Benchmarking the Sustainability of Sludge Handling Systems in Small Wastewater Treatment Plants in Ontario

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

This project quantitatively benchmarked all aspects of sludge handling in a cross-section of small wastewater treatment plants across Ontario. Using plant operational data and on-site measurements, a variety of sustainability metrics were evaluated: energy consumption, chemical use, biosolids disposition, biosolids quality, and greenhouse gas emissions. In addition, a desktop analysis was conducted to determine the sustainability impact of incorporating innovative technologies into facilities with conventional processes. Parameters from select new technologies within the study sample were applied to plants within the sample that employed conventional processes, and the impact on greenhouse gas (GHG) emissions was calculated. Overall electricity consumption for sludge handling ranged from 0.9 – 3.9 kWh per dry kg of raw sludge. The thermo-alkali hydrolysis and auto-thermal thermophilic aerobic digestion (ATAD) processes consumed the least (0.3 kWh/dry kg) and most (3.8 kWh/dry kg) amount of electricity for stabilization, respectively. Mechanical dewatering processes consumed minor amounts of electricity (2 – 5% of total sludge handling draw), however, associated polymer dosages were found to be higher than literature values in some cases. The disposition fuel requirements for plants with dewatering were up to 85% lower than facilities without dewatering. Biosolids contaminant (pathogen/metals) contents were observed to be substantially below Non-Agricultural Source Material (NASM) requirements. The copper content of the hauled biosolids exhibited the highest concentration relative to the NASM limit among all plants studied, ranging from 14 – 37% among facilities practicing land application of biosolids. Four plants generated a product that met Class A requirements for *E. coli* content, including one facility that generated it through a long-term storage approach (GeoTube™). Carbon emissions ranged from -119 to 299 kg CO_2 equivalents per dry tonne of raw sludge. Six of the eight facilities that practiced land application of biosolids exhibited net-negative GHG emissions, as the carbon credits gained from fertilizer production avoidance outweighed the emissions associated with sludge processing and transportation operations. Of these six plants, five employed sludge treatment configurations that are common in Ontario. Given that land application is the most common disposal practice among small treatment plants in Ontario, the findings indicate that current conventional practices can be sustainable with respect to GHG emissions. The innovative technology assessment revealed that existing trucking requirements and polymer dosage are the primary factors that determine whether new technology implementation would improve environmental sustainability. The benchmarking approach developed and information gathered is of value to plant owners and operators who seek to better understand how their utility is performing relative to peers, identify areas of need and further investigation, and improve the long-term sustainability of their operations.

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List of Acronyms

AD = anaerobic digestion

ADP = abiotic depletion potential

AP = acidification potential

ATAD = auto-thermal thermophilic aerobic digestion

BOD = biochemical oxygen demand

CAD = conventional aerobic digestion

CED = cumulative energy demand

CFU = colony forming unit

CO_2 = carbon dioxide

COD = chemical oxygen demand

DO = dissolved oxygen

DT = dry tonne

EP = eutrophication potential

EU/D = end use / disposition

ETP = ecotoxicity potential

FAETP = freshwater ecotoxicity potential

FEP = freshwater eutrophication potential

FRU = finite resources use

FU = functional unit

GHG = greenhouse gas

GWP = global warming potential

HP = horsepower

HRT = hydraulic retention time

HTP = human toxicity potential

I = current

IR = ionizing radiation

K = potassium

km = kilometer

KOH = potassium hydroxide

KPI = key performance indicator

kW = kilowatt

kWh = kilowatt hour

LCA = life cycle assessment

LU = land use

MAETP = marine aquatic ecotoxicity potential

MEP = marine eutrophication

MG = million gallons

MOECC = Ministry of Environment and Climate Change

ML = million litres

MLD = million litres per day

MLSS = mixed liquor suspended solids

MPN = most probable number

N = nitrogen

NASM = Non-Agricultural Source Material

NH_3 = ammonia

NRE = non-renewable energy

O = operational phase

OCWA = Ontario Clean Water Agency

ODP = stratospheric ozone depletion

P = phosphorus

PE = population equivalent

PF = power factor

PMF = particulate matter formation

POFP = photochemical oxidation potential

RAS = return activated sludge

SRT = solids retention time

T= transport phase

TA = terrestrial acidification

TETP = terrestrial ecotoxicity potential

TKN = total kjeldahl nitrogen

TN = total nitrogen

TP = total phosphorus

TS = total solids

TSS = total suspended solids

US EPA = United States Environmental Protection Agency

V = voltage

VS = volatile solids

VSS = volatile suspended solids

WAS = waste activated sludge

WW = wastewater

WWTP = wastewater treatment plant

Chapter 1

Introduction

Conventional treatment of municipal wastewater involves the generation of semi-liquid sludge. The sludges are mostly water by weight (~98% prior to any processing), however, the solids portion contains several constituents of interest including organic material, nutrients, pathogens, and heavy metals (Metcalf & Eddy, 2013). Sludge generation represents a challenge from a plant operations stand-point, as it is continuously generated and must therefore be regularly processed and disposed of.

Moving forward, enhancing the long-term sustainability of wastewater treatment and associated sludge handling in small communities is of increasing importance to all stakeholders involved: owners, operators, and regulators. The practice of benchmarking is a strategy by which the sustainability of sludge handling in wastewater treatment plants (WWTPs) may be improved. Such a practice can provide owners and operators with a tool to evaluate their plant's performance relative to others of similar capacity and scope of operation, and make informed decision-making based on the results.

Historically, much of the benchmarking of wastewater treatment operations has focused on a) broader, high-level metrics of overall WWTP process operations and performance (Vera *et al*., 2013; Yang *et al.*, 2010), and b) large treatment facilities with advanced sludge processing (Bailey *et al.*, 2014; Lindtner *et al*., 2008; Silva *et al*., 2016). Relatively little attention has been paid to small WWTPs (<10 MLD) that have limited capital, operating and human resources. Information gaps in the actual operation of such systems exist and the quality and disposition of biosolids from these systems is not well documented.

The objective of this study was to quantitatively benchmark the sustainability performance of a cross-section of sludge handling systems in small WWTPs in Ontario. All analysis was based on actual plant data and on-site measurements to obtain the most accurate representation of existing performance. To achieve the objective, a systematic plant audit methodology was developed and implemented in ten WWTPs to evaluate a variety of sustainability metrics: energy consumption, chemical use, biosolids quality, biosolids disposition, and greenhouse gas emissions.

The information gathered is of value to plant owners and operators that seek to enhance the sustainability of operations. The benchmarking approach developed can be applied to a broad range of small plants. Such an exercise can help small communities better understand how their utility is performing relative to peers of similar capacity and scope, identify areas of need and further investigation, and improve the long-term sustainability of their operations.

Chapter 2

Literature Review

The goal of the current study was to employ a detailed benchmarking approach to evaluating sludge handling performance of several WWTPs within a sustainability assessment framework. A literature review was conducted to determine the state-of-the-art in wastewater treatment benchmarking methodologies and approaches to evaluating the sustainability of sludge handling systems. This exercise provided the necessary context from which the selection of sustainability benchmarking metrics and plant audit methodology would be based. In total, the review revealed 37 papers related to benchmarking of wastewater treatment operations and 25 papers related to the sustainability of sludge handling in the municipal wastewater treatment industry. The following discussion includes an overview of previous benchmarking studies in the wastewater treatment industry, a more in-depth analysis of benchmarking studies that are particularly relevant to the current study, and an examination of previous studies related to sustainability of sludge handling systems.

2.1 Benchmarking in Wastewater Treatment

The literature was reviewed with the goal of identifying key aspects of prior studies that addressed wastewater treatment benchmarking (Tables 2-1 and 2-2). Of the 37 studies, only two (Bailey *et al*., 2014; Silva *et al*., 2016) solely examined sludge handling operations. The remaining studies employed benchmarking metrics to characterize the entire treatment facility. Less than half of the reports addressed the sludge handling processes employed at the plants (Table 2-1) and only five included metrics specifically related to sludge production or quality (Table 2-2). It is thus evident that, historically, benchmarking operations have not placed emphasis on the sludge handling component of wastewater treatment, and in many cases have excluded analysis of such operations entirely. Yet, sludge processing and its associated management can account for upwards of 40% of the operational costs for a WWTP (Lindtner *et al*., 2008; Haslinger *et al*., 2016), and any improvements to the efficiency and efficacy of treatment inputs and disposal practices can therefore have a beneficial impact on the environmental and economic sustainability of the entire operation. As such, it was determined that there is a clear need for additional studies that develop and employ detailed benchmarking methodologies to assess sludge handling operations.

Table 2-1: Characteristics of wastewater benchmarking studies

Study (Year)	Location	Number of WWTPs in Sample	Small WWTPs in Sample?	Only Small WWTPs Studied?	Evaluation Boundary	Treatment Types Noted	On-site measurements
AECOM (2018)	Canada	53	✓		Plant-wide		
AECOM (2012)	Canada	35	✓		Plant-wide	Liquid	
AMBI (2017)	Canada	5	✓		Plant-wide	Liquid	
Bailey *et al*. (2014)	USA	8			Sludge only	Sludge only	
Balmer (2000)	Several	5			Plant-wide	Liquid, sludge	
Balmer and Hellstrom (2012)	Sweden	24	✓		Plant-wide	Liquid, sludge	
Belloir *et al*. (2015)	England	2	✓	✓	Plant-wide	Liquid, sludge	Electrical Submetering
Benedetti *et al*. (2008)	Belgium	29	✓		Plant-wide	Liquid	
Bodik and Kubaska (2013)	Slovakia	68	✓		Plant-wide	Liquid, sludge	
Carlson *et al.* (2007)	USA	266	✓		Plant-wide	Liquid, sludge	
de Haas *et al*. (2015)	Australia	142	✓		Plant-wide	Liquid, sludge	
Foladori *et al*. (2015)	Italy	5	✓	✓	Plant-wide	Liquid, sludge	Electrical Submetering
Gallego *et al*. (2008)	Spain	13	✓	✓	Plant-wide	Liquid, sludge	Partial Submetering
Gu (2016)	China	9	✓		Plant-wide	Liquid	
Hanna *et al*. (2017)	USA	95	✓	✓	Plant-wide	Liquid, sludge (partial)	
Haslinger *et al*. (2016)	Austria	104	✓		Plant-wide	Liquid, sludge	
Krampe (2013)	Australia	24	✓		Plant-wide	Liquid, sludge	
Lindtner *et al*. (2008)	Austria	6			Plant-wide	Liquid, sludge	

Lorenzo-Toja *et al*. (2016)	Spain	22	✓		Plant-wide	Liquid, sludge	
Mamais *et al*. (2015)	Greece	10	✓		Plant-wide	Liquid, sludge	
Mizuta and Shimada (2010)	Japan	985 + 4	✓		Plant-wide	Liquid, sludge (partial)	Unclear
Nowak (2003)	Austria	12			Plant-wide	Liquid, sludge	
NYSERDA (1998)	USA	6	✓		Plant-wide	Liquid, sludge	Electrical Submetering
NYSERDA (2006)	USA	8			Plant-wide	Liquid, sludge	Electrical Submetering
NYSERDA (2008)	USA	174	✓		Plant-wide	Liquid	
Patziger (2017)	Hungary	21	✓	✓	Plant-wide	Liquid	
Rodriguez-Garcia *et al*. (2011)	Spain	24	✓		Plant-wide	Liquid	
SAIC (2006)	USA	85	✓		Plant-wide	Liquid	
Silva *et al*. (2012)	Portugal	17	✓		Plant-wide	Liquid, sludge	
Silva and Rosa (2015)	Portugal	17	✓		Plant-wide	Liquid	
Silva *et al*. (2016)	Portugal	17	✓		Sludge only	Liquid, sludge	
Singh *et al*. (2016)	India, UK	50	✓		Plant-wide	Liquid, sludge	
Tao and Chengwen (2012)	China	1856	✓		Plant-wide		
Vera *et al*. (2013)	Chile	14	✓		Plant-wide	Liquid	
Wang *et al*. (2016)	China	5	✓		Plant-wide	Liquid	
WERF (2015)	USA	86	✓		Plant-wide	Liquid	
Yang *et al*. (2010)	China	599 + 10	✓		Plant-wide	Liquid, sludge (partial)	

Table 2-2: Inputs/outputs evaluated in wastewater benchmarking studies

Study (Year)	Energy	GHG	Chemicals	WWTP Effluent Quality	Contaminant Removal Efficiency	Labour	Sludge Handling	Others
AECOM (2018)	✓							
AECOM (2012)	✓							
AMBI (2017)	✓							Economics
Bailey *et al*. (2014)	Sludge Only		Sludge			Sludge	Several	Economics
Balmer (2000)	✓		✓			✓	Production	Economics
Balmer and Hellstrom (2012)	✓		✓	✓		✓	Production, quality	Economics
Belloir *et al*. (2015)	✓	✓						
Benedetti *et al*. (2008)	✓			✓	✓			Several
Bodik and Kubaska (2013)	✓							
Carlson *et al.* (2007)	✓							
de Haas *et al*. (2015)	✓							
Foladori *et al*. (2015)	WW, Sludge							
Gallego *et al*. (2008)	✓	✓					Quality (metals)	LCA
Gu (2016)	✓	✓						
Hanna *et al*. (2017)	✓							
Haslinger *et al*. (2016)	✓							
Krampe (2013)	✓							
Lindtner *et al*. (2008)	✓							

Lorenzo-Toja *et al*. (2016)	✓	✓				LCA
Mamais *et al*. (2015)	✓	✓				
Mizuta and Shimada (2010)	✓					
Nowak (2003)	✓					
NYSERDA (1998)	WW, Sludge					
NYSERDA (2006)	WW, Sludge					
NYSERDA (2008)	✓					
Patziger (2017)	✓		✓	✓		
Rodriguez-Garcia *et al*. (2011)	✓	✓				LCA, Economics
SAIC (2006)	✓					
Silva *et al*. (2012)	✓				Production, TS, % Beneficial Use	Several
Silva and Rosa (2015)	✓					
Silva *et al*. (2016)					Several	
Singh *et al*. (2016)	✓	✓				
Tao and Chengwen (2012)	✓					
Vera *et al*. (2013)	✓		✓	✓	Production	
Wang *et al*. (2016)	✓	✓				
WERF (2015)	✓					
Yang *et al*. (2010)	✓					

Energy issues are a key element of sustainability assessments and hence the method of assessing energy utilization in prior studies (Table 2-2) was of interest. It was found that in prior benchmarking exercises, data-driven approaches using real plant data were common. This included multiple studies that developed benchmarking models within a region using advanced statistical techniques (AWWARF, 2007; Hanna *et al*., 2017; Mizuta and Shimada, 2010). However, the insights provided by this information were often limited in that they only employed utility bills for the entire plant to determine electricity consumption, and thus did not contain any information related to the performance of individual unit processes.

Four studies (Belloir *et al*., 2015, Foladori *et al*., 2015, NYSERDA, 1998, NYSERDA, 2006) reported the gathering of on-site power draw measurements (submetering) on individual pieces of equipment. Of the four studies, one (Belloir *et al*., 2015) only evaluated two plants and thus provided a limited sample for benchmarking purposes, and two (NYSERDA 1998, 2006) were commissioned by the same organization and performed in the same general geographical location (New York State). These studies revealed that while the submetering exercise can be time and labour intensive, it can provide a greater amount of insight into the performance of the individual unit processes employed. Thus, it provides a deeper level of information to plant owners and operators that seek to target specific areas of their operation for improvement. This benefit was evidenced in the NYSERDA (2006) investigation, which identified \$6.4 million in savings (representing 15% of total operation costs) through their study. A detailed discussion of the audit methodologies employed by all four studies, and their relevance to the present study, is presented in section 2.2.2.

The current study has a focus on small WWTPs and hence the size of facilities evaluated in the benchmarking analyses was of interest. It was found that all but five studies included small treatment plants as part of their sample (Table 2-1), however only six studies focused solely on WWTPs with average flows less than 12,000 m^3/d or less than 20,000 PE. Notably, several studies found that small WWTPs generally exhibited higher specific energy consumption than larger plants (Bodik and Kubaska, 2013; Mizuta and Shimada, 2010; Yang *et al*., 2010; Silva and Rosa, 2015; Haslinger *et al*., 2016; Singh *et al*., 2016) since the former do not benefit from the “economies of scale” that the larger facilities exhibit. For facilities in smaller communities where resources (economic, labour, etc.) are limited, minor improvements to process operation can have a beneficial impact on the sustainability of the operations. The relatively limited numbers of reported studies on small WWTPs confirmed the need for additional studies in this area.

Table 2-3: Normalizing bases employed in wastewater benchmarking studies

Study (Year)	Volume of WW treated	WWTP Influent Load	Liquid Contaminant Mass Removed	Other
AECOM (2018)	ML			
AECOM (2012)	ML			
AMBI (2017)	m^3			
Bailey *et al*. (2014)				dry tonne of biosolids
Balmer (2000)		PE (N)		ton TS (sludge chemicals)
Balmer and Hellstrom (2012)		PE (not specified)		
Belloir *et al*. (2015)	m^3			
Benedetti *et al*. (2008)	m^3	PE (BOD, TN)		
Bodik and Kubaska (2013)	m^3			(kWh/flow)/BOD load
Carlson *et al.* (2007)	MG			
de Haas *et al*. (2015)		BOD		
Foladori *et al*. (2015)	m^3	PE (COD)	COD	
Gallego *et al*. (2008)		PE ("organic load")		
Gu (2016)	m^3			
Hanna *et al*. (2017)	m^3			
Haslinger *et al*. (2016)		PE (COD)		
Krampe (2013)		PE (BOD)		
Lindtner *et al*. (2008)		PE (COD)		
Lorenzo-Toja *et al*. (2016)	m^3			

Mamais *et al*. (2015)		PE (not specified)		
Mizuta and Shimada (2010)	m^3			
Nowak (2003)		COD		
NYSERDA (1998)	MG			
NYSERDA (2006)	MG		BOD	lb. TSS removed (sludge ops)
NYSERDA (2008)	MG	BOD		
Patziger (2017)		COD	COD, TN	
Rodriguez-Garcia *et al*. (2011)	m^3			kg PO_4 removed
SAIC (2006)	MG	PE (not specified)	BOD	
Silva *et al*. (2012)	m^3			
Silva and Rosa (2015)	m^3		BOD, COD	
Silva *et al*. (2016)				dry tonne of sludge
Singh *et al*. (2016)	m^3			
Tao and Chengwen (2012)	m^3		COD	
Vera *et al*. (2013)				PE (inhabitants*year.)
Wang *et al*. (2016)	m^3		COD, NH3-N	
WERF (2015)	MG	BOD		
Yang *et al*. (2010)	m^3		Composite	

The selection of factors to consider in carrying out a benchmarking activity was identified as important in designing the proposed research program. A review of the studies detailed in Table 2-2 reveals that energy consumption was the only metric common to all studies [whether directly or through conversion to life cycle assessment (LCA) impact factors], and over half of the studies evaluated only this input. Of the non-energy benchmarking studies, four evaluated greenhouse gas (GHG) emission quantities, five benchmarked plant effluent quality (four of which also documented contaminant removal *rate*), six evaluated economic costs (*e.g.* labour, operating and maintenance), and four inventoried other inputs, such as chemicals. Given that facilities often face site-specific challenges of varying importance, the lack of comprehensive benchmarking investigations incorporating inputs and outputs beyond energy was identified as a knowledge gap. Further study in this regard is proposed, since improvements to any of the measures could benefit the environmental, economic, and social sustainability of operations.

Benchmarking is typically conducted using normalized metrics that allow for comparisons between facilities of differing scale. Of the 35 papers that evaluated plant-wide metrics, the most common normalizing basis was “unit volume of wastewater treated” (24 papers), half of which solely benchmarked on that basis (Table 2-3). While the easiest to obtain and calculate, thus making it the most convenient option for studies involving a large number of facilities, exclusively benchmarking on a flow treated basis can be limiting in that it does not account for the strength of the incoming wastewater, nor does it account for differences in the goals of the treatment facility. For example, some facilities may require high inputs to practice nutrient removal and meet stringent effluent quality targets; other plants may contain energy-intensive sludge handling processes while exhibiting economical liquid treatment performance. Thus, normalizing overall energy consumption (for example, through monthly electrical bills) by wastewater flow can facilitate a high-level comparison between facilities of similar configuration but provides limited insight into the performance of specific unit operations. Of the referenced studies, many (Table 2-1) did note the general category of treatment for any given plant (and some detailed the specific treatment types), thereby ensuring that the comparison between plants had some degree of “fairness”.

Other studies have included different normalizing bases with the goal of providing more insightful comparisons and moving toward addressing the limitation identified. Eleven studies normalized their data on the basis of influent contaminant mass loading [typically chemical or biochemical oxygen demand (COD or BOD)], commonly expressed as a population equivalent (PE), of which four also included a flow-normalized analysis. Such a basis provided a measure of the strength of incoming wastewater, although only normalizing on organic load did not account for wastewaters that were high in nutrients (only two studies based the PE on nitrogen load) and the methodology still lacked a measure for evaluating the efficiency of the inputs in removing contaminants.

The inability to address efficiency in resource utilization has been identified as a deficiency and seven studies normalized energy consumption by the extent of contaminant removal, in addition to flow and load normalized analyses. The former metric was found to provide insight into the effectiveness of the inputs (*e.g.* energy) as they relate to plant performance, which can help users identify opportunities of improvement and process optimization. Studies by NYSERDA (2006) and SAIC (2006) have confirmed the insightfulness of efficiency-based measures, as facilities were identified that, while performing better than their peers on an overall energy consumption basis, exhibited lower energy efficiency than their peers. Hence, it was concluded that opportunities for process improvement were likely present. Overall, it was concluded that investigations which incorporate both flow/loading and efficiency-based metrics can provide a greater level of insight into the systems of interest. The limited number of reports of benchmarking studies that have incorporated such analysis, suggests a knowledge gap and area of need for future study.

In summary, while benchmarking of wastewater treatment operations is not a novel practice, there has been a distinct lack of investigations into the following:

1. Benchmarking dedicated exclusively to sludge handling operations;
2. Benchmarking dedicated exclusively to small WWTP operations;
3. Detailed plant audits that feature on-site data collection of individual unit processes;
4. Benchmarking that extends beyond energy consumption to include all system inputs/outputs;
5. Methodologies that incorporate both quantity/composition of material treated and the efficiency of inputs as normalizing bases for evaluation and comparison between samples.

2.2 Detailed Analysis of Relevant Benchmarking Studies

A closer examination of the benchmarking studies that were particularly relevant to the present study was conducted to determine whether elements of the approaches employed previously could be incorporated into the current study. This review included two studies focused solely on sludge handling operations (section 2.2.1), and four studies that involved detailed energy audits with electrical submetering (2.2.2).

2.2.1 Sludge handling Benchmarking Studies

Bailey *et al*. (2014) benchmarked the sludge handling performance of three WWTPs (and two water treatment plants) in North Carolina with six comparable facilities within the United States. The additional plants were selected because they had similar features to the North Carolina plants: separate biosolids processing facilities with biosolids conveyance, a Class A EQ biosolids product, similar quantity of biosolids production, regional handling, and similar equipment and processes (as an optional requirement).

To assess the facilities, a variety of benchmarking metrics were evaluated: labour (full time equivalents and cost), power [kilowatt hour (kWh) consumption and cost], chemical costs, total combined operating and maintenance costs, and final product cost and revenue on a dry tonne of biosolids produced basis. Notably, the normalizing basis of biosolids production (end product) had the same limitation as the wastewater flow/loading functional unit noted in the previous section: it did not account for the efficiency of the inputs as they related to process performance. When compared to an alternative, one process may have had a higher power draw on a biosolids produced basis, but a lower draw when related to quantity of volatile solids destruction. It would therefore have been more insightful to include bases of both raw sludge mass production and, for the stabilization step, quantity of volatile solids destruction.

Silva *et al*. (2016) also focused solely on evaluating WWTP sludge handling performance in a study that extended from a prior WWTP performance assessment (Silva *et al*., 2012; Silva and Rosa, 2015). A list of performance indicators and indices that covered a range of aspects related to sludge handling was developed and evaluated for 17 WWTPs in Portugal. The metrics included quantity of sludge produced (per volume of wastewater treated, and per mass of BOD and COD removal), percentage of sludge used beneficially, quality compliance of sludge used in agriculture (binary compliant/non-compliant basis for each required parameter), percentage of phosphorus (P) reclaimed (*i.e.* through beneficial use), and sludge processing and disposal costs (both on a volume of treated wastewater basis and as a percentage of total operating costs). The sludge processing cost measures were partitioned into those associated with energy consumption and chemical use.

Some of the indicators in the Silva study provided insight into the sustainability of operations. These included the percentage of sludge used for beneficial purposes, percentage of P reclaimed, and quality compliance of the sludge used for agriculture. However, with respect to the latter indicator, simply reporting a composite binary metric of compliance/non-compliance was limited in that it did not give an indication of how close to the regulatory threshold any given parameter was. Thus, the consequence of a change in regulations to more stringent contaminant limits was not obtained. Further, the wastewater volume basis employed may be problematic since facilities that have higher sludge yields (for example, due to chemical sludge production) could receive a disproportionately unfavourable result when compared to those with lower sludge yields.

In summary, the benchmarking studies that have focused exclusively on sludge handling operations have been limited in scope and rigour. Neither study employed rigorous energy or process audits, nor did they comprehensively evaluate all the inputs and outputs of the systems being studied. The study of Silva *et al*. (2016) incorporated several metrics that could be insightful from a sustainability assessment perspective, but ultimately a need for a systematic methodology to comprehensively evaluate such systems remains.

2.2.2 Benchmarking Studies Involving Energy Audits

Detailed audits that included electrical submetering of process equipment were of interest as it was believed that they provide the most complete and accurate comparisons between peer facilities. The four papers featuring detailed plant audits were therefore examined to determine whether elements of the methodologies employed would be applicable to the current study. A summary of the key characteristics of the relevant studies is shown in Table 2-4.

Among the four studies, there was broad agreement in the basic set-up of an energy audit. For motors that had a constant power draw, single instantaneous measurements coupled with motor run-times (either through installation of hour-meters, evaluation of plant records, or discussion with plant operators) were employed to calculate the daily energy consumption. For motors that were equipped with variable frequency drives (VFDs) or were otherwise manually adjusted based on process conditions (load, flow, etc.) equipment that continuously measured the draw over a set period (typically 4-6 weeks) was installed to capture the hourly and daily variations in demand.

Differences were observed with respect to the nature of energy-related measurements taken and the corresponding method of energy data validation. Of the three parameters required for a power calculation [voltage, current, and power factor (PF)], the NYSERDA (1998) study only directly measured the former two parameters and the method for estimating the PF was not explicitly stated. The omission of direct measurements of the PF likely resulted in an error in the power estimates as evidenced by the observations that the sum of the sub-metered equipment draws represented only 61-93 percent of the total plant draw. The authors indicated that the discrepancy was due to miscellaneous draws not captured by the submetering equipment. However, given that the metered equipment included all motors, the discrepancy was likely due to sources beyond miscellaneous draws such as errors in the PF values.

Two of the studies (NYSERDA, 2006; Foladori *et al*., 2015) measured single phase current, voltage, and power factor (PF) separately, and then calculated the power draw (kW). The approach did not recognize that the WWTPs typically employ three-phase electricity and that the phases may not be aligned, thereby reducing the accuracy of the power draw estimates. In the Foladori *et al*. study, the data validation method involved comparing the summed sub-metered draw to the total provided by the utility and was found to occasionally yield differences of more than 10%. Only measured values that were less than this threshold were included in the final analysis and thus the study did not make use of all available data.

Table 2-4: Summary of submetering studies

Study (Year)	Number of WWTPs	# of Small WWTPs (< 10,000 m^3/d)	Basis for WWTP Selection?	Thickening processes	Stabilization processes	Dewatering Processes	Other sludge processes
Belloir *et al*. (2015)	2	2	Similar configuration	Scraper (x1), strain press (x1)	None	Centrifuge (x1)	Sludge storage tank/mixers (x2)
Foladori *et al*. (2015)	5	5	Similar configuration	Scraper (x3), Static (x2)	Aerobic Digestion (x5)	Centrifuge (x2), BFP (x2)	None
NYSERDA (1998)	6	2	Representative of NYS	None	Anaerobic Digestion (x2)	Drying bed (x2)	None
NYSERDA (2006)	8	0	Representative of NYS	N/A	N/A	N/A	N/A

Table 2-4: Summary of submetering studies

Study (Year)	Motors metered	Nature of measurements	Sampling period for variable motors	Instantaneous measurements for constant draw motors	Energy Data Validation
Belloir *et al*. (2015)	Yes (Clusters)	kW (via Fluke loggers)	Every 15 min for 4 weeks	N/A since used power loggers. Noted daily run-times of motors	Inventoried all nameplate info (fluke loggers are all-encompassing)
Foladori *et al*. (2015)	All (Individual)	V, I, PF	Every 5 min for 2 years	Hour meters installed to record on/off events	Summed draw, compared to total draw provided by utility
NYSERDA (1998)	All (Individual)	V, I	Every 15 min for 4-6 weeks	Hour meters installed to record on/off events	Compared to total draw every interval
NYSERDA (2006)	> 5 HP only	V, I, PF, kW	Every 15 min for 6 weeks	Estimated operating hours for on/off events	Not specified

V = voltage, I= Current, PF= power factor, kW = Kilowatts

The Belloir *et al*. study (2015) employed a Fluke™ 1735 power logger to measure the three-phase power draw to obtain the most accurate measure of power consumption. However, this study only installed power loggers on motor control centres that captured the draw of several motors at once. Hence, to allocate the consumption of individual pieces of equipment, nameplate parameters were used to calculate the theoretical draw of each motor. As a result, the actual draw measured (via Fluke™) was almost two-fold greater than the individual measurement sums. From these results, it is clear that when performing an energy audit, a three-phase monitoring should be employed to collect power draw data on every motor of interest, and thus eliminate uncertainty resulting from motors operating outside their stated voltage and power factor. This choice would be especially important for a study submetering only the sludge handling processes since it would not be possible to compare to the total utility bills for validation.

The Foladori *et al*. (2015) investigation was deemed to be particularly insightful when developing the methodology for the current study. It presented an energy audit methodology and detailed a case study of five WWTPs in Italy. The study was particularly relevant in that all five plants studied were small (less than 10,000 m^3/d flow) and employed aerobic digestion, which is commonly employed in similarly sized facilities in Ontario (Jin and Parker, 2017). Energy consumption was normalized for each treatment stage based on the nature of its purpose. As examples, the volume (m^3) of wastewater treated was employed for hydraulic based stages (pumping, settling etc.), COD removal was employed for COD-based stages (oxidation tanks), and PE was used for building stages (*e.g.* lighting). Notably, COD-removal was also used as the normalizing basis for the sludge handling stages.

In this study, it was acknowledged that energy consumption depended on waste sludge flows and solids content (*i.e.* the mass processed) but noted that these parameters were not readily available in the small WWTPs studied. Hence, COD-removal was employed as a proxy for sludge production. However, the use of COD-removal as an indicator was also found to be somewhat limiting. While it did provide an indicator of biological sludge production, it did not account for chemical sludge production (from precipitation of phosphorus removal chemicals) and the sludge derived from influent fixed suspended solids. Still, from a broader perspective, the recognition that small WWTPs frequently lack key process information highlighted a key driver for the current study. The results of this study reinforced the need for a systematic approach to auditing small WWTPs using real plant data, particularly as it relates to sludge handling processes and associated management.

The allocation of energy consumption amongst numerous unit processes was reported to be challenging. Specifically, for some plants (exact number not given), one blower supplied air to both the liquid train aeration basins and the digesters, yet the partitioning of the power draw between the two processes was not reported. It was thus evident that should the same situation be encountered in the current study, additional measures should be taken to address it.

Despite these limitations two important conclusions were derived from this study: 1) the observation of low energy *efficiency* in aerobic stabilization stages, and 2) low specific energy consumption required for mechanical dewatering. The former reinforced the need to further investigate such systems at a detailed level, while the latter represented an interesting finding from a sustainability standpoint. It suggests that implementation of dewatering, which generates a cake that requires substantially less trucking (and therefore less fuel consumption) than liquid sludges could improve environmental sustainability. This hypothesis was therefore further investigated in the current study.

The NYSERDA (1998, 2006) studies both included several plants that were selected to be representative of the region of interest (New York state). This approach differed from that of Foladori *et al*. and Belloir *et al*., where plants were chosen to have similar configurations. In the former case, plants were selected to capture the range of facility size, geographic location, and treatment technologies. It was elected to employ these criteria in the current study due to the diversity of treatment plant configurations in Ontario (Jin and Parker, 2017).

In summary, it was observed that obtaining instantaneous measurements for constant draw motors (coupled with run-times) is generally accepted for auditing purposes, while motors with VFDs should be monitored over a representative period of time to capture the fluctuations in draw. Advanced power loggers capable of recording 3-phase power systems were found to provide the most accurate energy measurements. Overall, performing detailed energy audits with equipment submetering has proved to be a valuable exercise in obtaining a deeper knowledge of the performance of individual processes and equipment within a WWTP.

2.3 Sludge handling Sustainability Studies

As previously described, benchmarking studies can provide insight into several metrics that are indicative of the sustainability of wastewater treatment. However, prior studies that have assessed the sustainability of sludge handling systems (Table 2-5) were performed with different goals and did not involve benchmarking components. Notably, none of the previous studies were conducted within Canada (or North America), which highlights an additional need for such a study to be performed. Of the studies that were conducted, the most common goal of such studies was to evaluate the impact of different sludge processing and end-use scenarios on sustainability. The studies have been conducted on the basis of either a single WWTP (either existing or hypothetical) or the cumulative production of several plants in a geographic region, based on the typical sludge type(s), volume(s), and composition(s) generated at the plant or within the region. Given that several studies were indeed based on a single hypothetical plant, further investigations into the sustainability performance of actual facilities (using real plant data) was identified as a need for future study.

Despite the differing objectives, it was found that there was broad agreement in the literature regarding the approach to conducting such evaluations. The approach involves a systematic assessment framework consistent with LCA practices that comprises the following core elements, per ISO standards (ISO 14040, 14044):

1. Selection of the system functional unit (FU), the normalizing basis (*i.e.* denominator) for each sustainability metric, that permits a standardized comparison between different options/scenarios;
2. Definition of system boundaries, which represent the system limits from which analysis will incorporate inputs and outputs;
3. Selection of LCA impact categories, the sustainability metrics to be evaluated for each system input and output;
4. Inventory of all relevant system inputs and outputs and conversion to selected LCA impact factors.

From Table 2-5 it can be seen that mass of sludge processed (dry weight basis) has most often been selected as the FU from which to evaluate such systems (17 of 25 studies). This quantity directly represents the quantity of material being processed, regardless of wastewater volume treated or COD load to the WWTP.

There was broad agreement among the literature regarding the boundaries that should be employed for such systems. Most studies included inputs and outputs related to the operation (*i.e.* processing/treatment), transport, and disposal of the sludge/biosolids. Some investigations also included the infrastructure construction phase in the analysis. However, multiple studies (Emmerson, 1995; Suh and Rousseaux, 2002) have shown that over the lifespan of such infrastructure, the impact of construction is negligible when compared to the cumulative impacts of continuous operation.

Among the LCA impact categories selected for evaluation, global warming potential (GWP) was the only selection common to each study. Fewer studies evaluated other categories, including acidification, eutrophication, human toxicity, and ecotoxicity potential. A variety of tools, typically a combination of LCA software packages, databases, literature values, and available models were employed to convert the inventoried inputs/outputs of each system to the desired impact category quantity. Such conversion calculations require knowledge or assumption of a pathway from any given LCA input (*e.g.* electricity production) to the impact category quantity.

Table 2-5: Summary of sludge handling sustainability studies

Author (Year)	Location	Goal of Evaluation	Number of WWTPs	Existing / Hypothetical WWTP
Alayna *et al*. (2015)	Australia	Sludge processing/disposal scenarios	2	Existing
Alvarez-Gaitan *et al*. (2016)	Spain		1	Existing
Barber (2008)	Australia	Sludge processing options with and w/o AD	1	Hypothetical
Beavis (2003)	Poland	LCA impact of converting from aerobic digestion to AD	1	Existing
Bridle and Skrypski-Mantele (2000)	UK	Sludge processing/disposal scenarios	1	Hypothetical
Chai *et al*. (2015)	USA	Wastewater treatment & sludge processing options	1	Hypothetical
Gallego *et al*. (2008)	Sweden	LCA benchmarking	13	Existing
Hara and Mino (2008)	Denmark	Sludge processing/disposal scenarios	12 (cumulative)	Existing
Hong *et al*. (2008)	Australia	Sludge processing/disposal scenarios	1	Hypothetical
Hospido *et al*. (2005)	Germany	Processing/disposal scenarios - AD vs thermal processes	1	Existing
Houillon and Jolliet (2005)	China	Sludge processing/disposal scenarios	1	Hypothetical
Johansson *et al*. (2008)	Spain	Sludge disposal options	1	Existing
Li *et al*. (2013)	Japan	Sludge processing/disposal scenarios	1	Hypothetical
Liu *et al*. (2013)	Japan	Sludge processing/disposal scenarios	1	Hypothetical
Lundin *et al*. (2004)	Australia	Sludge processing/disposal scenarios	1	Existing
Lorenzo-Toja *et al*. (2016)	Spain	LCA benchmarking	22	Existing
Murray *et al*. (2008)	Spain	Sludge processing/disposal scenarios	4 (cumulative)	Existing
Niu *et al*. (2013)	China	Sludge processing/disposal scenarios	1	Hypothetical
Peters and Lundie (2002)	Sweden	Sludge processing/disposal scenarios	3 (cumulative)	Existing
Poulsen and Hansen (2002)	China	Sludge processing/disposal scenarios	2 (cumulative)	Existing

Remy *et al*. (2013)	Switzerland	Sludge processing/disposal scenarios	1	Existing
Rodriguez-Garcia *et al*. (2011)	China	LCA benchmarking	24	Existing
Stefaniak *et al*. (2014)	China	Sludge processing/disposal scenarios	1	Hypothetical
Svanstrom *et al*. (2005)	Sweden	Sludge processing/disposal scenarios	1	Existing
Xu *et al*. (2014)	China	Sludge processing/disposal scenarios	1	Hypothetical

Table 2-5: Summary of sludge handling sustainability studies

Author (Year)	**Functional Unit**	**System Boundaries**	**LCA impact categories evaluated**	**Energy inventory**	**Chemicals inventory**	**Metal emissions inventory**	**Nutrients Inventory**
Alayna *et al*. (2015)	dry mass	O, T, EU/D	GWP	✓	✓	✓	✓
Alvarez-Gaitan *et al*. (2016)	Vol treated	O, T, EU/D	GWP, EP	✓	✓		✓
Barber (2008)	dry mass	O, T, EU/D	GWP	✓	✓		✓
Beavis (2003)	dry mass	O, T, EU/D	GWP, energy	✓	✓		✓
Bridle and Skrypski-Mantele (2000)	dry mass	O, T, EU/D	GWP	✓	✓		✓
Chai *et al*. (2015)	dry mass	O, T, EU/D	GWP, HTP, ETP, TETP, ADP, CED, TA, FEP, MEP	✓	✓		Unclear
Gallego *et al*. (2008)	dry mass	O, T, EU/D	GWP, AP, EP, finite resource depletion	✓	✓	✓	✓
Hara and Mino (2008)	COD load to WWTP	O, T, EU/D	GWP, non-renewable resource depletion, LU	✓			
Hong *et al*. (2008)	dry mass	C, O, T, EU/D	GWP, HTP, energy	✓	✓	✓	
Hospido *et al*. (2005)	PE (COD load to WWTP basis)	O, T, EU/D	GWP, CED	✓	✓	✓	✓

Houillon and Jolliet (2005)	Vol of treated WW	C, O, T, EU/D	GWP	✓	✓		✓
Johansson *et al*. (2008)	PE ("organic load")	O, T, EU/D	GWP, EP, TETP, AP, ADP, POFP, ODP	✓	✓	✓	✓
Li *et al*. (2013)	dry mass	O, T, EU/D	N/A	✓	✓		✓
Liu *et al*. (2013)	dry mass	C, O, T, EU/D	GWP, AP, HTP, LU	✓	✓		✓
Lundin *et al*. (2004)	Vol of treated WW	O, T, EU/D	GWP, CED, MEP, POFP, AP, HTP, TETP, FAETP, MAETP	✓	✓	✓	✓
Lorenzo-Toja *et al*. (2016)	Vol treated, kg PO_4 removed	O, T, EU/D	GWP, EP	✓	✓		
Murray *et al*. (2008)	dry mass	O, T, EU/D	GWP, EP, ODP, AP, POFP, ADP, HTP	✓	✓		✓
Niu *et al*. (2013)	wet mass	O, T, EU/D	GWP	✓			✓
Peters and Lundie (2002)	dry mass	O, T, EU/D	GWP, AP, EP, resource depletion	✓	✓	✓	
Poulsen and Hansen (2002)	dry mass	O, T, EU/D	GWP	✓			✓
Remy *et al*. (2013)	dry mass	C, O, T, EU/D	GWP, NRE	✓	✓		✓
Rodriguez-Garcia *et al*. (2011)	dry mass	O, T, EU/D	GWP, ODP, HTP, POFP, PMF, IR, TA, FEP, MEP, TETP, FAETP, MAETP, LU, ADP	✓	✓		✓
Stefaniak *et al.* (2014)	dry mass	O, T, EU/D	GWP	✓	✓	✓	
Svanstrom *et al*. (2005)	dry mass	T, EU/D	GWP, AP, EP, FRU	✓	✓		✓
Xu *et al*. (2014)	dry mass	O, T, EU/D	GWP, energy, AP	✓	✓	✓	

O = operation phase, T = transport phase, EU/D = end-use / disposition

With respect to the types of inputs/outputs inventoried within the respective system boundaries, from Table 2-5 it can be seen that all investigations quantified energy inputs and most inventoried chemical use. A smaller number of studies evaluated biosolids quality for the purposes of evaluating chemical fertilizer production offsets, and only nine studies evaluated heavy metal content of the biosolids product. Given that the nutrient and heavy metal content of a biosolids product partially dictates the type of end-use that can be employed, it is notable that studies to date have sometimes ignored such parameters, and the lack of documentation represents a knowledge gap and area of need for further study.

In summary, sustainability studies that incorporate all of the goals and objectives of the current study (*i.e.* a hybrid of benchmarking, energy/process audit, and sustainability) were not identified. However, the following methodological elements that have been consistently employed in sludge handling sustainability studies were identified as being relevant to the current study:

1. Employment of dry weight of sludge produced as the FU basis;
2. System boundaries drawn around the operation, transport and disposal phases of sludge management;
3. At a minimum, GWP evaluated as the primary LCA impact category.

Chapter 3
Methodology

To achieve the goal of documenting the current sludge handling performance of small WWTPs in Ontario, a methodology was developed to systematically evaluate the systems within a benchmarking/sustainability framework using existing plant data and on-site measurements. Whenever possible, the approach involved employing methodological elements that were consistent with those established in the literature (Chapter 2), and when necessary were further refined and tailored to meet the specific objectives of the study. The study can be broadly characterized into three components:

1. Selection of ten facilities for in-depth evaluation;
2. Development and implementation of a plant audit methodology, including selection of benchmarking metrics;
3. Innovative technology assessment.

3.1 Plant Selection

For the purposes of the study, a “small” plant was defined as one with a design hydraulic capacity of less than 10,000 m^3/day that does not employ anaerobic digestion. Only mechanical treatment systems (liquid train and sludge stabilization) were considered for evaluation; lagoon systems were excluded as sludge generation at these facilities is sporadic. However, if a mechanical plant incorporated a lagoon as part of its non-stabilization sludge handling process (e.g. for storage), it was still considered for selection.

To identify the facilities that met the initial screening criteria and would thus form the population of plants from which selections would be made, an Ontario Ministry of the Environment and Climate Change (MOECC) database containing basic plant information (location, hydraulic capacity, operator type, sludge treatment processes, disposition practice) of all facilities province-wide was analyzed. However, as the database was somewhat dated and incomplete in some areas, additional data were gathered on plants with hydraulic capacity greater than 1000 m^3/d to increase accuracy and completeness. The additional data gathering involved contacting municipalities directly and obtaining information from municipal websites. In total, 210 facilities met the initial screening criteria.

From the 210 plants that met the initial screening criteria, ten were selected (Table 3-1) to capture a range of on-site sludge processing technologies (thickening, stabilization, dewatering), disposition practices (land application, landfill), operator type [public, private, Ontario Clean Water Agency (OCWA)], geographical locations (Southern, Eastern, Northern Ontario), and septage reception (present/not-present).

Although most small facilities in the province are not currently using an “innovative” technology (*e.g.* thermo-alkali hydrolysis, GeoTube™, etc.) (Jin and Parker, 2017), it was considered important to have such plants represented in the study to assess the extent to which newer technologies may impact the sustainability of operations, and provide baseline knowledge for other communities considering upgrades to or replacements of their existing process. Furthermore, although technologies such as centrifuge and rotary press dewatering are reasonably well-established among large WWTPs, they are not as common in small treatment facilities (Metcalf & Eddy, 2013) and thus would represent an innovation within the context of small plants. Facilities that employed these technologies were thus included in the current ten plant sample.

3.2 Audit Methodology

A variety of key performance indicators (KPIs) were established (Table 3-2) that could be broadly categorized into energy consumption, chemical use, biosolids disposition, biosolids quality, and GHG emissions. The first four categories were selected to represent all the operational inputs and outputs of the systems studied, and to provide operational benchmarks for utilities seeking to quantify their individual plant performance relative to others of similar scale and scope of operation. The last category was selected as a means to cumulatively evaluate all previous categories on a common measure of environmental sustainability: the carbon footprint.

Different energy sources (electricity, natural gas, transportation fuel) and chemicals have different carbon emission debits associated with their respective production. Conversely, the land application of biosolids reduces chemical fertilizer requirements and thus provides the sludge handling system with carbon credits. Taken collectively, a metric that converted all the inputs to a single net carbon footprint was used to evaluate the magnitude of environmental impact for each system.

Where appropriate, the KPIs were normalized on the basis of raw sludge (dry mass) produced, defined as the mass of sludge entering the sludge handling process (from primary/secondary clarifiers) minus any mass quantities in return streams (*e.g.* digester decant and centrifuge centrate). The mass flows in the return streams were accounted for to ensure that facilities wasting large quantities of sludge did not receive a disproportionately favourable result if they were also returning high quantities back to the liquid stream, and thus had lower net sludge production than was apparent.

Table 3-1: Characteristics of selected WWTPs

ID	Operator	Thickening	Stabilization Technology	Dewatering Technology	Holding / Storage	Odour Control	Disposition	Location	Septage Reception
A	OCWA		CAD		On-site lagoon		Agricultural	South	
B	Private	Gravity Thickener	CAD		Off-site lagoon		Agricultural	South	
C	Public		CAD	Centrifuge	Off-site storage	Biofilter	Agricultural	South	
D	OCWA		CAD	Rotary Press			Landfill	North	
E	Public		CAD	GeoTube™	GeoTube™		Agricultural	East	✓
F	Public		CAD		Aerated holding		Agricultural	South	
G	Public		CAD		Aerated holding		Agricultural	South	
H	Public	Gravity Thickener	Thermo-alkali Hydrolysis	Centrifuge	Aerated holding (WAS), On-site storage	Biofilter	Agricultural	South	
I	OCWA		CAD	Off-Site Drying Bed			Landfill	North	
J	OCWA	Rotary Disc Thickener	ATAD	Rotary Press	On-site storage	Biofilter	Agricultural	East	✓

ATAD = auto-thermal thermophilic aerobic digestion
CAD = conventional aerobic digestion
OCWA = Ontario Clean Water Agency

Table 3-2: Selected key performance indicators

KPI	Category	Metric (Numerator) or Description						Normalizing Basis (Denominator)
1-6	Energy	kWh for thickening	kWh for stabilization	kWh for dewatering	kWh for pumping	kWh for odour control	kWh for aerated holding	dry kg of raw sludge produced
7	Energy	kWh for aerobic digestion						dry kg of VSS destruction
8	Energy	m^3 of natural gas consumption						dry kg of raw sludge produced
9-10	Chemicals	kg of polymer used			kg of KOH used			dry tonne of raw sludge produced
11	Disposition	Weighted average round-trip distance to end-use destination (km)						N/A
12	Disposition	Liters of fuel consumed by haulage trucks						dry tonne of raw sludge produced
13	Quality	Mean TP content of hauled biosolids (g/kg)						N/A
14	Quality	Mean TN content of hauled biosolids (g/kg)						N/A
15	Quality	Mean K content of hauled biosolids (g/kg)						N/A
16	Quality	$\frac{Mean\ metal\ concentration, dry\ mass\ basis}{NASM\ limit}$ ratio of hauled biosolids						N/A
17	Quality	Mean log pathogen (*E. coli*) content of hauled biosolids [log (CFU/g)]						N/A
18	Quality	Biosolids product meets “NASM” requirements for land application: No = 0, Yes = 1						N/A
19	Quality	Biosolids product meets “Class A” pathogen (*E. coli*) requirements for land application: No = 0, Yes = 1						N/A
21-25	GHG	kg CO_2 eq. for electricity consumption	kg CO_2 eq. for natural gas consumption	kg CO_2 eq. for chemical consumption	kg CO_2 eq. for fuel consumption	kg CO_2 eq. for disposition		dry kg of raw sludge produced

A BioWin™ model was generated for each plant to obtain a solids mass balance for the sludge handling process, estimate net sludge production, and screen for problematic data. The modelling exercise involved initial configuration to reflect reported operating conditions [influent/effluent characteristics, flows (influent, waste/return sludge), chemical addition(s)] based on three years of historical operational data (2014 – 2016, if available). Unknown return streams (*e.g.* digester decant, dewatering centrate) were then adjusted such that the predicted aeration basin mixed-liquor suspended solids (MLSS) matched the reported values and predicted biosolids quantities matched the reported amounts (if available).

3.2.1 KPI Category 1: Energy Consumption

For all but one of the plants studied, electricity was the only form of energy consumed. Several of the energy KPIs thus involved normalized electricity consumption (kWh per dry kg of raw sludge) for the sludge handling process. Individual electricity consumption KPIs for each stage of the sludge treatment process (thickening, stabilization, dewatering, holding), odour control, and pumping were selected to ensure information was obtained for each individual unit process. Additionally, recognizing that nine of the ten plants practiced some form of aerobic digestion, an additional indicator was selected to relate digester electricity consumption to the quantity of volatile solids reduction. The metric was selected to obtain a measure of the energy efficiency of the process. The quantity of solids destroyed was estimated from the BioWin™ model of each plant.

To determine the power draw of the various processing equipment (blowers, pumps, dewatering units, etc.), spot measurements were collected on-site using a Fluke™ 1735 power logger. Power draw was assumed to be constant over time since no major pieces of equipment incorporated variable frequency drives. Centrifuge back drives were the only exception, however, draw for these motors were found to only represent 5% of the total draw for the dewatering unit. The variation in draw was therefore assumed to be negligible. Electricity consumption (kWh) was estimated by multiplying daily equipment run-times (obtained from plant records and discussions with plant operators) with measured power readings (kW).

In most cases, the facilities employed dedicated blowers for aerobic digesters and holding tanks. Hence, power draw was directly allocated to the sludge handling process of interest from the measurements taken on-site. However, there were some instances where the same blower supplied air to both digesters and aeration basins (plants B, F, I, and J), or to both the digester and aerated holding tank (plant G). In the cases of plants B, G, and J, information on the air flow to each vessel was obtained to determine the percentage of air (and in turn, the proportion of electricity) supplied to the processes of interest.

Air flow information was not available for plant F. Hence, diffuser information and dissolved oxygen (DO) concentrations were employed in the BioWin™ model to estimate air flows and the corresponding allocation of power draw. Neither flow information nor diffuser information were available for plant I. Therefore, the proportioning was estimated based on the percentage of volume present in the aerobic digesters and the extended aeration basin. The need for these estimates introduced some uncertainty into the estimated KPIs for these five plants.

An additional energy KPI reflected the use of natural gas at plant H. It was calculated by subtracting the reported baseline usage (for plant-wide heating) from the total draw reported during stabilization operation and dividing the difference by the dry mass flow of sludge processed.

3.2.2 KPI Category 2: Chemical Usage

While several of the facilities only used chemicals in the liquid train (for phosphorus removal), those that practiced dewatering or mechanical thickening used polymer to enhance the liquid-solid separation process. In addition, one of the facilities (plant H) used potassium-hydroxide (KOH) for pH control and to boost the potassium content of the biosolids product. Two KPIs were selected to reflect these inputs. Chemical usage information was obtained from plant records and/or conversations with plant operators. However, the specific form in which the information was available was not consistent across all plants. Specific usage quantities were calculated using reported chemical purchase records (plant C), barrels/volumes consumed per month (plants D and J), dosing rates (plants E), and flow rates (plant H).

3.2.3 KPI Category 3: Biosolids Disposition

Separate indicators that employed the average distance that the biosolids travelled to their destination and the amount of fuel consumed (normalized to dry mass of solids processed) were created. The latter indicator was chosen to account for the variety in capacity and fuel economy of the trucks in use. Liquid biosolids are typically transported in large tanker trucks with capacities of approximately 40 m^3 per truck, while dewatered cake is often hauled in small-to-medium sized dump trucks that have smaller capacities and lower fuel requirements.

Biosolids disposition information [quantities and farm/landfill address(es)] was obtained from haulage reports and Google Maps™ was employed to determine the shortest driving distance from the WWTP to each destination. To calculate the normalized fuel consumption of each operation, the distance value was used in conjunction with truck fuel economy information obtained from the truck owner.

3.2.4 KPI Category 4: Biosolids Quality

Biosolids contain nutrients [phosphorus (P), nitrogen (N), potassium (K)] that are beneficial for agricultural crop growth, but also contain heavy metals and pathogens that can be harmful to human health at high concentrations. Limits for the latter two measures have been established in the Nutrient Management Act for Non-Agricultural Source Material (NASM) application (O. Reg. 267/03 – Schedule 5 and 6, CM2 and CP2). Further distinctions regarding pathogen content are stipulated under the US EPA regulatory framework (US EPA, 1993). Under EPA guidelines, a "Class A" product must contain less than 1000 MPN/g of *E. coli*, while a "Class B" product must have less than $2x10^6$ CFU/g (US EPA, 1993). The latter value is consistent with the NASM requirement in Ontario (O. Reg. 267/03 – Schedule 5, CM2). In Canada, if a biosolids product meets thresholds for pathogen content, it can qualify as a CFIA-certified fertilizer under the Fertilizers Act (R.S.C., 1985, c. F-10) and associated Fertilizers Regulations (C.R.C., c. 666).

KPIs for mean nutrient and log-mean *E. coli* concentrations were selected to identify the range of beneficial value (nutrients) and proximity to the NASM pathogen limit (*E. coli*) of the hauled biosolids. In addition, a KPI relating the highest ratio of mean metal concentration to its respective NASM limit was selected to determine whether any metals were at risk of exceeding regulatory thresholds. In addition, binary indicators were included to represent whether the biosolids were a) meeting NASM requirements for land application, and b) meeting *E. coli* requirements for classification as a Class A product. Quality data was obtained from plant records for eight of the ten plants practicing land application of biosolids. For the two plants landfilling their biosolids, such information was not available. To determine the quality characteristics for the latter two plants, a sampling program was implemented to characterize the biosolids product leaving the plant (cake and liquid for plants D and I, respectively). The sampling program involved measuring all parameters of interest (nutrients, *E. coli*, metals) for four months on a bi-weekly basis. All samples were collected by plant operators and sent to MOECC accredited labs for analysis.

3.2.5 KPI Category 5: Greenhouse Gas (GHG) Emissions

CO_2 emissions were calculated for each facility on the basis of emission factors that were obtained from the literature for each input and output. Where possible, emission factors specific to Ontario (electricity, natural gas production) or Canada (transportation fuel) were employed. In other cases, literature values for chemical production (polymer, KOH) and chemical fertilizer production (N, P, K) were utilized. The latter factors were used to determine the carbon off-sets gained by using biosolids as a fertilizer through the avoidance of chemical fertilizer production for each nutrient. The emission factors utilized are listed in Table 3-3.

Table 3-3: CO_2 emission factors utilized

Emission Factor	Value	Source
kg CO_2 eq. / kWh	0.040	Environment and Climate Change Canada, 2018
kg CO_2 eq. / m^3 natural gas	1.888	Environment and Climate Change Canada, 2018
kg CO_2 eq. / L fuel	2.681	Environment and Climate Change Canada, 2018
kg CO_2 eq. / kg polymer	2.62	IPCC, 2006
kg CO_2 eq. / kg KOH	1.934	Biograce, 2011
kg CO_2 eq. credits / kg N	4	Recycled Organics Unit, 2006
kg CO_2 eq. credits / kg P	2	Recycled Organics Unit, 2006
kg CO_2 eq. credits / kg K	0.7	Kongshaug, 1998

3.3 Innovative Technology Sustainability Assessment

To evaluate the sustainability impact of innovative technology incorporation within small WWTPs, a desktop analysis was conducted. The operating parameters and performance characteristics of the innovative technologies within the sample were incorporated into the process flow sheets of plants that practiced conventional processes (A, B, F, G, I), and the GHG emissions were re-calculated. Specifically, the BioWin™ process flow sheets for all sample conventional plants were modified to include a thickening or dewatering unit that generated a product consistent with the observed solids content for each technology. The predicted biosolids volume for each plant was used to calculate updated transportation fuel consumption based on the updated number of trips. Normalized energy requirements and chemical usage of each technologies were assumed to be consistent with those observed within the case studies. Updated energy, chemical, and fuel consumption were converted to CO_2 emissions using the established emission factors (Table 3-3) and the updated sum was compared to the base case for each WWTP of interest.

Chapter 4

Results

The benchmarking results associated with each system input and output were evaluated (sections 4.1 - 4.5) and a desktop analysis of the impacts of innovative technology implementation into plants with conventional process configurations was conducted (section 4.6). Where possible, uncertainties in the estimated values (expressed as the standard deviation as a percentage of the mean for each KPI) were calculated from the raw data set. Among the KPIs that involved raw sludge production, the variability in production represented the largest source of uncertainty. The standard deviations associated with raw sludge production were found to range from 11 – 34% of the mean values. The variability was attributed to differences in biological activity (biomass growth), influent fixed suspended solids, and chemical sludge production (if chemical addition for P-removal was practiced). There was also unquantifiable uncertainty associated with a) parameter estimates provided by operators (*e.g.* polymer use), and b) partitioning of electricity draw when one blower supplied air to both liquid stream aeration basins and digesters. These qualitative uncertainties were described in the methodology section. Where necessary, the implications of such uncertainties (quantitative and qualitative) on the extent to which conclusions may be drawn are discussed in subsequent results sections.

4.1 Energy KPI Results

Energy inputs represent a portion of a treatment facility's total operational costs and the GHG emissions associated with their production represent an environmental impact. As such, reductions in this area without compromising plant performance can potentially improve economic and environmental sustainability. The following discussion details the KPIs related to electricity and natural gas consumption.

4.1.1 Electricity Consumption – Overall

All ten plants within the study consumed electricity as part of the sludge-treatment process. Total electricity consumption with associated uncertainty for each facility is presented in Figure 4-1, while the contributions of individual processes to total consumption is shown in Figure 4-2. As shown in Figure 4-1, total consumption ranged from 0.9 – 3.9 kWh/dry kg of raw sludge among all plants studied. The 25th, 50th and 75th percentile values corresponded to 1.8, 2.2, and 2.7 kWh/dry kg, respectively.

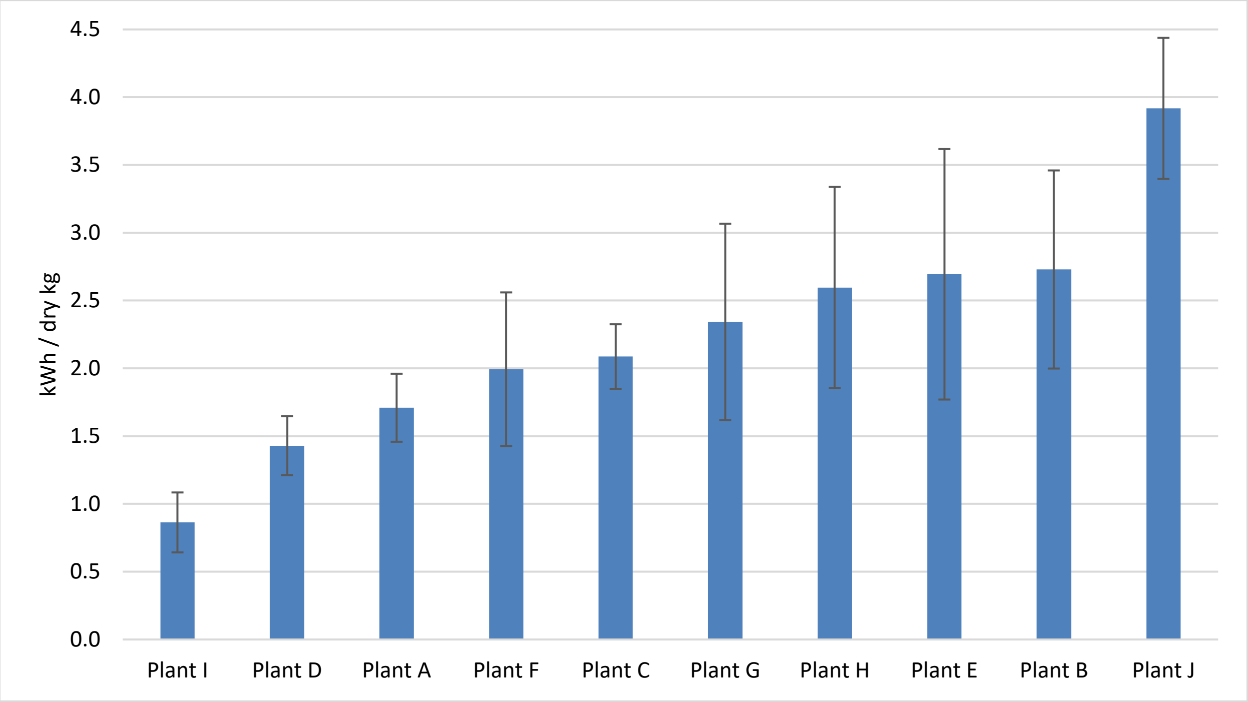

Figure 4-1: Total electricity consumption per dry mass of raw sludge produced

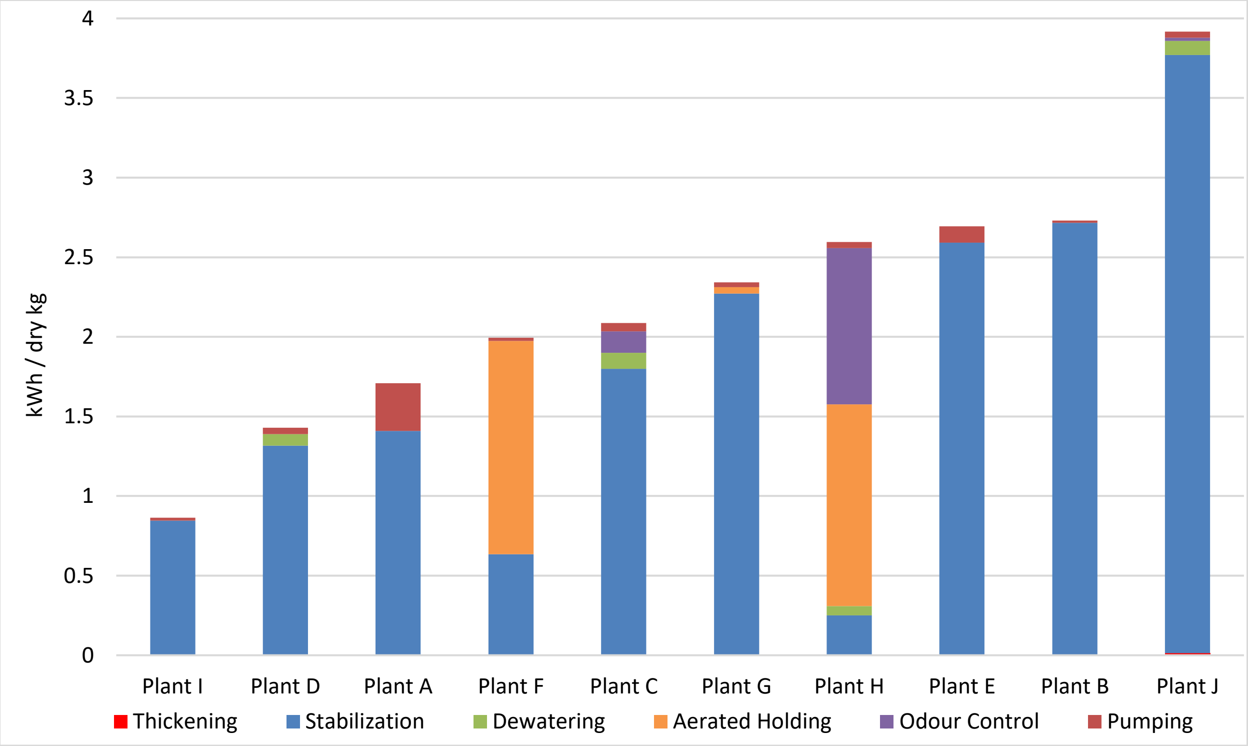

Figure 4-2: Total electricity consumption per dry mass of raw sludge produced (detailed)

When incorporating quantitative uncertainty into the analysis, it can be seen from Figure 4-1 that there was overlap in the uncertainty bars between all plants inclusive of the second (plant B) and eighth (plant A) highest consumers. The considerable overlap indicated that total electricity consumption was similar for a number of plants in the study. Notably, the lowest consumer (plant I) exhibited consumption that was statistically different than the next closest consumer (plant D). However, as discussed in the methodology, there was unquantified uncertainty in plant I estimates as it did not employ a dedicated digester blower. Hence, the low KPI for plant I may not be a feasible goal for plants seeking to reduce electricity consumption.

When the type of sludge handling technologies employed was considered, the facilities that did not practice conventional aerobic digestion exhibited the highest (ATAD) and fourth-highest (thermo-alkali hydrolysis) electricity consumption, respectively. The former facility consumed 44% more energy per unit of raw sludge mass than the next highest consumer, indicating that the ATAD technology was substantially more energy-intensive than the conventional aerobic digestion processes within the sample. Among the eight plants practicing conventional aerobic digestion, total electricity consumption ranged from 0.9 – 2.7 kWh/dry kg. For such plants, the 25th, 50th and 75th percentile corresponded to 1.6, 2.0, and 2.4 kWh/dry kg, respectively.

Two facilities (E and J) that practiced septage reception were evaluated to assess the impacts of this practice on KPI values. Septage is a partially stabilized material that directly contributes to sludge production via fixed suspended solids loading (Metcalf & Eddy, 2013). It was expected that plant would exhibit higher sludge production and aeration basin MLSS than predicted (modelled) values as the modeling did not account for this input. Plant E exhibited a lower MLSS value than the simulated concentrations. The facility also exhibited the highest uncertainty in raw sludge production (34%) among all plants studied. In addition, plant E was operated at a higher solids retention time (SRT) than all other facilities studied. Collectively, these factors contributed to the difficulty in ascertaining the impact of septage reception on the energy consumption at the plant. Plant J was an ATAD facility that required substantially greater energy input as a result of the chosen stabilization process, which resulted in difficulty extracting the energy consumption due to septage reception. It did generate similar quantities of sludge to the predicted value, which indicated that increased solids loading from septage was sufficiently represented by the BioWin™ model. Ultimately, no conclusions could be drawn regarding the impact of septage reception on sludge handling energy requirements because both case studies exhibited additional factors that could not be delineated from the reception of this material.

4.1.2 Electricity Consumption – Stabilization

As shown in Figure 4-2, the electricity allocated to stabilization represented the highest fraction of sludge handling electricity consumed for all but two of the plants studied (F and H). With the exception of these two plants, at least 82% of the electricity consumption in all of the facilities was used for stabilization. The high proportion of electricity utilized for stabilization suggests that this process should generally be an area of interest for plant owners and operators that seek to selectively target high usage unit processes within their overall treatment system. A reduction of the electricity required for stabilization would have a greater impact on total usage reduction than the same percent reduction achieved within other processes (*e.g.* dewatering).

Normalized power consumption values for the stabilization processes alone (with associated uncertainties) are shown in Figure 4-3. Among all the plants studied, electricity consumption for stabilization ranged from 0.3 to 3.8 kWh/dry kg. The 25th, 50th and 75th percentile values corresponded to 1.0, 1.6, and 2.5 kWh/dry kg, respectively. However, the results differed from the overall consumption results in that any given plant's uncertainty bar in Figure 4-3 generally overlapped with fewer other plants than those in the previous (overall) analysis. The most overlap any single plant exhibited in Figure 4-3 was four facilities, whereas some facilities exhibited as many as six overlapping values in Figure 4-1. The observation indicates that the ranking of consumers with respect to stabilization draw was more defined than that of the overall ranking. Furthermore, given that all the plants employed the same technology, the over two-fold increase in consumption between the 25th and 75th percentile indicates that opportunities for process optimization in some of the higher consumers may exist.

The maximum consumption associated with stabilization corresponded to the facility that employed ATAD, while the minimum value corresponded to the plant that employed thermo-alkali hydrolysis. The latter plant's uncertainty bars did not overlap with any other facility, which indicated that it was also the best performer when quantitative uncertainty was incorporated into the analysis. The observation that thermo-alkali hydrolysis was the lowest consumer for stabilization is noteworthy when considering the technology's application in other facilities. If the thermo-alkali hydrolysis process were to be implemented at a plant that did not require aerated holding or odour control (the two largest power consumers for sludge handling operations at plant H), the potential for electricity savings could be substantial relative to the conventional aerobic digestion process.

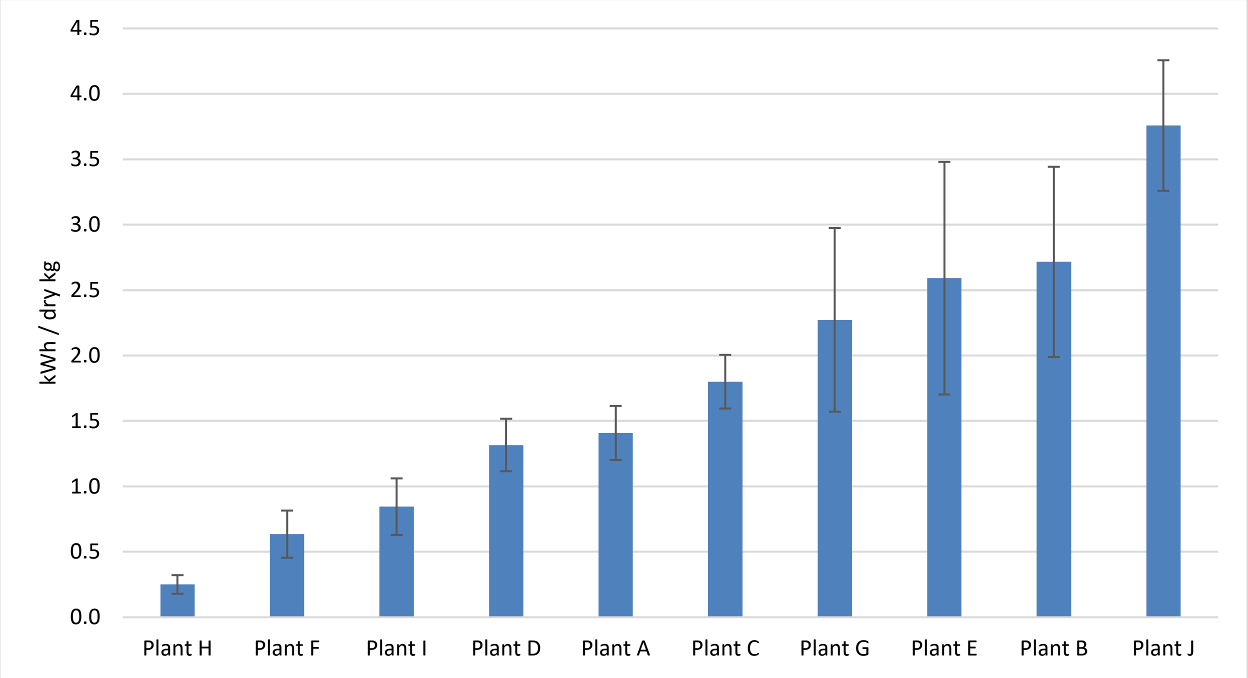

Figure 4-3: Stabilization electricity consumption per dry mass of raw sludge produced

Given that conventional aerobic digestion is the most common stabilization technology employed at small WWTPs in Ontario (Jin and Parker, 2017), the percentile benchmarks for plants employing this technology were evaluated separately. Among such plants, digester electricity consumption ranged from 0.6 – 2.7 kWh/dry kg, while the 25th, 50th, and 75th percentile corresponded to 1.2, 1.6, and 2.4 kWh/dry kg, respectively.

In addition to the analysis based on stabilization energy consumption normalized by raw sludge production, the power consumption of facilities that practiced aerobic digestion was evaluated on the basis of VSS destruction achieved (Figure 4-4). This measure provided an indicator of the energy efficiency of the digestion process, given that VSS destruction is one of the primary functions of an aerobic digester (Metcalf & Eddy, 2013). As shown in Figure 4-4, the ATAD plant exhibited the highest energy consumption on this basis, consuming 63 kWh per dry kg of VSS destroyed. Among the eight facilities employing conventional aerobic digestion, consumption ranged from 4.9 – 56 kWh/dry kg VSS. The 25th, 50th, and 75th percentile corresponded to 7.1, 8.7, and 19 kWh/dry kg VSS, respectively.

The minimum value (4.9 kWh/dry kg VSS) was statistically lower than any other value observed (no uncertainty bar overlap with other facilities), while the four next highest consumers (6.5 – 8.8 kWh/dry kg VSS) exhibited statistically equivalent consumption. Thus, the five lowest consumers could collectively serve as benchmarks for other utilities seeking to determine their performance relative to peers of similar scope and operation. The low consumption in plant C may have been due to the type of sludge being digested. The facility generated a mix of primary and secondary sludge, the former of which is more readily biodegradable than secondary sludge (Metcalf & Eddy, 2013). The resulting mixture thus generally requires less air to achieve a given quantity of VSS destruction than pure secondary sludges (Metcalf & Eddy, 2013). One other facility generated primary sludge (plant B) and exhibited the second lowest specific energy consumption (uncertainty bar overlap with three facilities), despite being the second highest overall consumer (Figure 4-1).

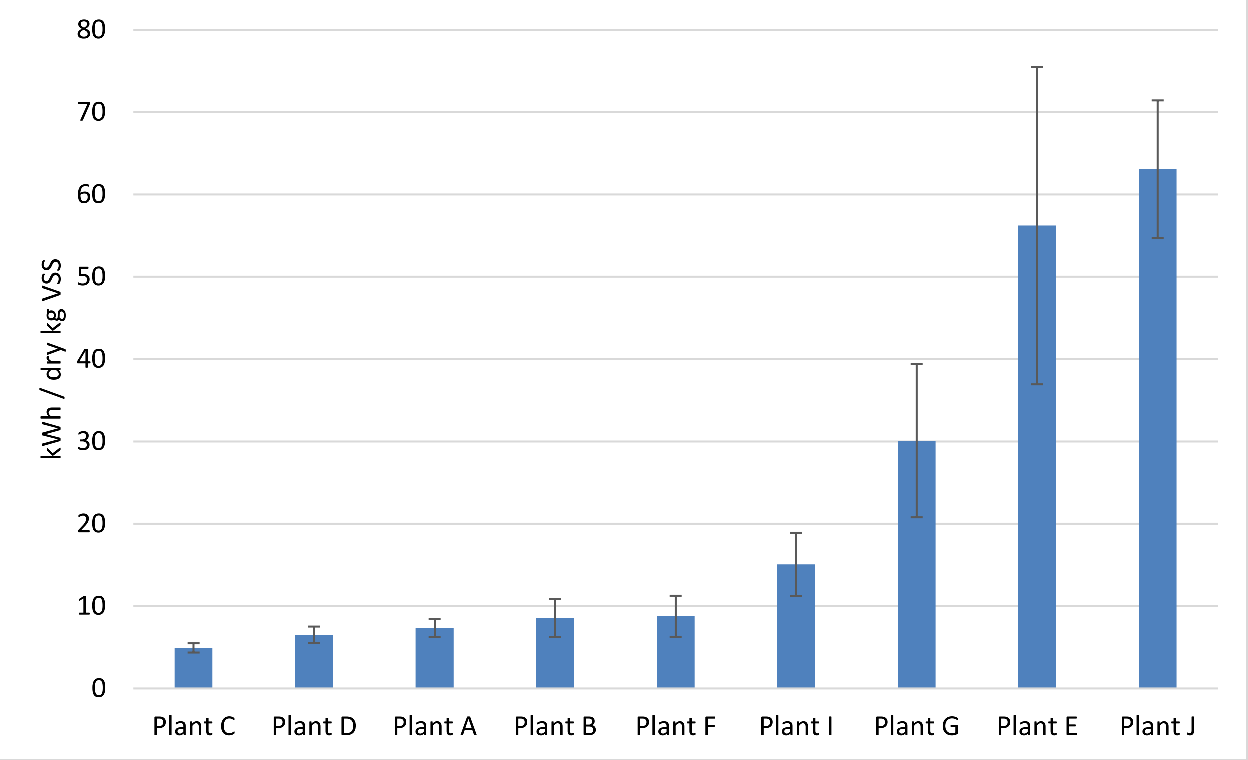

Figure 4-4: Digester electricity consumption per dry mass of VSS destruction

Plants G and E exhibited over three- and six- fold greater energy consumption than the median value, respectively. Both facilities exhibited higher specific consumption than the next highest consumer (plant I) even when considering the quantitative uncertainty associated with the raw sludge production (neither plant's uncertainty bar overlapped with plant I). To provide insight into why each facility exhibited notably higher consumption, the hydraulic residence time (HRT) of each facility was examined and found to be 48 and 58 days HRT, respectively. Both values were substantially higher than the MOECC (2008) design guideline of 15 days HRT, which suggests that both digesters are a) oversized based on the current loading to the digester, and/or b) have air requirements for mixing that exceed the air supply requirements for VSS destruction. Essentially, both units are effectively operating as aerated holding tanks in addition to their function as aerobic digesters.

The energy efficiency evaluation revealed that some of the facilities that performed best when evaluated on a raw sludge production basis were among the worst performers when evaluated on the basis of VSS destruction achieved, and vice versa. Among plants that practiced conventional aerobic digestion, plant I exhibited the second lowest energy consumption when normalized by raw sludge production, but the third highest consumption when normalized by VSS destruction achieved. Plant B exhibited the highest consumption under the former basis, but a value less than the median when evaluated on the latter basis. While plants G and E were among the highest consumers when normalized by raw sludge production, the extent to which they were the highest consumers when normalized by VSS destruction was substantially greater than when evaluated under the previous basis. As previously discussed, the digesters for both plants G and E were likely oversized based on the current VSS loading, which contributed to the high specific consumption observed.

Different bases of normalization provide opportunities to derive conclusions based on different aspects of the operation. Normalizing by raw sludge production provides a measure of overall performance, while normalizing by VSS destruction provides a measure of energy efficiency. The examination of energy efficiency in stabilization provided insight into areas where improvement might be possible and highlighted possible deficiencies that would not have been identified had energy consumption only been calculated on a raw sludge production basis. Given the broad range of values observed, opportunities for improvement from an energy efficiency basis may exist in several of the facilities studied.

4.1.3 Electricity Consumption – Dewatering

Dewatering is employed to convert liquid biosolids into a cake. Of the five plants that practiced dewatering, four employed a mechanical process that required electricity as part of its operation. The fifth plant employed a passive process (GeoTube™) that involved storing aerobically digested biosolids in large geo-membrane bags. In this process, leachate seeps through the pores of the bags and the dried solids are retained within the bag. Among plants with mechanical dewatering, the normalized power draw for dewatering ranged from 0.06 – 0.10 kWh/dry kg (Figure 4-5). The minimum and maximum values corresponded to centrifuge processes and did not exhibit overlap of the uncertainty bars (indicating distinctly higher and lower consumption between the two samples). The two rotary presses consumed between 0.07 – 0.09 kWh/dry kg, however, overlap between the uncertainty bars indicated that there was no statistical difference between the two values. Notably, the percentage of total sludge handling electricity consumed by the dewatering processes ranged from 2% (plants H and J) to 5% (plants C and D). The low percentages of total sludge handling power draw indicated that the additional energy required to convert liquid sludges into cake via mechanical dewatering was relatively minor.

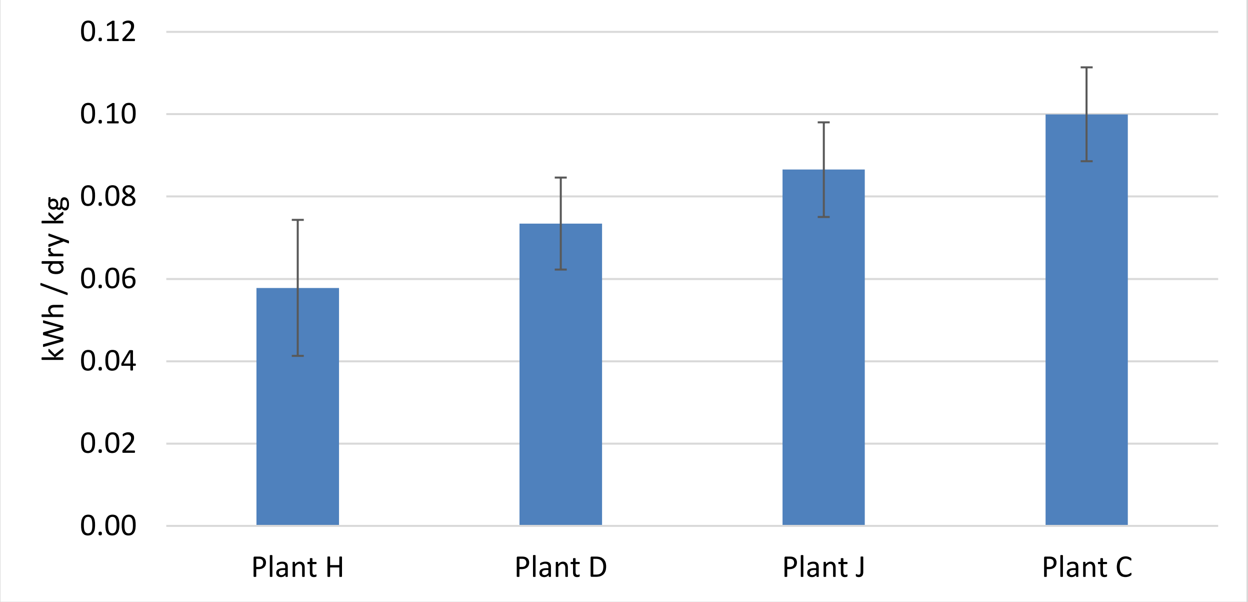

Figure 4-5: Mechanical dewatering electricity consumption per dry mass of raw sludge produced

4.1.4 Electricity Consumption – Pumping

For all but one of the plants studied, pumping represented a minor percentage of the total sludge handling draw (1 – 4 %). Among all plants studied, the 25th, 50th, and 75th percentile of pumping electricity consumption corresponded to 0.02, 0.04, and 0.05 kWh/dry kg, respectively. Plant A represented an extreme value in this regard where pumping represented 18% of the total draw. Its normalized consumption was 0.30 kWh/dry kg, which was a three-fold greater consumption than the next highest consumer (0.10 kWh/dry kg). The identification of the cause for the high use was beyond the scope of the study, but a possible explanation involved the solids content of the feed sludge. Specifically, the wasted secondary sludge was dilute (~ 0.5% TSS), which may have resulted in increased pumping requirements to waste the desired mass of sludge.

4.1.5 Electricity Consumption – Aerated Holding

Among the three plants that employed aerated holding of sludge, plants F and H exhibited similar consumption for the process (1.34 and 1.27 kWh/dry kg, respectively), while plant G exhibited a substantially lower value (0.04 kWh/dry kg). Both plants F and H employed a dedicated blower for their holding tank, while plant G utilized a portion of the air provided by its digester blower to aerate the holding tank (the reported air flow to each unit was used to determine its corresponding allocation of electricity consumption). The discrepancy in values may be explained by the observation that plant G employed an extended HRT in its digester (48 days), which indicated that it was effectively employing its digester as a holding tank.

4.1.6 Electricity Consumption – Odour Control

There was a broad range of electricity consumption values associated with odour control: plants J, C, and H consumed 0.02, 0.13, and 0.98 kWh/dry kg, respectively. The underlying cause of the wide range was beyond the scope of the study, however site-specific considerations likely influenced the quantity of electricity required to eliminate odours. All three facilities employed biofilters to remove odours. However, only the facility that practiced thermo-alkali hydrolysis (plant H) employed a highly engineered system and this corresponded to the highest normalized power draw. Since plant H did not practice aerobic digestion (which aids in odour removal), its odour control system would need to remove all the odours generated by the sludge, which likely increased the energy input requirements. One would have expected the ATAD system to require higher electricity requirements since ATADs have historically been associated with considerable odour emissions (Metcalf & Eddy, 2013). However, the sample facility employed a relatively new “second-generation” ATAD process which is substantially less odourous than early “first generation” systems (Metcalf & Eddy, 2013). One could also hypothesize that the ATAD process required lower volumes of air for treatment than the thermo-alkali hydrolysis process, thereby reducing the electricity requirements for odour control.

4.1.7 Natural Gas Consumption

In the current study, one facility consumed natural gas as part of its sludge treatment process (plant H). The observed consumption was 0.04 m^3 natural gas/dry kg. The lack of natural gas usage within the study sample suggests that it is not a common form of energy employed at small WWTPs for the purposes of sludge processing. Indeed, anecdotal conversations with owners and operators revealed that natural gas was typically only used to heat office buildings, if it was used at all.

4.2 Chemical Usage KPI Results

Chemical use is necessary to achieve the goals of some treatment processes. For all the thickening and dewatering processes within the study, polymers were used to enhance the liquid-solid separation process.

In addition, KOH was employed as part of the stabilization process in one instance. The purchase of chemicals represents an operational cost for plant owners and the GHG emissions associated with their production represent an environmental burden.

For the plants within the study that employed thickening and/or dewatering processes, normalized polymer usage and the corresponding biosolids cake total solids (TS) content are shown in Figure 4-6. Among the selected plants, one plant (J) employed a thickening technology (rotary disc thickener), one plant (E) employed a passive dewatering technology (GeoTube™), and four plants (C, D, J, H) employed mechanical dewatering processes. Plants C and H employed centrifuges, while plants D and J employed rotary presses.

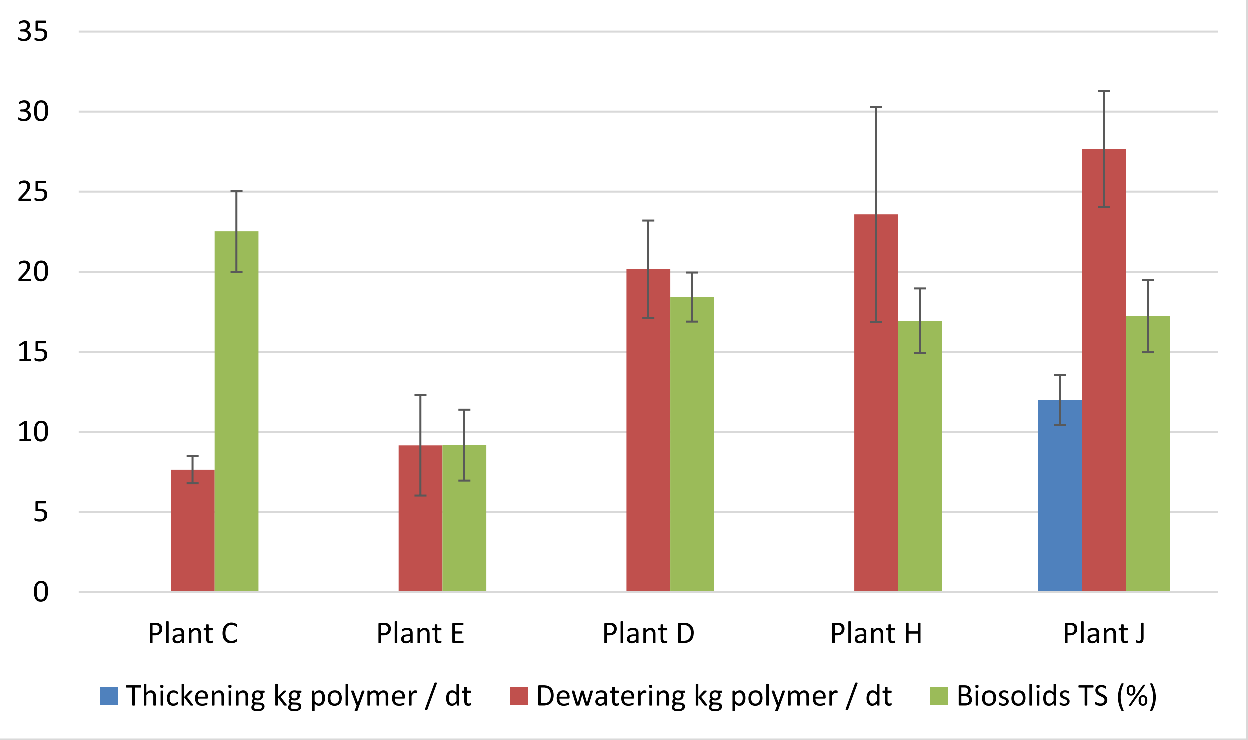

Figure 4-6: Chemical usage per dry mass of raw sludge produced and biosolids TS content

The rotary disc thickener consumed 12 kg of polymer per dry tonne (dt) of raw sludge and generated a 4.5% TS sludge product. The GeoTube™ consumed 9 kg polymer/dt and generated a 9.2% TS product. Polymer usage for rotary press operation ranged from 20 – 28 kg polymer/dt (no uncertainty bar overlap) and generated a biosolids cake ranging from 16.9 – 18.4% TS (uncertainty bar overlap). Polymer usage for centrifuge operation ranged from 8 – 24 kg polymer/dt (no uncertainty bar overlap) and generated a biosolids cake ranging from 17.2 – 22.5% TS (no uncertainty bar overlap). Notably, the lower centrifuge chemical usage value corresponded to the higher TS content. The lower dosage was employed at the plant that generated a mixed primary/secondary sludge, which typically exhibits higher dewaterability than pure secondary sludges (Metcalf & Eddy, 2013).

Among the two rotary disc thickeners evaluated, the polymer usage and solids content extended beyond the range of values reported in the literature. Rotary presses employed for dewatering aerobically digested waste activated sludges have been reported to consume a maximum of 17.5 kg polymer/dt and achieve 28 – 45% solids (Metcalf & Eddy, 2013). For centrifuge use, literature indicates that 10 – 15 kg polymer/dt can be employed to achieve between 18 – 25% solids (Metcalf & Eddy, 2013). The observed discrepancies between observed and literature values may indicate that excess polymer was being dosed in some cases, or that the polymers employed were less effective as coagulating/flocculating agents than those reported in literature. Finally, although operational inputs were not converted into economic costs in the current study, it is important to note that polymers can vary widely in price. It is therefore possible that the more effective polymers were more expensive, which is an additional sustainability aspect for plant owners to consider.

In addition to polymer usage for dewatering, plant H utilized KOH as part of its stabilization process. The observed usage was 19 kg KOH/dt. The relative impact of the KOH and polymer use at this plant on GHG emissions will be detailed in section 4.5.

Overall, there was a broad range of chemical use employed at the facilities within the sample. Rotary thickening and GeoTube™ dewatering generally consumed the least with 12 and 9 kg/dt, respectively. Rotary press and centrifuge dewatering operations consumed 20 – 28 kg/dt and 8 – 24 kg/dt, respectively. Three of the mechanical dewatering usage values were higher than those reported in literature. The observation suggests that the polymers may have been overdosed in the sample cases, or that the chemicals used were less effective as coagulants/flocculants than those reported in literature. One facility utilized KOH as part of its stabilization process and consumed 19 kg KOH/dt.

4.3 Disposition KPI Results

The disposal of biosolids represents an operational cost for wastewater treatment plant owners, and the carbon emissions associated with trucking fuel consumption represent an environmental burden. Disposition KPIs involving the average distance that biosolids were hauled and the associated normalized fuel consumption were evaluated (Figure 4-7). For the former calculation, uncertainty was assumed to be constant (0.5 km) since Google Maps™ was employed to obtain the exact address of each farm/landfill and uncertainty was therefore only associated with variation in distance travelled within a given farm.

Uncertainty for the fuel consumption was directly a result of the uncertainty in estimated raw sludge production for each plant.

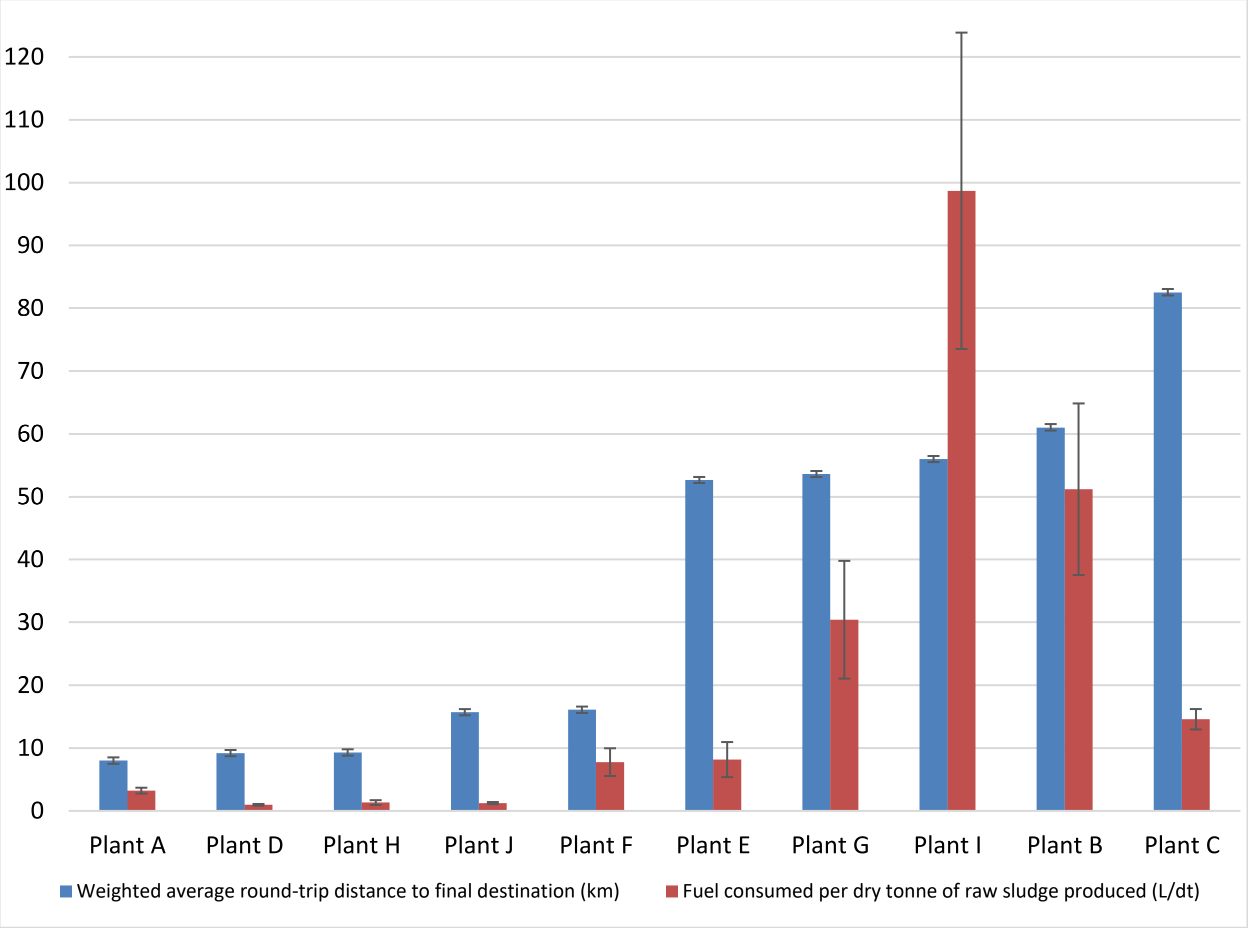

Figure 4-7: Disposition KPI results

From Figure 4-7 it can be seen that the average round-trip trucking distance ranged from 8 – 83 km. There was a substantial difference in trucking distance requirements between the lower and upper five facilities studied. Half of the plants required less than 16 km of round-trip trucking to dispose of their biosolids, while the other half required more than 52 km. The three highest distances corresponded to plants (C, B, I) that did not have on-site storage, which necessitated additional trucking. In each case, transport involved trucking the biosolids from the WWTP to an off-site location (storage building, lagoon, drying bed) and trucking from the off-site location to the final destination (farm, landfill) at a later date.

As shown in Figure 4-7, fuel consumption normalized by raw sludge production ranged from 1 – 99 litres per dry tonne of raw sludge produced. The broad range observed was influenced by multiple factors:

the distance required for trucking, the capacity and fuel economy of the trucks employed for transportation, and the presence (or lack thereof) of on-site dewatering. Notable observations were obtained when comparing facilities with similar trucking distances, but different dewatering practices. Among the three plants with the highest trucking distances, only plant C employed on-site dewatering (Plant I employed an off-site drying bed). As a result, plant C consumed 85% and 72% less fuel than plants I and B, respectively. Plants E and G required similar trucking distances (53 and 54 km, respectively), but the former facility consumed 75% less fuel as a result of on-site dewatering (GeoTube™). Similar observations were made for plants J and F, which exhibited similar trucking distances and a substantial difference in fuel consumption for the facility that employed dewatering (plant J).

A broad range of trucking distance requirements and normalized fuel consumption quantities were observed among the facilities studied. The difference between trucking distance and fuel consumption was largest when comparing facilities that employed chemically enhanced dewatering against those that did not. The results indicate that the implementation of dewatering processes to reduce trucking requirements is a consideration worthy of investigation. From an environmental sustainability standpoint, the reduced fuel consumption represents a savings in the carbon footprint associated with trucking. However, the manufacture of chemicals represents a source of GHG emissions. The impact of each input on net carbon emissions for each plant's sludge handling process will be detailed in section 4.5.

4.4 Biosolids Quality KPI Results

The quality (pathogens, nutrients, and metals content) of the biosolids product is an important consideration when considering the end-use of the biosolids product. For facilities that wish to land apply their biosolids for agricultural use in Ontario, both pathogen (*E. coli*) and metals (selection of 11) content are regulated by the Nutrient Management Act as Non-Agricultural Source Material (NASM) (O. Reg. 267/03 – Schedule 5 and 6, CM2 and CP2). Land application is a common practice in Ontario (Jin and Parker, 2017) given that the nutrients within the biosolids (N/P/K) reduce the chemical fertilizer requirements of the crop to which they are applied. The Ontario regulatory environment is different than the US, where EPA guidelines distinguish between a greater variety of pathogen levels (US EPA, 1993). Under EPA guidelines, a "Class A" product must contain less than 1000 MPN/g of *E. coli*, while a "Class B" product must have less than 2×10^6 CFU/g (US EPA, 1993). The latter value is identical to the NASM requirement in Ontario (O. Reg. 267/03 – Schedule 5, CM2) with respect to *E. coli* content. For each plant studied, the nutrient, metal, and pathogen (*E. coli*) content of the biosolids product was evaluated.

Figure 4-8 shows the mean total phosphorus (TP), total nitrogen (TN), and potassium (K) content of the biosolids products. TP content ranged from 19 – 40 g TP per kg of dry solids. The 25th, 50th, and 75th percentile corresponded to 26, 31, and 36 g TP/dry kg, respectively. TN values ranged from 25 – 69 g TN per dry kg of dry solids. The 25th, 50th, and 75th percentile corresponded to 39, 44, and 50 g TN/dry kg, respectively. Among the nine facilities that did not add K to their sludge during the treatment process, the product contents ranged from 0.9 – 6.0 g K per kg of dry solids. The 25th, 50th, and 75th percentile corresponded to 2.2, 3.3, and 4.0 g K/dry kg, respectively. The facility that did add supplemental K to its sludge (plant H) obtained a biosolids product with 53 g K/dry kg, albeit with a substantial degree of variability (standard deviation = 26 g K/dry kg). Across all facilities studied, the TP, TN, and K (non-supplemented) contents were broadly consistent with those found in literature (Metcalf & Eddy, 2013).

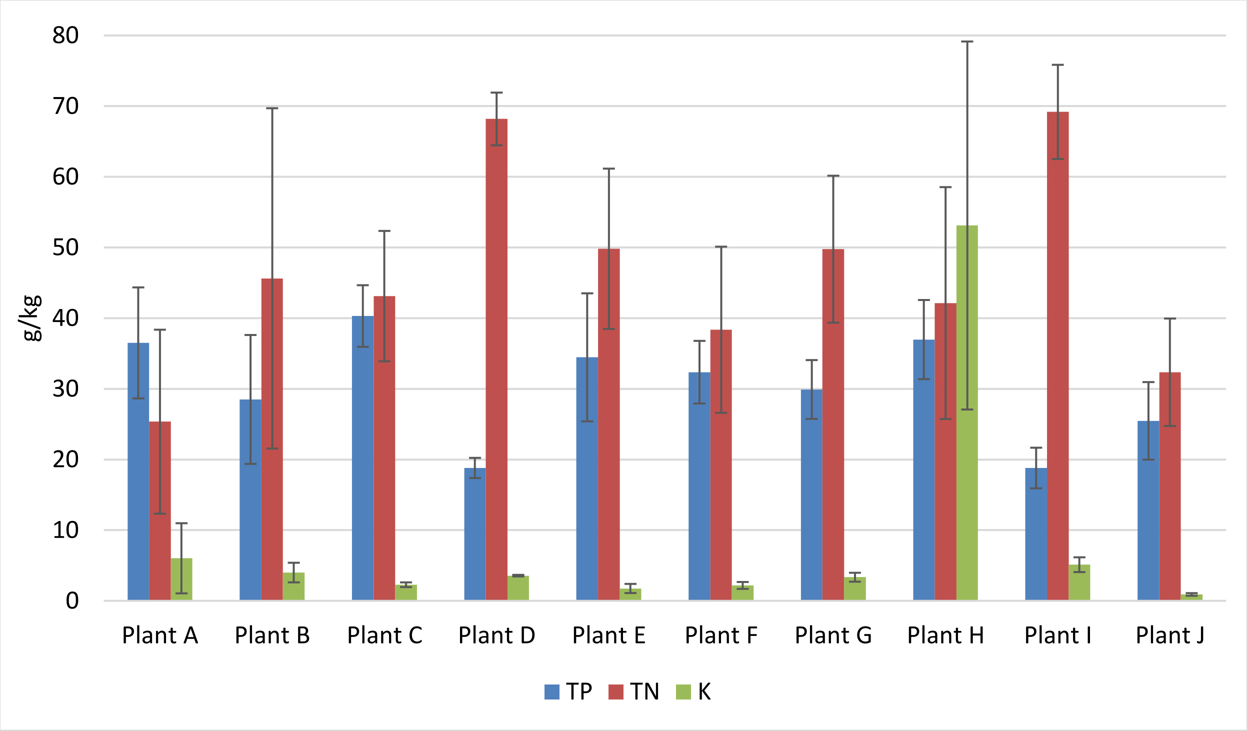

Figure 4-8: Mean nutrient content of hauled biosolids (dry mass basis)

Figure 4-9 shows the mean log of the biosolids *E. coli* content for each product evaluated. In all cases, the *E. coli* values were at least one log (*i.e.* 10-fold) lower than the NASM limit of 6.3 log (CFU/g). The content ranged from 2.1 – 5.2 log (CFU/g), while the 25th, 50th, and 75th percentile corresponded to 2.3, 3.8, and 4.4 log (CFU/g), respectively. Four facilities generated a product that met Class A requirements for *E. coli* content (plants D, E, G, J). This result was expected for plants G and J, since both facilities employed stabilization processes (thermo-alkali hydrolysis and ATAD, respectively) that disinfected the sludge

(Metcalf & Eddy, 2013). The result was more notable for plants D and E, which both employed conventional aerobic digestion. The former facility did not employ any on-site storage, while the latter employed the GeoTube™ process following the digestion process. As a form of long term storage, the GeoTube™ functions similar to a system implemented by Eyre *et al*. (2018), which also generated a Class A product with respect to *E. coli* content. Taken together, the observations indicate that long-term storage may emerge as a solution for obtaining a Class A product without substantial energy and labour inputs. Nonetheless, given that observed *E. coli* values were at least one log below the NASM limit of 6.3 log in each of the case studies, it is clear that pathogen content is not a concern under the current Ontario regulatory framework.

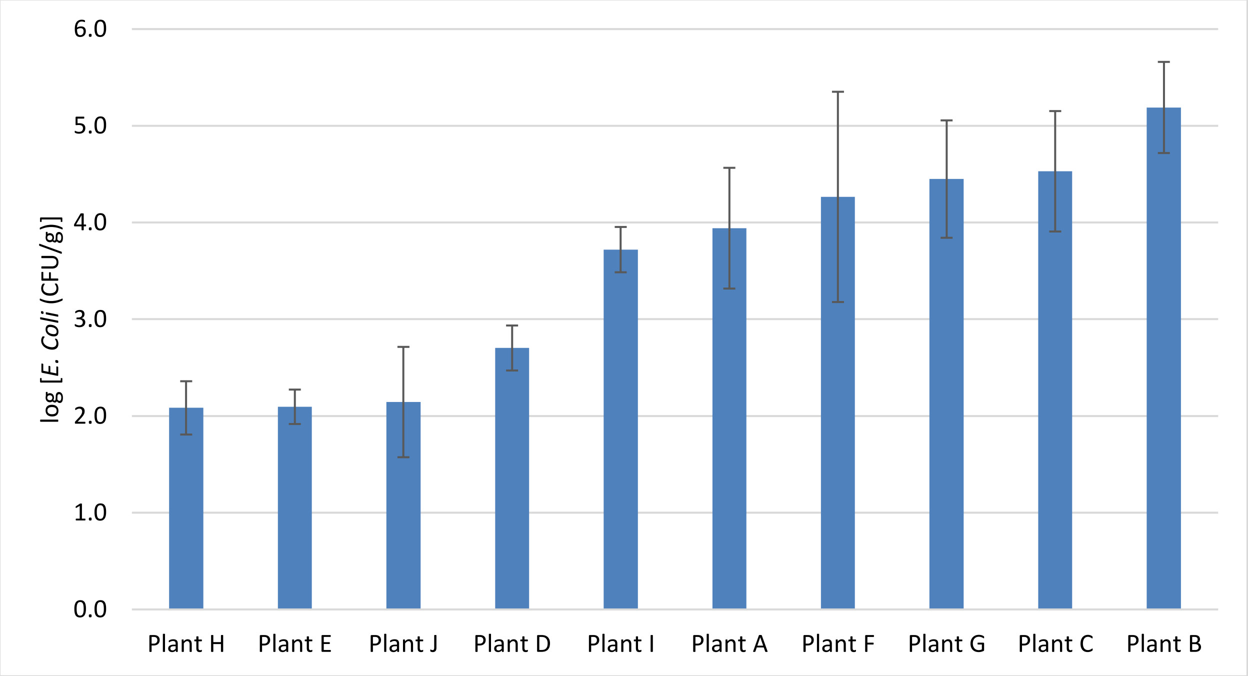

Figure 4-9: Mean log *E. coli* content of hauled biosolids

The ratio of each metal's mean dry weight concentration to the NASM limit was evaluated as a measure of the extent of metal contamination. Figure 4-10 displays the three highest ratios observed for the plants in the study. From Figure 4-10, it can be seen that all heavy metal concentrations were below regulatory limits for land application as a NASM. The highest ratio was observed for copper at all plants, and ranged from 14 – 69% of the NASM limit. Of the copper ratios observed, both the minimum (plant D) and maximum (plant I) occurrences corresponded to the northern facilities that did not practice land application of biosolids. Among the facilities that did practice land application of biosolids, copper ratios ranged from 17 – 37% of the NASM limit.

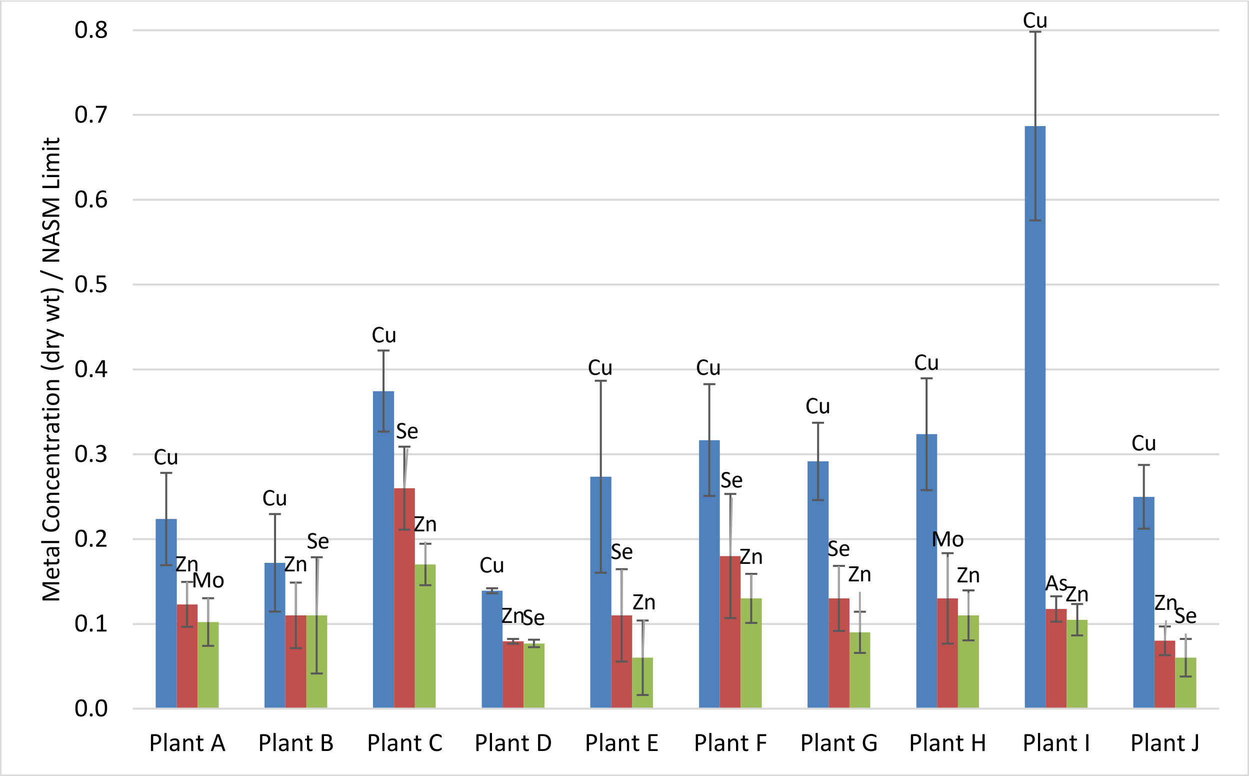

Figure 4-10: Metals content of hauled biosolids

Zinc and selenium were the most common metals to be observed as either the second or third highest ratio for the plants evaluated. The former metal was observed in ten occurrences, while the latter was observed in seven instances. The only other metals observed as either the second or third highest ratio were molybdenum (two occurrences) and arsenic (one occurrence). The arsenic observation corresponded to a facility that did not practice land application (plant I).

In summary, all plants in the study exhibited nutrient contents within expected ranges and met all applicable regulations for metals and pathogen content. Median values for TN, TP, and K (non-supplemented) were 31, 44, and 3.3 g/kg, respectively. All facilities met the pathogen (*E. coli*) and metal concentration requirements for application as a NASM. With respect to pathogens, all facilities exhibited at least one log (*i.e.* 10-fold) fewer pathogens than the NASM limit. Four facilities exhibited *E. coli* levels sufficiently low to be classified as a Class A product, one of which was achieved through a low-tech long-term storage technology. With respect to metals, the copper concentration of each product exhibited the closest proximity to the NASM limit. Copper concentrations ranged between 17 – 37% of the NASM metal limits for plants that currently practice land application. The most common metals corresponding to the second or third highest ratios were zinc (ten occurrences), and selenium (seven occurrences).

4.5 GHG Emissions KPI Results

To facilitate a comparison of all the sludge handling operations on the basis of a common metric of environmental sustainability, the inputs and outputs of each system were converted to normalized CO_2 equivalents. The exercise determined the cumulative impact of each input and output on the carbon footprint of the plant. Where possible, emission factors specific to Ontario (electricity, natural gas production) or Canada (transportation fuel) were used to calculate the emissions associated with each input. In other cases, literature values for chemical production (polymer, KOH) and chemical fertilizer production (N, P, K) were utilized. The latter factors were used to determine the carbon off-sets gained by using biosolids as a fertilizer through the avoidance of chemical fertilizer production for each nutrient.

The contributions of each system input and output to the net carbon footprint of each plant are shown in Figure 4-11. Net GHG emissions ranged from -119 to 299 kg CO_2 equivalents per dry tonne of raw sludge produced. Of the eight plants that practiced land application disposition, six exhibited net negative emissions, which ranged between -119 and -4 kg CO_2 eq./dt. In each case, the carbon credits gained from chemical fertilizer offsets exceeded the emissions associated with plant operations and biosolids trucking.

The outcome was due in large part to the reduction in carbon emissions associated with electricity production in Ontario, which have dropped over 75% since 2010 (Environment and Climate Change Canada, 2018). From a sustainability perspective, the outcome was noteworthy in two respects: a) land application is the most common disposal method for small WWTPs in Ontario (Jin and Parker, 2017), and b) all observations corresponded to facilities practicing conventional aerobic digestion, which is the most common stabilization technology among small WWTPs in Ontario (Jin and Parker, 2017). The results therefore indicate that when land application is practiced in combination with conventional treatment processes, sludge handling practices in Ontario can be sustainable from a GHG perspective.

Of the plants studied, two facilities practiced land application but did not exhibit negative emissions. A third facility (plant H) exhibited negative emissions (-4 kg CO_2 eq./dt) to a substantially lesser degree than other such plants within the sample [-119 to -86 kg CO_2 eq./dt]. Plant B exhibited emissions near zero (4 kg CO_2 eq./dt), while the emissions associated with plant J (128 kg CO_2 eq./dt) were substantially higher than its peers that practiced land application. The net positive emissions observed for plant B were primarily a result of the trucking emissions (137 kg CO_2 eq./dt), which exceeded those associated with electricity consumption (109 kg CO_2 eq./dt). In the case of plant J, emissions associated with energy consumption and chemical use exceeded the credits gained from fertilizer off-sets.

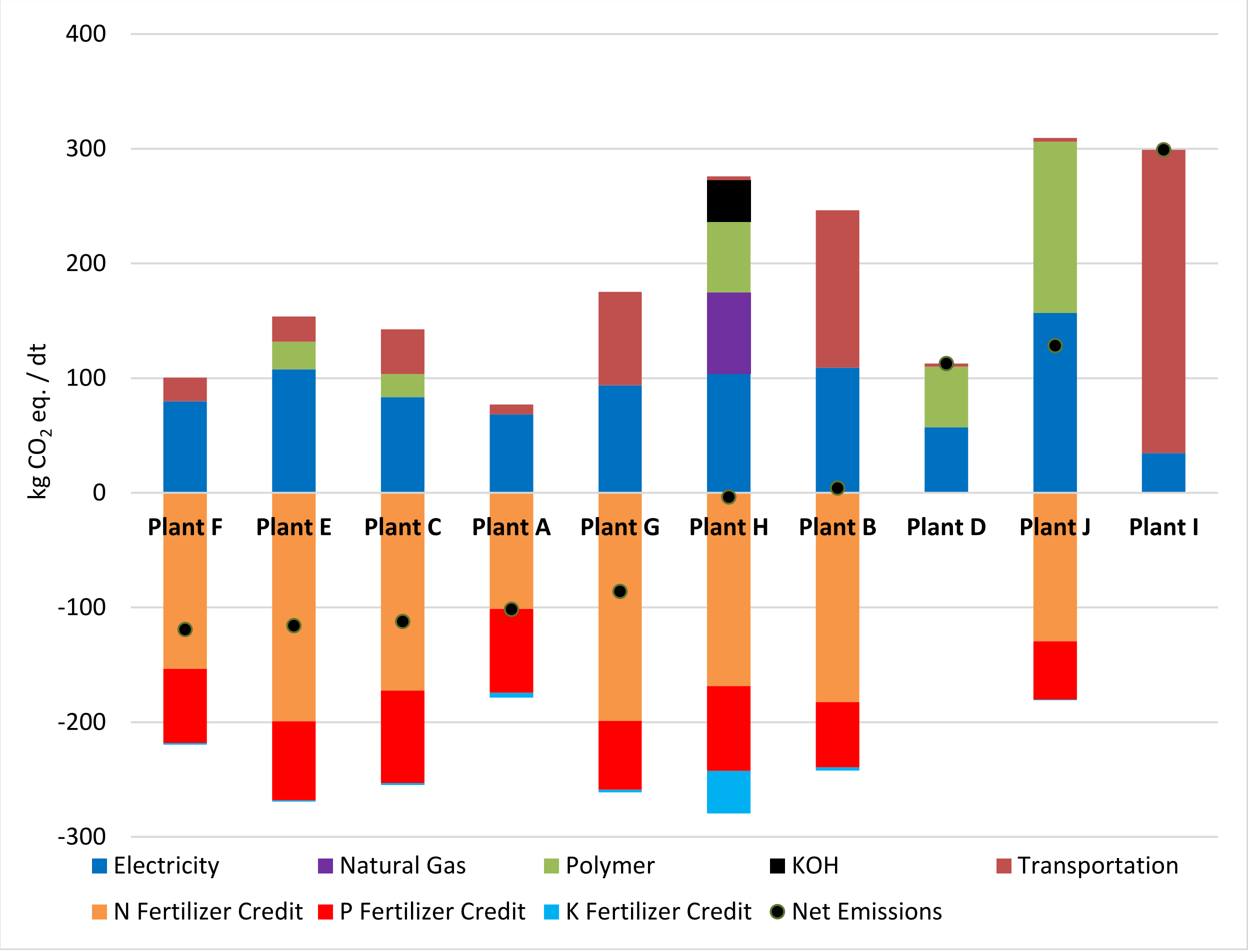

Figure 4-11: Sludge handling GHG emissions per dry mass of raw sludge produced

Among the plants that employed polymers for dewatering, the carbon intensity impact was pronounced for facilities that were identified as using chemical quantities that were greater than those reported in the literature (plants J, D, H). Notably, carbon emissions associated with polymer use was similar to electricity-associated emissions for plants D and J. Conversely, the plants that used polymer quantities consistent with literature values had the second (plant E) and third (plant C) lowest carbon footprint of all facilities studied. The result for plant C was particularly notable in that the facility exhibited the highest distance required for trucking among all plants studied.

The highest net quantity of carbon emissions was associated with plant I (299 kg CO_2 eq./dt), which did not receive any carbon credits (biosolids were landfilled). It exhibited 186 kg CO_2 eq./dt more emissions than the other plant (D) that landfilled its biosolids. The latter plant practiced on-site dewatering, thereby providing an indication of the environmental benefits that such a technology can provide. Plant H received a larger K fertilizer credit (-37 kg CO_2 eq./dt) than its peers, which off-set the emissions associated with the production of the KOH chemical used in the stabilization process (36 kg CO_2 eq./dt). Its electricity-related emissions totaled 104 kg CO_2 eq./dt, of which 90 kg CO_2 eq./dt were collectively associated with aerated holding and odour control. Therefore, if the technology were to be implemented at facilities with no aerated holding or odour control requirements (but with similar trucking distance), the technology would exhibit emissions similar to the other observed sludge handling systems that were carbon sinks.

Figure 4-12 shows the carbon emissions associated with processes upstream of and including stabilization for each plant in the study. The analysis provides insight into the emissions required for mechanical treatment processes to achieve the observed product quality (pathogen content), irrespective of downstream processes. As noted previously, plants D, J, and H generated a Class A product directly as a result of their mechanical stabilization process (plant E generated it via passive long-term storage). However, only the latter two facilities generated this quality of product using thermal processes that have historically been accepted as being able to consistently generate a Class A product (Metcalf & Eddy, 2013). Plant D employed conventional aerobic digestion, which would be expected to reduce pathogen levels to Class B requirements (Metcalf & Eddy, 2013). From Figure 4-12, it can be seen that the highest emissions were associated with plants H and J, which highlighted the environmental cost (GHG impact) of obtaining a Class A product through thermal-mechanical processes.

In the case of plant J, both the thickening and stabilization steps were necessary to generate the Class A product. Emissions associated with pumping, thickening, and stabilization electricity consumption (152 kg CO_2 eq./dt) and thickening polymer usage (31 kg CO_2 eq. / dt) summed to 183 kg CO_2 eq./dt. For plant H, electricity associated with pumping, stabilization, and upstream dewatering (14 kg CO_2 eq./dt), natural gas (71 kg CO_2 eq./dt), polymer usage (62 kg CO_2 eq./dt), and KOH (36 kg CO_2 eq./dt) were necessary to generate the final product. The addition of KOH generated a carbon credit of -35 kg CO_2 eq./dt (credits for N and P fertilizer avoidance were not a result of the treatment process selection). Subtracting the credits associated with the K fertilizer avoidance, the emissions associated with the inputs identified totaled 148 kg CO_2 eq./dt. Examining exclusively stabilization and related emissions, both plants J and H exhibited emissions substantially higher than the plants that generated a Class B/NASM quality product. The emissions associated with Class B generation ranged between 26 – 109 kg CO_2 eq./dt.

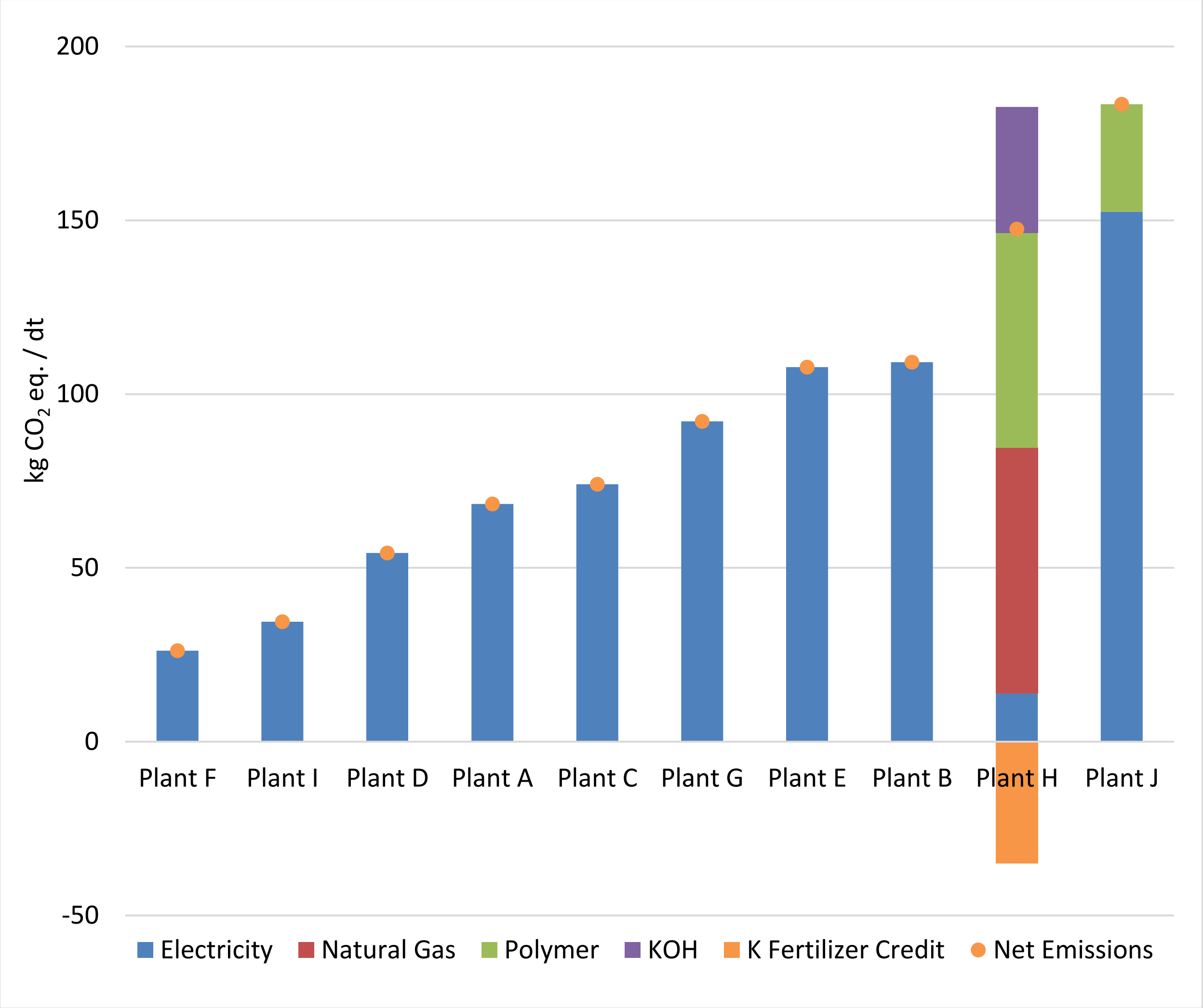

Figure 4-12: GHG emissions associated with processes upstream of and including stabilization

In summary, GHG emissions associated with sludge handling operations ranged from -119 to 299 kg CO_2 eq./dt among all plants studied. Six facilities exhibited net-negative emissions, which ranged between -119 to -4 kg CO_2 eq./dt. The five systems that yielded the lowest emissions employed process configurations that were relatively common province-wide, which suggests that other sludge handling systems across the province may be carbon sinks as well. Among the two plants (H and J) that practiced thermal stabilization processes (thermo-alkali hydrolysis and ATAD) for the purposes of generating a Class A product (*E. coli* content), total emissions associated with stabilization and auxiliary processes were 148 and 183 kg CO_2 eq./dt, respectively. Both values were higher than plants that generated Class B/NASM quality products, which ranged between 26 and 109 kg CO_2 eq./dt. The discrepancy highlighted the environmental trade-offs associated with Class A product generation through such stabilization methods.

4.6 Impact of Innovative Technology on Sustainability

Part of the rationale for evaluating WWTPs that employed innovative thickening, stabilization, and dewatering technologies was to quantify the impact on sustainability of implementing such technologies within other plants that currently employ conventional process configurations. From an economic sustainability standpoint, the operational inputs and outputs detailed in sections 4.1 – 4.5 could be used as benchmarks to determine the localized costs associated with operating each technology. However, to assess the environmental sustainability (through GHG impact analysis) of implementing such technologies in facilities with site-specific conditions (*e.g.* storage practices, trucking distance), further desktop analysis was conducted.

To perform the evaluation, all the innovative technologies within the plants studied (rotary disc thickening, thermo-alkali hydrolysis, ATAD, GeoTube™, rotary press, centrifuge) were considered for incorporation into the conventional plants (A, B, F, G, I) based on the input/outputs observed from the plants that employed the technologies (C, D, E, H, J). Upon initial screening, the thermo-alkali hydrolysis and ATAD technologies were removed from consideration due to the substantial GHG emissions observed in the study (H and J, respectively). For the remaining technologies, the KPIs were re-calculated using site-specific conditions, and the resulting GHG emissions were compared to the base case for each plant. Further scenarios involving low and high polymer usage were evaluated separately due to the discrepancy between the low and high observed usage for each technology (rotary press and centrifuge).

The change in plant GHG emissions after innovative technology implementation (relative to the base case) are shown in Figure 4-13. Two plants (B, I) exhibited a reduction in GHG emissions under all scenarios, one plant (A) exhibited an increase in emissions under all scenarios, and two facilities (F, G) exhibited increases and decreases depending on the technology/configuration selected. In each case, the base case trucking requirements were the primary factor regarding whether a new technology would increase or decrease emissions.

Among the five plants evaluated for new technology implementation, Plants B and I had the highest base case trucking requirements and did not employ on-site storage. Therefore, both plants exhibited the greatest reduction in transportation fuel consumption when scenarios involving thickening or dewatering implementation were implemented. In both cases, the fuel-related savings off-set the emissions associated with polymer production under all scenarios.

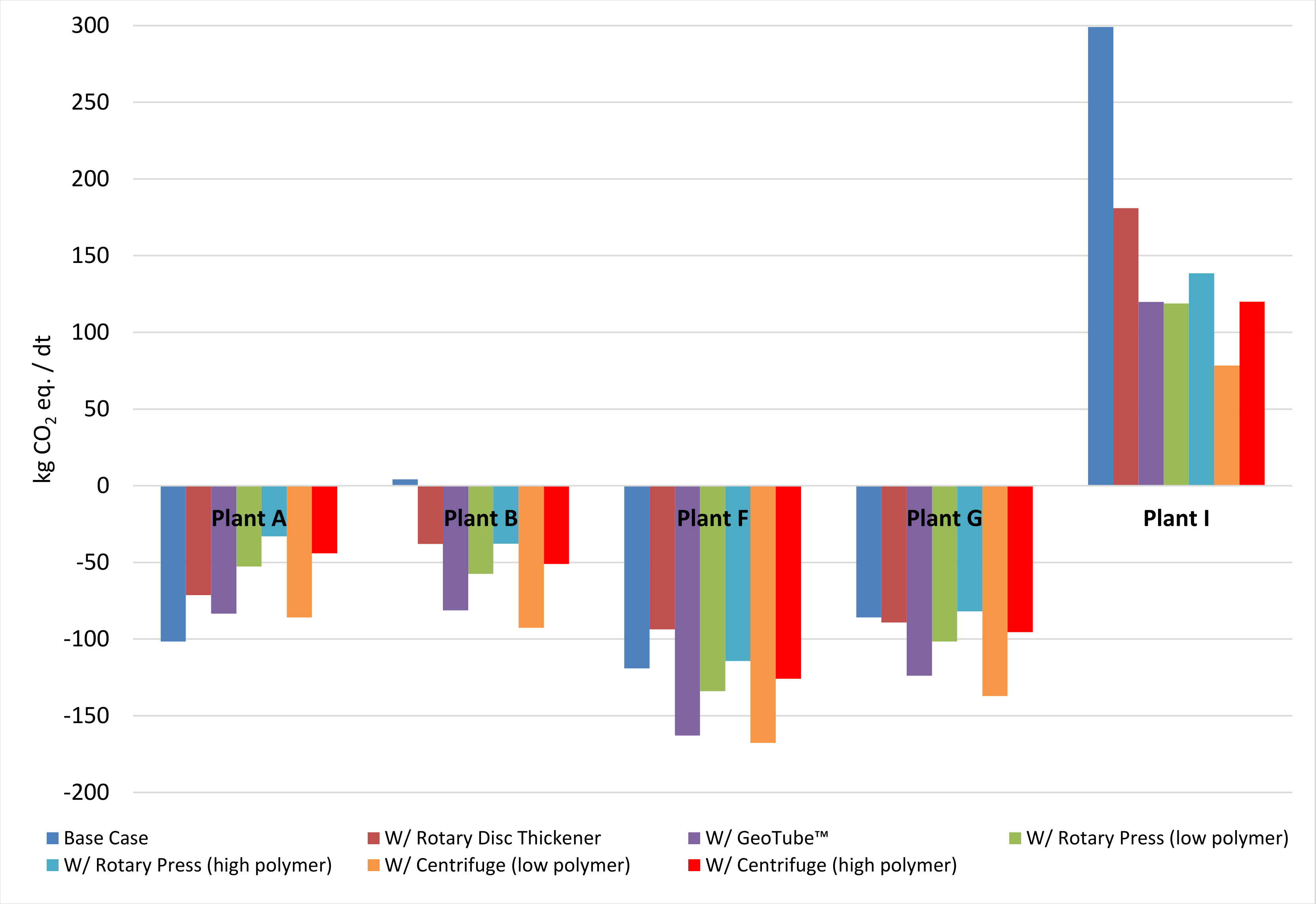

Figure 4-13: Total sludge handling GHG emissions per dry mass of raw sludge – with and without innovative technology incorporation

Plant I also benefited from two unique outcomes of dewatering technology implementation that resulted in additional GHG savings relative to its peers. The first outcome involved the change in the trucking route that was made possible under the new technology scenario relative to the base case. Under any scenario where cake was generated at the plant (centrifuge and rotary press), the biosolids product could be transported directly to the landfill. The need for transport to both the drying bed and landfill would be eliminated, thereby reducing net fuel requirements. For the plants that land applied their biosolids, the trucking route was assumed to be the same under the new technology scenarios since the facilities would not be able to land apply biosolids at new times under any new scenario.

The second outcome involved the volume and fuel economies of the trucks employed by the facilities. In the base case, Plant I employed a truck with a volume lower than that of the conventional trucks in place at other facilities (16.5 versus 40 m^3), but did not receive proportionally lower fuel economy (2.0 versus 1.72 L/km). Under scenarios where cakes were generated, Plant I could instead use a truck similar to that employed by its peer northern facility (plant D), which consumed 5.0 L/km and hauled 8.5 m^3 per trip. At all other plants, the truck selection would remain the same under the new scenarios since the different truck would not generate additional fuel (and related-GHG emission) savings.

Plant A was the only facility that did not exhibit emissions reduction under any innovative technology scenario. The outcome was primarily due to the short trucking distance required, which resulted in substantially less fuel savings than plants with higher trucking requirements (B, G, I). Under all new scenarios, the fuel-related emission savings did not off-set the added emissions associated with polymer usage for plant A.

Plant F exhibited similar base case trucking distance requirements to plant A (8 vs 3 km, respectively), but unlike its peer, there were some scenarios in which dewatering implementation would reduce plant F emissions. The difference was due to the changes in existing technologies that would be possible under the new scenarios. Unlike plant A, plant F employs electricity for aerated holding/storage that would be eliminated under all dewatering scenarios. Specifically, the cake products generated by mechanical dewatering processes do not require aeration in storage, and a GeoTube™ functions as both a dewatering and storage device. Under select new dewatering scenarios in plant F, the combination of electricity- and fuel- related emission savings resulted in a net GHG savings relative to the base case. Of note, the implementation of a thickening technology at plant F would not negate the need for aerated holding. In this case, a liquid product would still be formed and require aeration for the same reasons as for the existing process: to maintain solids suspension and facilitate easier pumping of the material during haulage events.

As such, the electricity-related emissions associated with holding were included in the thickening scenario, and the net impact was higher plant emissions under this scenario.

Two facilities (F, G) had scenarios where GHG emissions would either be reduced or increased depending on the technology and configuration selected. With rotary thickening implementation, Plant F exhibited an increase in carbon emissions, while plant G exhibited a minor decrease in emissions (- 3 kg CO_2 eq./dt). At both plants, the implementation of GeoTube™ or centrifuge technology resulted in GHG reductions in all scenarios. The net outcome (increased or decreased plant emissions) of implementing rotary press dewatering was dependent on the assumed polymer dosage. A high polymer dose resulted in higher plant emissions for both facilities, while a low polymer dose resulted in lower plant emissions. As a result, polymer usage was identified as an important parameter when considering whether to implement a new technology for the purpose of improving the environmental sustainability.

In summary, this desktop innovative technology analysis revealed cases where GHG emissions were reduced under all technology implementation scenarios (plants B and I), increased under all scenarios (plant A), and dependent on the configuration selected (plants F and G). For each scenario, the net outcome was primarily dependent on whether the GHG emissions saved from fuel consumption reduction off-set the emissions associated with thickening/dewatering polymer production. Plants B and I exhibited the highest base case trucking requirements, subsequently received the greatest reduction in trucking fuel consumption emissions, and reduced net carbon emissions under all scenarios. Conversely, the finding for plant A suggests that thickening or dewatering technology implementation at facilities with low initial trucking requirements may increase the plant's carbon impact if fuel-related GHG savings do not off-set the additional emissions associated with polymer usage. A possible exception (plant F) was noted for cases where the dewatering technology can replace an existing unit process (*e.g.* aerated holding tanks) and thus eliminate the emissions associated with the existing operation.

Chapter 5
Conclusions and Recommendations

5.1 Conclusions

A benchmarking exercise was completed to characterize the sustainability of sludge handling in small WWTPS in Ontario and a desktop analysis was conducted to determine the GHG impact of incorporating innovative technologies into conventional sludge handling configurations. The benchmarking component involved evaluating ten plants across the province on a variety of sustainability metrics: energy consumption, chemical use, biosolids disposition, biosolids quality, and GHG emissions. The desktop assessment involved applying select innovative technologies within the study sample to those that employed conventional processes, and calculating the resulting GHG impact.

Among all plants studied, overall electricity consumption for sludge handling ranged from 0.9 – 3.9 kWh/dry kg (median = 2.2 kWh/dry kg). The maximum consumption corresponded to the facility practicing ATAD stabilization, while the highest value among conventional aerobic digestion plants was 2.7 kWh/dry kg. Consumption for stabilization processes was found to range from 0.3 – 3.8 kWh/dry kg (median = 1.6 kWh/dry kg). The maximum value corresponded to the ATAD process, while the minimum consumption corresponded to the thermo-alkali hydrolysis process. The low value for the latter process indicated that such a technology may be a viable option for reducing electricity consumption in facilities where aerated holding and odour control are not necessary.

Among the eight plants that practiced conventional aerobic digestion, consumption normalized by quantity of VSS destruction was found to range from 4.9 – 56 kWh/dry kg VSS (median = 8.7 kWh/dry kg VSS). The ATAD facility exhibited the highest consumption among all plants (63 kWh/dry kg VSS). Of the eight plants that practiced conventional aerobic digestion, the range of the five lowest values (5 – 9 kWh/dry kg VSS) was substantially lower than the range of the three highest values (15 – 56 kWh/dry kg VSS).

Electricity consumption for mechanical dewatering processes ranged from 0.06 – 0.10 kWh/dry kg, which represented 2 – 5% of total sludge handling power draw for such plants. Chemical usage for dewatering processes ranged between 8 – 24 kg polymer/dt (centrifuges) and 20 – 28 kg polymer/dt (rotary presses), while the GeoTube™ process used 9 kg polymer/dt. The three highest observed chemical usage values were greater than those found in literature, which suggested that the polymers were either over-dosed to some extent and/or were not as effective coagulating/flocculating agents as those employed in literature case studies. The solids content of the product generated ranged between 16.9 – 22.5% (centrifuges) and 17.2 – 18.4% (rotary presses). The GeoTube™ process generated a 9.2% solids product.

The weighted average round-trip distance for disposition between the WWTP and the final destination ranged between 8 – 83 km and the normalized transportation fuel consumption ranged between 1 – 99 L/dt. The difference between trucking distance and transportation fuel consumption was largest when comparing facilities that employed chemically enhanced dewatering against those that did not. The plant with the maximum trucking distance (83 km) practiced mechanical dewatering and consumed between 72 – 85% less fuel than the plants with the second and third highest trucking distances (both of which did not practice dewatering).

All the sampled plants exhibited nutrient contents within expected ranges and contaminant (metals/pathogens) contents below regulated levels for application as a NASM. All facilities exhibited at least one log (*i.e.* 10-fold) fewer pathogens than the NASM limit. Four facilities generated product that met Class A requirements for *E. coli* content, one of which was achieved through a low-tech long-term storage technology (GeoTube™). The copper concentration of each product exhibited the closest proximity to the NASM limit. It ranged between 17 – 37% among plants that currently practiced land application. The most common metals corresponding to the second or third highest ratios were zinc and selenium.

Carbon emissions ranged from -119 to 299 kg CO_2 eq./dt among all plants studied. Six of the eight facilities that practiced land application exhibited net-negative emissions, ranging from -119 to -4 kg CO_2 eq./dt. Land application is the most common biosolids disposal method across Ontario, which indicates that sludge handling practices of several plants province-wide are sustainable from a GHG standpoint. Among the two plants that practiced an alternative stabilization processes (thermo-alkali hydrolysis and ATAD) for the purpose of generating a product that meets Class A requirements for *E. coli* content, emissions associated with stabilization and auxiliary processes were 148 and 183 kg CO_2 eq./dt, respectively. Both quantities were substantially higher than those associated with processes that generated Class B/NASM quality products (26 – 109 kg CO_2 eq./dt) and highlighted the environmental trade-offs associated with achieving Class A pathogen levels through such stabilization methods.

The innovative technology assessment suggests that existing trucking requirements and polymer dosage are the primary factors that determine whether or not the technologies evaluated would improve environmental sustainability if implemented. The assessment revealed one facility where GHG emissions would be increased under all new technology scenarios, two facilities where emissions would be decreased under all scenarios, and two facilities where GHG emissions would either be increased or decreased depending on the technology and polymer dosage selected.

From an operations and sustainability standpoint, the benchmarking approach developed can be employed by plant owners and operators who seek to better understand how their utility is performing relative to peers of similar capacity and scope of operations, identify areas of need and further investigation, and move toward improving the long-term sustainability of their operations. The substantially different levels of normalized inputs/outputs observed demonstrate the value of benchmarking: it provides owners and operators with a means to compare, evaluate, and potentially find opportunities for optimization within their own systems, and provides a base case from which to compare future technology implementation.

5.2 Recommendations

Regardless of the industry it is being applied in, the practice of benchmarking provides more insight if more specimens are included in the sample. Therefore, it is first recommended that sludge handling systems in additional small WWTPs be evaluated using the KPI framework and audit methodology developed in the present study. Different plants may potentially perform better than the ten facilities investigated in the current study, which would potentially provide insight into better sludge handling management practices for implementation elsewhere. Conversely, plants may be identified as lagging behind the current group in terms of sustainability performance. If changes were made to improve performance in such plants, the collective sustainability of sludge handling province-wide would increase as well. Facilities from other parts of Canada could also be evaluated to determine how facilities in differing provinces rank amongst each other, determine whether particular regional practices are more sustainable than others, and promote knowledge transfer between participating municipalities to move toward the goal of universally implementing best practices for sludge management.

Within the category of small WWTPs, it is recommended that the audit process be extended to include liquid stream operations. The inputs to the liquid train process at many of the facilities are similar to those for sludge handling: electricity to operate blowers and pumps, and chemicals to remove precipitate soluble phosphorus. Energy, chemical, GHG, and effluent quality-related metrics could be evaluated on a number of bases, depending on applicability: volume of flow treated, mass of pollutant load to the plant, and/or mass of pollutant removed from the wastewater. Such analyses would provide additional insight into the sustainability of the entire treatment facility.

Finally, it is recommended that the audit procedure be extended to include larger facilities. The current study focused on small WWTPs because of the unique challenges that such plants often encounter, but facilities of all sizes typically employ similar inputs and outputs that have associated economic and environmental impacts. As such, improving the performance of all plants would be beneficial to the long-term economic and environmental sustainability of the wastewater treatment industry.

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Appendix A
Plant A Summary

Overview

Plant A is an extended aeration WWTP located in Southern Ontario and operated by OCWA. Sludge is stabilized via aerobic digestion and the biosolids are stored in an on-site lagoon. During spreading season, the biosolids are hauled and applied to land for agricultural purposes.

BioWin Modelling

A BioWin™ model based on observed operational data was generated to estimate raw sludge production and VSS destruction, and to screen for problematic plant data. A summary of key model outputs and the corresponding mean observed value (where applicable) is shown in Table A1. The two observed MLSS values correspond to each train of liquid treatment. The model process flow sheet is shown in Figure A1. The model outputs were generally consistent with reported values.

Table A1: Plant A BioWin Model Results

Parameter	Units	Predicted Value	Observed Value (2014-2016)
MLSS	mg/L	2263	2327, 2410
Dry mass of sludge wasted per day	kg TSS/d	405	408
Dry mass of solids returned per day (digester decant)	kg TSS/d	88	--
Dry mass of solids returned per day (lagoon decant)	kg TSS/d	66	--
Net dry mass of sludge generated per day	kg TSS/d	251	--
Dry mass of VSS input to digester per day	kg VSS/d	247	--
Dry mass of VSS output by digester per day	kg VSS/d	199	--
Dry mass of VSS destroyed per day	kg VSS/d	48	--
Volume of biosolids generated per day	m^3	7.0	7.0
TSS content of hauled biosolids	%	2.8	4.9
VSS content of hauled biosolids	%	56	54.5

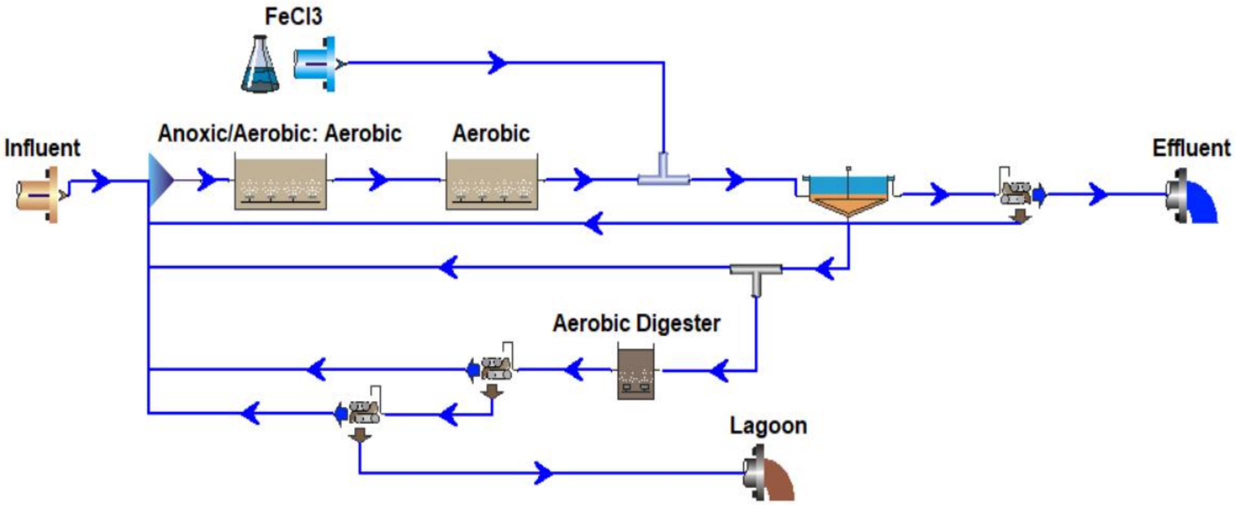

Figure A1: Plant A BioWin Model PFD

Uncertainty

To estimate uncertainty in raw sludge production, the standard deviation in reported sludge production (59 dry kg/d) was divided by the reported mean sludge production (408 dry kg/d) and converted to a percentage. Raw data was provided in the form of a daily average for each month within a two year period (2015-2016), hence the sample size was $n = 24$. Using this measure, the uncertainty was determined to be 15%.

Energy

On-site power draw measurements were taken on all pieces of equipment related to sludge handling and multiplied by the daily motor run-time (obtained from plant records) to determine the daily kWh consumption for each motor of interest (Table A2). The total draw for each category of equipment (stabilization, pumping) was calculated and divided by mass of raw sludge generated daily (Table A3). Digester electricity consumption was also divided by the daily quantity of VSS destruction (Table A3).

Table A2: Plant A Energy Measurements

Category/Motor	Voltage (V)	Current (A)	Power Factor (PF)	Power Draw (kW)	Motor Run-Time (Hr/d)	Daily Electricity Consumption (kWh/d)
Stabilization						
Digester Blower	607	11.4	0.965	14.7	24	353
					Sub-total	*353*
Pumping						
WAS pump 1	607	4.4	0.856	3.5	11.8	41
WAS pump 2	606	3.6	0.856	2.8	12.2	34
					Sub-total	*75*
					Total	*428*

Table A3: Plant A Energy KPI Results (Electricity Consumption)

Category	Normalized Electricity Consumption (kWh/dry kg)
Stabilization	1.41
Pumping	0.30
Total	1.71
Digester Efficiency	7.4 (kWh / dry kg VSS destroyed)

Chemical Usage

Plant A does not employ the use of chemicals for its sludge handling process.

Biosolids Disposition

Average round-trip distance of hauled biosolids

Plant A transports its biosolids to agricultural farms during spreading season. The same field received biosolids each year during 2013 – 2015 (information for 2016 was not available). The field was 4 km from the WWTP, hence the weighted average round-trip distance was ***8 km***.

Transportation Fuel Consumption

Table A4 lists the parameters obtained to calculate normalized transportation fuel consumption. Both the volumetric capacity of the haulage truck (40 m^3) and truck fuel economy (1.72 km/L) are standard values. The volume of biosolids generated per year is the 2013 – 2015 average (2016 data was not available). The number of trips per year was calculated by dividing the volume of biosolids generated per year by the volumetric capacity of the haulage truck. The kilometers travelled per year was calculated by multiplying the number of trips per year by the average round-trip distance. The fuel consumed per year was calculated by dividing the kilometers travelled per year by the truck fuel economy. Finally, the volume of fuel consumed per dry tonne of raw sludge produced was calculated by dividing the fuel consumed per year by the quantity of dry mass of raw sludge generated per year.

Table A4: Plant A Transportation Fuel Consumption

Parameter	Units	Value
Volumetric capacity of haulage truck	m^3	40
Volume of biosolids generated per year	m^3	2529
Number of trips per year	trips / year	63
Kilometers travelled per year	km	506
Truck fuel economy	km / L	1.72
Volume of fuel consumed per year	L / year	294
Fuel consumed per dry tonne of raw sludge produced	***L / dt***	***3.22***

Biosolids Quality

A variety of statistical measures detailing the metals content of the hauled biosolids is listed in Table A5. Similar measures for the solids, nutrients, and *E. coli* content of the hauled biosolids are presented in Table A6.

Table A5: Plant A Biosolids Quality – Metals

	As	**Cd**	**Co**	**Cr**	**Cu**	**Hg**	**Mo**	**Ni**	**Pb**	**Se**	**Zn**
	mg/kg	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**
MEAN	6.0	0.8	5.8	96	380	0.30	10	25	19	2.7	528
MEDIAN	6.0	0.8	5.7	98	407	0.27	10	25	19	2.6	517
STD DEV	1.5	0.2	1.7	25	93	0.14	3	7	6	0.8	111

MIN	1.0	0.1	0.4	5.2	27	0.01	0.7	1.6	1.0	0.2	345
MAX	9.0	1.0	9.0	136	525	0.62	14.3	39	30	4.0	770
n	33	33	33	33	33	33	33	33	33	33	32
NASM LIMIT	170	34	340	2800	1700	11	94	420	1100	34	4200
MEAN÷NASM LIMIT	***0.04***	***0.02***	***0.02***	***0.03***	***0.22***	***0.03***	***0.10***	***0.06***	***0.02***	***0.08***	***0.13***
STD DEV÷NASM LIMIT	0.009	0.006	0.005	0.009	0.05	0.01	0.03	0.02	0.005	0.02	0.03

Table A6: Plant A Biosolids Quality – Solids, Nutrients, *E. coli*

	TS	**VS**	**TN**	**TP**	**K**	***E. coli***
	%	**%**	**mg/kg**	**mg/kg**	**mg/kg**	**Log (CFU/g)**
MEAN	5.8	54.5	***27209***	***36925***	***8779***	***3.9***
MEDIAN	4.9	54.4	25350	36500	6021	3.8
STD DEV	3.0	6.7	13016	7855	4963	0.6
MIN	1.6	42.8	9000	22900	2654	2.9
MAX	14.3	65.3	70000	54000	19608	5.3
n	34	33	32	32	37	35

Innovative Technology Assessment

To evaluate the sustainability impact of implementing innovative technologies into Plant A, the previously generated BioWin™ model was modified to incorporate each innovative technology within the study sample (Rotary Disc Thickener, GeoTube™, Rotary Press, Centrifuge). For each technology implementation, the predicted biosolids volume was manipulated such that the predicted solids content of the sludge/biosolids product matched the known/observed value where the technology was employed. The annual number of trips, kilometers travelled, fuel consumption, and normalized fuel consumption (litres consumed per dry tonne of raw sludge generated) were evaluated using the updated volume of biosolids as the basis for calculation. The volumetric capacity of the haulage truck (40 m^3) and average round-trip distance of the final destination (8 km) was assumed to identical to the base case. The operational results of each technology implementation are listed in Table A7, while the impact of each technology on GHG emissions is detailed in section 4.6. The BioWin™ process flow sheets associated with thickening and dewatering technology implementation are shown in Figures A2 and A3, respectively.

Table A7: Plant A Innovative Technology Assessment

	Units	Base Case	Rotary Disc Thickener	GeoTube™	Rotary Press	Centrifuge
TSS of product, per BioWin	%		4.5	9.1	16.7	22.3
Volumetric capacity of truck	m^3	40	40	40	40	40
Volume per year	m^3	2529	2008	803	438	329
Number of trips per year	trips / year	63	50	20	11	8
Kilometers travelled per year	km	506	402	161	88	66
Truck fuel economy	km / L	1.72	1.72	1.72	1.72	1.72
Fuel consumed per year	L / year	294	233	93	51	38
Fuel consumed per dry tonne of raw sludge generated	L / dt	3.22	2.55	1.02	0.56	0.42

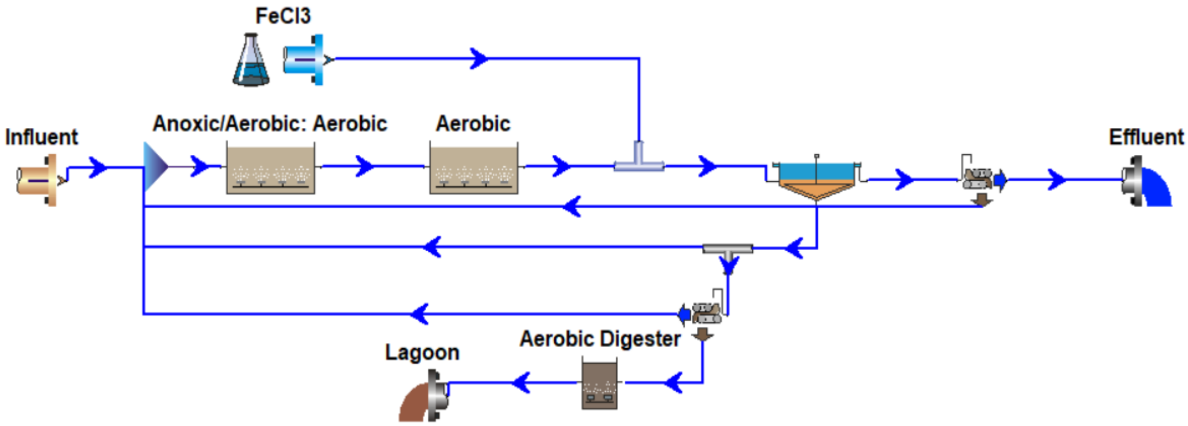

Figure A2: Plant A Thickening New Tech PFD

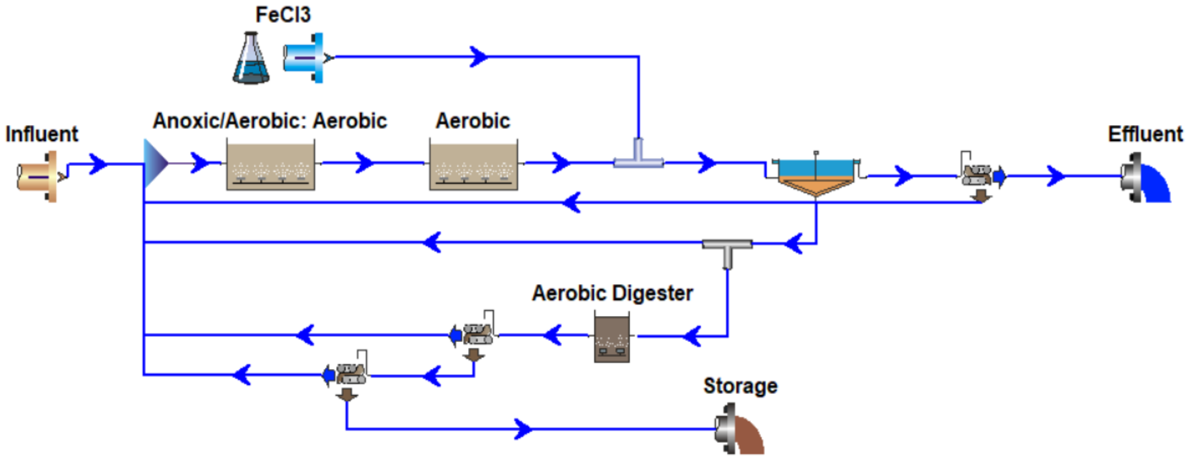

Figure A3: Plant A Dewatering New Tech PFD

Appendix B
Plant B Summary

Overview

Plant B is a conventional activated sludge WWTP located in Southern Ontario and operated by Veolia. Sludge is stabilized via aerobic digestion and the biosolids are stored in an off-site lagoon (no on-site storage). During spreading season, the biosolids are hauled and applied to land for agricultural purposes.

BioWin Modelling

A BioWin™ model based on observed operational data was generated to estimate raw sludge production and VSS destruction, and to screen for problematic plant data. A summary of key model outputs and the corresponding mean observed value (where applicable) is shown in Table B1. The two observed MLSS values correspond to each train of liquid treatment. The model process flow sheet is shown in Figure B1. The model outputs were generally consistent with reported values.

Table B1: Plant B BioWin Model Results

Parameter	Units	Predicted Value	Observed Value (2014-2016)
MLSS	mg/L	3553	3490, 3441
Dry mass of sludge wasted per day	kg TSS/d	851	856
Dry mass of solids returned per day (digester decant)	kg TSS/d	158	--
Net dry mass of sludge generated per day	kg TSS/d	693	--
Dry mass of VSS input to digester per day	kg VSS/d	624	--
Dry mass of VSS output by digester per day	kg VSS/d	404	--
Dry mass of VSS destroyed per day	kg VSS/d	220	--
Volume of biosolids generated per day	m^3	37.1	37.1
TSS content of hauled biosolids	%	1.3	1.6
VSS content of hauled biosolids	%	64	65
Dry mass of biosolids generated per day	kg/d	474	586

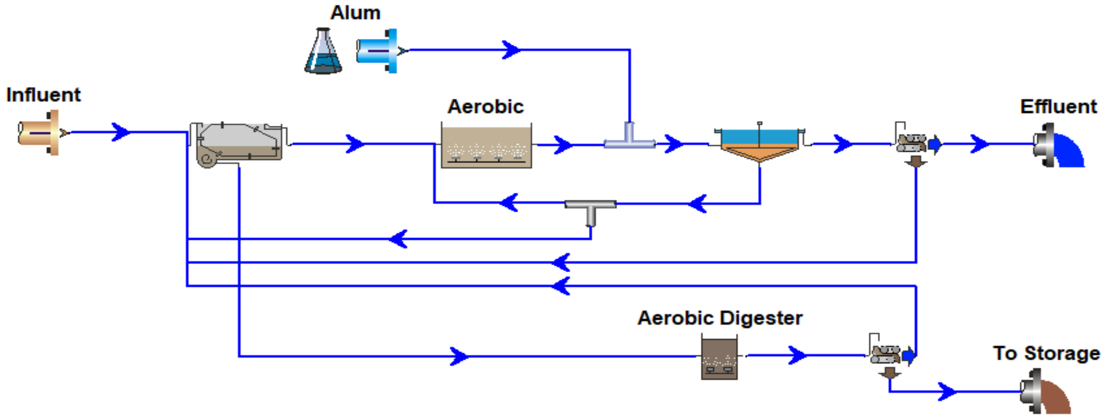

Figure B1: Plant B BioWin Model PFD

Uncertainty

To estimate the uncertainty in raw sludge production, the standard deviation of reported raw sludge production (228 dry kg/d) was divided by the mean reported sludge production (856 dry kg/d) and converted to a percentage. Using this measure, the uncertainty was determined to be 27% (sample size, *n* = 191).

Energy

On-site power draw measurements were taken on all pieces of equipment related to sludge handling and multiplied by the daily motor run-time (obtained from plant records) to determine the daily kWh consumption for each motor of interest (Table B2). The plant does not employ dedicated digester blowers, therefore, the percentage of air flow to the digester (obtained from plant records) was used to allocate the fraction of blower electricity consumed by the digester. The total draw for each category of equipment (stabilization, pumping) was calculated and divided by mass of raw sludge generated daily (Table B3). Digester electricity consumption was also divided by the daily quantity of VSS destruction to obtain a measure of energy efficiency (Table B3).

Table B2: Plant B Energy Measurements

Category/Motor	Voltage (V)	Current (A)	Power Factor (PF)	Power Draw (kW)	Motor Run-Time (Hr/d)	Daily Electricity Consumption (kWh/d)
Stabilization						
Blower 1 (aeration + digester)	604	101.3	0.839	91.4	24	2194
Blower 2 (aeration + digester)	604	105	0.838	94.2	24	2261
				Sub-total (42% to digester)		*1871*

Pumping						
WAS Pump 1	604	1.8	0.7	1.3	1.8	2.3
WAS Pump 2	605	1.9	0.7	1.4	1.6	2.2
Primary pump 1	604	5.0	0.806	4.4	0.35	1.5
Primary pump 2	604	5.1	0.817	4.5	0.27	1.2
Biosolids loading pump	603	7.1	0.81	6.2	0.381	2.4
					Sub-total	*9.6*
					Total	1881

Table B3: Plant B Normalized Electricity Consumption

Category	**Normalized Electricity Consumption (kWh/dry kg)**
Stabilization	2.72
Pumping	0.01
Total	2.73
Digester Efficiency	8.6 (kWh / kg VSS destroyed)

Chemical Usage

Plant B does not employ the use of chemicals for its sludge handling process.

Biosolids Disposition

Average round-trip distance of hauled biosolids

Plant B transported biosolids from the WWTP to a storage lagoon and then to various fields during spreading season. Some biosolids were also transported directly from the WWTP to various fields. Based on plant records, the weighted average round-trip distance the biosolids travelled during 2014 – 2016 was ***61 km***. The measure accounts for the fact that a smaller volume of biosolids is transported from the lagoon to the fields due to gravity thickening at the lagoon.

Transportation Fuel Consumption

Table B4 lists the parameters obtained to calculate normalized transportation fuel consumption. Both the volumetric capacity of the haulage truck (40 m^3) and truck fuel economy (1.72 km/L) are standard values. The volume of biosolids generated per year is the 2014 – 2016 average. The number of trips per year was calculated by dividing the volume of biosolids generated per year by the volumetric capacity of the haulage truck. The kilometers travelled per year was calculated by multiplying the number of trips per year by the average round-trip distance. The fuel consumed per year was calculated by dividing the kilometers travelled per year by the truck fuel economy. Finally, the volume of fuel consumed per dry tonne of raw sludge produced was calculated by dividing the fuel consumed per year by the quantity of dry mass of raw sludge generated per year.

Table B4: Plant B Transportation Fuel Consumption

Parameter	Units	Value
Volumetric capacity of haulage truck	m^3	40
Volume of biosolids generated per year	m^3	13534
Number of trips per year	trips / year	338
Kilometers travelled per year	km	22271
Truck fuel economy	km / L	1.72
Volume of fuel consumed per year	L / year	12948
Fuel consumed per dry tonne of raw sludge produced	L / dt	51.2

Biosolids Quality

A variety of statistical measures detailing the metals content of the hauled biosolids is listed in Table B5. Similar measures for the solids, nutrients, and *E. coli* content of the hauled biosolids are presented in Table B6.

Table B5: Plant B Biosolids Quality – Metals

	As	**Cd**	**Cr**	**Co**	**Cu**	**Pb**	**Hg**	**Mo**	**Ni**	**Se**	**Zn**
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
MEAN	7.8	1.8	17	2.8	292	10	N/A	8.1	13	3.9	464
MEDIAN	5.1	0.9	18	1.9	316	11	N/A	7.3	13	3.7	471
STD DEV	5.8	1.5	6.3	1.9	98	4.8	N/A	3.4	5.8	2.3	162
MIN	0.6	0.3	2.2	0.1	30	1.0	N/A	1.3	1.6	0.6	53
MAX	17	4.1	26	5.8	381	17	N/A	14	22	8.2	682
n	11	11	11	11	11	11	11	11	11	7	11
NASM LIMIT	170	34	2800	340	1700	1100	11	94	420	34	4200

AVG÷NASM LIMIT	***0.05***	***0.05***	***0.01***	***0.01***	***0.17***	***0.01***	***All but one value below detection limit***	***0.09***	***0.03***	***0.11***	***0.11***
STD DEV÷NASM LIMIT	0.03	0.04	0.002	0.006	0.06	0.004	N/A	0.04	0.01	0.07	0.04

Table B6: Plant B Biosolids Quality – Solids, Nutrients, *E. coli*

	TS	**VS**	**TN**	**TP**	**K**	***E. coli***
	(%)	(%)	mg/kg	mg/kg	mg/kg	Log (CFU/g)
MEAN	1.7	67.1	***45630***	***28497***	***4001***	***5.2***
MEDIAN	1.6	67.9	53183	28875	4356	5.2
STD DEV	0.7	3.7	24078	9121	1389	0.5
MIN	0.2	53.2	31	3188	754	4.5
MAX	3.7	72.7	69330	37021	5553	6.6
n	50	50	11	11	11	36

Innovative Technology Assessment

To evaluate the sustainability impact of implementing innovative technologies into Plant B, the previously generated BioWin™ model was modified to incorporate each innovative technology within the study sample (Rotary Disc Thickener, GeoTube™, Rotary Press, Centrifuge). For each technology implementation, the predicted biosolids volume was manipulated such that the predicted solids content of the sludge/biosolids product matched the known/observed value where the technology was employed. The annual number of trips, kilometers travelled, fuel consumption, and normalized fuel consumption (litres consumed per dry tonne of raw sludge generated) were evaluated using the updated volume of biosolids as the basis for calculation. The volumetric capacity of the haulage truck (40 m^3) and average round-trip distance of the final destination (61 km) was assumed to identical to the base case. The operational results of each technology implementation are listed in Table B7, while the impact of each technology on GHG emissions is detailed in section 4.6. The BioWin™ process flow sheets associated with thickening and dewatering technology implementation are shown in Figures B2 and B3, respectively.

Table B7: Plant B Innovative Tech Assessment Results

	Units	Base Case	Rotary Disc Thickener	GeoTube	Rotary Press	Centrifuge
BioWin TSS	%		4.5	9.1	16.9	22.5
Volume per truck	m3	40	40	40	40	40
Volume per year	m3	13534	5658	1898	1022	767
Number of trips per year	trips / year	338	141	47	26	19
Kilometers travelled per year	km	22271	10253	4517	3181	2791
Truck fuel economy	km / L	1.72	1.72	1.72	1.72	1.72
Fuel consumed per year	L / year	12948	5961	2626	1849	1622
Fuel consumed per dry tonne of raw sludge generated	L / dt	51.2	23.6	10.4	7.3	6.4

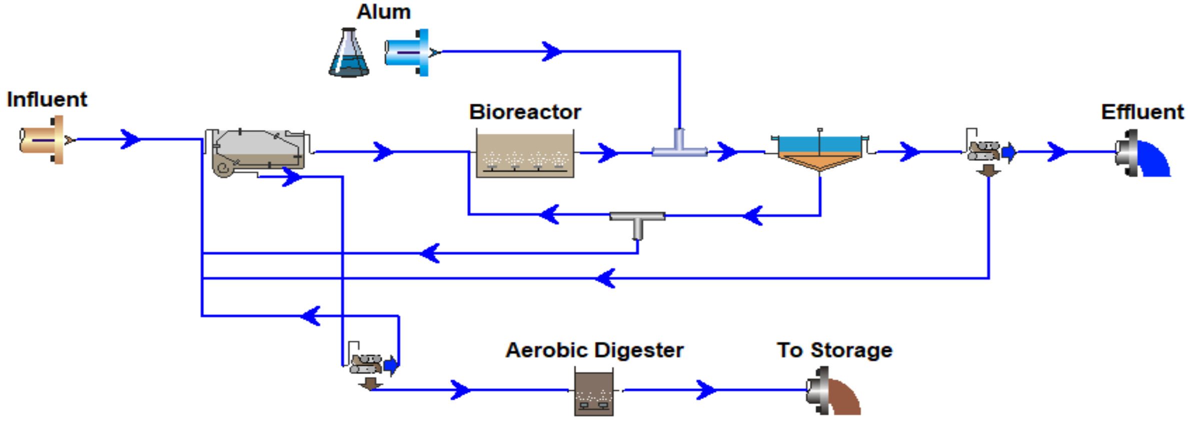

Figure B2: Plant B Thickening Innovative Tech PFD

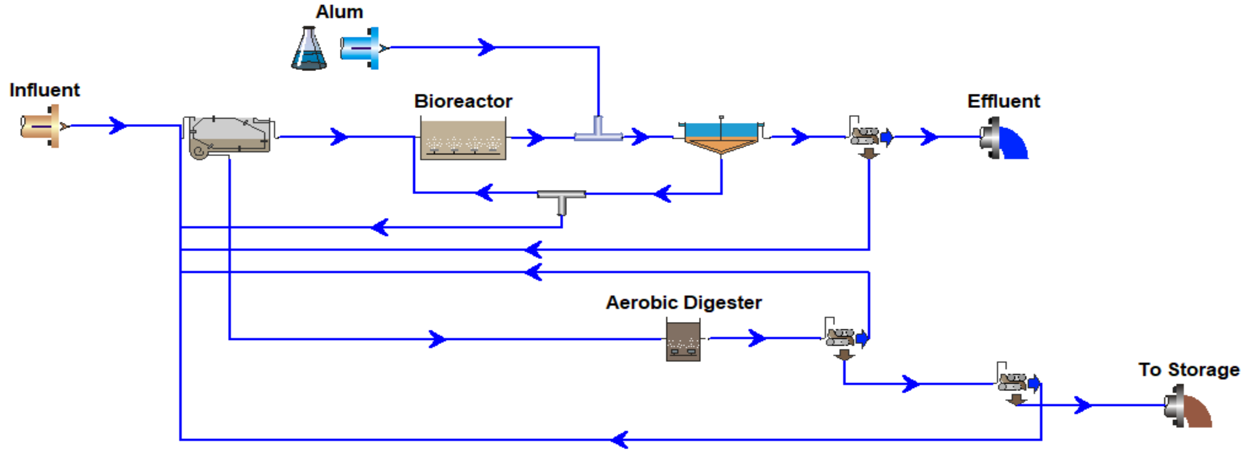

Figure B3: Plant B Dewatering Innovative Tech PFD

Appendix C

Plant C Summary

Overview

Plant C is a conventional activated sludge WWTP located in Southern Ontario and operated by the municipality (owner). Normal sludge handling operations consist of aerobic digestion stabilization, centrifuge dewatering, and trucking to an off-site storage building. During spreading season, the biosolids are hauled and applied to land for agricultural purposes.

BioWin Modelling

A BioWin™ model based on observed operational data was generated to estimate raw sludge production and VSS destruction, and to screen for problematic plant data. A summary of key model outputs and the corresponding mean observed value (where applicable) is shown in Table C1. The two observed MLSS values correspond to each train of liquid treatment. The model process flow sheet is shown in Figure C1. The values predicted by the model were generally consistent with observed values.

Table C1: Plant C BioWin Model Results

Parameter	Units	Predicted Value	Observed Value (2014-2016)
MLSS	mg/L	3200	3169, 3185
Dry mass of sludge wasted per day	kg TSS/d	2051	--
Dry mass of solids returned per day (digester decant)	kg TSS/d	820	--
Net dry mass of sludge generated per day	kg TSS/d	1108	--
Dry mass of VSS feed to digester per day	kg VSS/d	1346	--
Dry mass of VSS output by digester per day	kg VSS/d	941	--
Dry mass of VSS destroyed per day	kg VSS/d	405	--
Volume of biosolids generated per day	m^3	3.10	--
TSS content of hauled biosolids	%	22.5	22.5
VSS content of hauled biosolids	%	57.4	67.0
Dry mass of biosolids generated per day	kg/d	697	697

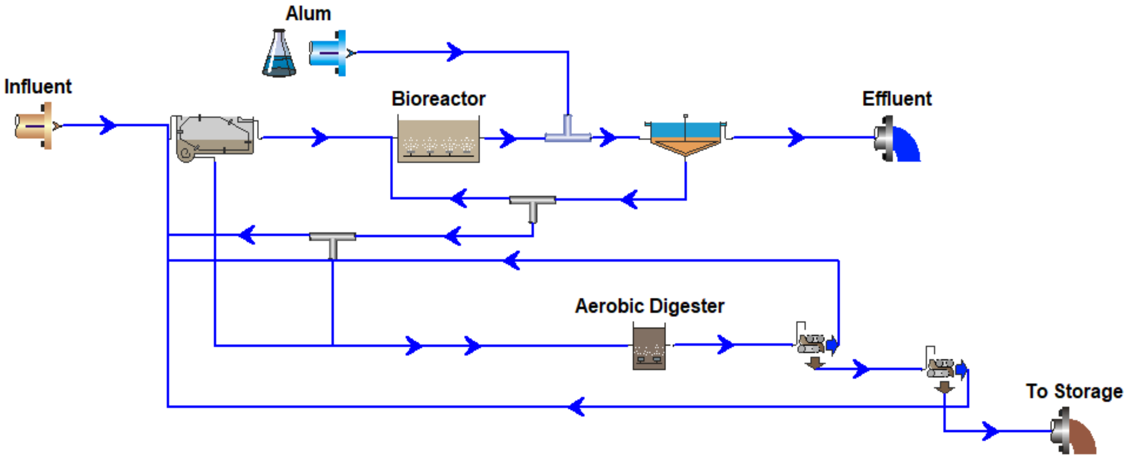

Figure C1: Plant C BioWin Model PFD

Uncertainty

Raw sludge production uncertainty was not calculated directly because the solids content of the raw primary sludge not available. Instead, given that predicted biosolids mass matched the known reported value (254.6 dt/year vs 254.4 dt/year) if average TS values were employed in the reported value calculation, all uncertainty was assumed to be associated with variation in TS content. To calculate uncertainty, the standard deviation in TS content (2.5 %) was divided by the mean TS content (22.5%) and converted to a percentage. Using this measure, the uncertainty was determined to be 11% (sample size, n = 95).

Energy

On-site power draw measurements were taken on all pieces of equipment related to sludge handling and multiplied by the daily motor run-time (obtained from plant records) to determine the daily kWh consumption for each motor of interest (Table C2). Additional measurements for individual motors within the biosolids dewatering building are presented in Table C3 (total dewatering building draw is listed in Table C2). The total draw for each category of equipment (stabilization, pumping, dewatering, odour control) was calculated and divided by mass of raw sludge generated daily (Table C4). Digester electricity consumption was also divided by the daily quantity of VSS destruction to obtain a measure of energy efficiency (Table C4).

Table C2: Plant C Power Draw Measurements

Category/Motor	Voltage (V)	Current (A)	Power Factor (PF)	Power Draw (kW)	Motor Run-Time (Hr/d)	Daily Electricity Consumption (kWh/d)
Stabilization						
Digester blower	605	91	0.845	83.1	24	1994
					Sub-total	*1994*
Pumping						
WAS pump North	607	2.66	0.741	2.16	12	26
WAS pump south	607	2.66	0.741	2.16	12	26
Raw sludge pump	605	9.95	0.638	6.61	1	6.6
					Subtotal	*59*
Dewatering						
Dewatering Building	605	24.8	0.756	19.1	5.8	111
					Sub-total	*111*
Odour Control						
Biofilter	605	7.5	0.783	6.2	24	149
					Sub-total	*149*
					TOTAL	**2311**

Table C3: Additional Dewatering Energy Measurements

Motor	Voltage (V)	Current (A)	PF	kW	Hr/d	kWh/d
Centrifuge – Both Drives	603	16.3	0.81	12.3	5.8	71
Centrifuge – Back Drive	604	1.2	0.69	0.9	5.8	5
Centrifuge – Main Drive	603	14.4	0.8	11.2	5.8	65
Centrifuge – Grinder	602	2.4	0.75	1.8	5.8	10
Discharge Conveyor 1	602	1.8	N/A	1.5	5.8	9
Discharge Conveyor 2	602	1.8	N/A	1.5	5.8	9
Sludge Feed Pump	602	1.7	0.78	1.2	5.8	7

Table C4: Plant C Normalized Electricity Consumption

Category	Normalized Electricity Consumption (kWh/dry kg)
Stabilization	1.80
Pumping	0.05
Dewatering	0.10
Odour Control	0.13
Total	2.09
Digester Efficiency	4.9 (kWh / kg VSS destroyed)

Chemical Usage

Plant C uses polymer as part of its mechanical dewatering process. To determine normalized chemical usage, purchase records of polymer were used in conjunction with the quantity of raw sludge production. The facility purchases polymer at a rate of \$5.00 per kg of polymer. The money spent during the last three years of fully operational centrifuge usage was used to determine the average mass of polymer used per year (Table C5). This value was then divided by the mass of raw sludge generated per year (1108 dry kg) to obtain the normalized polymer usage (7.7 kg polymer/dt).

Table C5: Plant C Chemical Usage

Year	Money spent on polymer (\$5.00 / kg polymer)	Mass of polymer purchased (kg)
2013	\$15,893	3179
2014	\$7,632 (Centrifuge not running all year)	N/A
2015	\$15,264	3053
2016	\$15,264	3053
	Average	3095
	kg polymer used per dry tonne of raw sludge generated	***7.7 (kg polymer/dt)***

Biosolids Disposition

Average round-trip distance of hauled biosolids

Plant C transports biosolids from the WWTP to an off-site storage facility and then to various fields during spreading season. The weighted average round-trip distance from the storage facility to farms was 40.5 km, while the round-trip distance between the WWTP and storage facility is 42 km. Therefore, the total average round-trip distance is ***82.5 km***.

Transportation Fuel Consumption

Table C6 lists the parameters obtained to calculate normalized transportation fuel consumption. The capacity (3 wet tonnes) and fuel economy (2.7 km/L) of the truck that hauls biosolids from the WWTP to the storage facility was obtained from the plant owner. The capacity (40 m^3) and fuel economy (1.72 km/L) of the truck that hauls biosolids from the storage facility to the farms are standard values.

Table C6: Plant C Transportation Fuel Consumption

WWTP to Storage Facility			**Notes**
Wet tonnes per truck	3	wet tonnes	Per owner/operator
Wet tonnes per year	1001	wet tonnes	2014 – 2016 average
Number of trips per year	334	trips / year	
Kilometers travelled per year	14018	km / year	
Truck fuel economy	2.7	km / L	Per owner/operator
Fuel consumed per year	5215	L / year	
Storage Facility to Farm			
Volume per truck	40	m^3/truck	Standard value
Volume per day (per BioWin)	3.1	m3/d	BioWin calculation
Volume per year	1132	m^3/year	
Number of trips per year	29	trips / year	
Kilometers travelled per year	1175	km / year	
Truck fuel economy	1.72	km / L	Standard value
Fuel consumed per year	683	L / year	
Total fuel consumed per year	5898	L / year	
Fuel consumed per dry tonne of raw sludge generated	***14.6***	***L/dt***	

Biosolids Quality

A variety of statistical measures detailing the metals content of the hauled biosolids is listed in Table C7. Similar measures for the solids, nutrients, and *E. coli* content of the hauled biosolids are presented in Table C8.

Table C7: Plant C Biosolids Quality – Metals

	As	**Cd**	**Co**	**Cr**	**Cu**	**Hg**	**Mo**	**Ni**	**Pb**	**Se**	**Zn**
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
MEAN	4.5	0.7	2.4	24	637	0.7	8.3	46	20	9.1	733
MEDIAN	4.8	0.7	2.3	23	630	0.6	8.0	46	21	9.0	730
STD DEV	1.2	0.2	0.7	4	81	0.4	1.9	7	4	1.7	103
MIN	1.0	0.1	1.0	16	430	0.3	4.0	30	13	3.0	510
MAX	12	1.2	4.0	34	850	2.3	12	62	31	15	940
n	95	95	95	95	95	95	95	95	95	95	95
NASM LIMIT	170	34	340	2800	1700	11	94	420	1100	34	4200
MEAN÷NASM LIMIT	***0.03***	***0.02***	***0.01***	***0.01***	***0.37***	***0.07***	***0.09***	***0.11***	***0.02***	***0.27***	***0.17***
STD DEV÷NASM LIMIT	0.007	0.006	0.002	0.001	0.05	0.03	0.02	0.02	0.004	0.05	0.02

Table C8: Plant C Biosolids Quality – Solids, Nutrients, *E. Coli*

	TS	**VS**	**TN**	**TP**	**K**	***E. coli***
	%	%	mg/kg	mg/kg	mg/kg	Log(CFU/g)
MEAN	*22.5*	*67*	***43119***	***40303***	***2278***	***4.5***
MEDIAN	22.3	67	41711	40000	2200	4.5
STD DEV	2.5	2.1	9226	4361	334	0.6
MIN	17.6	63	22069	29000	1600	3.0
MAX	32.1	72	74037	52000	3100	6.4
n	95	95	95	95	95	95

Appendix D
Plant D Summary

Overview

Plant D is an extended aeration WWTP located in Northern Ontario and operated by OCWA. Normal sludge handling operations consist of aerobic digestion stabilization, rotary press dewatering, and trucking to an off-site landfill.

BioWin Modelling

A BioWin™ model based on observed operational data was generated to estimate raw sludge production and VSS destruction, and to screen for problematic plant data. A summary of key model outputs and the corresponding mean observed value (where applicable) is shown in Table D1. The BioWin™ model process flow sheet is shown in Figure D1. The predicted values were consistent with observed values.

Table D1: Plant D BioWin Model Results

Parameter	**Units**	**Predicted Value**	**Observed Value (2016-2017)**
MLSS	mg/L	5581	5570
Dry mass of sludge wasted per day	kg TSS/d	800	--
Dry mass of solids returned per day (digester decant)	kg TSS/d	98	--
Dry mass of solids returned per day (rotary press centrate)	kg TSS/d	28	--
Net dry mass of sludge generated per day	kg TSS/d	674	--
Dry mass of VSS input to digester per day	kg VSS/d	515	--
Dry mass of VSS output by digester per day	kg VSS/d	379	--
Dry mass of VSS destroyed per day	kg VSS/d	136	--
Volume of biosolids generated per day	m^3/d	3.10	--
TSS content of hauled biosolids	%	17.0	16.9
VSS content of hauled biosolids	%	58	--
Dry mass of biosolids generated per day	kg/d	528	--

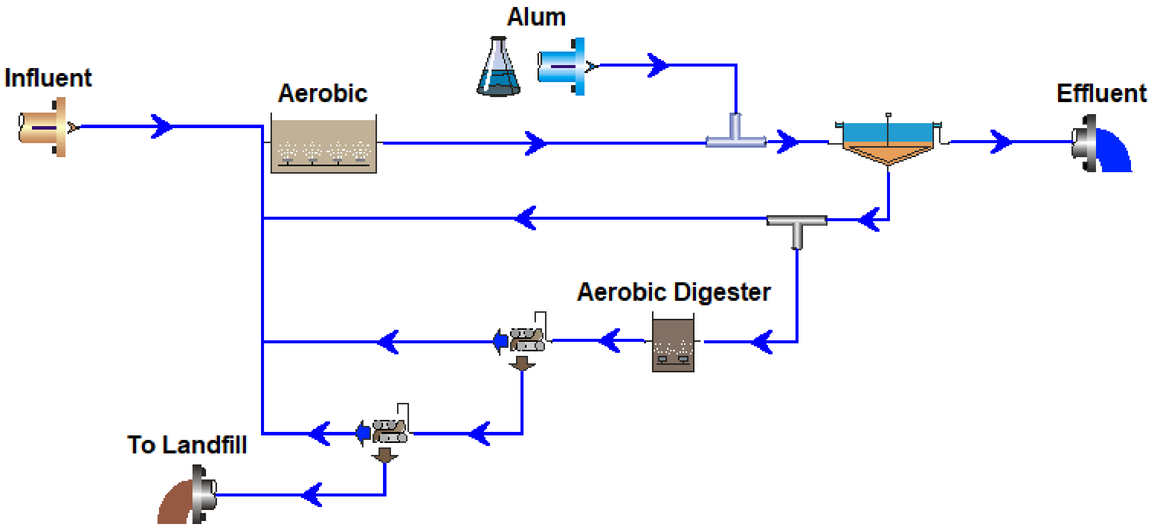

Figure D1: Plant D BioWin Model PFD

Uncertainty

Raw sludge production uncertainty was not calculated directly because the solids content of the waste sludge not available. As a proxy for raw sludge production, all uncertainty was assumed to be associated with variation in MLSS concentration (2016 – 2017 data). To calculate uncertainty, the standard deviation in MLSS concentration (718 mg/L) was divided by the mean MLSS concentration (5570 mg/L) and converted to a percentage. Using this measure, the uncertainty was determined to be 13% (sample size, $n = 430$).

Energy

On-site power draw measurements were taken on all pieces of equipment related to sludge handling and multiplied by the daily motor run-time (obtained from plant records) to determine the daily kWh consumption for each motor of interest (Table D2). The total draw for each category of equipment (stabilization, pumping, dewatering) was calculated and divided by mass of raw sludge generated daily (Table D3). Digester electricity consumption was also divided by the daily quantity of VSS destruction to obtain a measure of energy efficiency (Table D3).

Table D2: Plant D Power Draw Measurements

Category/Motor	Voltage (V)	Current (A)	Power Factor (PF)	Power Draw (kW)	Motor Run-Time (Hr/d)	Daily Electricity Consumption (kWh/d)
Stabilization						
Digester Blower	596	15.5	0.724	11.8	24	283
Digester Mixer 1	600	19.5	0.989	20.5	24	492
Digester Mixer 2	600	21	0.62	14	8	112
					Sub-total	*887*
Pumping						
WAS Pump	N/A	4.2	N/A	3.36	4	13
Digester Sludge Transfer Pump	600	5.7	0.65	2.7	5	14
					Sub-total	*27*
Dewatering						
Rotary press	600	6.4	0.772	4.4	5	22
Conveyor 1	N/A	N/A	N/A	1.5	5	7.5
Conveyor 2	N/A	N/A	N/A	1.5	5	7.5
Conveyor 3	N/A	N/A	N/A	1.5	5	7.5
Lighting + Centrate Pump	N/A	N/A	N/A	1	5	5
					Sub-total	*50*
					TOTAL	964

Table D3: Plant D Normalized Electricity Consumption

Category	Normalized Electricity Consumption (kWh/dry kg)
Stabilization	1.32
Pumping	0.04
Dewatering	0.07
Total	1.43
Digester Efficiency	6.5 (kWh / kg VSS destroyed)

Chemical Usage

Plant D uses polymer as part of its mechanical dewatering process. To determine normalized polymer usage, information related to consumption was obtained from the plant operations staff. Polymer is supplied to the plant in 200 kg drums, each of which contains 90 kg of active polymer (~45% solution). Per conversations with the operator, the facility uses one drum per week. Per Table D1, the facility generates 674 dry kg of raw sludge per day, which translates to 4.72 dry tonnes per week. The quantity of polymer used per week (90 kg) was divided by the mass of raw sludge generated per week (4.72 dt) to determine normalized polymer consumption (19 kg polymer/dt). The results are summarized in Table D4.

Table D4: Plant D Polymer Usage

Parameter	Value
kg polymer per drum	90
Number of polymer drums used per week	1
kg polymer used per week	90
dry tonnes raw sludge per week	4.72
kg polymer per dry tonne of raw sludge generated	***19***

Biosolids Disposition

Average round-trip distance of hauled biosolids

Plant D transports its biosolids to a landfill year-round. The landfill is 4.6 km from the WWTP, hence the weighted average round-trip distance is ***9.2 km***.

Transportation Fuel Consumption

Since the rotary press practice commenced in 2016, an average of 10.7 bins of biosolids were transported to the landfill per month. The number therefore represented the number of trips per month, which projected to 129 trips per year. The fuel economy of the haulage truck (5 km/L) was provided by the owner. The kilometers travelled per year was calculated by multiplying the number of trips per year by the round-trip distance (9.2 km). The fuel consumed per year was calculated by dividing the kilometers travelled per year by the truck fuel economy. Finally, the fuel consumed per dry tonne of raw sludge produced was calculated by dividing the fuel consumed per year by the quantity of raw sludge produced (246 dt) per year. The results are presented in Table D5.

Table D5: Plant D Transportation Fuel Consumption

Number of trips per year	129	trips / year
Kilometers travelled per year	1184	km
Truck fuel economy	5	km / L
Fuel consumed per year	237	L / year
Fuel consumed per dry tonne of raw sludge generated	***0.96***	***L / dt***

Biosolids Quality

A variety of statistical measures detailing the metals content of the hauled biosolids is listed in Table D6. Similar measures for the solids, nutrients, and *E. coli* content of the hauled biosolids are presented in Table D7.

Table D6: Plant D Biosolids Quality – Metals

	As	**Cd**	**Co**	**Cr**	**Cu**	**Hg**	**Mo**	**Ni**	**Pb**	**Se**	**Zn**
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
MEAN	5.6	0.47	1.7	13	236	0.6	3.4	9.2	10	2.6	333
MEDIAN	5.5	0.46	1.7	13	236	0.6	3.4	9.2	10	2.7	332
STD DEV	0.7	0.03	0.1	1.3	5	0.1	0.2	0.3	0.4	0.1	12
MIN	4.8	0.4	1.6	12	231	0.6	3.2	8.9	9.2	2.3	322
MAX	6.6	0.5	1.9	15	245	0.7	3.6	9.6	10	2.7	355
n	6	6	6	6	6	6	6	6	6	6	6
NASM LIMIT	170	34	340	2800	1700	11	94	420	1100	34	4200
AVG÷NASM LIMIT	***0.03***	***0.01***	***0.005***	***0.005***	***0.14***	***0.06***	***0.04***	***0.02***	***0.009***	***0.08***	***0.08***
STD DEV÷NASM LIMIT	0.004	0.001	0.000	0.000	0.003	0.008	0.002	0.001	0.0003	0.004	0.003

Table D7: Plant D Biosolids Quality – Solids, Nutrients, *E. coli*

	VS	**TS**	**TN**	**TP**	**K**	***E. coli***
	%	%	mg/kg	mg/kg	mg/kg	log (CFU/g)
MEAN	76.1	16.9	***68192***	***18800***	***3563***	***2.7***
MEDIAN	76.3	16.9	67518	18350	3590	2.7
STD DEV	0.7	0.4	3725	1430	113	0.2
MIN	75.1	16.3	63000	17200	3370	2.4
MAX	76.7	17.3	74200	20800	3680	3.0
n	6	6	6	6	6	6

Appendix E
Plant E Summary

Overview

Plant E is an extended aeration WWTP located in Eastern Ontario and operated by the municipality (owner). Normal sludge handling operations consist of aerobic digestion stabilization and GeoTube™ dewatering/storage. During spreading season, the biosolids are hauled and applied to land for agricultural purposes.

BioWin Modelling

A BioWin™ model based on observed operational data (influent parameters, flows, etc.) was generated to estimate raw sludge production and VSS destruction, and to screen for problematic plant data. All operations inclusive of aerobic digestion were modeled (GeoTube™ excluded). A summary of key model outputs and the corresponding mean observed value (where applicable, based on 2016 – 2017 data) is shown in Table E1. The two observed MLSS values correspond to each train of liquid treatment. The model process flow sheet is shown in Figure E1. The predicted MLSS concentration was substantially greater than the observed value, however, the predicted waste sludge mass (178 dry kg/d) was similar to the reported value (171 dry kg/d).

Table E1: Plant E BioWin Model Results

Parameter	Units	Predicted Value	Observed Value (2016-2017)
MLSS	mg/L	6699	1967, 2023
Dry mass of sludge wasted per day	kg TSS/d	178	171
Dry mass of solids returned per day (digester decant)	kg TSS/d	25.6	--
Net dry mass of sludge generated per day	kg TSS/d	152	--
Dry mass of VSS input to digester per day	kg VSS/d	76	--
Dry mass of VSS output by digester per day	kg VSS/d	69	--
Dry mass of VSS destroyed per day	kg VSS/d	7	--
TSS content of digested biosolids	%	2.1	2.2
VSS content of digested biosolids	%	40.4	--
Dry mass of biosolids generated per day	kg/d	145	--

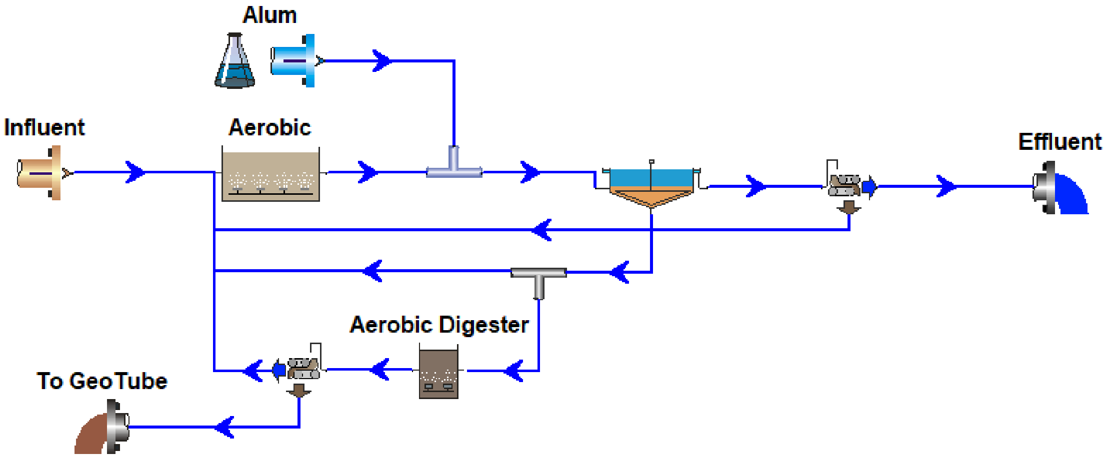

Figure E1: Plant E BioWin Model PFD

Uncertainty

To estimate the uncertainty in raw sludge production, the standard deviation of reported raw sludge production was divided by the mean reported sludge production and converted to a percentage. Using reported WAS TSS values in conjunction with daily WAS volumes, the calculated uncertainty was 96%. However, the operator reported that WAS TSS varied substantially depending on the sampling technique, and therefore recommended that a constant TSS content of 13,000 mg/L be employed in the calculation. Using this measure, the daily sludge production mean and standard deviation was 171 and 59 dry kg/d, respectively. The resulting uncertainty was determined to be 34% (sample size, *n* = 122).

Energy

On-site power draw measurements were taken on all pieces of equipment related to sludge handling and multiplied by the daily motor run-time (obtained from plant records) to determine the daily kWh consumption for each motor of interest (Table E2). The total draw for each category of equipment (stabilization, pumping) was calculated and divided by mass of raw sludge generated daily (Table E3). Digester electricity consumption was also divided by the daily quantity of VSS destruction to obtain a measure of energy efficiency (Table E3).

Table E2: Plant E Energy Measurements

Category/Motor	Voltage (V)	Current (A)	Power Factor (PF)	Power Draw (kW)	Motor Run - Time (Hr/d)	Daily Electricity Consumption (kWh/d)
Stabilization						
Digester blower	627	20.1	0.787	16.4	24	394
					Sub-total	*394*
Pumping						
WAS pump	627	1.6	0.755	1.3	12	16
					Sub-total	*16*
					TOTAL	***410***

Table E3: Plant E Normalized Electricity Consumption

Category	Normalized Electricity Consumption (kWh/dry kg)
Stabilization	2.59
Pumping	0.10
Total	2.69
Digester Efficiency	56 (kWh / kg VSS destroyed)

Chemical Usage

Plant E uses polymer as part of its GeoTube™ dewatering process. The operator reported that a 110 mg/L solution of polymer was dosed into a sludge feed concentration of 12000 mg/L, which corresponded to a 0.0092 dt polymer/dt raw sludge ratio. Converting the numerator into kg yields a normalized polymer usage of ***9.2 kg polymer/dt***.

Biosolids Disposition

Average round-trip distance of hauled biosolids

Plant E transports biosolids from the WWTP to agricultural farms during spreading season. The weighted average round-trip distance from the WWTP to the farms between 2016 – 2017 was ***53 km***.

Transportation Fuel Consumption

Table E4 lists the parameters obtained to calculate normalized transportation fuel consumption. Both the volumetric capacity of the haulage truck (40 m^3) and truck fuel economy (1.72 km/L) are standard values. The volume of biosolids generated per year is the 2016 – 2017 average. The number of trips per year was calculated by dividing the volume of biosolids generated per year by the volumetric capacity of the haulage truck. The kilometers travelled per year was calculated by multiplying the number of trips per year by the average round-trip distance. The fuel consumed per year was calculated by dividing the kilometers travelled per year by the truck fuel economy. Finally, the volume of fuel consumed per dry tonne of raw sludge produced was calculated by dividing the fuel consumed per year by the quantity of dry mass of raw sludge generated per year.

Table E4: Plant E Transportation Fuel Consumption

Parameter	Value	Units
Volumetric capacity of haulage truck	40	m^3
Volume of biosolids generated per year	584	m^3
Number of trips per year	15	trips / year
Kilometers travelled per year	769	km
Truck fuel economy	1.72	km / L
Volume of fuel consumed per year	447	L / year
Fuel consumed per dry tonne of raw sludge produced	***8.1***	***L / dt***

Biosolids Quality

A variety of statistical measures detailing the metals content of the hauled biosolids is listed in Table E5. Similar measures for the solids, nutrients, and *E. coli* content of the hauled biosolids are presented in Table E6.

Table E5: Plant E Biosolids Quality – Metals (Combined Digester + GeoTube™)

	As	**Cd**	**Co**	**Cr**	**Cu**	**Pb**	**Hg**	**Mo**	**Ni**	**Se**	**Zn**
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
MEAN	4.5	1.2	1.8	12.9	465	14.2	0.9	4.0	11.8	4.6	311
MEDIAN	3.6	1.1	1.8	11.5	436	13.7	0.6	4.0	11.1	3.6	247
STD DEV	1.9	0.6	0.6	5.0	192	6.8	0.4	1.0	2.9	1.9	184
MIN	2.9	0.5	1.0	6.6	268	5.5	0.5	1.7	7.6	3.0	158
MAX	8.0	2.2	3.0	24	864	28	1.6	6.0	16.4	8.0	719
n	13	13	13	13	13	13	13	13	13	13	13
NASM LIMIT	170	34	340	2800	1700	11	94	420	1100	34	4200
AVG÷NASM LIMIT	***0.03***	***0.03***	***0.01***	***0.005***	***0.27***	***0.01***	***0.08***	***0.04***	***0.03***	***0.13***	***0.07***
STD DEV÷NASM LIMIT	0.01	0.02	0.002	0.002	0.11	0.006	0.04	0.01	0.01	0.05	0.04

Table E6: Plant E Biosolids Quality – Solids, Nutrients, *E. coli*

	TS (GeoTube™ only)	**TKN (digester + GeoTube™)**	**TP (digester + GeoTube™)**	**K (digester + GeoTube™)**	***E. coli (GeoTube™ only)***
	%	mg/kg	mg/kg	mg/kg	Log (CFU/g)
MEAN	9.2	***49816***	***34458***	***1749***	***2.1***
MEDIAN	8.7	47782	32294	1564	2.1
STD DEV	2.2	11344	9057	648	0.2
MIN	7.2	31893	21176	1000	1.9
MAX	12.0	67754	47200	3463	2.3
n	4	13	13	13	4

Appendix F

Plant F Summary

Overview

Plant F is an extended aeration WWTP located in Southern Ontario and operated by the municipality (owner). Normal sludge handling operations consist of aerobic digestion stabilization and on-site aerated storage. During spreading season, the biosolids are hauled and applied to land for agricultural purposes.

BioWin Modelling

A BioWin™ model based on observed operational data was generated to estimate raw sludge production and VSS destruction, and to screen for problematic plant data. A summary of key model outputs and the corresponding mean observed value (where applicable) is shown in Table F1. The BioWin™ model process flow sheet is shown in Figure F1. Predicted values were generally consistent with observed values.

Table F1: Plant F BioWin Model Results

Parameter	Units	Predicted Value	Observed Value (2014-2016)
MLSS	mg/L	4071	4097
Dry mass of sludge wasted per day	kg TSS/d	355	--
Dry mass of solids returned per day (digester decant)	kg TSS/d	102	--
Dry mass of solids returned per day (holding tank decant)	kg TSS/d	72	--
Net dry mass of sludge generated per day	kg TSS/d	181	--
Dry mass of VSS input to digester per day	kg VSS/d	189.6	--
Dry mass of VSS output by digester per day	kg VSS/d	176.5	--
Dry mass of VSS destroyed per day	kg VSS/d	13.1	--
Volume of biosolids generated per day	m^3/d	6.0	6.0
TSS content of hauled biosolids	%	2.8	2.6
VSS content of hauled biosolids	%	52	--
Dry mass of biosolids generated per day	kg/d	167	--

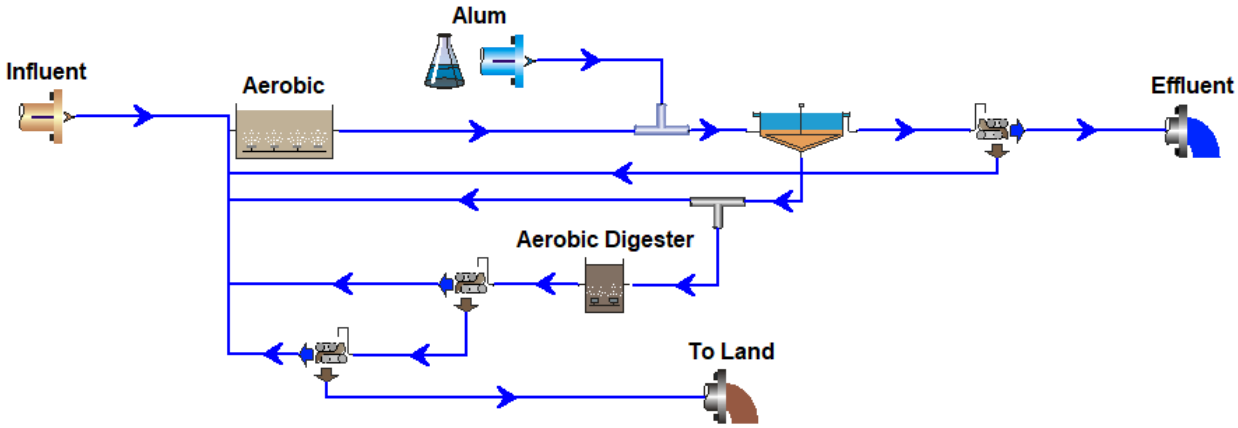

Figure F1: Plant F BioWin Model PFD

Uncertainty

Raw sludge production uncertainty was not calculated directly because the solids content of the waste sludge not available. As a proxy for raw sludge production, all uncertainty was assumed to be associated with variation in MLSS concentration (2014 – 2016 data). To calculate uncertainty, the standard deviation in MLSS concentration (1160 mg/L) was divided by the mean MLSS concentration (4097 mg/L) and converted to a percentage. Using this measure, the uncertainty was determined to be 28% (sample size, *n* = 102).

Energy

On-site power draw measurements were taken on all pieces of equipment related to sludge handling and multiplied by the daily motor run-time (obtained from plant records) to determine the daily kWh consumption for each motor of interest (Table F2). The plant does not employ dedicated digester blowers, therefore, the percentage of air flow to the digester (obtained from the BioWin™ model) was used to allocate the fraction of blower electricity consumed by the digester. The total draw for each category of equipment (stabilization, pumping, aerated holding) was calculated and divided by mass of raw sludge generated daily (Table F3). Digester electricity consumption was also divided by the daily quantity of VSS destruction to obtain a measure of energy efficiency (Table F3).

Table F2: Plant F Energy Measurements

Category/Motor	Voltage (V)	Current (A)	Power Factor (PF)	Power Draw (kW)	Motor Run-Time (Hr/d)	Daily Electricity Consumption (kWh/d)
Stabilization						
Blower 1 (aeration + digester)	617	34	0.951	34.2	24	821
				Sub-total (14% of draw to digester)	*24*	*115*
Pumping						
WAS pump	617	1.8	0.7	1.2		4
				Sub-total		4
Aerated Holding						
Holding Tank Blower	618	10.4	0.956	10.1	24	242
				Sub-total		242
				Total		***361***

Table F3: Plant F Normalized Electricity Consumption

Category	Normalized Electricity Consumption (kWh/dry kg)
Stabilization	635
Pumping	20
Aerated Holding	1339
Total	1994
Digester Efficiency	8.8 (kWh / kg VSS destroyed)

Chemical Usage

Plant F does not employ the use of chemicals for its sludge handling process.

Biosolids Disposition

Average round-trip distance of hauled biosolids

Plant F transports biosolids from the WWTP to agricultural farms during spreading season. The weighted average round-trip distance from the WWTP to the farms between 2014 – 2016 was ***16 km***.

Transportation Fuel Consumption

Table F4 lists the parameters obtained to calculate normalized transportation fuel consumption. Both the volumetric capacity of the haulage truck (40 m^3) and truck fuel economy (1.72 km/L) are standard values. The volume of biosolids generated per year is the 2014 – 2016 average. The number of trips per year was calculated by dividing the volume of biosolids generated per year by the volumetric capacity of the haulage truck. The kilometers travelled per year was calculated by multiplying the number of trips per year by the average round-trip distance. The fuel consumed per year was calculated by dividing the kilometers travelled per year by the truck fuel economy. Finally, the volume of fuel consumed per dry tonne of raw sludge produced was calculated by dividing the fuel consumed per year by the quantity of dry mass of raw sludge generated per year.

Table F4: Plant F Transportation Fuel Consumption

Volumetric capacity of haulage truck	m^3	40
Volume of biosolids generated per year	m^3	2190
Number of trips per year	trips / year	55
Kilometers travelled per year	km	881
Truck fuel economy	km / L	1.72
Volume of fuel consumed per year	L / year	512
Fuel consumed per dry tonne of raw sludge produced	***L / dt***	***7.8***

Biosolids Quality

A variety of statistical measures detailing the metals content of the hauled biosolids is listed in Table F5. Similar measures for the solids, nutrients, and *E. coli* content of the hauled biosolids are presented in Table F6.

Table F5: Plant F Biosolids Quality – Metals

	As	**Cd**	**Co**	**Cr**	**Cu**	**Hg**	**Mo**	**Ni**	**Pb**	**Se**	**Zn**
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
MEAN	4.7	0.5	2.0	24	538	0.9	5.5	13	29	6.9	528
MEDIAN	4.3	0.5	1.9	20	505	0.7	5.4	13	27	6.1	546
STD DEV	1.4	0.2	0.4	11	112	0.5	2.0	3	8	2.5	121
MIN	2.9	0.18	1.5	13	407	0.01	2.6	9.4	16	4.1	325
MAX	7.5	0.73	2.6	51	797	1.8	2.6	18	47	11	773

n	11	11	11	11	11	11	11	11	11	11	11
NASM LIMIT	170	34	340	2800	1700	11	94	420	1100	34	4200
AVG÷NASM LIMIT	***0.03***	***0.01***	***0.01***	***0.01***	***0.32***	***0.08***	***0.06***	***0.03***	***0.03***	***0.20***	***0.13***
STD DEV÷NASM LIMIT	0.01	0.005	0.001	0.004	0.07	0.05	0.02	0.01	0.01	0.07	0.03

Table F6: Plant F Biosolids Quality – Solids, Nutrients, *E. coli*

	TS	**TN**	**TP**	**K**	***E. coli***
	%	mg/kg	mg/kg	mg/kg	Log (CFU/g)
MEAN	2.6	38359	32355	2180	4.3
MEDIAN	2.5	36621	31937	1951	4.7
STD DEV	0.6	11756	4428	490	1.1
MIN	1.7	20508	25610	1774	2.6
MAX	3.8	65523	41802	2978	5.4
n	11	10	11	5	11

Innovative Technology Assessment

To evaluate the sustainability impact of implementing innovative technologies into Plant F, the previously generated BioWin™ model was modified to incorporate each innovative technology within the study sample (Rotary Disc Thickener, GeoTube™, Rotary Press, Centrifuge). For each technology implementation, the predicted biosolids volume was manipulated such that the predicted solids content of the sludge/biosolids product matched the known/observed value where the technology was employed. The annual number of trips, kilometers travelled, fuel consumption, and normalized fuel consumption (litres consumed per dry tonne of raw sludge generated) were evaluated using the updated volume of biosolids as the basis for calculation. The volumetric capacity of the haulage truck (40 m^3) and average round-trip distance of the final destination (16 km) was assumed to identical to the base case. The operational results of each technology implementation are listed in Table F7, while the impact of each technology on GHG emissions is detailed in section 4.6. The BioWin™ process flow sheets associated with thickening and dewatering technology implementation are shown in Figures F2 and F3, respectively.

Table F7: Plant F Innovative Tech Assessment Results

		Base Case	Disc Thickener	GeoTube	Fournier Press	Centrifuge
BioWin TSS	%		4.5	9.0	17.0	22.7
Volume per truck	m3	40	40	40	40	40
Volume per year	m3	2190	1497	694	365	274
Number of trips per year	trips / year	55	37	17	9	7
Kilometers travelled per year	km	881	602	279	147	110
Truck fuel economy	km / L	1.72	1.72	1.72	1.72	1.72
Fuel consumed per year	L / year	512	350	162	85	64
Fuel consumed / dt sludge	***L / dt***	***7.8***	***5.3***	***2.5***	***1.3***	***0.97***

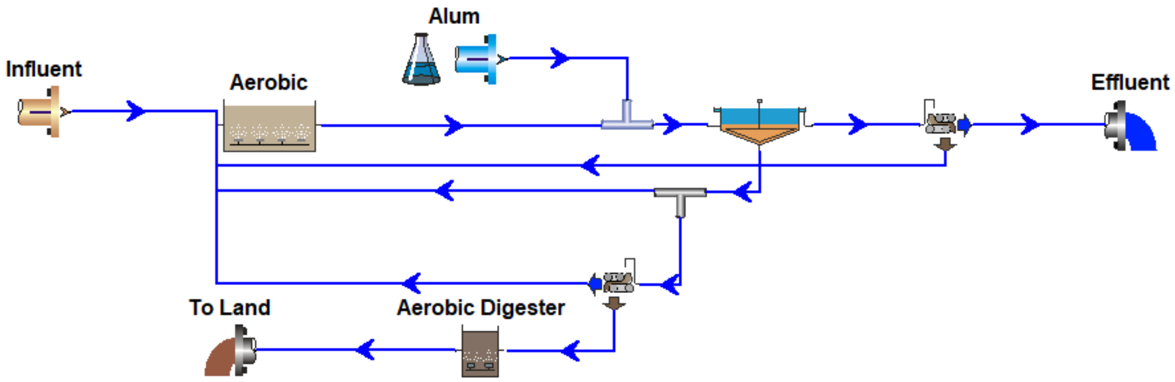

Figure F2: Plant F Thickening Innovative Tech PFD

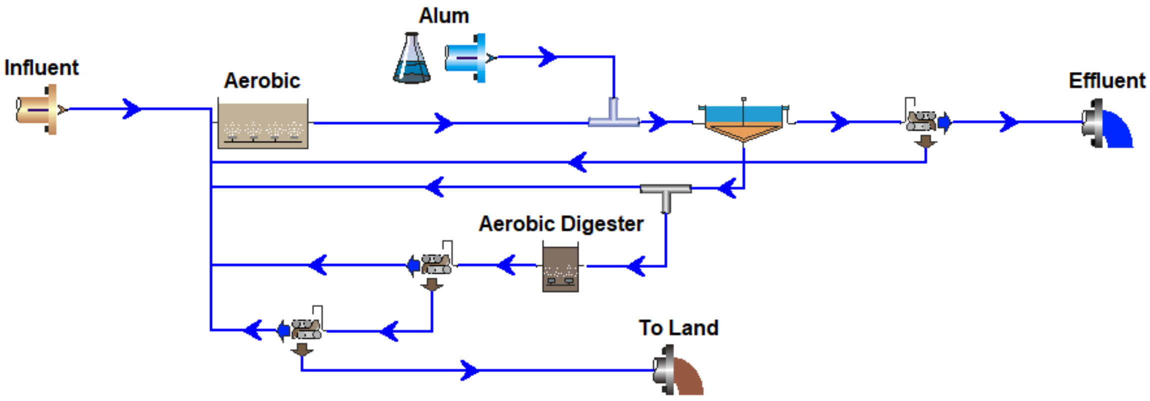

Figure F3: Plant F Dewatering Innovative Tech PFD

Appendix G

Plant G Summary

Overview

Plant G is an extended aeration WWTP located in Southern Ontario and operated by the municipality (owner). Normal sludge handling operations consist of aerobic digestion stabilization and on-site aerated storage. During spreading season, the biosolids are hauled and applied to land for agricultural purposes.

BioWin Modelling

A BioWin™ model based on observed operational data was generated to estimate raw sludge production and VSS destruction, and to screen for problematic plant data. A summary of key model outputs and the corresponding mean observed value (where applicable) is shown in Table G1. The three observed MLSS values correspond to each train of liquid treatment. The model process flow sheet is shown in Figure G1. The predicted values were generally consistent with observed values.

Table G1: Plant G BioWin Model Results

Parameter	Units	Predicted Value	Observed Value (2014-2016)
MLSS	mg/L	7480	8078, 6720, 7206
Dry mass of sludge wasted per day	kg TSS/d	535	--
Dry mass of solids returned per day (digester decant)	kg TSS/d	151	--
Net dry mass of sludge generated per day	kg TSS/d	384	--
Dry mass of VSS input to digester per day	kg VSS/d	327	--
Dry mass of VSS output by digester per day	kg VSS/d	298	--
Dry mass of VSS destroyed per day	kg VSS/d	29	--
Volume of biosolids generated per day	m^3/d	15	--
TSS content of hauled biosolids	%	2.4	2.4
VSS content of hauled biosolids	%	59	67

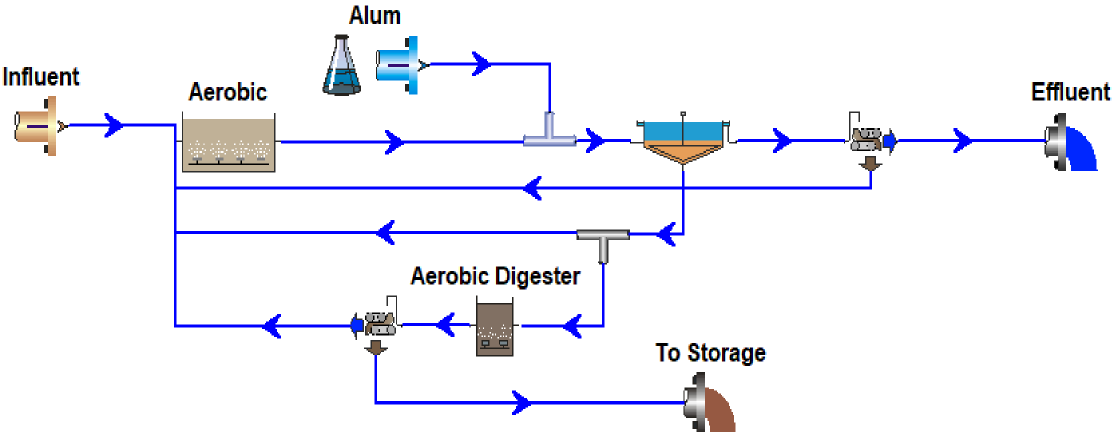

Figure G1: Plant G BioWin Model PFD

Uncertainty

Raw sludge production uncertainty was not calculated directly because the solids content of the waste sludge was not available. As a proxy for raw sludge production, all uncertainty was assumed to be associated with variation in MLSS concentration. Given that the plant employs multiple liquid treatment trains (and thus exhibits multiple MLSS concentrations), the uncertainty was calculated for each train and the highest value was used in subsequent KPI calculations. To calculate uncertainty, the standard deviation in MLSS concentration (2077 mg/L) was divided by the mean MLSS concentration (6720 mg/L) and converted to a percentage. Using this measure, the uncertainty was determined to be 31% (sample size, $n = 64$).

Energy

On-site power draw measurements were taken on all pieces of equipment related to sludge handling and multiplied by the daily motor run-time (obtained from plant records) to determine the daily kWh consumption for each motor of interest (Table G2). The plant does not employ dedicated digester blowers; one blower services both the digesters and holding tank. An analysis of air flow data from 2016–2017 revealed that 98% of the sludge blower air serviced the digesters, while 2% serviced the holding tank. Therefore, 98% of the electricity associated with blower operation was allocated to digester operation, while 2% was allocated to aerated holding tank operation. The total draw for each category of equipment (stabilization, pumping, aerated holding) was calculated and divided by mass of raw sludge generated daily (Table G3). Digester electricity consumption was also divided by the daily quantity of VSS destruction to obtain a measure of energy efficiency (Table G3).

Table G2: Plant G Energy Measurements

Category/Motor	Voltage (V)	Current (A)	Power Factor (PF)	Power Draw (kW)	Motor Run-Time (Hr/d)	Daily Electricity Consumption (kWh/d)
Stabilization						
Blower (digester + aerated holding tank)	605	45.2	0.8	37	24	888
				Sub-total (98% to digester)		*870*
Pumping						
WAS Pump	607	7.1	0.778	6.5	1.8	11.7
					Sub-total	*11.7*
Aerated Holding						
Blower (digester + aerated holding tank)	605	45.2	0.8	37	24	888
				Sub-total (2% to aerated holding tank)		*18*
					Total	***900***

Table G3: Plant G Normalized Electricity Consumption

Category	Normalized Electricity Consumption (kWh/dry kg)
Stabilization	2.27
Pumping	0.03
Aerated Holding	0.04
Total	2.34
Digester Efficiency	30 (kWh / kg VSS destroyed)

Chemical Usage

Plant G does not employ the use of chemicals for its sludge handling process.

Biosolids Disposition

Average round-trip distance of hauled biosolids

Plant F transports biosolids from the WWTP to agricultural farms during spreading season. The weighted average round-trip distance from the WWTP to the farms between 2014 – 2016 was ***54 km***.

Transportation Fuel Consumption

Table G4 lists the parameters obtained to calculate normalized transportation fuel consumption. Both the volumetric capacity of the haulage truck (40 m^3) and truck fuel economy (1.72 km/L) are standard values. The volume of biosolids generated per year is the 2014 – 2016 average. The number of trips per year was calculated by dividing the volume of biosolids generated per year by the volumetric capacity of the haulage truck. The kilometers travelled per year was calculated by multiplying the number of trips per year by the average round-trip distance. The fuel consumed per year was calculated by dividing the kilometers travelled per year by the truck fuel economy. Finally, the volume of fuel consumed per dry tonne of raw sludge produced was calculated by dividing the fuel consumed per year by the quantity of dry mass of raw sludge generated per year.

Table G4: Plant G Transportation Fuel Consumption

Parameter	Units	Value
Volumetric capacity of haulage truck	m^3	40
Volume of biosolids generated per year	m^3	5475
Number of trips per year	trips / year	137
Kilometers travelled per year	km	7336
Truck fuel economy	km / L	1.72
Volume of fuel consumed per year	L / year	4265
Fuel consumed per dry tonne of raw sludge produced	***L / dt***	***30.4***

Biosolids Quality

A variety of statistical measures detailing the metals content of the hauled biosolids is listed in Table G5. Similar measures for the solids, nutrients, and *E. coli* content of the hauled biosolids are presented in Table G6.

Table G5: Plant G Biosolids Quality – Metals

	As	Cd	Co	Cr	Cu	Hg	Mo	Ni	Pb	Se	Zn
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
MEAN	5.3	0.6	4.6	17	496	0.3	5.6	13	88	4.7	385
MEDIAN	4.8	0.6	4.6	16	506	0.2	5.5	14	66	4.5	369
STD DEV	2.1	0.3	0.9	4	78	0.2	1.3	3	65	1.3	102
MIN	0.6	0.07	2.4	9.4	315	0.08	3.7	4.1	17	2.1	176
MAX	12	1.4	6.5	27	643	1.3	9.4	20	304	7.8	585

n	32	32	32	32	32	32	32	32	32	32	32
NASM LIMIT	170	34	340	2800	1700	11	94	420	1100	34	4200
AVG÷NASM LIMIT	***0.03***	***0.02***	***0.01***	***0.01***	***0.29***	***0.02***	***0.06***	***0.03***	***0.08***	***0.14***	***0.09***
STD DEV÷NASM LIMIT	0.01	0.01	0.003	0.001	0.05	0.02	0.01	0.007	0.06	0.04	0.02

Table G6: Plant G Biosolids Quality – Solids, Nutrients, *E. coli*

	TS	**VS**	**TN**	**TP**	**K**	***E. coli***
	%	%	mg/kg	mg/kg	mg/kg	Log (CFU/g)
MEAN	2.4	67	49759	29908	3341	4.4
MEDIAN	2.3	67	49527	30154	3189	4.5
STD DEV	0.7	3	10397	4159	630	0.6
MIN	1.3	58	20782	21176	2180	2.9
MAX	4.9	74	83914	38554	4661	5.5
n	33	33	32	32	32	32

Innovative Tech Assessment

To evaluate the sustainability impact of implementing innovative technologies into Plant G, the previously generated BioWin™ model was modified to incorporate each innovative technology within the study sample (Rotary Disc Thickener, GeoTube™, Rotary Press, Centrifuge). For each technology implementation, the predicted biosolids volume was manipulated such that the predicted solids content of the sludge/biosolids product matched the known/observed value where the technology was employed. The annual number of trips, kilometers travelled, fuel consumption, and normalized fuel consumption (litres consumed per dry tonne of raw sludge generated) were evaluated using the updated volume of biosolids as the basis for calculation. The volumetric capacity of the haulage truck (40 m^3) and average round-trip distance of the final destination (54 km) was assumed to identical to the base case. The operational results of each technology implementation are listed in Table G7, while the impact of each technology on GHG emissions is detailed in section 4.6. The BioWin™ process flow sheets associated with thickening and dewatering technology implementation are shown in Figures G2 and G3, respectively.

Table G7: Plant G Innovative Tech Assessment Results

		Base Case	Disc Thickener	GeoTube	Fournier Press	Centrifuge
BioWin TSS	%		4.5	9.0	16.8	22.0
Volume per truck	m^3	40	40	40	40	40
Volume per year	m^3	5475	3103	1424	767	584
Number of trips per year	trips / year	137	78	36	19	15
Kilometers travelled per year	km	7336	4157	1907	1027	782
Truck fuel economy	km / L	1.72	1.72	1.72	1.72	1.72
Fuel consumed per year	L / year	4265	2417	1109	597	455
Fuel consumed / dt sludge	**L / dt**	**30.4**	**17.2**	**7.9**	**4.3**	**3.2**

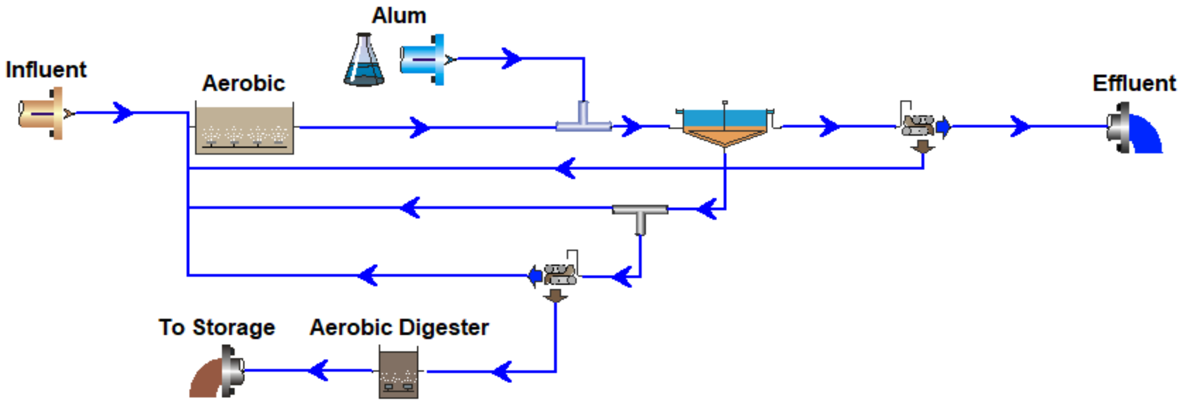

Figure G2: Plant G Thickening Innovative Tech PFD

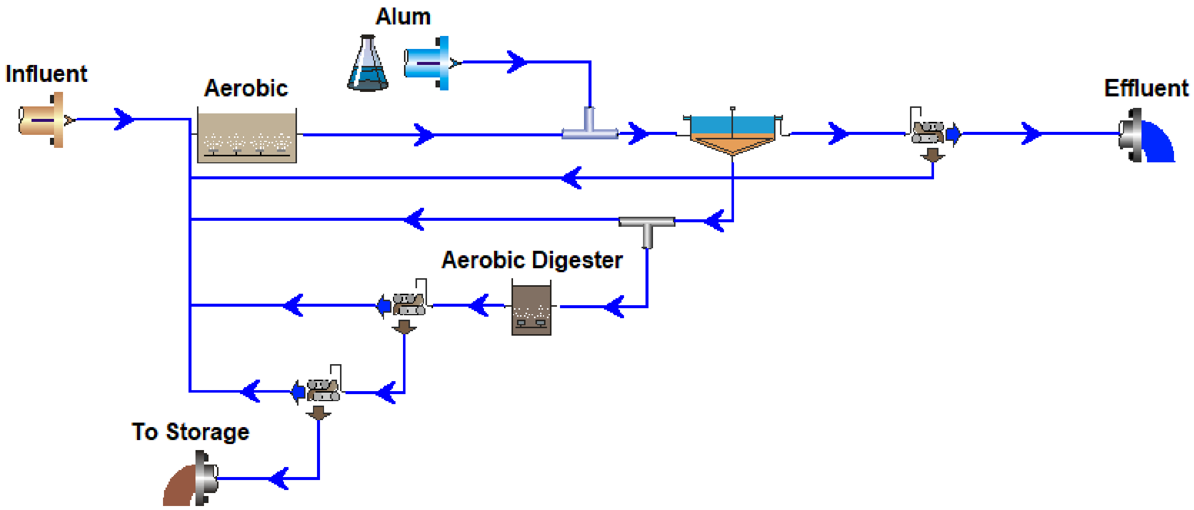

Figure G3: Plant G Dewatering Innovative Tech PFD

Appendix H

Plant H Summary

Overview

Plant H is an extended aeration WWTP located in Southern Ontario and operated by the municipality (owner). Normal sludge handling operations consist of aerated holding, centrifuge dewatering (upstream), thermo-alkali hydrolysis stabilization, and on-site storage. During spreading season, the biosolids are hauled and applied to land for agricultural purposes.

BioWin Modelling

A BioWin™ model based on observed operational data was generated to estimate raw sludge production and VSS destruction, and to screen for problematic plant data. All operations inclusive of centrifuge dewatering were incorporated in the model. The thermo-alkali reactor was not modeled. A summary of key model outputs and the corresponding mean observed value (where applicable) is shown in Table H1. The BioWin™ model process flow sheet is shown in Figure H1. The predicted values were consistent with observed values.

Table H1: Plant H BioWin Model Results

Parameter	Units	Predicted Value	Observed Value (2015-2017)
MLSS	mg/L	5469	5525
Dry mass of sludge wasted per day	kg TSS/d	963	1094
Dry mass of solids returned per day (digester decant)	kg TSS/d	674	--
Dry mass of solids returned per day (centrifuge centrate)	kg TSS/d	14	--
Net dry mass of sludge generated per day	kg TSS/d	275	--
TSS content of sludge (centrifuge product)	%	17.2%	16.9%
Dry mass of biosolids generated per day	kg/d	274 kg/d	274 kg/d

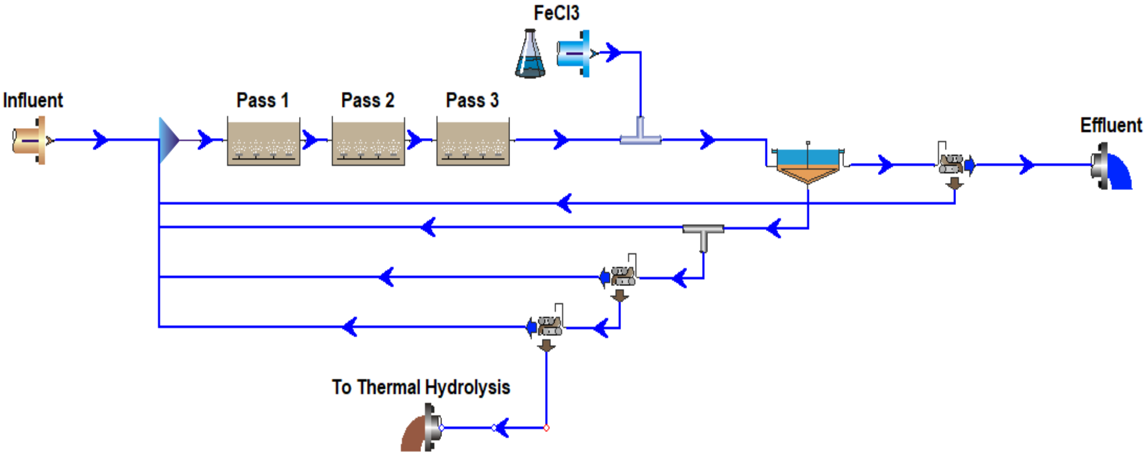

Figure H1: Plant H BioWin Model PFD

Uncertainty

To estimate the uncertainty in raw sludge production, the standard deviation of reported raw sludge production (306 dry kg/d) was divided by the mean reported sludge production (1094 dry kg/d) and converted to a percentage. Using this measure, the uncertainty was determined to be 28% (sample size, n = 339).

Electricity

On-site power draw measurements were taken on all pieces of equipment related to sludge handling and multiplied by the daily motor run-time (obtained from plant records) to determine the daily kWh consumption for each motor of interest (Table H2). The total draw for each category of equipment (stabilization, pumping) was calculated and divided by mass of raw sludge generated daily (Table H3).

Table H2: Plant H Energy Measurements

Category/Motor	Voltage (V)	Current (A)	Power Factor (PF)	Power Draw (kW)	Motor Run-Time (Hr/d)	Daily Electricity Consumption (kWh/d)
Stabilization						
Reactor (all)	605	38.1	0.803	34.4	2	69
					Sub-total	*69*
Pumping						
WAS pump	606	2.5	0.652	1.7	4	7
Sludge loading pump	604	25.6	0.96	26	0.14	4
					Sub-total	*11*

Dewatering						
Centrifuge (all)	606	10.3	0.841	9.1	1.5	14
Sludge transfer pump	606	1.8	0.734	1.5	1.5	2
					Sub-total	*16*
Aerated Holding						
Blower 1	605	26.6	0.809	24.9	4.8	119
Blower 2	605	26.6	0.809	24.9	4.5	111
Blower 3	604	11.3	0.852	10.5	11.4	119
					Sub-total	*349*
Odour Control						
Sludge Building BioRem	605	11	0.833	9.9	24	238
Reactor BioRem	606	9.7	0.85	8.1	4	32
					Sub-total	*270*
					TOTAL	**715**

Table H3: Plant H Normalized Electricity Consumption

Category	Normalized Electricity Consumption (kWh/dry kg)
Stabilization	0.25
Pumping	0.04
Dewatering	0.06
Aerated Holding	1.27
Odour Control	0.98
Total	2.60

Natural Gas

Natural gas is employed as part of the stabilization process at plant H. Its usage was calculated by subtracting the reported baseline usage (for plant-wide heating) from the total draw reported during stabilization operation and dividing the difference by the dry mass flow of sludge processed. The usage was determined to be ***0.037 m^3/dt***.

Chemical Usage

Plant H uses polymer as part of its mechanical dewatering process and KOH as part of its stabilization process. To determine normalized consumption for each chemical, process information obtained from the operator was used in conjunction with raw sludge production. Per conversations with the operator, polymer is dosed at a rate of 2.6 gallons per hour during centrifuge operation, which on average operates for 1.5 hr./d. Thus, polymer is consumed at a rate of 3.8 gallons/d, which corresponds to 6.5 kg polymer/d (polymer is 45% solution). Dividing by the daily mass of raw sludge production (0.275 dt) yields a normalized polymer usage value of 24 kg polymer/dt. Per conversations with the operator KOH is dosed at a rate of 7.7 litres of KOH per batch of operation, the reactor runs 2-3x per week, and 10-12 batches are generated per day. Using the average number of runs per week (2.5) and batches per day (11), the average volume of KOH consumed per day is 30.3 L, which corresponds to 5.1 kg KOH per day (solution density = 1.134 kg/L and solution = 15 % KOH). Dividing by the daily mass of raw sludge production (0.275 dt) yields a normalized KOH usage value of 19 kg KOH/dt. The chemical usage results are summarized in Table H4.

Table H4: Plant H Chemical Usage Results

Chemical	Value	Units	Comment
Polymer	2.6	gal / hr.	Per operator
	3.8	gal/d	Centrifuge runs 1.5 hr./d
	14.4	L/d	
	6.5	kg/d	
	24	***kg polymer/dt***	
KOH	7.7	L / batch	Per operator
	30.3	L/d	Per operator, TH runs 2-3x per week, 10-12 batches per day. Calculation = 7.7 x 2.5 x 11 ÷ 7
	5.1	kg/d	
	125	***kg KOH/dt***	

Biosolids Disposition

Average round-trip distance of hauled biosolids

Plant H transports its biosolids to agricultural farms during spreading season. During 2016, the first year the thermo-alkali product was generated, the weighted average round trip distance between the WWTP and fields was ***9.3 km***.

Transportation Fuel Consumption

Table H5 lists the parameters obtained to calculate normalized transportation fuel consumption. Both the volumetric capacity of the haulage truck (40 m^3) and truck fuel economy (1.72 km/L) are standard values. The volume of biosolids generated per year is the reported 2016 value. The number of trips per year was calculated by dividing the volume of biosolids generated per year by the volumetric capacity of the haulage truck. The kilometers travelled per year was calculated by multiplying the number of trips per year by the average round-trip distance. The fuel consumed per year was calculated by dividing the kilometers travelled per year by the truck fuel economy. Finally, the volume of fuel consumed per dry tonne of raw sludge produced was calculated by dividing the fuel consumed per year by the quantity of dry mass of raw sludge generated per year.

Table H5: Plant H Fuel Consumption

Volumetric capacity of haulage truck	40	m3
Volume of biosolids generated per year	984	m3
Number of trips per year	25	trips / year
Kilometers travelled per year	228	km
Truck fuel economy	1.72	km / L
Volume of fuel consumed per year	133	L / year
Fuel consumed per dry tonne of raw sludge produced	***1.3***	***L / dt***

Biosolids Quality

A variety of statistical measures detailing the metals content of the hauled biosolids is listed in Table H6. Similar measures for the solids, nutrients, and *E. coli* content of the hauled biosolids are presented in Table H7.

Table H6: Plant H Biosolids Quality – Metals

	Ar	**Cd**	**Co**	**Cr**	**Cu**	**Hg**	**Mo**	**Ni**	**Pb**	**Se**	**Zn**
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
MEAN	2.9	0.8	3.1	46	550	0.75	13	14	27	3	456
MEDIAN	3.0	0.8	3.1	38	550	0.66	12	15	14	2	448
STD DEV	1.5	0.3	1.4	24	112	0.45	5	4	36	1	124
MIN	1	0	1	14	230	0	6	7	7	1	190
MAX	7	2	6	96	807	3	26	22	160	7	798
n	35	35	35	35	35	33	35	35	35	35	35
NASM LIMIT	170	34	340	2800	1700	11	94	420	1100	34	4200
AVG÷NASM LIMIT	***0.02***	***0.02***	***0.01***	***0.02***	***0.32***	***0.07***	***0.14***	***0.03***	***0.02***	***0.09***	***0.11***
STD DEV÷NASM LIMIT	0.009	0.01	0.004	0.009	0.07	0.04	0.05	0.01	0.03	0.04	0.03

Table H7: Plant H Biosolids Quality – Solids, Nutrients, *E. coli*

	TS	**TN**	**TP**	**K**	***E. coli***
	mg/kg	mg/kg	mg/kg	mg/kg	Log (CFU/g)
MEAN	99314	42130	36968	53111	2.1
MEDIAN	100400	39637	35500	53000	2.0
STD DEV	24113	16410	5602	26036	0.28
MIN	11900	12038	28879	8000	1.5
MAX	145000	80428	49381	105263	2.9
n	35	34	32	32	19

Appendix I
Plant I Summary

Overview

Plant I is an extended aeration WWTP located in Northern Ontario and operated by OCWA. Normal sludge handling operations consist of aerobic digestion stabilization and off-site drying bed dewatering (no on-site storage). Once per year, the biosolids are hauled from the drying beds to the landfill.

BioWin Modelling

. A BioWin™ model based on observed operational data was generated to estimate raw sludge production and VSS destruction, and to screen for problematic plant data. A summary of key model outputs and the corresponding mean observed value (where applicable) is shown in Table I1. The BioWin™ model process flow sheet is shown in Figure I1. The predicted values were generally consistent with observed values.

Table I1: Plant I BioWin Model Results

Parameter	Units	Predicted Value	Observed Value (2014-2016)
MLSS	mg/L	2033	2346
Dry mass of sludge wasted per day	kg TSS/d	121	--
Dry mass of solids returned per day (digester decant)	kg TSS/d	23	--
Net dry mass of sludge generated per day	kg TSS/d	98	--
Dry mass of VSS input to digester per day	kg VSS/d	75	--
Dry mass of VSS output by digester per day	kg VSS/d	69.5	--
Dry mass of VSS destroyed per day	kg VSS/d	5.5	--
Volume of biosolids generated per day	m^3/d	5.6	5.6
TSS content of hauled biosolids	%	1.6	1.6
VSS content of hauled biosolids	%	60	--
Dry mass of biosolids generated per day	kg/d	92	--

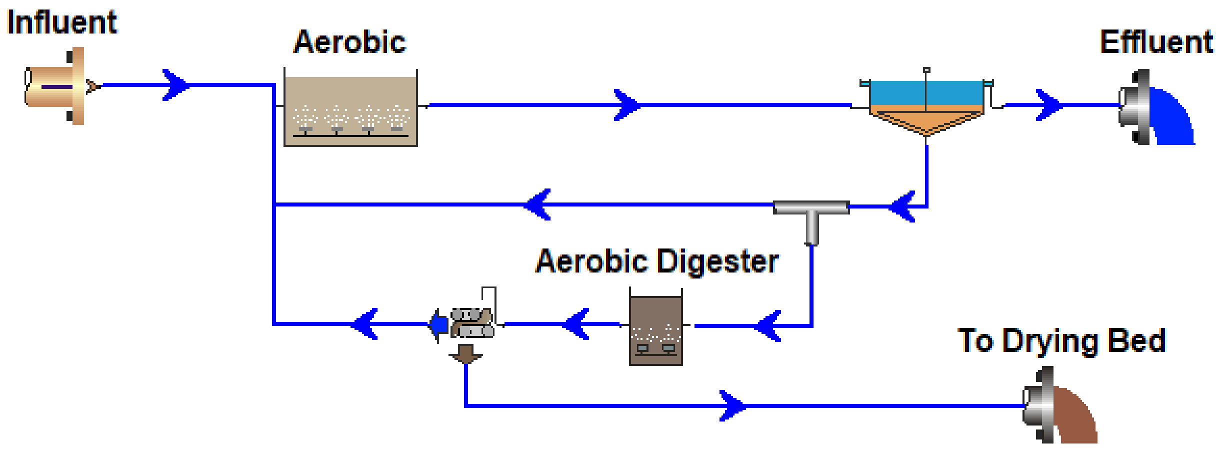

Figure I 1: Plant I BioWin Model PFD

Uncertainty

Raw sludge production uncertainty was not calculated directly because the solids content values of the waste sludge were limited in number. Instead, given that the biosolid volumes were known, all uncertainty was assumed to be associated with variation in biosolids TS content. To calculate uncertainty, the standard deviation in TS content (0.42 %) was divided by the mean TS content (1.64%) and converted to a percentage. Using this measure, the uncertainty was determined to be 26% (sample size, n = 59).

Energy

On-site power draw measurements were taken on all pieces of equipment related to sludge handling and multiplied by the daily motor run-time (obtained from plant records) to determine the daily kWh consumption for each motor of interest (Table I2). The plant does not employ dedicated digester blowers; one blower services both the aeration basin and digester. The percentage of air flow to the digester was assumed to be equal to the percentage of volume the digester utilizes within the treatment unit (14%). The percentage was then used to allocate the fraction of blower electricity consumption to the digester. The total draw for each category of equipment (stabilization, pumping) was calculated and divided by mass of raw sludge generated daily (Table I3). Digester electricity consumption was also divided by the daily quantity of VSS destruction to obtain a measure of energy efficiency (Table I3).

Table I2: Plant I Energy Measurements

Category/Motor	Voltage (V)	Current (A)	Power Factor (PF)	Power Draw (kW)	Motor Run-Time (Hr/d)	Daily Electricity Consumption (kWh/d)
Stabilization						
Blower (aeration + digester)	620	25.2	0.85	17.1	24	410
				Sub-total (15% to digester)		*61.5*
Pumping						
WAS/RAS 1*	618	3.2	0.85	3.6	0.25	0.9
WAS/RAS 2*	618	3.2	0.85	3.6	0.25	0.9
					Sub-total	*1.8*
					Total	***63.3***

*6 min/d in winter, 24 min/d summer → 15 min/d overall = 0.25 hr./d

Table I3: Plant I Normalized Electricity Consumption

Category	Normalized Electricity Consumption (kWh/dry kg)
Stabilization	0.84
Pumping	0.02
Total	0.86
Digester Efficiency	15 (kWh / kg VSS destroyed)

Chemical Usage

Plant I does not employ the use of chemicals for its sludge handling process.

Biosolids Disposition

Average round-trip distance of hauled biosolids

The round-trip distance from the WWTP to the drying bed is 52 km. 182.5 m^3 (out of 1856 m^3 total) is eventually transported from the drying bed to the landfill (a round-trip distance of 40 km). The weighted average round-trip distance of the entire operation is ***56 km.***

Transportation Fuel Consumption

Table I4 lists the parameters obtained to calculate normalized transportation fuel consumption. Both the volumetric capacity of the haulage truck (16.5 m^3) and truck fuel economy (2.0 km/L) were obtained from the plant owner. The volume of biosolids generated per year is the 2014 – 2016 average. The number of trips per year was calculated by dividing the volume of biosolids generated per year by the volumetric capacity of the haulage truck. The kilometers travelled per year was calculated by multiplying the number of trips per year by the average round-trip distance. The fuel consumed per year was calculated by dividing the kilometers travelled per year by the truck fuel economy. Finally, the volume of fuel consumed per dry tonne of raw sludge produced was calculated by dividing the fuel consumed per year by the quantity of dry mass of raw sludge generated per year.

Table I4: Plant I Transportation Fuel Consumption

Volumetric capacity of haulage truck	m^3	16.5
Truck fuel economy	km / L	2.0
Volume of biosolids generated per year	m^3	2039
Number of trips to drying bed per year	trips / year	124
Kilometers travelled per year to/from WWTP → drying bed	km / year	6917
Volume of fuel consumed per year (WWTP → drying bed)	L / year	3459
Volume of fuel consumed per year (drying bed → landfill)	km / year	71
Volume of fuel consumed per year (total)	L / year	3530
Fuel consumed per dry tonne of raw sludge produced	***L / dt***	***99***

Biosolids Quality

A variety of statistical measures detailing the metals content of the hauled biosolids is listed in Table I5. Similar measures for the solids, nutrients, and *E. coli* content of the hauled biosolids are presented in Table I6.

Table I5: Plant I Biosolids Quality – Metals

	As	**Cd**	**Co**	**Cr**	**Cu**	**Hg**	**Mo**	**Ni**	**Pb**	**Se**	**Zn**
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
MEAN	20	0.7	3.4	12	1168	1.0	4.2	16	31	2.5	440
MEDIAN	21	0.8	3.5	12	1137	1.0	4.2	16	30	2.5	453
STD DEV	3	0.1	0.3	2	189	0.1	0.4	2	3	0.3	78
MIN	17	0.5	2.9	9	929	1.0	3.6	14	28	2.0	331
MAX	22	0.9	3.7	15	1420	1.1	4.8	19	35	2.7	523
n	5	5	5	5	5	5	5	5	5	5	5
NASM LIMIT	170	34	340	2800	1700	11	94	420	1100	34	4200

AVG÷NASM LIMIT	***0.12***	***0.02***	***0.01***	***0.004***	***0.69***	***0.09***	***0.04***	***0.04***	***0.03***	***0.07***	***0.10***
STD DEV÷NASM LIMIT	0.015	0.004	0.001	0.001	0.11	0.006	0.005	0.005	0.003	0.01	0.02

Table I6: Plant I Biosolids Quality – Solids, Nutrients, *E. coli*

	VS	**TN**	**TP**	**K**	***E. coli***
	%	mg/kg	mg/kg	mg/kg	Log(CFU/g)
MEAN	0.79	***69186***	***18794***	***5114***	***3.7***
MEDIAN	0.81	66240	19274	5323	3.7
STD DEV	0.03	6664	2875	1047	0.2
MIN	0.75	64032	14894	3624	3.4
MAX	0.82	80153	22672	6481	4.1
n	5	5	5	5	5

Innovative Technology Assessment

To evaluate the sustainability impact of implementing innovative technologies into Plant F, the previously generated BioWin™ model was modified to incorporate each innovative technology within the study sample (Rotary Disc Thickener, GeoTube™, Rotary Press, Centrifuge). For each technology implementation, the predicted biosolids volume was manipulated such that the predicted solids content of the sludge/biosolids product matched the known/observed value where the technology was employed. The annual number of trips, kilometers travelled, fuel consumption, and normalized fuel consumption (litres consumed per dry tonne of raw sludge generated) were evaluated using the updated volume of biosolids as the basis for calculation. Under scenarios where thickening or GeoTube™ were implemented, volumetric capacity of the haulage truck (16.5 m^3) and average round-trip distance of the final destination (52 km) was assumed to identical to the base case since the biosolids would still need to be dewatered at the off-site drying bed prior to disposal at the landfill (to meet solids content requirements). Under the mechanical dewatering scenarios, however, the solids content of the biosolids product would be sufficiently high to directly truck the dewatered biosolids to the landfill using a truck with identical capacity (8.5 m^3) and fuel economy (5 km/L) as the one employed at plant D. The operational results of each technology implementation are listed in Table I7, while the impact of each technology on GHG emissions is detailed in section 4.6. The BioWin™ process flow sheets associated with thickening and dewatering technology implementation are shown in Figures F2 and F3, respectively.

Table I7: Plant I Innovative Tech Assessment Results

		Base Case	**Disc Thickener**	**GeoTube™**	**Fournier Press**	**Centrifuge**
BioWin TSS %	%		4.5	9.2	16.7	22.9
Volume per truck	m^3	16.5	16.5	16.5	8.5	8.5
Volume per year	m^3	2039	803	365	201	146
Number of trips to drying bed per year	trips / year	124	49	22	24	17
Kilometers travelled per year	km / year	6917	2993	1602	1889	1374
Truck fuel economy	km / L	2.0	2.0	2.0	5.0	5.0
Fuel consumed per year	L / year	3530	1527	817	378	275
Fuel consumed / dt sludge	***L / dt***	***99***	***43***	***23***	***11***	***7.7***

Note: 80 km to landfill for FP and CF options

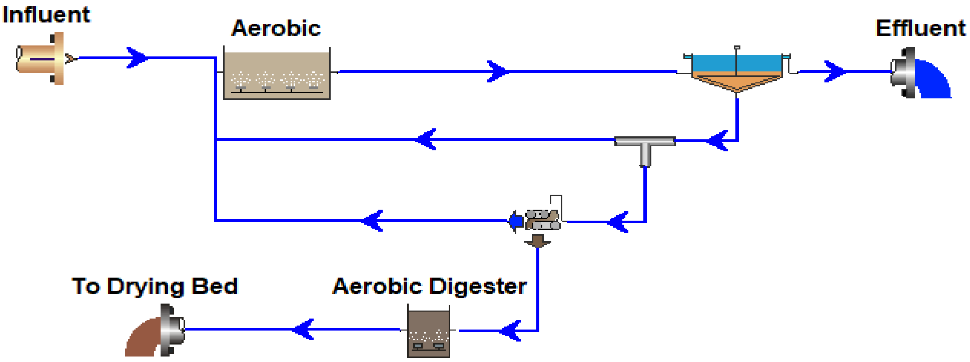

Figure I2: Plant I Innovative Tech Thickening PFD

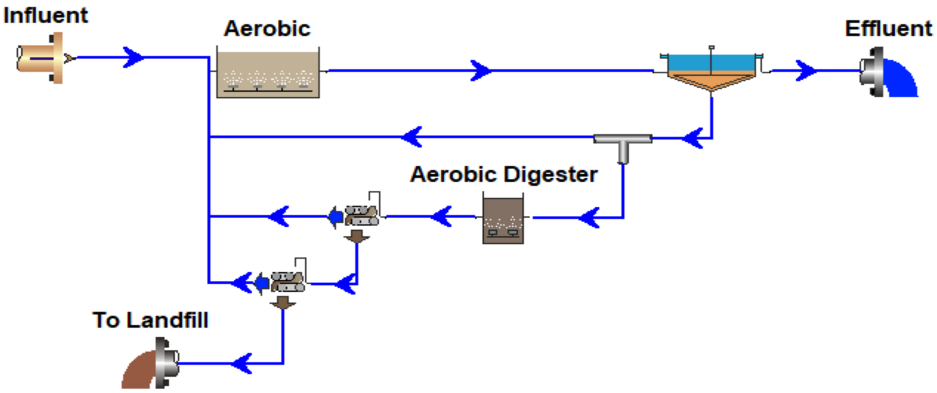

Figure I3: Plant I Innovative Tech Dewatering PFD

Appendix J

Plant J Summary

Overview

Plant J is an extended aeration WWTP located in Eastern Ontario and operated by OCWA. Normal sludge handling operations consist of rotary disc thickening, ATAD stabilization, rotary press dewatering, and on-site storage. During spreading season, the biosolids are hauled and applied to land for agricultural purposes.

BioWin Modelling

A BioWin™ model based on observed operational data was generated to estimate raw sludge production and VSS destruction, and to screen for problematic plant data. A summary of key model outputs and the corresponding mean observed value (where applicable) is shown in Table J1. The two observed MLSS values correspond to each train of liquid treatment. The model process flow sheet is shown in Figure J1. The predicted values were consistent with observed values.

Table J1: Plant J BioWin Model Results

Parameter	Units	Predicted Value	Observed Value (2014-2016)
MLSS	mg/L	4600	4208, 5374
Dry mass of sludge wasted per day	kg TSS/d	545	--
Dry mass of solids returned per day (rotary thickener centrate)	kg TSS/d	82	--
Dry mass of solids returned per day (rotary press centrate)	kg TSS/d	44	--
Net dry mass of sludge generated per day	kg TSS/d	420	--
Dry mass of VSS input to digester per day	kg VSS/d	238	--
Dry mass of VSS output by digester per day	kg VSS/d	213	--
Dry mass of VSS destroyed per day	kg VSS/d	25	--
TSS content of hauled biosolids	%	17.1	17.2
VSS content of hauled biosolids	%	49	--
Dry mass of biosolids generated per day	kg/d	394	393

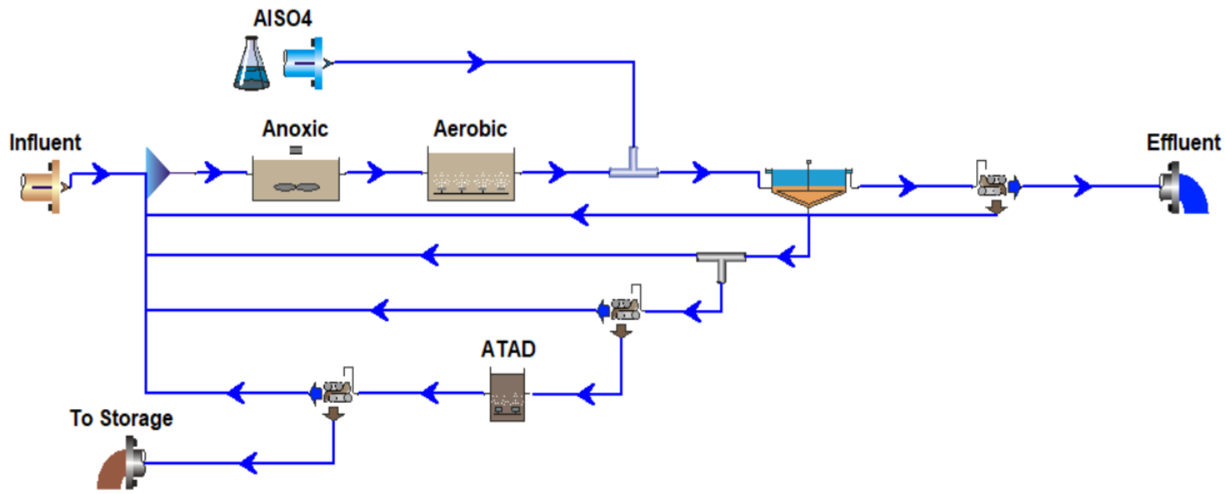

Figure J1: Plant J BioWin Model PFD

Uncertainty

Raw sludge production uncertainty was not calculated directly because limited WAS TSS values were available. Instead, given that predicted biosolids mass matched the known reported value (393 dt/year) if average TS values were employed in the reported value calculation, all uncertainty was assumed to be associated with variation in TS content. To calculate uncertainty, the standard deviation in TS content (2.3 %) was divided by the mean TS content (17.2%) and converted to a percentage. Using this measure, the uncertainty was determined to be 13% (sample size, n = 77).

Energy

On-site power draw measurements were taken on all pieces of equipment related to sludge handling and multiplied by the daily motor run-time (obtained from plant records) to determine the daily kWh consumption for each motor of interest (Table J2). The plant does not employ dedicated digester blowers, therefore, the percentage of air flow to the digester (obtained from plant records) was used to allocate the fraction of blower electricity consumed by the digester. The total draw for each category of equipment (stabilization, pumping, aerated holding) was calculated and divided by mass of raw sludge generated daily (Table J3). Digester electricity consumption was also divided by the daily quantity of VSS destruction to obtain a measure of energy efficiency (Table J3).

Table J2: Plant J Energy Measurements

Category/Motor	**Voltage (V)**	**Current (A)**	**Power Factor (PF)**	**Power Draw (kW)**	**Motor Run-Time (Hr/d)**	**Daily Electricity Consumption (kWh/d)**
Stabilization						
Blower (aeration + digester)	589	56.8	0.905	53.6	24	1286
ATAD- Thermaer pump 1 (mixer)	594	22.8	0.908	20.9	24	502
ATAD- Thermaer pump 2 (mixer)	594	22.3	0.908	20.8	24	499
ATAD- SNDR Pump (mixer)	594	14.2	0.908	13.3	24	318
				Sub-total (20% of blower to ATAD)		*1576*
Pumping						
WAS pump	594	4.6	0.7	N/A	5	17
					Sub-total	*17*
Dewatering						
Rotary press	594	6.1	0.67	3.9	4	16
Feed Pump 1	594	1.1	0.93	1	4	4
Feed Pump 2	594	1.1	0.93	1	4	4
Conveyor 1	N/A	N/A	N/A	1.5	4	6
Conveyor 2	N/A	N/A	N/A	1.5	4	6
Centrate pump	594	3.1	0.601	1.9	4	8
					Sub-total	*44*
Thickening						
Rotary drum thickener	594	0.5	0.716	0.55	10	6
					Sub-total	*6*
Odour Control						
Biofilter	594	0.5	0.7	0.4	24	9
					Sub-total	*9*
					TOTAL	1652

Table J3: Plant J Normalized Electricity Consumption

Category	**Normalized Electricity Consumption (kWh/dry kg)**
Stabilization	3.76
Pumping	0.04
Dewatering	0.10
Odour Control	0.02
Thickening	0.01
Total	3.93
Digester Efficiency	63 (kWh / kg VSS destroyed)

Chemical Usage

Plant J uses polymer as part of its mechanical thickening and dewatering processes. To determine normalized consumption for each chemical, process information obtained from the operator was used in conjunction with raw sludge production. Per conversations with the operator, thickening polymer is dosed at a rate of 12000 mg polymer per kg of sludge, which corresponds to 12 kg polymer/dt. Per conversations with the operator, polymer is consumed at a rate of 45 gallons per week, which corresponds to 6.4 gallons per day (24.3 L/d). Thus, polymer is consumed at a rate of 6.5 kg polymer per day (polymer is 45% solution). Dividing by the daily mass of raw sludge production (0.42 dt) yields a normalized polymer usage value of 28 kg polymer/dt. The results are summarized in Table J4.

Table J4: Plant J Chemical Usage

Chemical	**Value**	**Units**
Dewatering Polymer	45	gal /week
	6.4	gal/d
	24.3	L/d
	24.3	kg polymer/d
	28	**kg polymer/dt raw sludge**
Thickening Polymer	12000	mg polymer / kg sludge
	0.012	kg polymer / kg sludge
	12	**kg polymer / dt raw sludge**

Biosolids Disposition

Average round-trip distance of hauled biosolids

Plant J transports biosolids from the WWTP to agricultural farms during spreading season. During 2014 – 2016, the weighted average round-trip distance between the WWTP and fields was ***15.7 km***.

Transportation Fuel Consumption

Table J5 lists the parameters obtained to calculate normalized transportation fuel consumption. Both the volumetric capacity of the haulage truck (40 m^3) and truck fuel economy (1.72 km/L) are standard values. The volume of biosolids generated per year is the 2014 – 2016 average. The number of trips per year was calculated by dividing the volume of biosolids generated per year by the volumetric capacity of the haulage truck. The kilometers travelled per year was calculated by multiplying the number of trips per year by the average round-trip distance. The fuel consumed per year was calculated by dividing the kilometers travelled per year by the truck fuel economy. Finally, the volume of fuel consumed per dry tonne of raw sludge produced was calculated by dividing the fuel consumed per year by the quantity of dry mass of raw sludge generated per year.

Table J5: Plant J Transportation Fuel Consumption

Parameter	**Units**	**Value**
Volumetric capacity of haulage truck	m^3	40
Volume of biosolids generated per year	m^3	839.5
Number of trips per year	trips / year	21
Kilometers travelled per year	km	329
Truck fuel economy	km / L	1.72
Volume of fuel consumed per year	L / year	192
Fuel consumed per dry tonne of raw sludge produced	**L / dt**	**1.25**

Biosolids Quality

A variety of statistical measures detailing the metals content of the hauled biosolids is listed in Table J6. Similar measures for the solids, nutrients, and *E. coli* content of the hauled biosolids are presented in Table J7.

Table J6: Plant J Biosolids Quality – Metals

	As	**Cd**	**Co**	**Cr**	**Cu**	**Hg**	**Mo**	**Ni**	**Pb**	**Se**	**Zn**
	mg/kg	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**
MEAN	2.2	0.6	1.7	20	425	0.36	2.8	12	28	2.2	326
MEDIAN	2.0	0.5	2.0	19.5	422	0.36	3.0	11	23	2.0	343
STD DEV	0.7	0.1	0.7	4.5	64	0.09	0.9	2.3	18	0.8	71
MIN	0.5	0.5	1.0	9.0	233	0.01	2.0	7.0	1.0	0.60	150
MAX	4	0.9	3.0	32	671	0.70	9.0	19	73	4.0	483
n	81	82	82	82	82	82	82	82	82	81	80
NASM LIMIT	170	34	340	2800	1700	11	94	420	1100	34	4200
AVG÷NASM LIMIT	***0.01***	***0.02***	***0.005***	***0.007***	***0.25***	***0.03***	***0.03***	***0.03***	***0.03***	***0.06***	***0.08***
STD DEV÷NASM LIMIT	0.004	0.003	0.002	0.002	0.04	0.01	0.01	0.01	0.02	0.02	0.02

Table J7: Plant J Biosolids Quality – Solids, Nutrients, *E. coli*

	TS	**TN**	**TP**	**K**	***E. coli***
	%	**mg/kg**	**mg/kg**	**mg/kg**	**Log (CFU/g)**
MEAN	17.2	32347	25466	906	2.1
MEDIAN	16.7	30136	25200	900	2.0
STD DEV	2.3	7599	5486	187	0.57
MIN	12.9	19315	10100	0	0.03
MAX	29	60000	47600	1420	3.1
n	77	79	82	82	84