$P_{mass_i} = P_{influent_i} - P_{effluent_i} \qquad i = 1\ to\ 88 \qquad (14)$$

The P mass in sludge from these 118 WWTPs was then used to estimate the P concentration of these plants as below by their dry sludge mass ($D_i$ , $metric\ tons/y$), as shown in Equation 15:

$$C_{P\ i} = \frac{P_{mass_i}}{D_i} \qquad i = 1\ to\ 118 \qquad (15)$$

For the 430 plants where P concentration data was not available, we used the estimated P concentration from 118 plants (Equation 16) to calculate the median P concentration ($\tilde{C}_P$, $metric\ tons - P\ /metric\ tons\ dry\ sludge$), as well as the interquartile values. This median concentration, along with each plant's dry sludge mass ($D_i$, $metric\ tons/y$) , was then used to estimate the phosphorus mass in sludge( $P_{mass_i}$, $metric\ tons/y$) , as shown in Equation 16:

$$P_{mass_i} = D_i * \tilde{C}_{\mathrm{p}} \quad i = 119\ to\ 548 \qquad (16)$$

# Chapter 4 - Results

## 4.1 Comparison of process-specific coefficients to literature estimates

The process-specific dry solids (DS) factors and generation per capita (GC) median and IQR estimates using the data from the 146 WWTPs with annual reports are presented in Table 4. The first column lists the grouped treatment and stabilization processes (k = 1, 6), followed by the number of plants with available data for each process. Median and interquartile ranges (Q1 and Q3) of DS are presented on the third column and GC median on the fifth column. These results reflect inherent differences between treatment process: each process has different DS factors due to the variation in solids content (Oleszkiewicz & Mavinic, 2002), which arises from differences in process configuration and sludge management practices, such as the presence of digesters (Seiple et al., 2017; Skaggs et al., 2018).

**Table 4:** Comparison of estimated dry solid ($DS$) coefficients, MECP reported values, and generation per capita ($GC$)

| **Treatment and stabilization processes** | Number of WWTPs with available data | $\widetilde{DS_k}$ $(g/m^3)$ (Q1 - Q3) | $DS$ reported by MECP $(g/m^3)$ | $\widetilde{GC_k}$ (kg/person/year) |
|---|---|---|---|---|
| Extended Aeration with Digested Sludge | 65 | 116.6 (68.9 - 154.5) | 110 | 18.2 |
| Extended Aeration with Undigested Sludge | 14 | 130.0 (90.9 - 238.4) | 120 | 23.3 |
| CAS with Anaerobic Digester | 42 | 151.8 (90.5 - 209.4) | 150 | 21.9 |
| CAS with Aerobic Digester | 6 | 125.6 (61.7 - 172.1) | 155 | 15.4 |
| CAS with Undigested Sludge | 6 | 240.9 (236.1 - 313.1) | 210 | 38.9 |
| SBR with Digested Sludge | 13 | 142.7 (101.4 - 224.5) | 155 | 26.8 |
| Overall | 146 | 130.6 (82.9 - 198.8) | | 21.3 |

Estimated $DS$ coefficients were compared with values reported by the Ontario Ministry of the Environment, Conservation and Parks (MECP), with median values differing by an average of 9.5% (range 1–19%) across process categories. The close agreement between the estimated medians and MECP-reported values was generally expected, as both datasets reflect Ontario WWTPs and use process-specific $DS$ ($\widetilde{DS_k}$) estimation methods. However, our estimates are based on 2022 data, reflecting more recent operational conditions, whereas the MECP values were calculated prior to

2008. This agreement supports the validity of our estimation approach while the interquartile ranges highlight the variability among facilities within the same treatment and stabilization categories, capturing differences in each plant.

Figure 4 shows a boxplot of estimated $DS$ (g/m³) across different treatment and stabilization categories. Variability in $DS$ values reflect expected differences driven by treatment type and stabilization method. Most median values align closely with MECP-reported data. In the figure, the whiskers represent the range of values excluding outliers, which arise due to extreme values, non-standardized reporting across facilities, and the limited number of data points in some categories.

For instance, the extended aeration with digested sludge had a median of 116.6g/m³ (range 68.9–154.5 g/m), closely matching the MECP value of 110 g/m³, CAS with anaerobic digestion had a median of 151.8 g/m³ (range 90.5–209.4 g/m³) aligned with the MECP estimate of 150 g/m³; SBR with digested sludge had a median of 142.7 g/m³ (range 101.4–224.5 g/m³) compared to the MECP value of 155 g/m³; extended aeration with undigested sludge had a median of 130.0 g/m³ (range 91.0–238.4 g/m³) versus 120 g/m³ reported by MECP.

Categories with fewer data points exhibited larger discrepancies. Specifically, CAS with undigested sludge, represented by only 6 facilities, showed a higher median DS of 240.0 g/m³ (range 236.1–313.1 g/m³) compared to the MECP value of 210 g/m³, whereas CAS with aerobic digestion, also with 6 facilities, had a lower median of 125.6 g/m³ (range 61.7–172.1 g/m³) relative to the MECP estimate of 155 g/m³. Overall, these results demonstrate that treatment type, stabilization process, and non-standardized reporting practices are key factors influencing $DS$ variability across Ontario WWTPs.

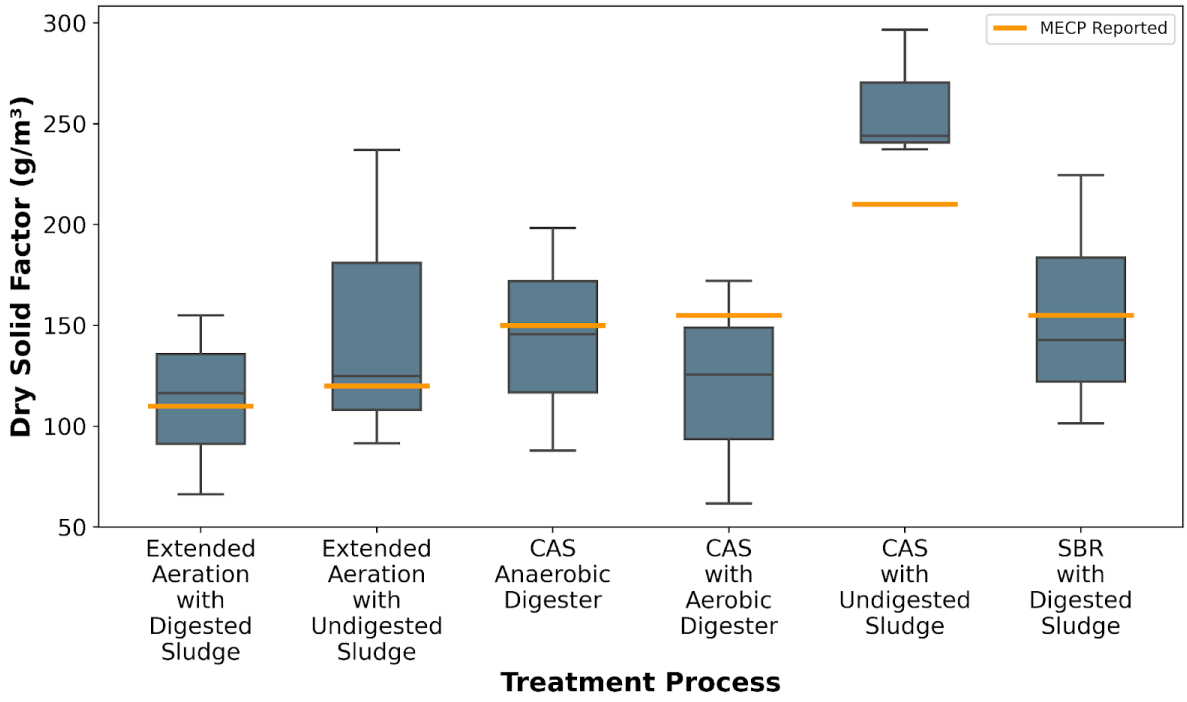



**Figure 4:** Comparison of estimated median DS values and MECP-reported DS values by treatment and stabilization process.

Lagoon systems were analyzed separately due to operational differences and lack of consistent data reported. For these systems, coefficients were derived using values corresponding to CAS with undigested sludge due to comparable effluent quality and treatment performance (Calabrò et al., 2024; Pileggi et al., 2008).

Overall, our findings of higher median $DS$ values for undigested sludge relative to digested sludge/biosolids align with existing literature. Gibbs & Angelidis (1988) noted that undigested sludge comprises a complex mixture of high-molecular-weight organic materials distinctly different from digested biosolids. Additionally, CAS processes have extended retention times and complex biochemical reactions inherent to anaerobic digestion, which lead to higher solids (Andreoli et al., 2007). In contrast, extended aeration systems with digestion exhibited lower median $DS$ values compared with other treatments, consistent with literature indicating reduced solids yields due to prolonged retention times (Mohammadi et al., 2012). Also, SBR have been shown to achieve higher solids volumes then CAS processes due to their superior pollutant removal efficiencies (Mohan et al., 2005).

The following section shows how the dry solids factor ($\widetilde{DS_k}$, g/m$^3$) and the sludge generation per capita ($\widetilde{GC_k}$, kg/person/y), developed based on the data collected from the 146 WWTP annual reports, are used to estimate the annual sludge generation for the remaining 402 WWTPs in Ontario. Figure 6 provides a visualization clearly separating the reported vs. estimated sludge generation values to help readers interpret the output of this analysis.

## 4.2 Sludge Generation Estimates

We estimated that Ontario's 548 WWTPs generated approximately 356,265 ± 35,859 dry metric tons or 15,060,266 ± 3,034,422 metric tons of liquid sludge mass in 2022. Of this, 244,711 metric tons of dry sludge were reported directly from 146 plants through annual reports. The remaining 402 plants, lacking direct reporting, accounted for an estimated 111,554 ± 35,859 metric tons of dry or 11,064,459 ± 3,034,422 of liquid sludge.

Spatial analysis shows that sludge generation is highest in densely populated urban areas such as Greater Toronto, Hamilton, Ottawa, Waterloo region and London (Figure 5). This finding is expected, as this spatial pattern aligns closely with Ontario's population distribution. According to the 2021 Statistics Canada census (Government of Canada, 2022), approximately 75% of the province's residents live in these areas.. The high population density in these areas drives increased wastewater production, necessitating larger treatment facilities and consequently leading to higher sludge generation. Moreover, reported wastewater sludge data is concentrated in densely populated areas of southern Ontario, particularly near major urban centers around the Great Lakes. In contrast, estimated values are more widely distributed across rural and northern regions, especially north Lake Superior, filling gaps where direct reporting was unavailable.

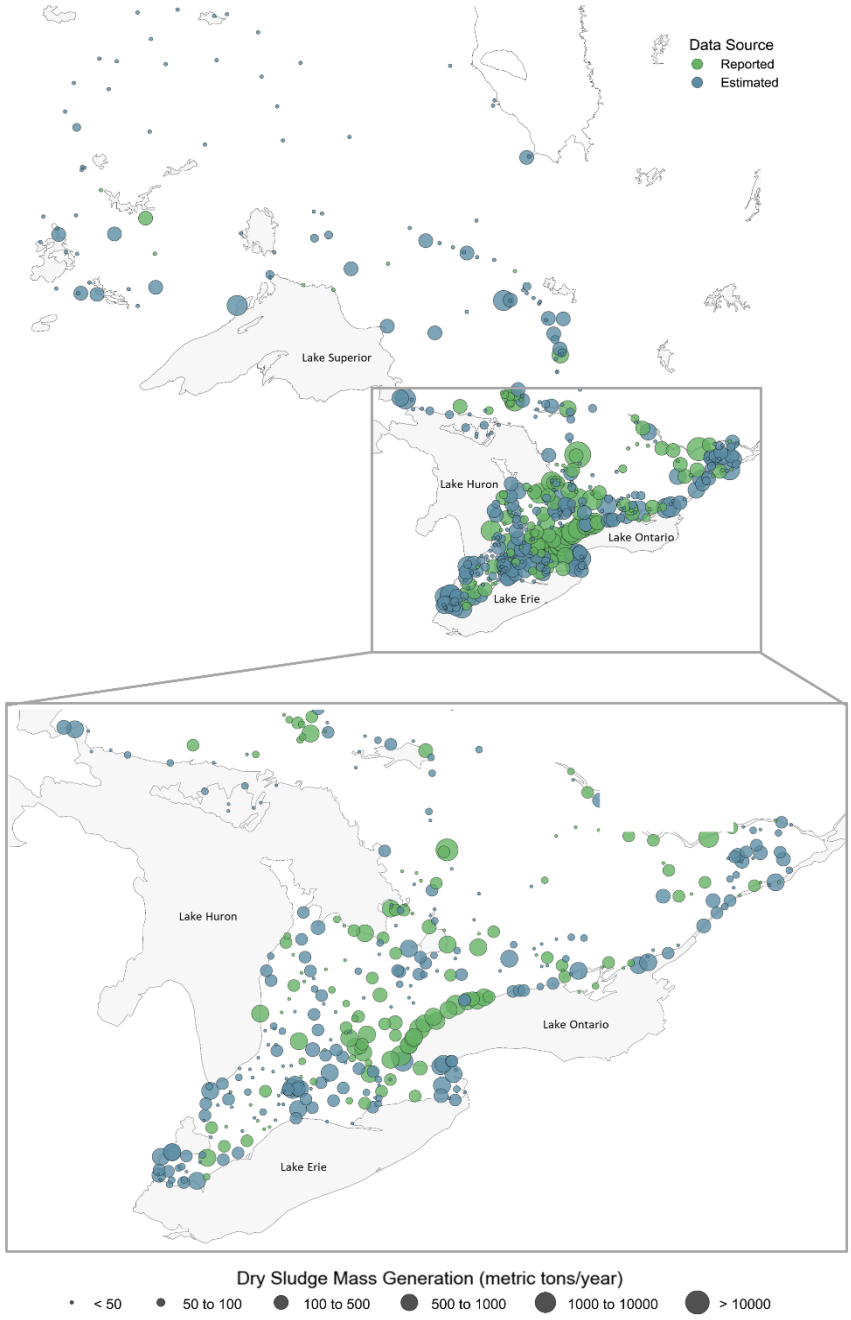



**Figure 5:** Spatial variation in dry sludge generation (dry metric tons/y) across the province, with circle sizes indicating generation levels and colors distinguishing between reported and estimated values.

*Note: Circle sizes are kept consistent across both maps to allow for a single, shared legend. Sizes are not scaled proportionally to each map's dimensions.*

This spatial distribution of data reflects broader patterns in Ontario's wastewater treatment infrastructure. The province's WWTP network is predominantly composed of small-scale facilities, classified based on average daily effluent flow using definitions from U.S. government agencies (EPA and FEMA). Out of 548 WWTPs, 75% (410 plants) are small-scale (<3,785 $m^3$/day), 21% (112 plants) are medium-scale (3,785–37,850 $m^3$/day), and only 4% (25 plants) are large-scale (>37,850 $m^3$/day). The high number of small facilities is largely due to lagoon-based systems, with 162 of the 195 lagoon systems identified as small-scale.

**Table 5:** Dry sludge generation by wastewater treatment plant size

| Plant Size | Number of plants | Dry sludge mass (metric tons/y) |
|---|---|---|
| Small | 410 | 30,353 |
| Medium | 113 | 87,495 |
| Large | 25 | 238,417 |

Data availability is closely linked to plant size. Figure 5 shows that only 22% of small plants report sludge generation quantities directly in annual data, compared to 36.3% of medium and 64.0% of large-size plants. This difference reflects operational and regulatory factors, as larger plants generally have more rigorous data tracking and reporting practices, as they are responsible for most of the sludge generation. Smaller WWTPs, especially lagoons, typically lack consistent reporting due to operational practices where sludge accumulates over multiple years before removal.

Of the 548 WWTPs, 244 operate digesters, producing digested sludge, while 109 operate without digesters, and 195 utilize lagoon systems. Digesters are predominantly found at larger facilities, while lagoons are common at smaller plants.

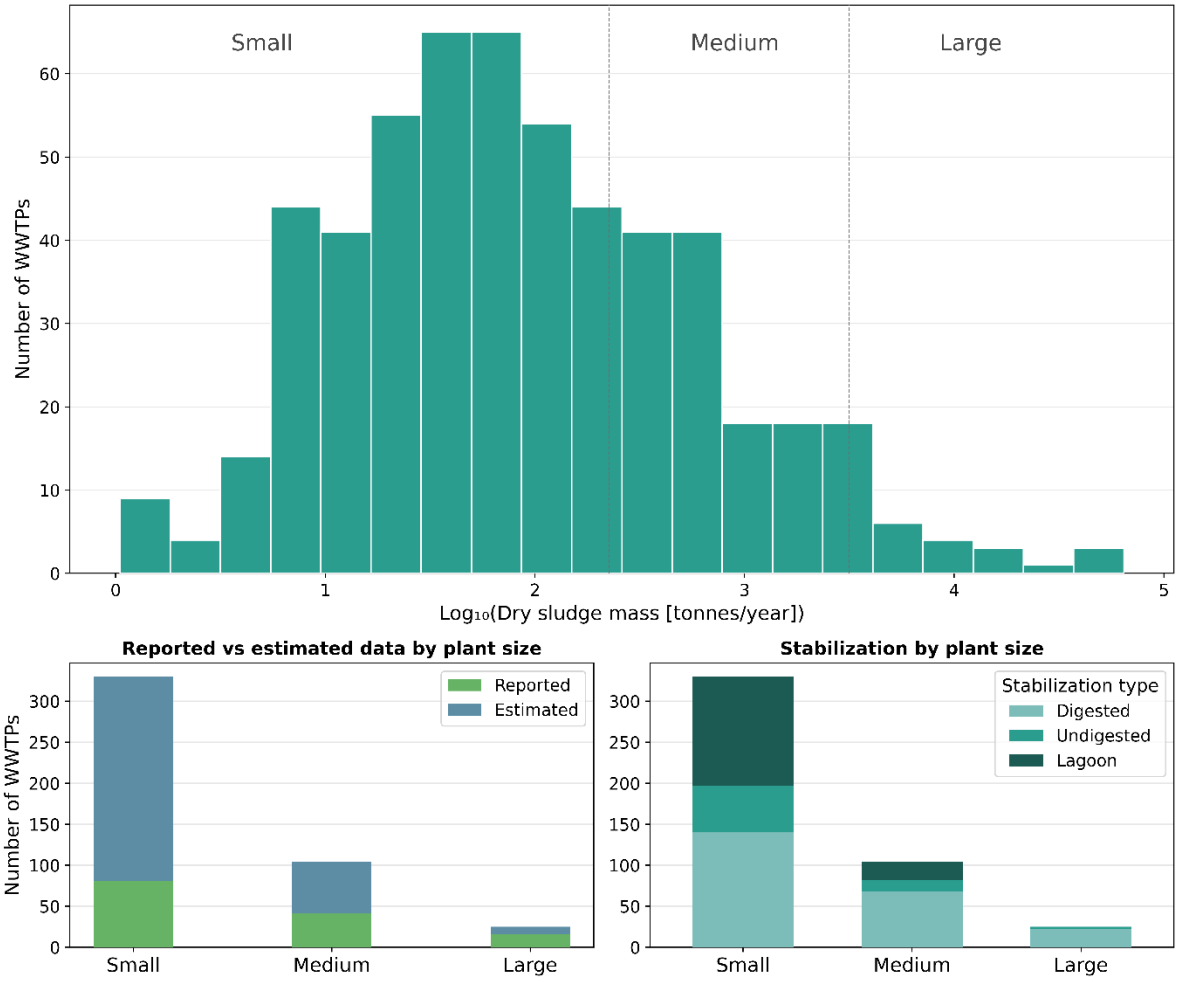



**Figure 6:** Distribution of dry sludge mass generation, data reporting status and stabilization types by facility size in Ontario.

### 4.2.1 Comparison with previous studies

Ontario's wastewater sludge generation rate for 2022 was approximately 0.02 metric tons/person/y (23.5 kg/person/year), based on a population of approximately 15.141 million (Government of Ontario, 2024). This per capita value is compared in Table 6 with national and international estimates drawn from studies using a range of data source and estimation approaches.

**Table 6:** Comparison of per capita generation estimates across selected studies.

| Study | Country | Year | Sludge generated (million metric tons/year) | Population (millions) | Per Capita (kg/person/y) |
|---|---|---|---|---|---|
| Beecher et al. (2007) | U.S. | 2004 | 7.18 (stabilized) | 292.8 | 24.5 (stabilized) |
| Canadian Council of Ministers of the Environment (2012) | Canada | 2012 | 0.66 (stabilized) | 32.8 | 18.9 (stabilized) |
| Okoffo et al. (2020) | Australia | 2016 | 0.4 (stabilized) | 23.4 | 19 (stabilized) |
| Seiple et al. (2017) | U.S. | 2017 | 12.6 (non-stabilized) 6.62 (stabilized) | 325.1 | 38.8 (non-stabilized) 20.4 (stabilized) |
| Rauch-Williams et al. (2018) | U.S. | ~2018 | 6.71 (stabilized) | 326.8 | 20.5 (stabilized) |
| Eurostat (2022) | Austria | 2022 | 0.2 | 9.02 | 21.8 |
| Eurostat (2022) | Czech Republic | 2022 | 0.24 | 10.7 | 22.8 |
| Eurostat (2022) | Germany | 2021 | 1.7 | 83.2 | 20.6 |
| Beecher et al. (2023) | U.S. | 2018 | 5.81 (stabilized) | 326.8 | 17.8 (stabilized) |
| Krause & Bronstein (2024) | U.S. | 2010 – 2020 | 6.1–10.3 | 309.3–331.1 | 18.4 - 31.0 |
| **This study** | **Canada (Ontario)** | **2022** | **0.356** | **15.1** | **23.5** |

Beecher et al. (2007), reported a stabilized sludge generation rate of 24.5 kg/person/y for the U.S., which is very similar to Ontario's 23.5 kg/person/y, where most sludge is also stabilized. Although the study did not detail the specific treatment technologies, survey responses indicate that stabilization and digestion were widely used, similar to the situation in Ontario. Comparable values are observed in Europe. Eurostat (2022), lists the generation rates of 21.8 kg/person/year in Austria, 22.8 kg/person/year in the Czech Republic, and 20.6 kg/person/y in Germany. Their data, specific for each country, are derived through a mix of direct measurements and estimation methods. The estimations use influent organic load and process information when available, and per-capita generation or flow-based coefficients derived from facilities with reliable measured data. These coefficients reflect each country's treatment infrastructure, which mostly are biological secondary treatment (e.g., activated sludge) and stabilization through digesters, similarly to the configuration of many treatment plants in Ontario, contributing to closer per capita generation rate.

Rauch-Willians et al. (2018) building on the work of Beecher et al. (2007), incorporated more recent and detailed facility-level data into the original dataset, resulting in a revised national estimate of 20.5 kg/person/year of biosolids. The lower value likely reflects the replacement of earlier extrapolated values with updated reported data, which may have replaced some overestimates of stabilized sludge generation. A further methodological shift occurred in Beecher et al. (2023), which reported an even lower national estimate of approximately 5.81 million dry metric tons per year. This decline is largely attributable to changes in the estimation approach, which combined elements of Seiple et al. (2017)—using influent flow and population-based methods—while also choosing not to extrapolate stabilized sludge generation for smaller facilities that did not respond to the survey. Although it is unclear how much this specific decision contributed to the overall decrease, the updated methodology reflects a more conservative, data-driven estimate based primarily on available plant-level information.

Seiple et al. (2017) presented a higher estimate of 38.8 kg/person/y for non-stabilized sludge and 20.4 kg/person/year when adjusted for stabilization, after digester (digestate biosolids), which again closely matching Ontario with most of the sludge stabilized though digesters. Their approach was based on a detailed mass balance model that related sludge generation to influent flow and solids concentrations. This method applied a set of coefficients about influent characteristics, such as $BOD_5$ and TSS, and process efficiencies, such as the fraction of total suspended solids removed in primary settling, the ratio of average influent volatile suspended solids to total suspended solids, and the fraction of influent $BOD_5$ that becomes excess biomass.

The estimate by Okoffo et al. (2020) (19.0 kg/person/y) is approximately 19.1% lower than Ontario's value. Their population-based approach relied on a smaller sample of large plants, potentially overlooking variations in treatment and stabilization practices across plant sizes.

The Canadian Council of Ministers of the Environment (2012) reported 18.9 kg/person/year, slightly lower than Ontario's. However, the methodology used to derive this value was not reported, limiting direct comparison. Similarly, Krause & Bronstein (2024) relate landfilled wastewater sludge data and population ratios (assuming similar sludge generation per person across region) by resulting in a broader per capita range of 18.4 to 31.0 kg/person/year, which still aligns well with other studies in this section.

Overall, Ontario's estimate of 23.5 kg/person fits well within the range of previous studies (18–31 kg/person/year), particularly those that use direct estimation data. The variations seen across all studies, including this one, reflect key methodological uncertainties and limitations As a large-scale estimate, this methodology does not account for certain plant-specific factors, such as internal recycling of sludge, microbiological efficient and the daily fluctuation in influent quality. This study, for instance, relied on a subset of available plant data and utilized an estimation methodology with coefficients that, while updated, were based on limited samples. Furthermore, this analysis specifically included sludge from lagoon-systems, a detail that is often not explicitly stated in other studies. The inclusion or exclusion of these systems in other research could contribute to the observed differences in per capita generation rates. These differences in data sources, estimation methods, and regional wastewater practices help explain the variation seen across studies and underscore the value of regionally tailored approaches.

### 4.3 Disposal methods in Ontario

Disposal methods vary significantly across regions, influenced by population density, treatment capacity and local infrastructure. As shown in Figure 7, WWTPs located near the western shore of Lake Ontario, including the Greater Toronto Area and Hamilton, as well as plants in Southern Ontario, particularly in the area between Lake Huron and Erie, such as the London area, generate the highest sludge volumes but also employ a diverse range of disposal strategies. These include agricultural land application, landfilling, incineration, and transportation off site. In contrast, facilities located in more remote and less populated regions, particularly in Northern Ontario and inland areas north of Lake Huron, exhibit a higher proportion of unknown disposal methods. This trend aligns

with the prevalence of lagoon-based systems in small communities, which often operate with limited sludge treatment, making disposal activities more difficult to track and document consistently.

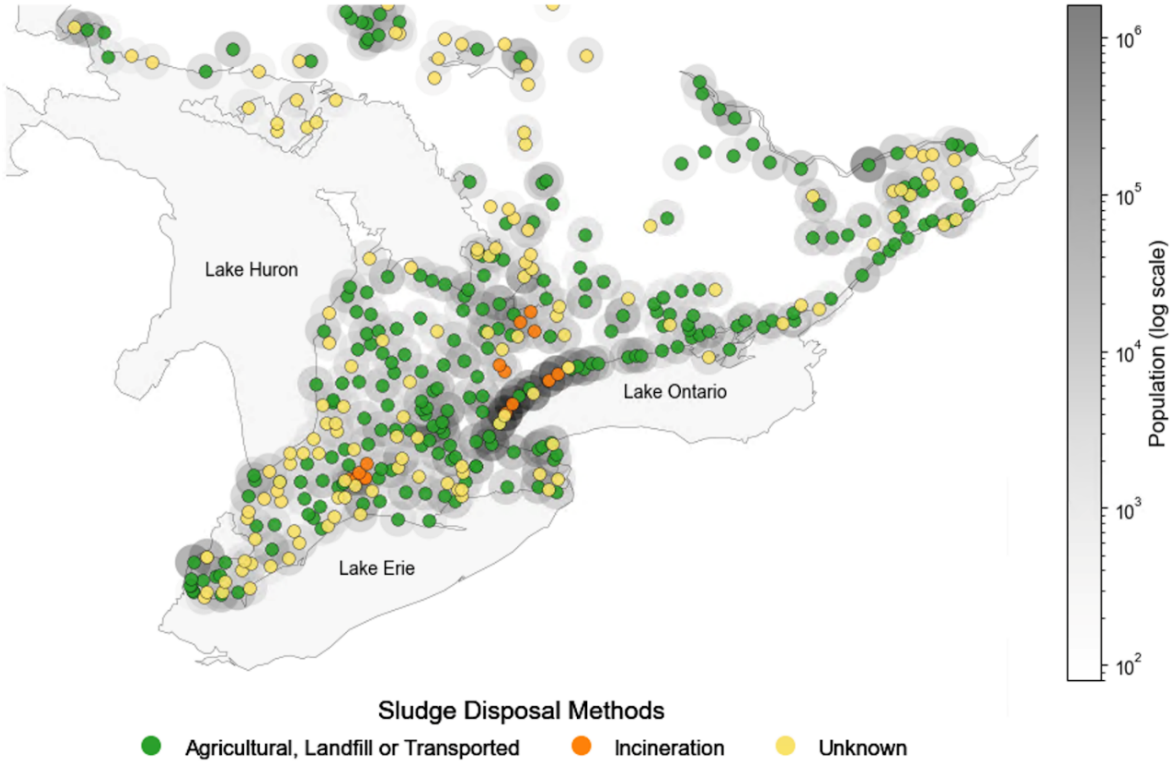



**Figure 7:** Spatial distribution of disposal methods across Ontario and population density.

Agricultural application, landfill, and transported disposal methods together account for approximately 70% of the disposal strategies adopted across Ontario, while 26% fall under the "Unknown" category and only 4% are managed through incineration. Facilities with unknown disposal information are predominantly small WWTPs serving fewer than 5,000 people. However, this data gap is also seen in populated areas, and it represents 15% of these plants above that population threshold, highlighting persistent information gaps even among medium and large facilities.

Incineration is observed almost exclusively in highly urbanized areas such as the Greater Toronto Area and London, where WWTPs serve a median population of around 100,000. These regions require advanced infrastructure to manage the high volume of sludge produced, making incineration a feasible option.

To further explore spatial patterns among the most prevalent disposal types, a separate subplot was created highlighting only agricultural application, landfill, and transported categories (Figure 8). Among facilities using these methods, 32% rely solely on agricultural application, a trend influenced not only by population size but also by proximity to available farmland. For example, Ottawa, located in eastern Ontario, operates a structured land application program that enables the beneficial reuse of biosolids, the stabilized sludge, on nearby agricultural land.

Landfilling remains in use at approximately 14.5% of plants, mostly in moderately populated areas with a median population of around 80,000. In some urban centers, such as the Waterloo Region, digestate biosolids are landfilled after the digester process as a secondary disposal method when primary options are insufficient to manage the total generated volume.

Transported sludge are commonly observed in major urban regions with multiple WWTPs as well as in some remote areas. In urban settings, sludge is often transferred between facilities for further treatment before final disposal or reuse. In other cases, sludge is transported to third-party facilities or directly to some application.

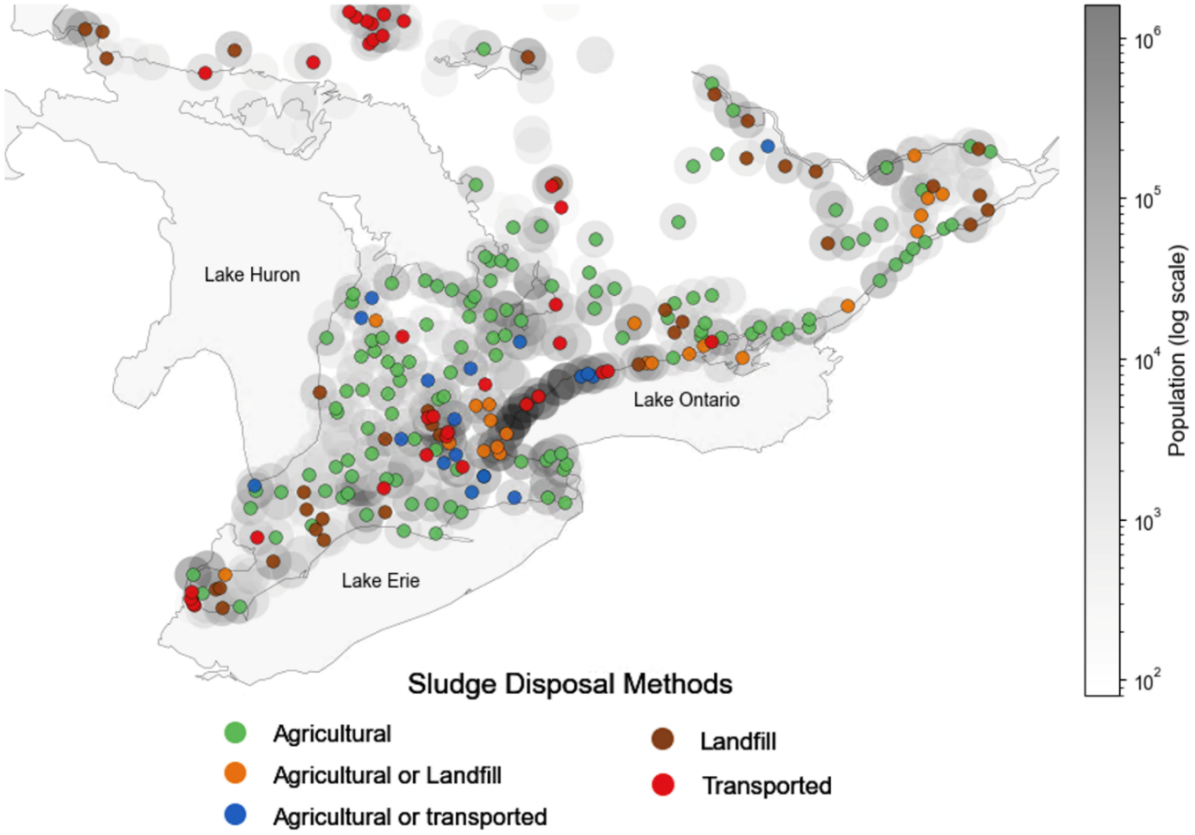



**Figure 8:** Subplot with land application and transported for spatial distribution of disposal methods across Ontario and population density.

Overall, the spatial distribution of disposal methods reflects differences in WWTP size, population served, and land availability. Larger urban centers, specifically close to Lake Ontario which generates a significant amount of sludge, tend to adopt more diverse disposal strategies to deal with the higher amount of sludge generated, while smaller or remote facilities are often constrained by infrastructure limitations or lack of reporting, reinforcing the need for improved data collection and regional planning.

While Figures 7 and 8 explored the spatial distribution of disposal methods and their relationship to population served, Figure 9 shifts focus to investigate how plant-level characteristics, specifically facility size and the presence or absence of digester, relate to disposal practices. To support this analysis, WWTPs were classified by average daily flow as small (≤ 3,785 m³/day), medium (3,785–37,850 m³/day), and large (≥ 37,850 m³/day). They were also categorized by stabilization method

(digested and undigested) and lagoon-based systems as a separate category. This breakdown provides additional insight into how infrastructure scale and stabilization technologies may influence the selection of disposal strategies across Ontario.

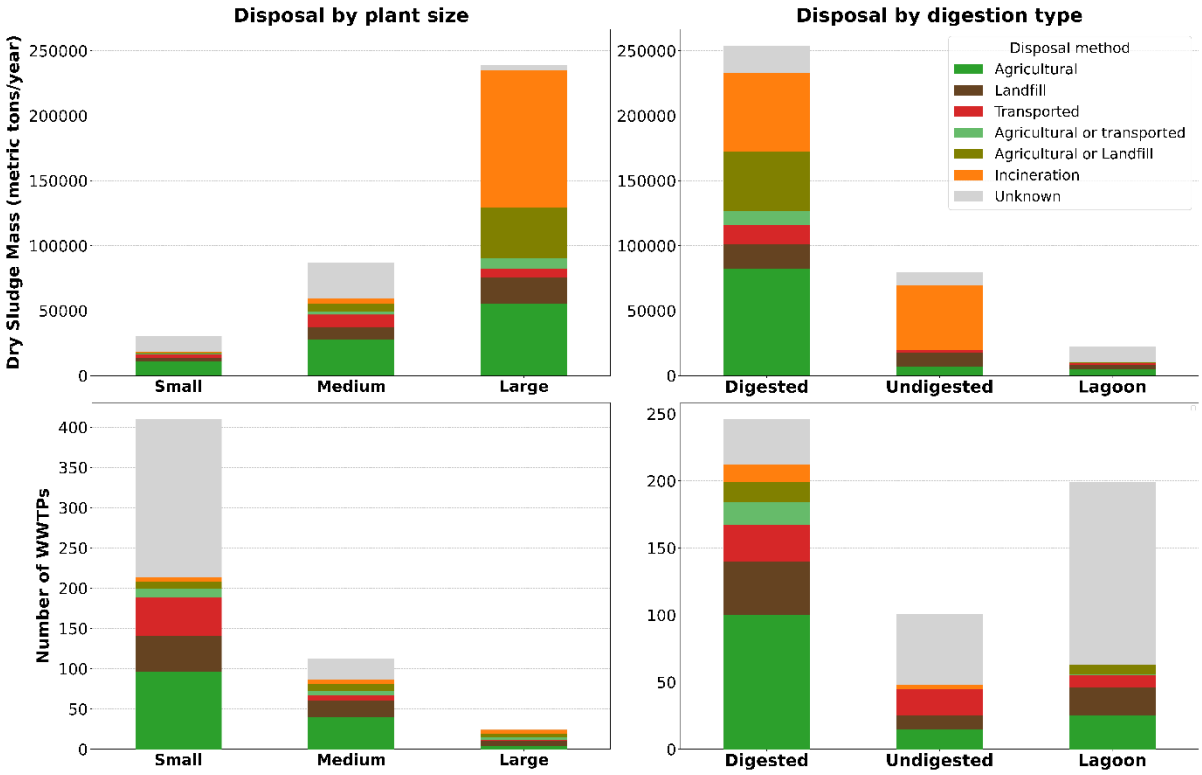



**Figure 9:** Disposal methods in relation to: a) Dry sludge mass generated by plant size, b) Number of WWTPs by plant size, c) Dry sludge mass generated by digestion type, and d) Number of plants by digestion type.

While small plants make up 75% (410 of 548) of WWTPs in Ontario (see Figure 9b), they contribute to only 8% (30,353 of 356,265 dry metric tons/year) of the province's total sludge generated mass (Figure 9a). These plants are typically lagoon systems (195 of 410 small plants) with limited sludge treatment infrastructure. Consequently, 42% (82 of 195 lagoons) fall into the “Unknown” disposal category (Figure 9b). This gap in reporting reflects both operational limitations and lack of standardized reporting data, an issue found in literature, where sludge disposal represents a significant operational cost for small wastewater treatment plants (Grobelak et al., 2019).

Medium-sized plants manage a significant portion of sludge, approximately 25% of the total dry mass generated in the province (Figure 9a). Of this nearly 25% (21,187 dry metric tons/year) is applied to agricultural land, and about 11% is transported off-sit, likely to nearby facilities with more advanced treatment or disposal capacity. Still, nearly 39% of sludge from these plants fall into the "Unknown" category, highlighting persistent reporting gaps, even among plants with generally greater capacity and infrastructure than smaller plants.

Large WWTPs, although fewer in number (25 of 548), (Figure 9b), produce and manage the handling of approximately 67% (238,417 of 356,265 dry metric tons/year) of the total dry mass generated in the province (Figure 9a). These plants are also responsible for the majority of incinerated mass and agricultural application, Figure 9(a) shows that almost 44% (105,665 dry metric tons/year) of the dry mass in this category goes to the incineration method and 23% applied to agricultural land. Additionally, 28% of the large plants adopt more than one method for sludge disposal such as agricultural and landfill or agricultural and transportation, which is particularly important during winter months when land application may be restricted. This trend suggests a correlation between plant size and the adoption of multiple management strategies, to maintain consistent sludge management throughout the year.

Digestion type also plays a key role in sludge disposal outcomes. As shown in Figure 9d, plants equipped with anaerobic or aerobic digesters are more likely to adopt sustainable disposal practices – such as agricultural application - due to the generation of the stabilized material, biosolids, during digestion. However, despite these environmental advantages, Figure 9c shows that a substantial portion of biosolids (~29%) still ends up in landfills (~6%) or is incinerated (~23%). In contrast, undigested sludge is even more likely to be incinerated, accounting for approximately 62%, due to limited end uses options for non-stabilized material.

Lagoon-based systems, also highlighted in Figure 9d, often lack documented disposal pathways, and tend to rely on less sustainable methods, such as landfilling. While these systems generate a relatively small share of total mass (Figure 9c), they represent a large proportion of facilities across the province (Figure 9d). This presents an opportunity to inform targeted provincial strategies aimed at these smaller facilities. For example, the data provided in this study can be used to identify specific regions with a high concentration of lagoon systems and to develop pilot programs that promote better disposal practices, such as land application, and to improve data reporting and documentation.

## 4.2 Nutrients content

The estimated phosphorus and nitrogen concentrations provide insight into their potential as a nutrient resource. Figure 10 presents boxplots that show the distribution of these nutrient concentrations, highlighting the medians, quartiles (variability), and potential outliers. This allows us to see how the data is spread and where the central values lie. The median phosphorus concentration in sludge was 29 kg/metric tons of dry mass (IQR: 17–42 kg/metric tons), and the median nitrogen concentration was 42 kg/metric tons (IQR: 17–67 kg/metric tons). These values align closely with reported literature ranges with phosphorus concentrations typically between 12–40 kg/metric tons and nitrogen between 16–60 kg/metric tons, depending on treatment process and stabilization (Collivignarelli et al., 2019; Elgarahy et al., 2024; Fytili & Zabaniotou, 2008).

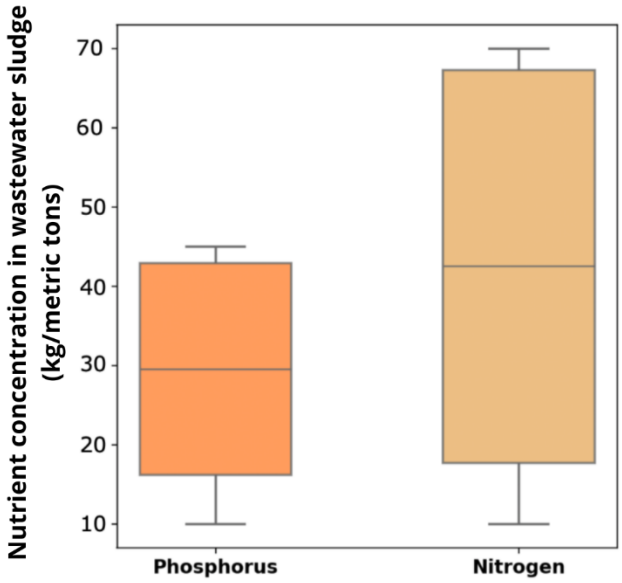



**Figure 10:** Boxplot of phosphorus and nitrogen concentrations in sludge, showing median and interquartile ranges.

These concentrations are consistent with the assumed values used by Rauch-Williams et al. (2018), which correspond to approximately 20 kg/metric tons of phosphorus and 45 kg/metric tons of nitrogen. They are also close to the average ranges reported by Beecher et al. (2023), who cited values of 20–23 kg/metric tons of phosphorus and 34–48 kg/metric tons of nitrogen. This close alignment with literature-reported values demonstrates that Ontario concentrations are comparable to these international benchmarks reported in the cited studies.

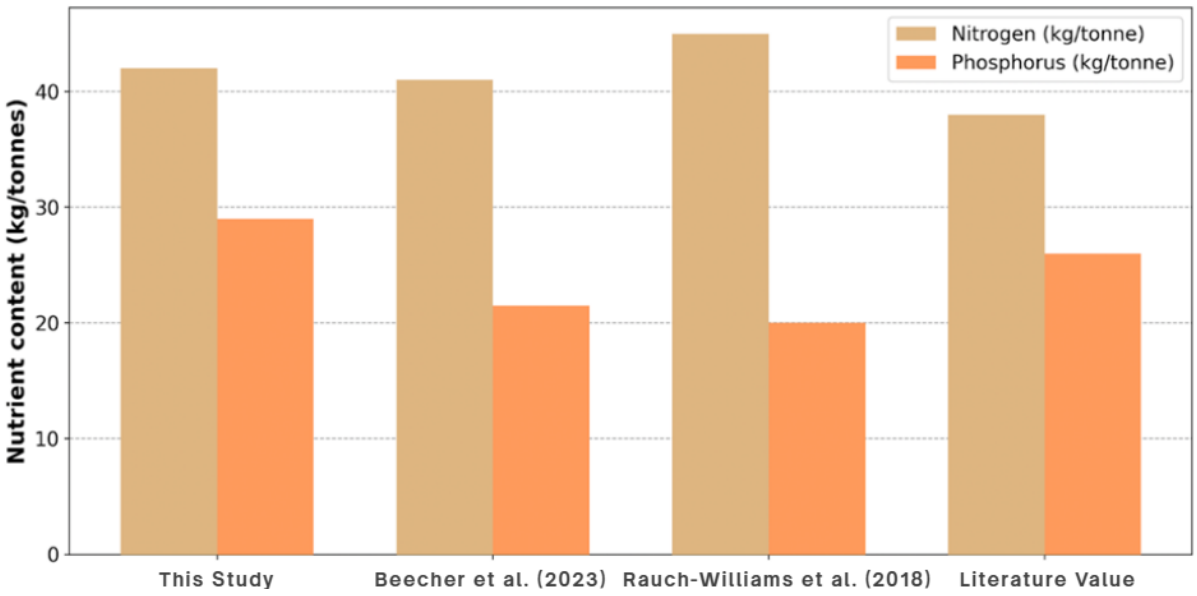



**Figure 11:** Comparison of nutrient content across studies.

By applying the observed phosphorus and nitrogen concentrations to the estimated dry sludge mass, the total nutrient content in sludge across Ontario is calculated to be approximately 9,937 ± 1,837 metric tons of phosphorus and 15,302 ± 9,044 metric tons of nitrogen in 2022.

The phosphorus estimates in this study differ from those in the *Mapping Phosphorus Flows in the Ontario Economy* report (Pollution Probe, 2022), which estimated approximately 6,800 metric tons of P per year generated in wastewater facilities. This difference is primarily due to the methodological variations. The Pollution Probe report employed an upscaling approach using 2019 data from the NPRI, calculating P concentration by combining values reported under both the "Release" (typically associated with effluent) and "Disposal" (typically associated with biosolids) categories. These totals were then divided by effluent volumes from corresponding facilities (sourced from the 2019 WSER dataset), and the resulting average concentrations were applied to facilities with known effluent flows to estimate total provincial P outputs from WWTPs. However, this approach did not account for phosphorus disposal at facilities that only reported releases, excluding 29 medium and large WWTPs in Ontario, which likely resulted in a lower overall phosphorus estimate.

This study focuses specifically on the P content retained in wastewater sludge. As described in Chapter 3, the NPRI data reported exclusively under the "Disposal" category was used, which reflects P contained in wastewater sludge. We then calculated P concentrations by dividing the total amount

disposed by the mass of sludge generated at each corresponding facility. This approach isolates the solid-phase phosphorus, which is significantly more concentrated than the diluted phosphorus present in effluent. As a result, the higher phosphorus values observed in this study reflect the accumulation of phosphorus in the solid fraction, whereas the effluent discharged to receiving water bodies contains much lower concentrations.

The spatial distribution of nutrient generation in wastewater sludge reveals pronounced regional variation, particularly in areas with large WWTPs serving urban populations (Figures 12). For phosphorus, facilities that generate more than 75 metric tons/y are located in the Greater Toronto Area, Ottawa, London, and surrounding regions (Figure 12a). Similarly, nitrogen generation follows this trend, and several plants exceeding 100 metric tons/year clustered in southern Ontario, particularly along Lake Ontario and Lake Erie (Figure 12b). These patterns reflect the concentration of treatment capacity and sludge output in urbanized regions. Facilities generating <25 metric tons/year of phosphorus or nitrogen are distributed more diffusely across northern and rural Ontario, consistent with smaller plant sizes and lower sludge volumes.

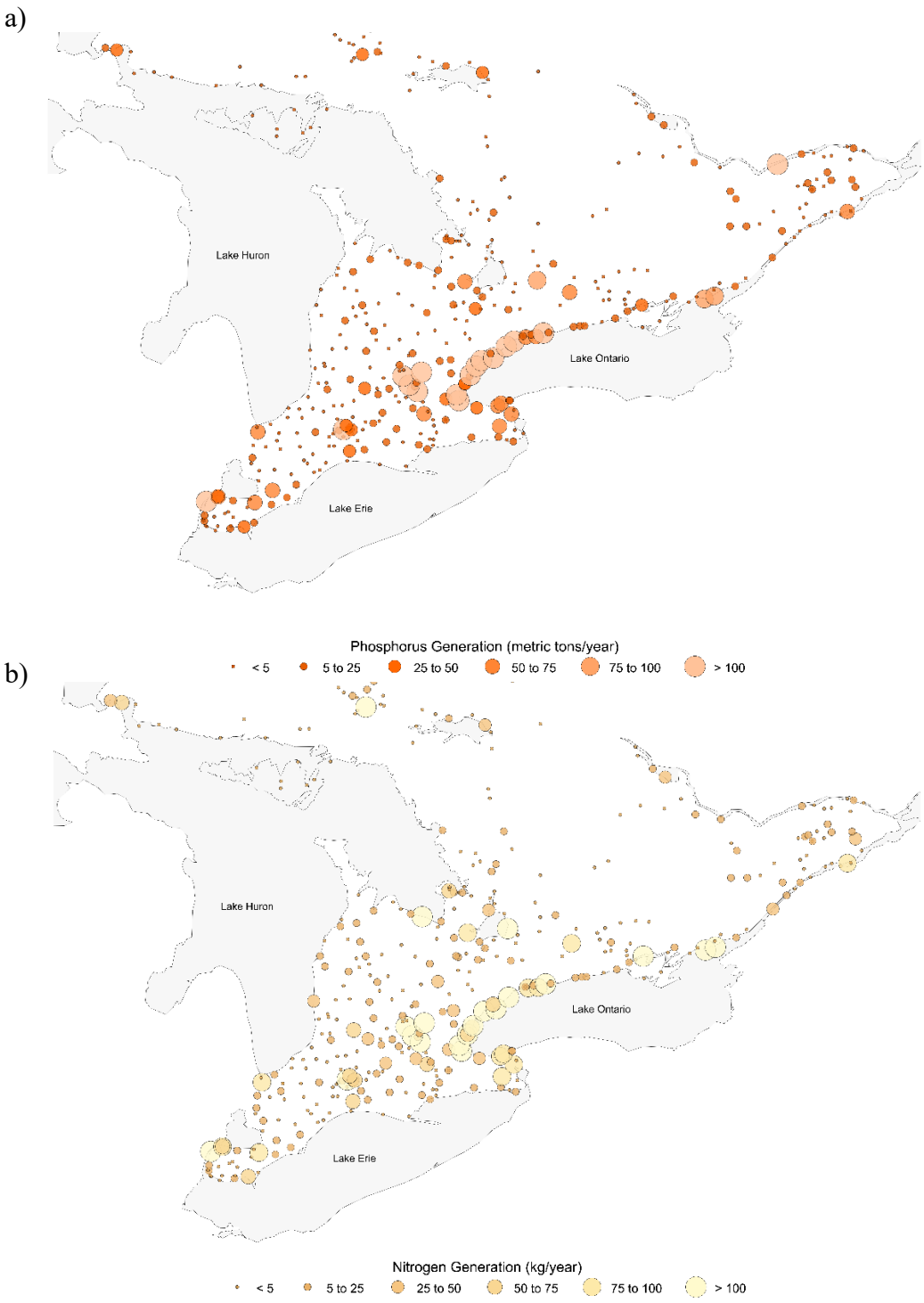



**Figure 12:** Spatial distribution of phosphorus (a) and nitrogen (b) generation across Ontario.

The distribution of nutrient content can also be analyzed by facility size, as shown in Table 7. Small plants, defined as those with average daily flow rates below 3,785 $m^3$/day, contribute only approximately 7% of phosphorus and 8% of nitrogen. In contrast, medium-sized facilities (3,785–37,850 $m^3$/day) generate nearly 26% of phosphorus and 24% of nitrogen. Large plants, with flows exceeding 37,850 $m^3$/day, account for roughly 64% of total phosphorus and 66% of total nitrogen.

**Table 7:** Estimated nutrient content by wastewater treatment plant size

| Plant Size | Number of plants | P in sludge (metric tons/year) | N in sludge (metric tons/year) |
|---|---|---|---|
| Small | 410 | 761 | 1,305 |
| Medium | 113 | 2,457 | 3,793 |
| Large | 25 | 6,767 | 10,205 |

To better understand the relationship between sludge treatment and nutrient recovery, Figure 13 illustrates the total mass of nitrogen and phosphorus in sludge by digestion category. The purpose of this figure is to evaluate how much nutrient mass is associated with each digestion type, helping to assess where nutrients are ultimately directed within Ontario's wastewater treatment systems.

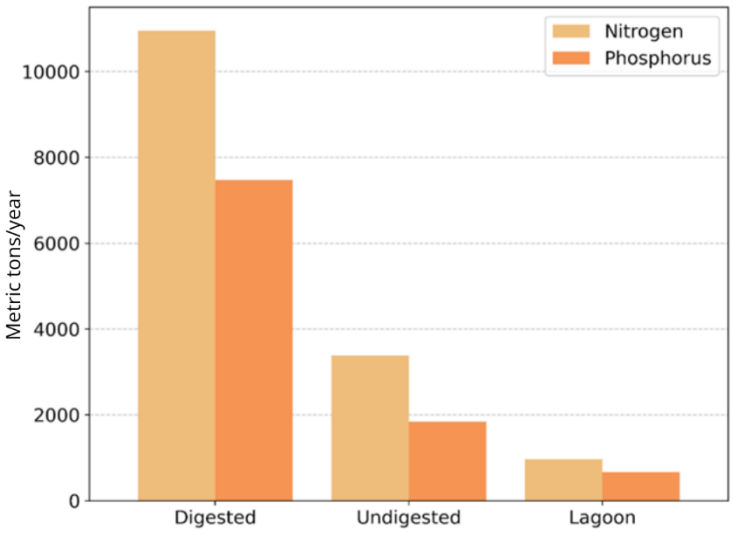



**Figure 13:** Mass of nutrient content by sludge digestion.

Digested sludge contains the highest nutrient loads, with approximately 10,900 metric tons of nitrogen and 7,400 metric tons of phosphorus annually. This aligns with earlier findings that digesters are primarily found in large plants, which handle the greatest sludge volumes and have more advanced infrastructure for treatment and nutrient tracking.

In contrast, undigested systems contribute approximately 3,400 metric tons of nitrogen and 1,900 metric tons of phosphorus, reflecting the smaller amount of sludge generated by these plants compared to large facilities. Lagoon-based systems account for the lowest nutrient contributions, about 1,100 metric tons of nitrogen and 800 metric tons of phosphorus, which is consistent with the lower volumes of wastewater typically treated by these facilities, rather than simply the number of plants.

This reflects the responsibility of WWTPs, especially those with digesters, to manage sludge in a way that minimizes nutrient loss and maximizes recovery potential, particularly given their significant contribution to the province's overall nutrient load. As major generators of stabilized sludge, these facilities play a critical role in advancing nutrient circularity through appropriate treatment and disposal practices. However, the extent to which these utilities are incentivized or able to fulfill this role is a key factor that influences the adoption of such practices.

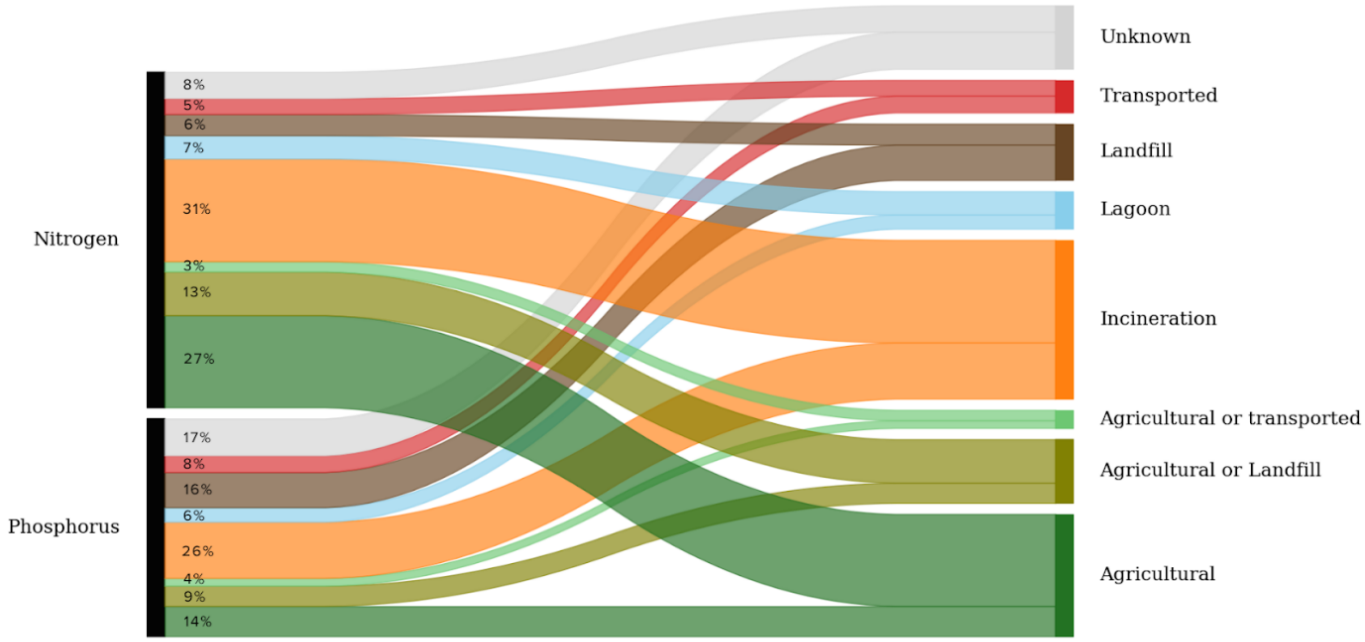



**Figure 14:** Mass percentage of P and N used by disposal methods.

The distribution of phosphorus and nitrogen in sludge across disposal methods reveals important trends in nutrient recovery and loss, as shown on Figure 13. A significant portion of both nutrients is directed toward incineration, 30.6% for nitrogen 25.8% for phosphorus, indicating a substantial loss of recoverable nutrients through thermal treatment. In contrast, land application pathways, including direct agricultural use and transported, account for a larger share of nitrogen (27.4%) than phosphorus (13.9%), suggesting a greater emphasis on nitrogen reuse. Mixed categories such as Agricultural or Landfill and Agricultural or Transported reflect uncertainties in final use, while the presence of Unknown categories highlights gaps in tracking and reporting.

# Chapter 5 - Conclusion

This study provides the most comprehensive province-wide estimate to date of sludge generation, nutrient content, and disposal practices across Ontario's municipal wastewater treatment plants. In doing so, it addresses longstanding data gaps that have hindered coordinated planning and constrained the adoption of more sustainable wastewater sludge management strategies.

We estimate that Ontario generated approximately 356,265 ± 35,859 dry metric tons of sludge in 2022. Of this, 244,711 tons were reported directly through annual data, and 111,554 tons were estimated based on flow or population data. This corresponds to a per capita generation rate of 23.5 kg/person/y—consistent with other national and international studies (17.8–31.0 kg/person/ y), reinforcing the validity of the treatment-process-specific coefficients used in our approach. Moreover, the sludge generation coefficient shows alignment with values reported previously.

Despite accounting for only 4% of facilities, large WWTPs (>37,850 $m^3$/day) contributed 67% of total dry mass, 66% of nitrogen, and 64% of phosphorus generated, respectively. In contrast, 75% of WWTPs are classified as small (<3,785 $m^3$/day), but together contribute only 12% of generation, 8% of nitrogen, and 7% of phosphorus. These figures illustrate the nutrients concentration and management responsibilities in a relatively small number of high-capacity plants.

Lagoon-based systems—common among small facilities—present significant data and infrastructure gaps. Many lack clear disposal reporting, and their passive sludge accumulation practices make it difficult to track sludge generation volumes and nutrient content. Despite their small share of total sludge generated, they represent over one-third of facilities in Ontario, reinforcing the need for better documentation.

Disposal practices are strongly influenced by the stabilization method. Plants with digesters, mainly large facilities, are more likely to adopt sustainable disposal options such as land application. Digesters stabilize sludge by reducing pathogens and odors, forming biosolids which are more suitable for beneficial use. However, limited storage capacity and seasonal restrictions on land application force many plants to rely on incineration, even for biosolids. Approximately 23% of biosolids from digesters are incinerated, contributing to nutrient losses of 30.6% for nitrogen and 25.8% for phosphorus.

Undigested sludge, mostly generated by smaller plants without stabilization systems, face even more limited reuse options. Approximately 62% of undigested sludge are incinerated, highlighting the dual challenge of limited treatment capacity and constrained end-use options among small-scale systems.

Nutrient content in Ontario's sludge is substantial. The median concentrations were 29 kg/ dry metric tons for phosphorus and 42 kg/ dry metric tons for nitrogen—closely aligned with international benchmarks. Applying these concentrations to the estimated sludge mass yields a total nutrient recovery potential of 9,937 ± 1,837 tons of phosphorus and 15,302 ± 9,044 tons of nitrogen per year. These resources are largely concentrated in Southern Ontario, where large plants dominate sludge production, further reinforcing their central role in advancing circular nutrient management.

Ultimately, this study provides a foundational dataset that can inform evidence-based planning for policymakers, municipal engineers, and wastewater managers By quantifying wastewater sludge generation, stabilization methods, and nutrient losses across the province, this work lays a data-driven foundation for future efforts to modernize Ontario's sludge management system and advancing the province's circular economy goals.

## 5.1 Limitations and Uncertainties

The approach used in this thesis provides valuable large-scale estimates but is subject to limitations. The primary source of uncertainty arises from the reliance on extrapolation and the use of coefficients derived from a subset of available data , including sludge generation, average effluent flow, population served by WWTP, and treatment and stabilization processes.

In Ontario, data were compiled for 548 WWTPs; however, detailed sludge generation data were available for only 146 WWTPs, primarily larger facilities (effluent >37,850 $m^3$/day) with more comprehensive monitoring and reporting. Consequently, the extrapolation factors were derived mainly from large plants, which may not accurately represent the operational efficiencies of medium-sized (effluent 3,785 - 37,850 $m^3$/day) or small facilities (effluent <3,785 $m^3$/day). Since larger plants typically have more efficient treatment and dewatering processes, applying their coefficients to smaller plants could result in underestimate the total generation. Additionally, for some treatment processes, only a few data points were available, leading to coefficients with higher associated uncertainty.

Another source of potential error is the exclusion of solids that are recycled within treatment processes (e.g., returned activated sludge or internal side streams). Failing to account for these flows can result in an overestimation of sludge produced for final disposal or reuse.

Furthermore, reliance on generation factors for extrapolation creates uncertainty, particularly when detailed operational data are unavailable. We believe that a mechanistic model approach assuming data on key operational factors, such as influent wastewater characteristics, operational efficiency, internal recycling of sludge and retention time, would likely yield more accurate and robust estimates than those derived from factors based on treatment type, stabilization process, effluent flow, and population served.

## 5.2 Future work

While this thesis focuses on estimating sludge generation and nutrient content across Ontario, future work is to build on these findings to support more coordinated and informed management decisions. This could begin with the development of a digital portfolio to share the compiled data and findings in a centralized, accessible format. Such a resource would offer municipalities, regulators, and industry stakeholders a clear overview of wastewater sludge generation, treatment processes, and nutrient characteristics across the province, supporting more coordinated and informed management decisions.

Building on this resource, the methodology developed in this work could be improved to derive more precise generation coefficients. Future studies could collect more detailed plant-specific data on influent wastewater characteristics (e.g. BOD and TSS concentrations), operational parameters, and sludge removal efficiency. By integrating these variables into a more complex mass balance, it would be possible to derive more precise generation factors that better account for the operation diversity of individual WWTPs.

Moreover, the dataset developed in this work could also be used to identify facilities where undigested sludge may be redirected for co-digestion with other organic wastes, such as manure and food waste. By evaluating the benefits and limitations of integrating undigested sludge into anaerobic digestion systems, and considering the feasibility through logistical and financial analysis, a clearer understanding of optimal management strategies and circular resource use can be developed.

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# Appendix

## Appendix A: Data Sources

This appendix provides a detailed list of the data sources used to estimate sludge generation rates across Ontario.

### 1. WWTP-Specific Annual Reports

Annual reports from various municipalities were retrieved from the publicly accessible sections of their official websites. These documents provided key operational data, including treatment processes, effluent flow, sludge generation, and population served. The list of plants with available information is as follows:

| | Facility Name | Company |
|---|---|---|
| 1 | Acton Wastewater Treatment Plant | The Regional Municipality of Halton |
| 2 | Alvinston Wastewater Treatment Plant | Municipality of Brooke-Alvinston |
| 3 | Amherstview Wastewater Treatment Plant | Corporation of Loyalist Township |
| 4 | Angus Wastewater Treatment Plant | Township of Essa |
| 5 | Arnprior Water Pollution Control Centre | Town of Arnprior |
| 6 | Arthur Wastewater Treatment Plant | Township of Wellington North |
| 7 | Ashbridges Bay Wastewater Treatment Plant | City of Toronto |
| 8 | Ayr Wastewater Treatment Plant | Regional Municipality of Waterloo |
| 9 | Azilda Wastewater Treatment Plant | City of Greater Sudbury |
| 10 | Bancroft Wastewater Treatment Plant | Town of Bancroft |
| 11 | Barry's Bay Wastewater Treatment Plant | Township of Madawaska Valley |
| 12 | Batawa Wastewater Treatment Plant | The Corporation of the City of Quinte West |
| 13 | Bath Wastewater Treatment Plant | Corporation of Loyalist Township |
| 14 | Blyth Wastewater Treatment Plant | The Corporation of the Township of North Huron |
| 15 | Bobcaygeon Wastewater Treatment Plant | City of Kawartha Lakes |
| 16 | Brantford Wastewater Treatment Plant | The Corporation of the City of Brantford |

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| 17 | Campbellford Wastewater Treatment Plant | The Corporation of the Municipality of Trent Hills |
| 18 | Carleton Place Wastewater Treatment Plant | Town of Carleton Place |
| 19 | Chatham Wastewater Treatment Plant | The Public Utilities Commission for the Municipality of Chatham-Kent |
| 20 | Chelmsford Wastewater Treatment Plant | City of Greater Sudbury |
| 21 | Clarkson South-Peel Wastewater Treatment Plant | Regional Municipality of Peel |
| 22 | Cochrane Wastewater Treatment Plant | The Corporation of the Town of Cochrane |
| 23 | Coldwater Wastewater Treatment Plant | Township of Severn |
| 24 | Collingwood Wastewater Treatment Plant | Corporation of the Town of Collingwood |
| 25 | Conger Wastewater Treatment Plant | District Municipality of Muskoka |
| 26 | Coniston Wastewater Treatment Plant | City of Greater Sudbury |
| 27 | Corbett Creek Wastewater Treatment Plant | Regional Municipality of Durham |
| 28 | Courtice Wastewater Treatment Plant | Regional Municipality of Durham |
| 29 | Craigleith Wastewater Treatment Plant | Corporation of The Town of The Blue Mountains |
| 30 | Deep River Wastewater Treatment Plant | Town of Deep River |
| 31 | Deseronto Wastewater Treatment Plant | The Corporation of the Town of Deseronto |
| 32 | Dowling Wastewater Treatment Plant | City of Greater Sudbury |
| 33 | Dresden Wastewater Treatment Plant | The Public Utilities Commission for the Municipality of Chatham-Kent |
| 34 | Duffin Creek (York-Durham) Wastewater Treatment Plant | Regional Municipality of Durham |
| 35 | Dundas Wastewater Treatment Plant (Hamilton) Wastewater Treatment Plant | City of Hamilton |
| 36 | Durham Wastewater Treatment Plant | The Corporation of the Municipality of West Grey |
| 37 | Ear Falls Wastewater Treatment Plant | The Corporation of the Township of Ear Falls |
| 38 | Eganville Wastewater Treatment Plant | Township of Bonnechere Valley |
| 39 | Elmira (Combined Flow) Wastewater Treatment Plant | Regional Municipality of Waterloo |
| 40 | Elora Wastewater Treatment Plant | The Corporation of the Township of Centre Wellington |
| 41 | Espanola Wastewater Treatment Plant | Corporation of the Town of Espanola |
| 42 | Esten Lake Wastewater Treatment Plant | The Corporation of the City of Elliot Lake |
| 43 | Fenelon Falls Wastewater Treatment Plant | City of Kawartha Lakes |

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| 44 | Fergus Wastewater Treatment Plant | The Corporation of the Township of Centre Wellington |
| 45 | Flesherton Wastewater Treatment Plant | Municipality of Grey Highlands |
| 46 | Frankford Wastewater Treatment Plant | The Corporation of the City of Quinte West |
| 47 | G.E.Booth (Lakeview)Wastewater Treatment Plant | Regional Municipality of Peel |
| 48 | Galt Wastewater Treatment Plant | Regional Municipality of Waterloo |
| 49 | Georgetown Wastewater Treatment Plant | The Regional Municipality of Halton |
| 50 | Glen Walter Wastewater Treatment Plant | Township of South Glengarry |
| 51 | Goderich Wastewater Treatment Plant | The Corporation of the Town of Goderich |
| 52 | Golden Pheasant Wastewater Treatment Plant | District Municipality of Muskoka |
| 53 | Grimsby-Baker Road Wastewater Treatment Plant | Regional Municipality of Niagara |
| 54 | Guelph Wastewater Treatment Plant | Corporation of the City of Guelph |
| 55 | Haldimand-Caledonia Wastewater Treatment Plant | Haldimand County |
| 56 | Haldimand-Dunnville Wastewater Treatment Plant | Haldimand County |
| 57 | Haldimand-Hagersville Wastewater Treatment Plant | Haldimand County |
| 58 | Haliburton Wastewater Treatment Plant | Municipality of Dysart et al |
| 59 | Harmony Creek Wastewater Treatment Plant | Regional Municipality of Durham |
| 60 | Hastings Wastewater Treatment Plant | The Corporation of the Municipality of Trent Hills |
| 61 | Hespeler Wastewater Treatment Plant | Regional Municipality of Waterloo |
| 62 | Highland Creek (Scarborough) Wastewater Treatment Plant | City of Toronto |
| 63 | Hornepayne Wastewater Treatment Plant | The Corporation of the Township of Hornepayne |
| 64 | Humber (Etobicoke) Wastewater Treatment Plant | City of Toronto |
| 65 | Huntsville (Mountview) Wastewater Treatment Plant | District Municipality of Muskoka |
| 66 | Ignace Wastewater Treatment Plant | The Corporation of the Township of Ignace |
| 67 | Ingleside Wastewater Treatment Plant | Corporation of the Township of South Stormont |
| 68 | Kemptville Wastewater Treatment Plant | The Corporation of the Municipality of North Grenville |
| 69 | Killaloe Water Pollution Control Plant | Township of Killaloe, Hagerty and Richards |
| 70 | Kitchener Wastewater Treatment Plant | Regional Municipality of Waterloo |

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| 71 | Lagoon City Wastewater Treatment Plant | The Corporation of the Township of Ramara |
| 72 | Lake Simcoe Wastewater Treatment Plant | Regional Municipality of Durham |
| 73 | Levack Wastewater Treatment Plant | City of Greater Sudbury |
| 74 | LFCA TC Meaford Wastewater Treatment Plant | LFCA TC Meaford |
| 75 | Lindsay Wastewater Treatment Plant | City of Kawartha Lakes |
| 76 | Lively Wastewater Treatment Plant | City of Greater Sudbury |
| 77 | Long Sault Wastewater Treatment Plant | Corporation of the Township of South Stormont |
| 78 | L'Orignal Wastewater Treatment Plant | Township of Champlain |
| 79 | Marathon Wastewater Treatment Plant | The Corporation of the Town of Marathon |
| 80 | Meaford Wastewater Treatment Plant | Township of Meaford |
| 81 | Merrickville Wastewater Treatment Plant | Village of Merrickville-Wolford |
| 82 | Mid-Halton Wastewater Treatment Plant | The Regional Municipality of Halton |
| 83 | Midland Wastewater Treatment Plant | Corporation of the Town of Midland |
| 84 | Mildmay Wastewater Treatment Plant | The Corporation of the Municipality of South Bruce |
| 85 | Milton Wastewater Treatment Plant | The Regional Municipality of Halton |
| 86 | Mississippi Mills Wastewater Treatment Plant | Municipality of Mississippi Mills |
| 87 | Mitchell (West Perth) Wastewater Treatment Plant | The Corporation of the Municipality of West Perth |
| 88 | Morrisburg Wastewater Treatment Plant | Municipality Of South Dundas |
| 89 | Mount Forest Wastewater Treatment Plant | Township of Wellington North |
| 90 | Napanee Wastewater Treatment Plant | Town of Greater Napanee |
| 91 | Newcastle Wastewater Treatment Plant | Regional Municipality of Durham |
| 92 | Norfolk-Delhi Wastewater Treatment Plant | Norfolk County Public Works & Environmental Services |
| 93 | Norfolk-Simcoe Wastewater Treatment Plant | Norfolk County Public Works & Environmental Services |
| 94 | North Bay Wastewater Treatment Plant | The City of North Bay |
| 95 | North Toronto Treatment Plant | City of Toronto |
| 96 | Oakville Southeast Wastewater Treatment Plant | The Regional Municipality of Halton |
| 97 | Oakville Southwest Wastewater Treatment Plant | The Regional Municipality of Halton |

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| 98 | Orangeville Wastewater Treatment Plant | Town of Orangeville |
| 99 | Orilla Wastewater Treatment Centre | The Corporation of the City of Orillia |
| 100 | Paisley Wastewater Treatment Plant | Corporation of Municipality of Arran-Elderslie |
| 101 | Penetanguishene (Fox) Wastewater Treatment Plant | The Corporation of the Town of Penetanguishene |
| 102 | Petawawa Wastewater Treatment Plant | Town of Petawawa |
| 103 | Philip H. Jones Pollution Control Plant | The Corporation of the Town of Penetanguishene |
| 104 | Picton Wastewater Treatment Plant | The Corporation of the County of Prince Edward |
| 105 | Port Carling Medora Wastewater Treatment Plant | District Municipality of Muskoka |
| 106 | Port Darlington Wastewater Treatment Plant | Regional Municipality of Durham |
| 107 | Port Elgin Wastewater Treatment Plant | Town of Saugeen Shores |
| 108 | Port Severn Lone Pine Wastewater Treatment Plant | District Municipality of Muskoka |
| 109 | Preston Wastewater Treatment Plant | Regional Municipality of Waterloo |
| 110 | Renfrew Wastewater Treatment Plant | Town of Renfrew |
| 111 | Ridgetown Wastewater Treatment Plant | The Public Utilities Commission for the Municipality of Chatham-Kent |
| 112 | Robert Pickard Env Centre Wastewater Treatment Plant | City of Ottawa |
| 113 | Rockland Sewage Treatment Plant | City of Clarence-Rockland |
| 114 | Rodney Lagoon and Wastewater Treatment Plant | Municipality of West Elgin |
| 115 | Schreiber Wastewater Treatment Plant | The Corporation of the Township of Schreiber |
| 116 | Shakespeare Wastewater Treatment Plant | Corporation of the Township of Perth East |
| 117 | Shelburne Wastewater Treatment Plant | Town of Shelburne |
| 118 | Sioux Lookout Wastewater Treatment Plant | The Corporation of the Municipality of Sioux Lookout |
| 119 | Skyway (Burlington) Wastewater Treatment Plant | The Regional Municipality of Halton |
| 120 | Smiths Falls Wastewater Treatment Plant | Corporation Town of Smiths Falls |
| 121 | Southampton Wastewater Treatment Plant | Town of Saugeen Shores |
| 122 | St George Wastewater Treatment Plant | County of Brant |
| 123 | St Marys Wastewater Treatment Plant | Town of St. Marys |
| 124 | St. Jacobs Wastewater Treatment Plant | Regional Municipality of Waterloo |

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| 125 | Strathroy Sewage Treatment Plant | Municipality of Strathroy-Caradoc |
| 126 | Sudbury Wastewater Treatment Plant | City of Greater Sudbury |
| 127 | Teeswater Wastewater Treatment Plant | The Corporation of the Municipality of South Bruce |
| 128 | Thamesford Wastewater Treatment Plant | County of Oxford |
| 129 | Thornbury Wastewater Treatment Plant | Corporation of The Town of The Blue Mountains |
| 130 | Thorndale Wastewater Treatment Plant | Municipality of Thames Centre |
| 131 | Tilbury Wastewater Treatment Plant | The Public Utilities Commission for the Municipality of Chatham-Kent |
| 132 | Trenton Wastewater Treatment Plant | The Corporation of the City of Quinte West |
| 133 | Uxbridge Brook Wastewater Treatment Plant | Regional Municipality of Durham |
| 134 | Valley East Wastewater Treatment Plant | City of Greater Sudbury |
| 135 | Victoria Harbour Wastewater Treatment Plant | Township of Tay |
| 136 | Walden Wastewater Treatment Plant | City of Greater Sudbury |
| 137 | Walkerton Wastewater Treatment Plant | Corporation of the Municipality of Brockton |
| 138 | Wallaceburg Wastewater Treatment Plant | The Public Utilities Commission for the Municipality of Chatham-Kent |
| 139 | Wardsville Wastewater Treatment Plant | Municipality of Southwest Middlesex |
| 140 | Wasaga Beach Wastewater Treatment Plant | Town of Wasaga Beach |
| 141 | Waterloo Wastewater Treatment Plant | Regional Municipality of Waterloo |
| 142 | Wellington Wastewater Treatment Plant | The Corporation of the County of Prince Edward |
| 143 | West Lorne Wastewater Treatment Plant | Municipality of West Elgin |
| 144 | Wheatley Wastewater Treatment Plant | The Public Utilities Commission for the Municipality of Chatham-Kent |
| 145 | Wingham Wastewater Treatment Plant | The Corporation of the Township of North Huron |
| 146 | Wyoming Wastewater Treatment Plant | Town of Plympton-Wyoming |

## 2. Public and Agency Datasets

This section provides more detailed information on the public and agency datasets used in this study, including hyperlinks for access.

### a. Ontario Clean Water Agency (OCWA)

Description: The OCWA dataset was a crucial source of information for this study, providing two distinct types of data. This data was made available as two Excel files.

The first file contained extensive information on 536 WWTPs managed by OCWA. Key columns included:

- Wastewater plant name
- Municipality Name
- Wastewater system status (Active or not)
- Level of treatment
- Population served
- Type of systems
- Preliminary treatment
- Primary treatment
- Secondary treatment
- Secondary equivalent treatment
- Sludge stabilization process
- Method of sludge disposal

The second dataset provided detailed information on the chemical composition of sludge on various forms of nitrogen. This data was made available as an Excel file containing and the following key columns:

- Wastewater plant name
- Station name (Biosolids)
- Sample date
- Parameter name
- Value

- Unit

Access: Data was provided directly by the agency.

**b. Wastewater Systems Effluent Regulations (WSER) Dataset**

Description: The WSER dataset, developed by Environment and Climate Change Canada (ECCC), is a comprehensive public database of wastewater facilities across Canada. It has information for 497 WWTPs in Ontario. The following columns were used in this project:

- Facility name
- City
- Province
- Average daily flow
- Types of treatment
- Description of other treatments
- Latitude
- Longitude

Access: The WSER dataset is publicly accessible through the Government of Canada's Open Data Portal. The specific dataset used in this study can be found at: https://open.canada.ca/data/en/dataset/9e11e114-ef0d-4814-8d93-24af23716489

**c. National Pollutant Release Inventory (NPRI) Dataset**

Description: The NPRI dataset provided crucial information for this study, specifically on the total disposal of phosphorus from wastewater systems. This public database, managed by Environment and Climate Change Canada, allowed us to identify the amount of phosphorus being disposed of as biosolids. The dataset was queried using specific criteria to isolate relevant data, including the reporting year (2022), province (Ontario), and key industrial sector (Water and Wastewater Systems). It was only counted the Total Disposal category, which is where biosolids are reported. The key data points extracted were:

- NPRI ID
- Year
- Company

- Facility name
- Units
- Total Disposal

Access: The NPRI database is publicly accessible online. The specific dataset used in this study can be found at: https://pollution-waste.canada.ca/national-release-inventory/

## Appendix B: Metadata

This appendix provides metadata describing the data available in the compiled dataset. The metadata outlines the structure of the dataset, including column headers, data categories, and measurement units. The table below summarizes the metadata structure for the complete dataset.

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W | X | Y | Z | AA | AB | AC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Facility Name | Company | Datasource (WSER / OCWA) | City | First Nation Facility (Yes/No) | 2020 Average daily effluent (m3/day) | 2020 Reported Liquid Biosolids (m3/y) | 2020 Reported TS (%) | 2020 Reported Dewatered Biosolids (metric tons/y) | 2020 Reported TS Dewatered (%) | 2020 Reported Dry Biosolids (metric tons/y) | 2021 Average daily effluent (m3/day) | 2021 Reported Liquid Biosolids (m3/y) | 2021 Reported TS (%) | 2021 Reported Dewatered Biosolids (metric tons/y) | 2021 Reported TS Dewatered (%) | 2021 Reported Dry Biosolids (metric tons/y) | 2022 Average daily effluent (m3/day) | 2022 Reported Liquid Biosolids (m3/y) | 2022 Reported TS (%) | 2022 Reported Dewatered Biosolids (metric tons/y) | 2022 Reported TS Dewatered (%) | 2022 Reported Dry Biosolids (metric tons/y) | Latitude | Longitude | Population Served | Type of System | Treatment process | Sludge Stabilization Process |
| 2 | Acton Wpcp | The Regional Municipality of Halton | BOTH | Halton Hills | | | | | | | | | | | | | | 4094 | 10408 | | | | | 43.6278 | -80.0225 | 9900 | Treatment and Collection System | Extended Aeration | Digested |
| 3 | Adelaide Wpcp | Corporation of the City of London | BOTH | London | | | | | | | | | | | | | | 23380 | | | | | | 43.015 | -81.2486 | 85180 | Treatment and Collection System | Conventional Activated Sludge (CAS) | Anaerobic Digestion |

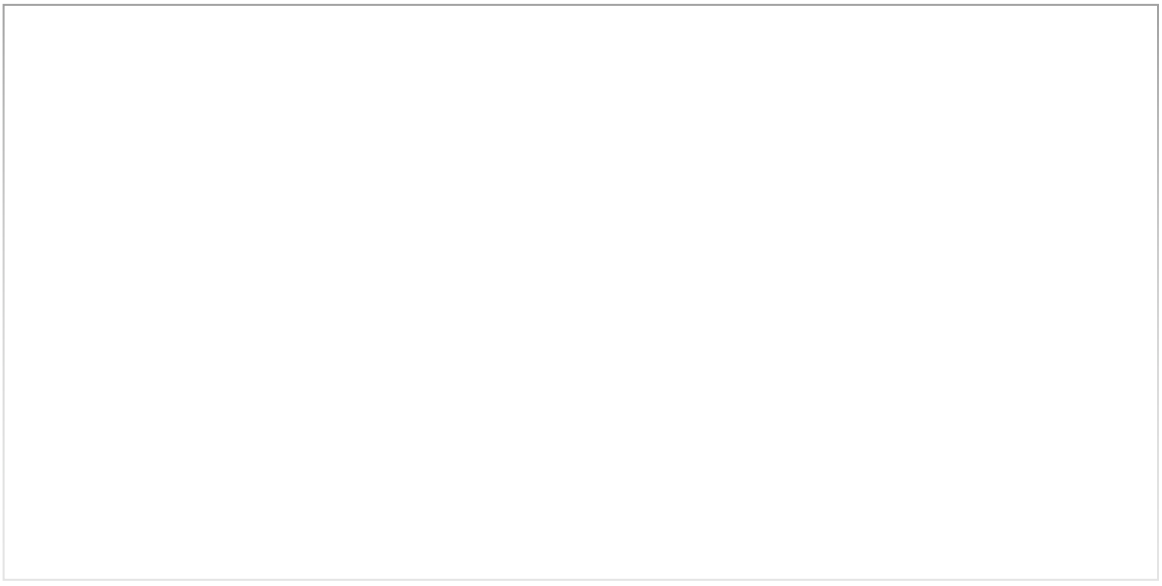
| | AD | AE | AF | AG | AH | AI | AJ | AK | AL | AM | AN | AO | AP | AQ | AR | AS | AT | AU | AV | AW | AX | AY | AZ | BA | BB | BC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Sludge Digestion | Primary Treatment | Dry Biosolids (metric tons/y) | Max Dry Biosolids (metric tons/y) | Min Dry Biosolids (metric tons/y) | Liquid Biosolids Mass (metric tons/y) | Max Liquid Biosolids Mass (metric tons/y) | Min Liquid Biosolids Mass (metric tons/y) | Reported /Estimated Dry Biosolids | Reported / Estimated Liquid Biosolids | Dry biosolid per capita (kg/person/y) | Liquid biosolid per capita (kg/person/y) | Dry solid Factor (g/m3) | Phosphorus Reported | P concentration (%) | P biosolid (metric tons/y) | P min range (metric tons/y) | P max range (metric tons/y) | Reported/ Estimated P | Reported Total N (%) | Total N (metric tons/y) | N min range (metric tons/y) | N max range (metric tons/y) | Reported / Estimated Total Nitrogen | Method of Biosolids Disposal | Other Disposal Method |
| 2 | Digested | Grit Removal | 206.0784 | 260.2 | 149.8752 | 10408 | | | Reported | Reported | 20.816 | 1.051313 | 137.9087 | | | 5.976274 | 3.565156 | 8.717116 | Estimated | | 8.773788 | 3.65274 | 13.86908 | Estimated | Agricultural; Landfill; Other-Mine Reclamation | |
| 3 | Digested | Grit Removal | 1242.241 | 1662.115 | 750.4008 | 48148.86 | 61803.01 | 36971.44 | Estimated | Estimated | 15.2058 | 0.589372 | | | | 37.56166 | 22.40748 | 54.78822 | Estimated | | 55.14441 | 22.95795 | 87.16897 | Estimated | Incineration | |

## Appendix C: Sample calculation

This appendix provides step-by-step examples for estimating dry and liquid sludge for two representative WWTPs, demonstrating the application of the dry solids factor ($\widetilde{DS_k}$) and sludge generation per capita ($\widetilde{GC_k}$) under different data availability scenarios. The plants index $i$ refers to each facility.

For this study, we have sludge generation data for 146 WWTPs. Plants 147 to 482 have effluent flow data available from the WSER dataset, while plants 483 to 548 lack effluent flow but have population served information from OCWA. For these stations, sludge was estimated using the dry solids and per-capita generation factors, respectively. This calculation approach is repeated for all 336 plants with effluent data and for all 66 plants with only population served information.

The following steps illustrate the methodological framework and estimation procedures used to calculate municipal sludge generation across Ontario (summarized in Figure 3).



**C.1 Example 1:** WWTP with effluent data from WSER dataset

**Plant Details:**

- Plant index: $i = 147$ (of 336 facilities with effluent data $i = 147\ to\ 482$)

- Effluent flow: 300,000 m³/y
- Treatment type ($k$): Conventional Activated Sludge (CAS) with anaerobic digestion

**Step 1 – Estimate Dry Sludge Mass ($D_{i,k}$):**

Using the dry solids factor ($\widetilde{DS_k}$) for CAS with anaerobic digestion, from Table 4

$$\widetilde{\mathrm{DS}}_{CAS\ anaerobic} = 151.8\ (g/m^3)$$

Applying Equation 3 (Section 3.1.3) for this plant:

$$D_{147,CAS\ anaerobic} = Q_{147} * \widetilde{\mathrm{DS}}_{CAS\ anaerobic} * 10^{-6} \quad \text{(C. 1)}$$

Substituting values:

$$D_{147,CAS\ anaerobic} = 300{,}000\ (\mathrm{m}^3/\mathrm{y}) * 151.8\ (\mathrm{g}/\mathrm{m}^3) * 10^{-6}(metric\ tons/g) \quad \text{(C.2)}$$

$$\boldsymbol{D_{147,CAS\ anaerobic} = 45.54\ (\mathbf{metric\ tons/y})}$$

**Step 2 – Convert to Liquid Sludge Mass ($L_{i,k}$):**

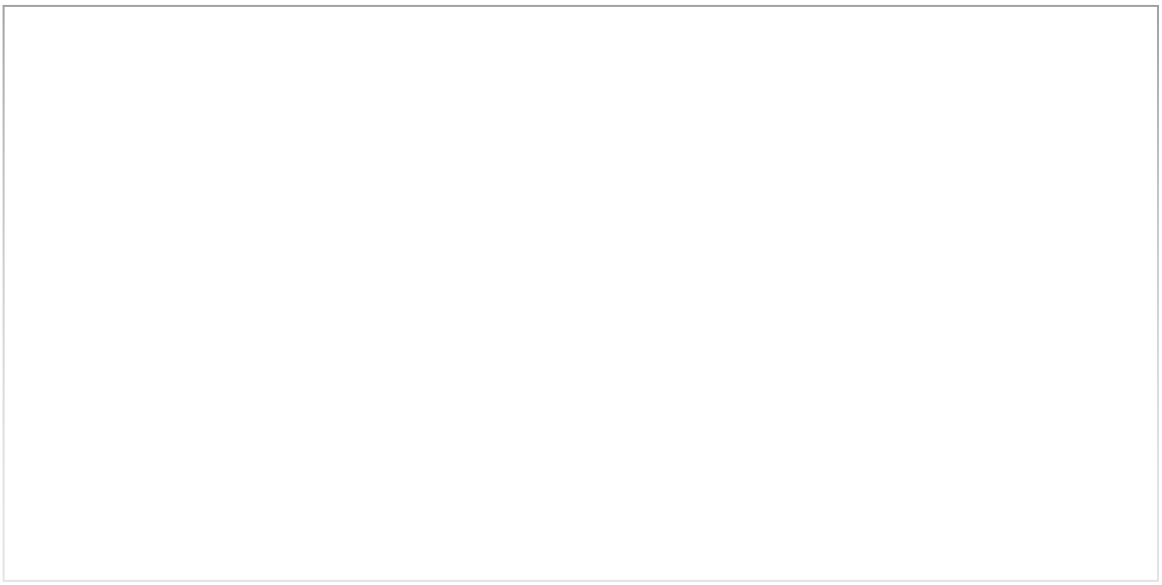
Using the total solids value ($\widetilde{TS_k}$) for CAS with anaerobic digestion, from Table 1:
$\widetilde{\mathrm{TS}}_{CAS\ anaerobic\ digestion} = 2.6\ \%$

Using Equation 9 from Section 3.1.5:

$$L_{147,CAS\ anaerobic} = \frac{D_{147,CAS\ anaerobic}}{\widetilde{\mathrm{TS}}_{CAS\ anaerobic}} \quad \text{(C.3)}$$

$$L_{147,CAS\ anaerobic} = \frac{45.54\ (\mathrm{metric\ tons/y})}{0.026} \quad \text{(C.4)}$$

$$\boldsymbol{L_{147,CAS\ anaerobic} = 1{,}751.54\ (\mathbf{metric\ tons/y})}$$



**C.2 Example 2:** WWTP with no effluent data but population served from OCWA dataset

**Plant Details:**

- Plant index: $i = 483$ (of 66 facilities lacking in effluent data but population served $i = 483\ to\ 548$)
- Population served: 50,000 people/y
- Treatment type: Extended Aeration with Digested Sludge

**Step 1 – Estimate Dry Sludge Mass ($D_{i,k}$):**

Using the generation per capita factor ($\widetilde{GC_k}$) for extended aeration digested sludge, from Table 4

$$\widetilde{\mathrm{GC}}_{Ext.\ aeration\ digested} = 18.2\ (kg/person/y)$$

Applying Equation 6 (Section 3.1.4) for this plant:

$$D_{148,\ Ext.aeration\ digested} = \widetilde{\mathrm{GC}}_{Ext.\ aeration\ digested} * P_{148} * 10^{-3}\ \text{(C. 5)}$$

Substituting values:

$$D_{148,\ Ext.aeration\ digested} = 18.2 \frac{\frac{\text{kg}}{\text{person}}}{\text{y}} * 50{,}000 \frac{\text{people}}{\text{y}} * 10^{-3} \quad \text{(C. 6)}$$

$$\boldsymbol{D_{148,\ Ext\ aeration\ digested} = 910\ (\text{tons/y})}$$

**Step 2 – Convert to Liquid Sludge Mass ($L_{i,k}$):**

Using the total solids value ($\widetilde{TS}_k$) for Extended Aeration with Digested Sludge, from Table 1:

$$\widetilde{\text{TS}}_{Ext.\ aeration\ digested} = 1.9\ \%$$

Using Equation 9 from Section 3.1.5:

$$L_{148,\ Ext\ aeration\ digested} = \frac{D_{148,\ Ext\ aeration\ digested}}{\widetilde{\text{TS}}_{Ext.\ aeration\ digested}} \quad \text{(C.7)}$$

$$L_{148,Ext\ aeration\ digested} = \frac{910\ (\text{metric tons/y})}{0.019} \quad \text{(C.8)}$$

$$\boldsymbol{L_{148,Ext\ aeration\ digested} = 47{,}894.7\ (\text{metric tons/y})}$$

**Note on Dry Solids ($DS$) Factor, Total Solids ($TS$) and Generation per capita ($GC$) selection:**

The dry solids factor ($\widetilde{DS_k}$), total solids ($\widetilde{TS}_k$) and generation per capita ($\widetilde{GC}_k$) must correspond to the treatment process $k$ listed in the Tables.

- If the treatment process is a lagoon-system, apply the same factor as CAS with undigested sludge.
- If the treatment process is an advanced system or is not explicitly listed in Tables, use the overall median factor ($\widetilde{DS}$ , $\widetilde{TS}$ and $\widetilde{GC}$ ) provided.