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Estimation of Greenhouse Gases Emissions from Biological Wastewater Treatment Plants at Windsor

by

Seema Rani Das

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2011

Estimation of Greenhouse Gases Emissions from Biological Wastewater Treatment Plants at Windsor

by

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ABSTRACT

Wastewater treatment processes and biosolids treatment operations are considered as sources of GHGs (greenhouse gases) production in all industrialized countries. Gases like CO_2, N_2O etc., which are GHGs, are produced during biological wastewater treatment process. Off-site power generation also contributes a significant amount of CO_2. In this study, based on energy consumption, it was found that 0.02 kg CO_2 was released per m^3 of wastewater treated in the Biological Aerated Filter (BAF) system, whereas 0.03 kg CO_2 was released per m^3 of wastewater treated in the Activated Sludge System. The amount of on-site GHGs emissions from microbial processes varied with the incoming wastewater characteristics and temperature. The on-site results indicated that plug flow reactors emitted about 45 % higher CO_2 than completely mixed reactors at the Little River Pollution Control Plant (LRPCP). The overall GHGs emissions results showed that off-site emissions were significantly higher than the on-site emissions.

DEDICATION

The author dedicates the thesis to her family members for their unconditional love, support and encouragement over the course of the study.

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The author is indebted to her advisor Dr. N. Biswas for his advice, guidance, support and continuous encouragement throughout this period. Grateful acknowledgement is given to the department reader Dr. J. Bewtra for taking time to review the thesis and for his constructive criticism and guidance which helped the author to overcome many difficulties during the study.

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LIST OF NOMENCLATURE

GHGs	Greenhouse gases
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
BOD	Biochemical Oxygen Demand
TKN	Total Kjeldahl Nitrogen
NH_4^+	Ammonium
TSS	Total Suspended Solids
VSS	Volatile Suspended Solids
WWTPs	Wastewater Treatment Plants

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CHAPTER I

INTRODUCTION

1.1 General

According to Baede et al., (2001) the earth surface average temperature without the effect of greenhouse gases (GHGs) would be -19°C compared to the existing average temperature of 14°C. Therefore, it is a significant atmosphere characteristic. The present concern is a rapid increase in the concentration of these gases which will disrupt the energy flow in the atmosphere of earth and eventually result in the global warming (Kemp, 1994).

Incoming solar radiation strikes the surface of the planet and some part of this energy is reflected from the surface as infrared radiation. Clouds and the atmosphere also radiate infrared radiation (IR). Part of this radiation is absorbed by GHGs and it increases the kinetic energy of their molecules. Increased concentrations of GHGs stimulate the atmospheric heat retention capacity and cause GHGs to act as a blanket that keeps solar heat inside atmosphere. As a result, the temperature of the earth increases (Baede et al., 2001; IPCC, 1996).

Increases of GHGs concentrations in the atmosphere have led to further studies of GHGs estimation and sources/sinks. A municipal wastewater treatment plant receives wastewater and produces treated water for discharge by using different processes such as aerobic treatment, anaerobic treatment and hybrid treatment. On-site greenhouse gases emissions are generated by liquid treatment processes, solids treatment processes, and the combustion of biogas and fossil fuels for energy generation. Off-site greenhouse gases may also be generated because of solids disposal (transportation and off-site degradation of solids), off-site energy production, and off-site chemical production (Monteith et al., 2005).

1.2 Necessity to Quantify Emissions of Greenhouse Gases

In recent years, global warming and climate change have become most important issues in the environment sector because of their effects on environment, economy and energy production (Yerushalmi et al., 2009). The Intergovernmental Panel on Climate Change (IPCC) recognized that the excessive greenhouse gases generation, mainly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from anthropogenic sources are partly liable for global warming and climate change (El-Fadel and Massoud, 2001).That is why, the identification and quantification of all sources, both natural and anthropogenic, is needed for developing strategies to control and reduce the rate of increase of the GHGs emissions into the atmosphere. Due to the generation of CO_2, CH_4, and N_2O during the treatment processes and CO_2 from the energy demand, wastewater treatment plants (WWTPs) are considered as a GHGs emissions source in the commercial sector (EIA, 2003). The international protocols and organizations have restricted the GHGs emissions, related regulations, obligatory limitations, carbon taxes, and penalties (EIA, 2003; IPCC 2006; Specified Gas Reporting regulation, 2007). Therefore, the generation of GHGs emissions from wastewater treatment plants must be estimated before any meaningful mitigation and reduction strategy can be designed and implemented. There is an interest to identify carbon footprints from wastewater treatment plants in terms of GHGs emissions, energy and natural gas usage, and energy production.

The Government of Canada ratified the Kyoto protocol on 17 December 2002 (UNFCCC, 2004). According to this commitment, Canada is expected to reduce GHGs emissions by 6% from 1990 emission levels during the period 2008-2012 (UNFCCC, 1997). Each sector of economy can assist to attain this target. Approximately, 24.8 mega tonnes (Mt) of carbon dioxide equivalent (CO_2 equiv) were produced from the waste sectors such as landfill gas generation, wastewater treatment, and incineration in Canada in 2001(Mohareb et al. 2004). The Canadian national inventories account for greenhouse gases emissions from the wastewater treatment sector (or wastewater handling) under the "Waste" sector including solid waste disposal on land and waste incineration (Sahely, 2006a). According to Greenfield and Batstone (2005), Kyoto and subsequent protocols demand specific regulations and/or fines for emissions of CH_4 and N_2O from wastewater treatment plants.

1.3 Greenhouse Gases and the International Protocol

The Kyoto protocol is a protocol to the United Nations Framework Convention on Climate Change (UNFCCC) adopted on 11 December 1997 in Kyoto, Japan and came into force on 16 February 2005 to reduce greenhouse gas emissions. Furthermore, the UNFCCC is an international environmental agreement with the goal to achieve stabilization of GHGs concentrations in the atmosphere at a level that would prevent dangerous anthropogenic intrusion with the climate system. Canada signed the Kyoto protocol on 29 April, 1998 and approved the protocol on 17 December, 2002 (UNFCCC, 2004). The Government of Canada at the time agreed to reduce GHGs emissions by 6 % from the national levels of 1990 over the five-year period 2008-2012 (UNFCCC, 1997).

1.4 Objectives

The main objectives of this study were to:

1. select an appropriate procedure for estimating GHGs emissions from municipal wastewater treatment plants, and
2. estimate the carbon based and non-carbon based GHGs emissions per cubic meter of treated wastewater at the Little River Pollution Control Plant and compare the off-site GHGs emissions between the Lou Romano Water Reclamation Plant and the Little River Pollution Control Plant.

1.5 Scope

The quantity and distribution of greenhouse gases produced depend on the characteristics of the influent wastewater, the treatment processes and the off-site processes (EI-Fadel and Massoud, 2001; Barton and Atwater, 2002). In this study, the estimation of GHGs was done by using field data. Only the GHGs emissions of carbon based (CO_2 and CH_4) and non-carbon based (N_2O) on-site processes were considered. Off-site GHGs emissions were estimated from electricity production, natural gas generation, remaining nutrient (BOD and TKN) degradation, remaining biodegradable biosolids degradation, and collection and transportation of biosolids. The seasonal temperature variations have been considered in this research.

All data and process parameters were collected from the Little River Pollution Control Plant and the Lou Romano Water Reclamation Plant for three years (from 2007 to 2009). Life cycle analysis (LCA) has not been considered in this study. For instance, the GHGs emissions associated with the construction of infrastructure (e.g. primary clarifier, aeration tank, secondary clarifier) were not estimated.

In accordance with the IPCC default methodology, estimation of N_2O emissions in wastewater treatment processes was calculated only for human waste based on annual per capita protein intake. In the present methodology, the industrial nitrogen loading, non-consumption protein from kitchen, bath, and laundry discharges were included. The emission factor was modified for quantifying the emissions of nitrous oxide from wastewater.

CHAPTER II

REVIEW OF LITERATURE

2.1 General

In the last few years, GHGs emissions from wastewater treatment processes and operations have become a significant concern and are increasingly being measured and assessed while determining the long term sustainability of a treatment scheme (Scanlan et al., 2008). Atmospheric concentrations of greenhouse gases have increased due to anthropogenic activities such as production and use of fossil fuels and other agricultural and industrial activities during the last 200 years (El-Fadel and Massoud, 2001). According to the U.S. EPA (1997), wastewater treatment plants (WWTPs) are one of the larger minor sources of GHGs emissions. These plants produce the three important GHGs namely carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) during the treatment processes, both directly and indirectly. Direct emissions occur during the treatment process through gaseous byproducts such as CO_2, CH_4, and N_2O, while indirect emissions occur during the use of energy and ancillary activities. Specifically, aerobic biological treatment plants emit a significant quantity of greenhouse gases because of using considerable amounts of power (Shaw et al., 2008).

2.2 Global Warming Potential

Gases in the atmosphere can contribute to the greenhouse effect both directly and indirectly. Direct effects occur when the gas itself absorbs radiation. Indirect effects occur when a gas changes the lifetimes of other gases, chemical transformations of the substance produce other greenhouse gases, and/or when a gas affects atmospheric processes (EPA, 2004). For comparing the ability of each greenhouse gas to trap heat in the atmosphere relative to another gas, the IPCC developed the Global Warming Potential (GWP) concept. The GWP of a greenhouse gas gives the ratio of time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas (IPCC 2001). Thus, the GWP is a relative measure used to compare the radiative effects of different gases. It also means that, the GWP of a GHG is the ratio of heat trapped by one unit mass of the gas compared to one unit mass of CO_2 over a certain time period, usually 100 years.

The N_2O and CH_4 gases are capable of absorbing more infrared radiation or heat per unit mass and this property translates into their greater global warming potential (EI-Fadel and Massoud, 2001). For example, the GWP of N_2O is 296 which mean that N_2O is able to absorb infrared radiation 296 times of an equivalent mass of CO_2 over 100 years. According to Wallington et al., (2004) the present atmospheric concentration of CH_4 is 1750 ppb, which means that 1750 molecules of CH_4 are present in one billion molecules of ambient air. The relative GWP, radiative forcing, residence time, and atmospheric concentrations of the three major GHGs related to municipal WWTPs operations are shown in Table 2.1.

Table 2.1: The GWP, radiative forcing, residence time, and atmospheric concentrations of GHGs produced in the WWTPs (Wallington et al., 2004)

GHG	Radiative Forcing (W/m^2)	Global warming potential over 100-year period	Atmosphere residence time (years)	Atmospheric concentration (ppb)
CO_2	0.000018	1	5-200*	370,000
CH_4	0.00037	23	12	1750
N_2O	0.0032	296	114	314

*No single life time can be allotted to CO_2 because of different rates of uptake by different removal processes.

The radiative forcing is an absolute measure of the strength of a GHG on a per volume basis, whereas the GWP is a relative measure on a per mass basis.

2.3 Different Types of GHGs Emissions

Carbon dioxide, methane, and nitrous oxide are three major greenhouse gases emitted in a typical wastewater treatment plant.

2.3.1 Carbon Dioxide Emissions

Sahely (2006a) suggested that CO_2 is generated from the oxidation of organic material during wastewater treatment and combustion of fossil fuel on-site for heating. According to EI-Fadel and Massoud (2001) and IPCC (1996), the national greenhouse gas inventory of Canada does not include the emissions of CO_2 from biomass based wastes. However, IPCC method includes the CO_2 emissions from fossil fuel produced for wastewater treatment processes and combustion of these fuels in boilers within the “Energy” sector (Sahely, 2006a).

The alkalinity consumption is considered as the other main source of off-site CO_2 production, which converts inorganic carbon to carbon dioxide (Diagger et al., 2004). Alkalinity consumption is mostly in the bicarbonate form (HCO_3^-) at near neutral pH. The reaction is in the following form:

$$HCO_3^- + H^+ \rightleftharpoons CO_2 + H_2O \qquad (2.1)$$

Alkalinity as $CaCO_3$ is used during nitrification process and it is generated during biomass decay as well as denitrification process (Shahabadi, 2008).

2.3.2 Methane Emissions

Methane gas is usually produced under anaerobic condition during organic matter decomposition. Untreated wastewater may also generate CH_4 if anaerobic condition is maintained there (Scheehle and Doorn, 2001). The CH_4 emissions rate from wastewater management practices varies from country to country and depends on organic fraction, level of treatment and estimation method (El-Fadel and Massoud, 2001).

The methane gas can be emitted from four types of sources. Energy, agriculture and waste management are three major sources and industrial process is a minor source. Approximately 28.6 % of CH_4 was emitted from waste management sector in the United States in 2002 and it can be subdivided into two categories, anaerobic decomposition of municipal solid waste in landfills and wastewater treatment facilities. The United States methane emissions from waste management sector dropped by 7.3 % from 8.2 million metric tons in 2001 to 7.6 million metric tons in 2002 (EIA, 2003). The changes for the United States during 1990 -2002 are shown in Table 2.2.

Table 2.2: The U.S. methane emissions from domestic and commercial wastewater treatment, 1990-2002 (EIA, 2003)

	CH_4 (Millions Metric Tonnes)	CO_2 equivalent (Million Metric Tonnes)
Estimated 2002 Emissions	0.7	15.3
Change Compared to 2001	Less than 0.05	0.2
Change from 2001 (%)	1.3%	1.3%
Change Compared to 1990	0.1	2.1
Change from 1990 (%)	15.6%	15.6%

2.3.3 Nitrous Oxide Emissions

Both domestic and industrial wastewaters may be a source of nitrous oxide emissions. Certain industrial wastewaters associated with significant nitrogen loadings are discharged to the municipal sewers, which are mixed with domestic, commercial, and institutional wastewaters. Domestic wastewater generally includes human waste and discharges from kitchen, bath, laundry, etc. Collection system of this type of wastewater can be an on-site or decentralized wastewater treatment system such as a septic tank system, or a centralized wastewater treatment system (Scheehle and Doorn, 2001).

Not only solid waste and wastewater sludge incineration contribute to the increase in atmospheric N_2O, but also biological nutrient removal processes are potential source of N_2O (Barton and Atwater, 2002; Schulthess and Gujer, 1996). Furthermore, N_2O may be produced by both nitrification and denitrification of the nitrogen present in the form of urea, ammonia and proteins during biological wastewater treatment processes. These are converted to nitrates (NO_3^-) by nitrification in aerobic process. Denitrification is an anaerobic biological conversion of nitrates (NO_3^-) into dinitrogen gas (N_2). Nitrous oxide is an intermediated product of both processes (Thomsen and Lyck, 2005).

Nitrous oxide is important as a greenhouse gas due to its higher potential in comparison to CO_2 to absorb infrared radiation which produces heat. The atmospheric mixing rate of N_2O is increasing at a rate of 0.25 to 0.31 % per year and its mixing ratio was around 310 ppbv (Khalil and Rasmussen, 1992). Lifetime of N_2O is around 114 years in the atmosphere and its radiative forcing is much higher than that of CO_2 (IPCC, 2001). According to Cicerone (1989) and Bliefert and Perraud (2001), N_2O is the major source for formation of stratospheric NO which causes the destruction of stratospheric ozone. Hanaki et al., (2001) identified wastewater treatment as a potential source among various anthropogenic sources which produce N_2O. Hong et al., (1993) and Debruyn et al., (1994) also reported that the transport and management of municipal wastewater results in N_2O emission and bacterially mediated denitrification is the key factor of N_2O production.

2.4 Characteristics of Municipal Wastewater

Municipal wastewater treatment plants remove contaminants from the wastewater to make it suitable for discharge into surface water. Generally, several stages are included in the treatment process, preliminary treatment, primary treatment, secondary treatment and tertiary treatment. The sludge which is removed from treatment process may be processed by aerobic/anaerobic digestion, dewatering, alkaline stabilization, composting, thermal drying or air drying or incineration.

The wastewater treatment process selection is greatly influenced by the ratio between the various pollutants parameters in the wastewater. Table 2.3 shows typical component ratios in municipal wastewater.

Table 2.3: Typical ratios between pollutant parameters in municipal wastewater (Henze et al., 2008)

Ratio	High strength of wastewater	Medium strength of wastewater	Low strength of wastewater
COD/BOD	2.5-3.5	2.0-2.5	1.5-2.0
COD/TN	12-16	8-12	6-8
BOD/TN	6-8	4-6	3-4
COD/VSS	1.6-2.0	1.4-1.6	1.2-1.4
VSS/TSS	0.8-0.9	0.6-0.8	0.4-0.6
COD/TOC	3.0-3.5	2.5-3.0	2.0-2.5

COD = chemical oxygen demand, BOD = biochemical oxygen demand, TN = total nitrogen, VSS = volatile suspended solids, TOC = total organic carbon

2.5 Different Types of Treatment Processes in the Municipal WWTPs

Wastewater can be generated from different sources such as domestic, commercial and industrial sources. Household used water is called domestic wastewater and industrial wastewater is collected from industrial operations only, whereas municipal wastewater is a combination of household, commercial and non-hazardous industrial wastewaters. The treatment process of wastewater can be on-site (uncollected) or sewered to a centralized plant (collected) (IPCC, 2006).

In developed countries, the most common methods of treatment processes are centralized aerobic treatment processes and lagoons for both domestic and industrial wastewaters. Centralized aerobic wastewater treatment methods are subdivided as preliminary or/and primary, secondary and tertiary treatment processes. Different pathways for wastewater discharges and treatment are shown in Figure 2.1. Physical barriers move out larger solids particle from the wastewater through preliminary and primary treatment, while in secondary treatment, organic-matters are biodegraded by microbial oxidation. Generally, it may consist of aerobic stabilization ponds, trickling filters, activated sludge processes, rotating biological contractors or/and anaerobic reactors, lagoons. Tertiary treatment is implied to further treat or remove the pathogens, remaining contaminants and nutrients such as nitrogen and phosphorus compounds. This may include maturation ponds, biological processes, advanced filtration, carbon adsorption, ion exchange, and disinfection with chlorine or other disinfecting compounds such as ozone or ultraviolet light (IPCC, 2006).

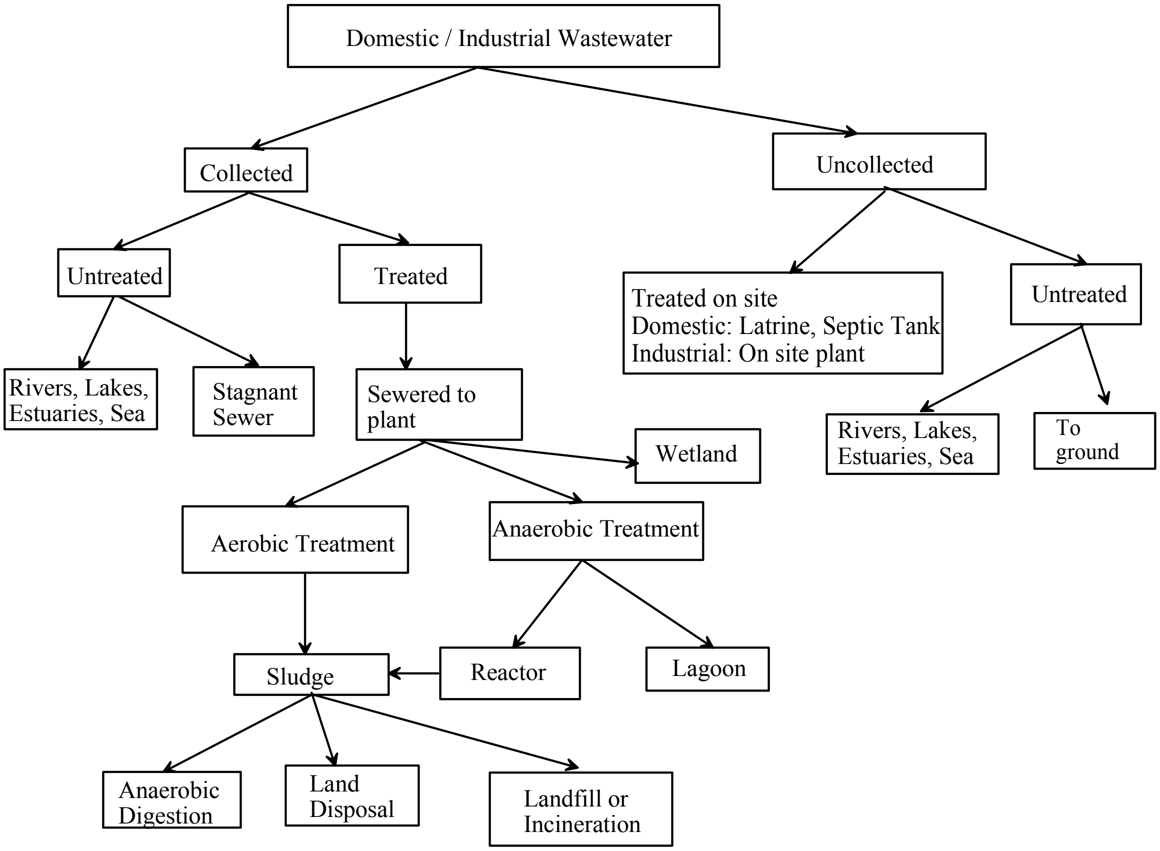


Figure 2.1: Different pathways of wastewater treatment systems and discharges (adapted from IPCC, 2006).

The wastewater treatment plants generally include the unit operations which are mentioned in Table 2.4.

Table 2.4: Unit processes of the municipal wastewater treatment plant (Metcalf and Eddy, 1995)

Treatment Process		Unit Operation	Removed Contaminants	Equipments	Significance
Physical unit operation	Preliminary treatment	-Mechanical bar screens and comminution -Gravitational bar screening -Floatation	-Debris rags and grit -Suspended solids -Heavier inorganic particles	-Bar screen -Fine particle sieving -Grit chamber -Pre aeration -Grease wall -Scraping chamber	To avoid clogging of equipment
	Primary treatment	-Sedimentation -Coagulation -Floatation	-A portion of the suspended solids and organic matter -Colloidal substances with the help of coagulants	-Primary clarifier -Sedimentation tank	- To remove most of the suspended solids
Chemical and biological unit process	Secondary treatment	-Biological	- Organic matter	-Aeration tank -Trickling Filter	-To remove all organic matter by micro-organisms

2.5.1 Anaerobic Wastewater Treatment

Anaerobic processes are classified as biological treatment processes that occur in the absence of oxygen (Metcalf and Eddy, 1995). Generally, anaerobic treatment has been used to treat sludges and medium to high strength wastewaters (2,000 to 20,000 mg/L COD). As shown in Figure 2.2, wastewater is usually stabilized by using three steps such as hydrolysis, acid fermentation, and methanogenesis in anaerobic treatment process (Cakir and Stenstrom, 2005). Anaerobic decomposition by methanogenic bacteria of the organic matter produces CH_4 and CO_2. Therefore, global CH_4 is the main emission from anaerobic wastewater treatment. In Jordan, it accounted for 4.663Gg/year from domestic and commercial wastewater, whereas 0.075 Gg/year was emitted from industrial wastewater (Abdulla and AI-Ghazzawi, 1998). In Canada, it is estimated that 1600 Mg/year of CH_4 was emitted from municipal wastewater treatment plants in 2000 (Sahely et al., 2006).

Anaerobic treatment process has the potential to reduce greenhouse gases, specifically CO_2 emissions through energy conservation (Cakir, 2004). However, according to Yerushalmi et al., (2009) in anaerobic and hybrid treatment systems, the overall off-site emissions of GHGs are higher than the on-site processes. Flow diagram of anaerobic treatment system is shown in Figure 2.3.

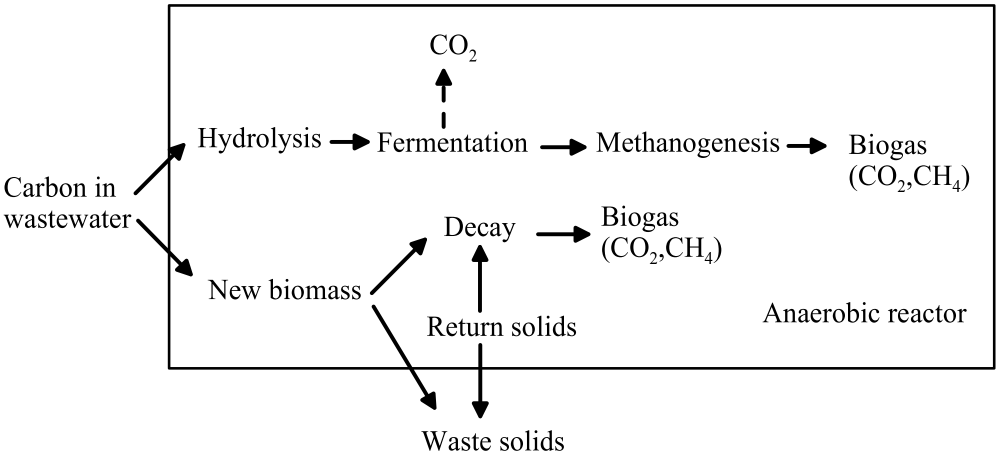


Figure 2.2: GHGs production in anaerobic process (adapted from Yurushalmi et al., 2009)

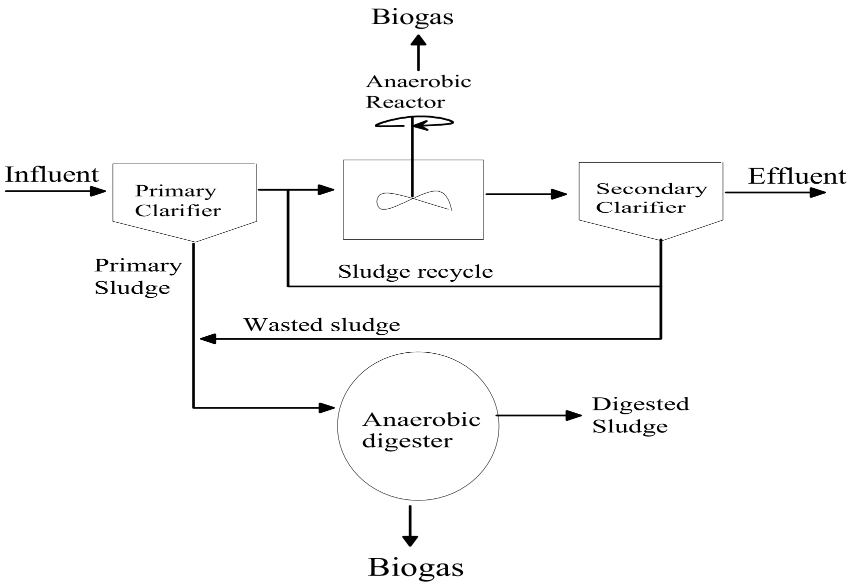


Figure 2.3: Flow diagram of anaerobic treatment system with digester (adapted from Shahabadi et al., 2009)

2.5.2 Aerobic Wastewater Treatment

Aerobic treatment process can consist of activated sludge process, biological aerated filter, trickling filters, rotating biological contractors, and similar other unit operations. Furthermore, aeration is needed for biodegradation of organic matter by microorganisms in this type of treatment processes. That is why this process leads to higher greenhouse gases emissions due to high energy demands (Shahabadi, 2008). When the biodegradable organic matter is stabilized by aerobic treatment, the carbon in the organic matter is converted to CO_2 as shown in Eq. 2.2 (Grady et al., 1998). If the same amount of organic matter is stabilized anaerobically, CO_2 and CH_4 are produced as illustrated in Eq. 2.3. The GWP of CH_4 is 21 times greater than of CO_2. Therefore, aerobic stabilization of organic matter significantly reduces greenhouse gas impact in comparison to anaerobic stabilization.

$$CH_2O + O_2 \longrightarrow CO_2 + H_2O \qquad (2.2)$$

$$2CH_2O \longrightarrow CO_2 + CH_4 \qquad (2.3)$$

Flow diagram of aerobic treatment system is shown in Figure 2.4 (Shahabadi et al., 2009).

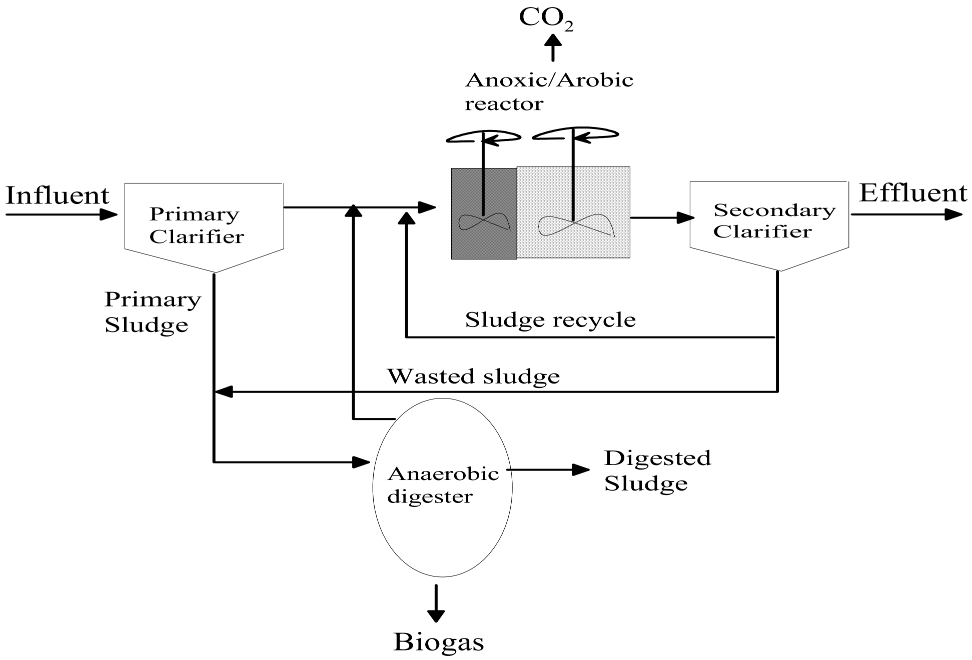


Figure 2.4: Flow diagram of aerobic treatment system with digester (adapted from Shahabadi et al., 2009)

2.5.3 Conventional Activated Sludge System

Conventional activated sludge system is shown in Fig. 2.5. Sludge age or sludge retention time is an important design factor for an activated sludge system. Sludge retention time (SRT) depends on several factors which are shown in Table 2.5.

Table 2.5: Important factors for selection of sludge retention time in activated sludge system (Henze et al., 2008).

Sludge retention time (SRT)	1 to 5 days (short)	10 to 15 days (Intermediate)	Greater than 20 days (Long)
Types	High rate, Step feed, aerated lagoon, contact stabilization.	Same to high rate but with nitrification and sometimes denitrification, Biological nitrogen removal (BNR) systems.	Extended aeration, BNR systems.
Objectives	BOD/COD removal only.	BOD/COD removal, nitrification, biological N removal, and/or biological P removal.	BOD/COD removal, biological N removal, biological P removal.
Settled activated sludge quality	High sludge production, very active, stabilization required.	Medium sludge production, quite active, stabilization required.	Low sludge production, inactive, no stabilization required.
Oxygen demand	Very low	High due to nitrification.	Very high due to nitrification and long sludge age.
Advantages	Low capital costs, energy self sufficient with anaerobic digestion.	Relatively low capital costs for biological N and or P removal	Low sludge handling costs, no primary and secondary sludge.
Disadvantages	High operation costs.	Complex and expensive sludge handling costs.	Large reactor, high oxygen demand, high capital cost.

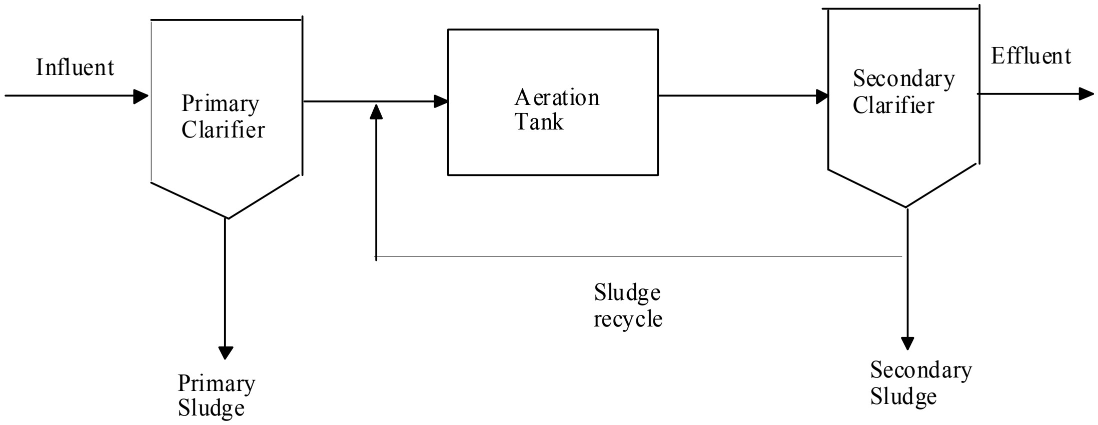


Figure 2.5: Conventional activated sludge systems

2.6 Sources of GHGs in the WWTPs

Greenhouse gas emissions from wastewater treatment plants can be classified into three different sources, namely energy, liquid process emissions and emissions from biosolids processing (Diagger et al., 2004). In the case of energy source, it can be considered as off-site or upstream emission because, it occurs outside of the treatment plant. Alkalinity consumption is also considered as off-site CO_2 emission source (Shahabadi, 2008). One of the main on-site sources of GHGs is the liquid treatment process. This is mainly contributed through biodegradable organic matter stabilization and on-site fossil fuel combustion for energy and heat production (Yerushalmi et al., 2009).

2.6.1 Off-site GHGs Emissions

Electrical energy is used in wastewater treatment plants in a variety of ways such as for aeration, heating purposes etc. Electricity may be produced from different primary sources such as coal, oil, hydropower, natural gas, etc. (Diagger et al., 2004). The estimations of GHGs emissions from WWTPs are associated with off-site emissions which are due to generation and transportation of energy, electricity and chemicals for on-site use and biosolids transport. The off-site GHGs emissions due to electricity generation based on the electricity generation mix in Canada have been reported by Yerushalmi et al., (2009). These off-site GHGs emissions were estimated to be 0.65 kg CO_2-equiv/kg BOD. The off-site GHGs emissions were estimated to be 40.2% of the overall greenhouse gas emissions in the aerobic treatment system without recovery and use of the generated biogas. However, due to on-site material usage and energy demand, the higher value of off-site GHGs emissions were estimated in anaerobic and hybrid treatment.

2.6.2 On-site GHGs Emissions

The on-site GHGs emissions from WWTPs result from liquid and bio-solids treatment processes as well as biogas and fossil fuel combustion for energy generation. The WWTPs release CO_2 through the oxidation of soluble organic matter, endogenous respiration of the microbial cell mass responsible for BOD removal, incineration of waste solids and combustion of fossil fuel such as natural gas for heating, which is considered to be on-site GHGs (Sahely et al., 2006b).

Yerushalmi et al., (2009) estimated that the total GHGs emissions from the aerobic, anaerobic and hybrid treatment systems were 1.6, 3.3 and 3.8 kg CO_2-equiv/kg BOD, respectively.

According to Shahabadi et al., (2009) and Yerushalmi et al., (2009) in the aerobic treatment system, the highest amount of greenhouse gases was emitted by the on-site biological processes. In 2000, approximately 0.2% of total Canadian GHG emissions were estimated from on-site wastewater handling, which means 703 Gg CO_2 eqiuv/yr. Within this amount 343 Gg CO_2 eqiuv/yr was emitted from on-site in Ontario (Sahely et al., 2006b).

2.7 GHGs Emissions from Unit Operations

2.7.1 Primary Clarifiers

The heavier suspended solids are settled by gravity in the primary clarifiers, and then these settled solids are removed (Metcalf and Eddy, 1995). A primary clarifier also removes some biodegradable organic matter by simple sedimentation, which is not stabilized. An increase in the sludge production in primary clarifiers results in less GHGs emissions (Diagger et al., 2004).

Czepiel et al., (1995) estimated the amount of N_2O emissions from the surface of the primary settling tank to be negligible.

2.7.2 Aeration Tanks

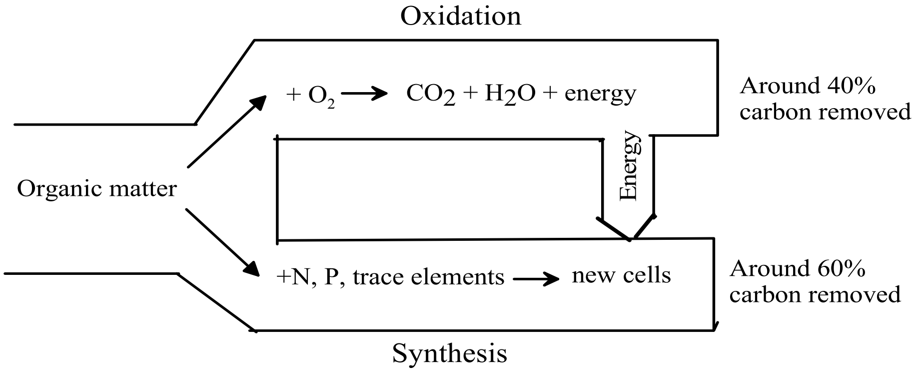


Figure 2.6: Pathways for the removal of BOD in aerobic reactor in the biological wastewater treatment (adapted from Manahan, 2005).

Czepiel et al., (1995) identified that the highest amount of N_2O was emitted from aeration tanks as compared to other unit operations. The estimated annual emissions from aeration tanks was $3.2*10^4$ g N_2O/person per yr whereas the total estimated annual N_2O emissions accounted for $3.5*10^4$ g N_2O/yr from Durham, NH, wastewater treatment plant.

2.7.3 Secondary Clarifiers

A secondary clarifier separates the biosolids from the liquid and removes settled solids from the bottom of clarifier. The N_2O emissions from secondary clarification tank were negligible (Czepiel et al., 1995).

2.8 Different Processes Responsible for N_2O Emissions

The different sources of N_2O emissions to the environment are shown in Figure 2.7. The possible pathways for N_2O emissions from wastewater treatment processes are presented in Figure 2.8.

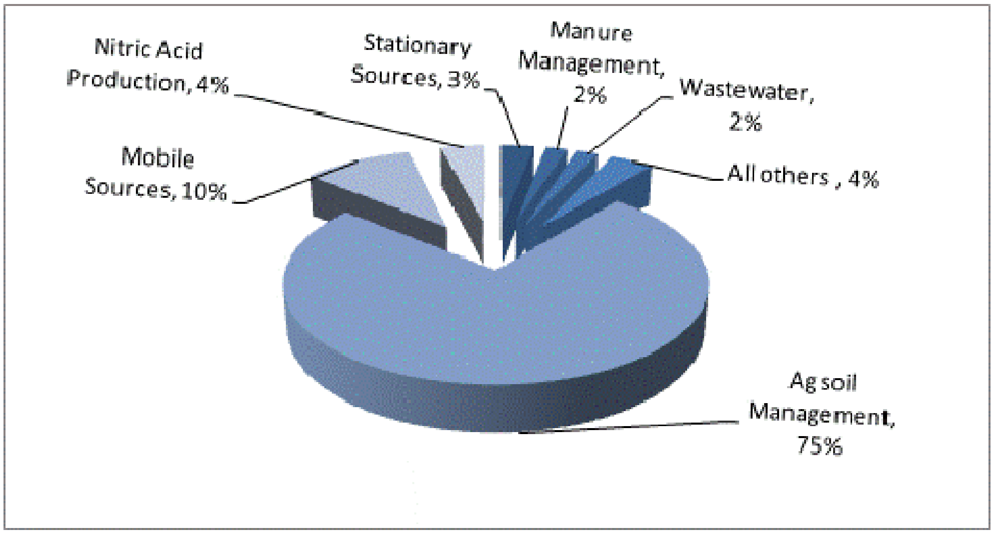


Figure 2.7: EPA distribution of nitrous oxide sources (adapted from Crawford, 2009)

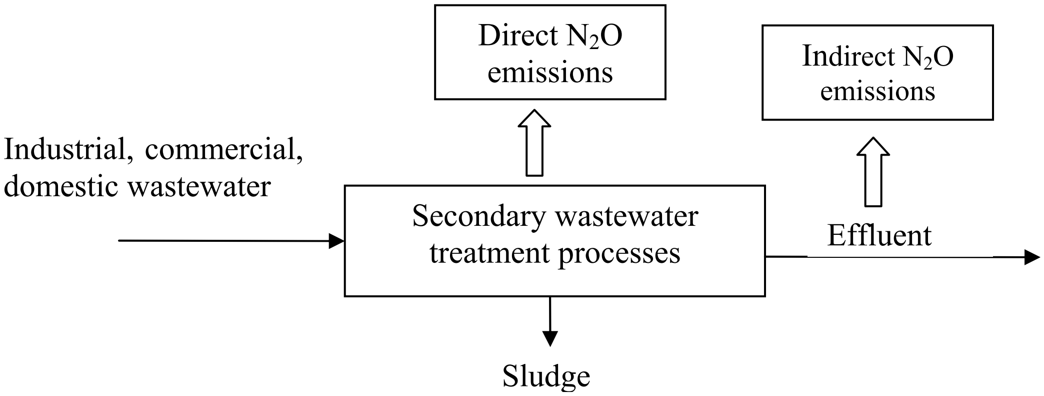


Figure 2.8: Possible pathways of nitrous oxide sources in conventional wastewater treatment process (adapted from Crawford, 2009).

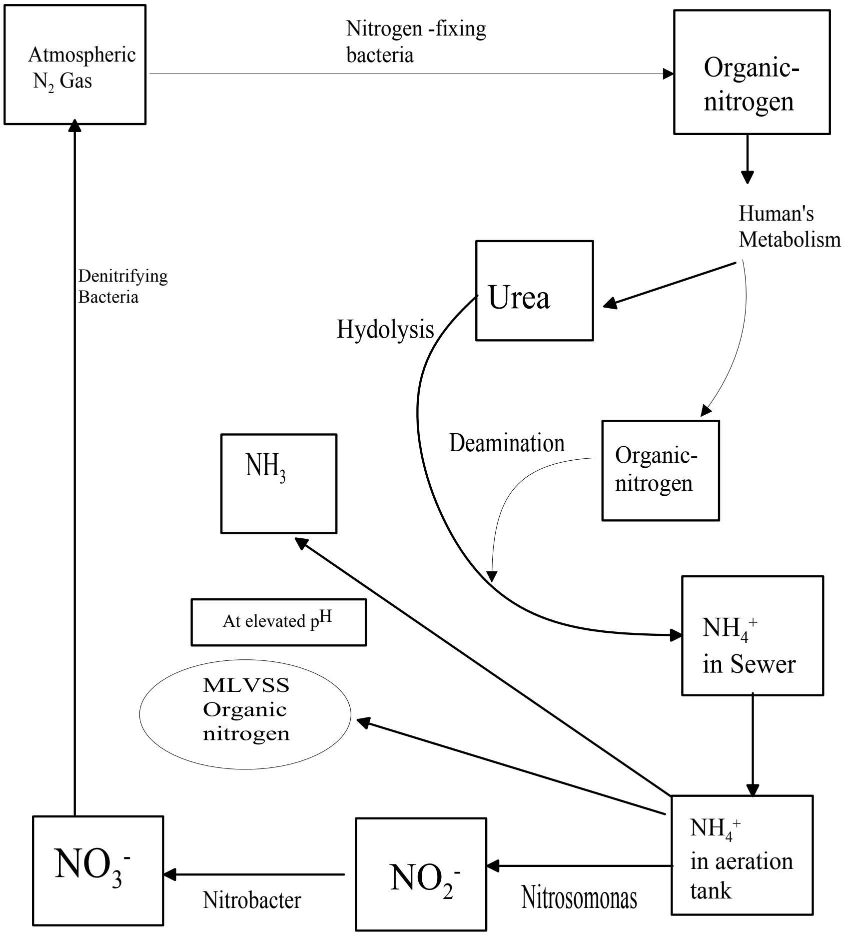


Figure 2.9: Wastewater nitrogen cycle (adapted from Gerardi, 2002)

The greenhouse gases, N_2O can be generated during biological wastewater treatment processes (Fig. 2.9). Since, N_2O has around 300 hundred times effect as compared to CO_2; it is an important GHG (IPCC, 2001) even if it is emitted in low amounts. Based on literature reviews, it is relatively difficult to identify the source and magnitude of N_2O emissions in WWTPs. Generally, N_2O emissions depend on many operational parameters of WWTPs and environmental conditions. Therefore, the emissions of N_2O fluxes are highly unstable (Kampschreur et al., 2009a).

2.8.1 Production of Nitrous Oxide during Nitrification

Usually, nitrogen is present in wastewater as ammonium ions and it is removed by two sequential biological processes such as nitrification and denitrification during conventional wastewater treatment processes. The ammonium (NH_4^+) is oxidized to NO_3^- via NO_2^- using O_2 as electron acceptor in nitrification process (Colliver and Stephenson, 2000). Nitrous oxide is generated as one of the by-products of NH_4^+ oxidation to nitrite (NO_2^-) (Prosser, 1989).

Table 2.6: Oxidation of ammonia to nitrites by Nitrosomonas (Colliver and Stephenson, 2000)

Step	Reaction
1	$NH_3 + O_2 + 2H^+ + 2e^- \longrightarrow NH_2OH + H_2O$ Ammonia mono-oxygenase
2	$NH_2OH + H_2O \longrightarrow NO_2^- + 5H^+ + 4e^-$ Hydroxyl amine oxidoreductase
3	$0.5O_2 + 2H^+ + 2e^- \longrightarrow H_2O$
Total	$NH_3 + 1.5O_2 \longrightarrow NO_2^- + H^+ + H_2O$

Table 2.7: Oxidation of nitrite to nitrate by Nitrobacter (Colliver and Stephenson, 2000)

Step	Reaction
1	$HONO + H_2O \longrightarrow HONO_2 + 2H^+ + 2e^-$ Nitrite oxidoreductase
2	$0.5O_2 + 2H^+ + 2e^- \longrightarrow H_2O$
Total	$HNO_2 + 0.5O_2 \longrightarrow HNO_3$

Nitrite has been considered as an important factor causing N_2O production which reduces the advantages of nitrogen removal via nitrite. Nitrous oxide production during nitrogen removal via nitrite was 1.5 times higher than that of nitrogen removal via nitrate (Yang et al., (2009). Based on the literature, there are several key factors leading to N_2O production such as low dissolved oxygen (DO), high ammonia concentration, high nitrite concentration, low chemical oxygen demand (COD) to NO_x^- N ratio and short SRT.

Jetten et al., (1997) suggested that bacteria able to carry out complete nitrogen cycle and autotrophic nitrifying bacteria can reduce NO_2^- to the intermediates NO and N_2O or N_2 at reduced oxygen level. Recently, a number of studies have shown that NO and N_2O were produced due to biological activity by ammonia oxidizer, which is called nitrifier denitrification (Stuven et al., 1992; Anderson et al., 1993; Colliver and Stephenson, 2000). Figure 2.10 shows the nitrifier denitrification pathway and the probable enzymes.

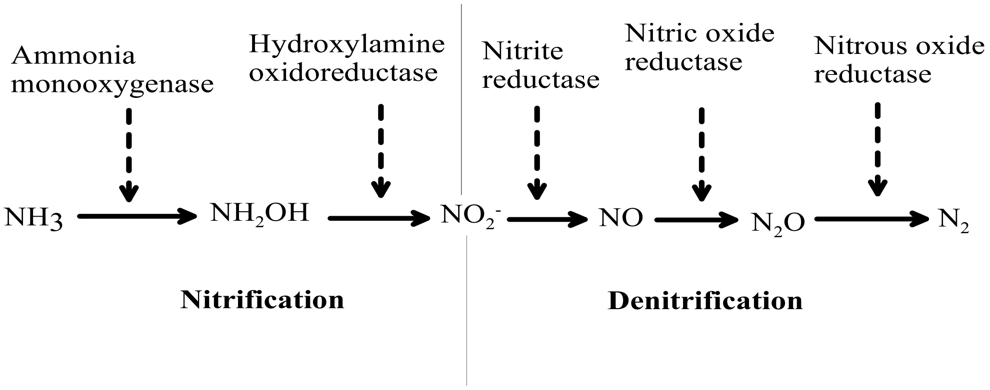


Figure 2.10: Nitrifier denitrification: hypothetical pathway and enzymes involved (adapted from Poth and Focht, 1985)

2.8.2 Production of Nitrous Oxide during Denitrification

USPA (2006), reported that N_2O production was more associated with denitrification processes. Denitrification is an anoxic process in which heterotrophs use N-oxide as an electron acceptor instead of O_2 (Colliver and Stephenson, 2000). The denitrification follows the four steps which are shown in Figure 2.11. Therefore, incomplete denitrification can produce and release N_2O in to the atmosphere.

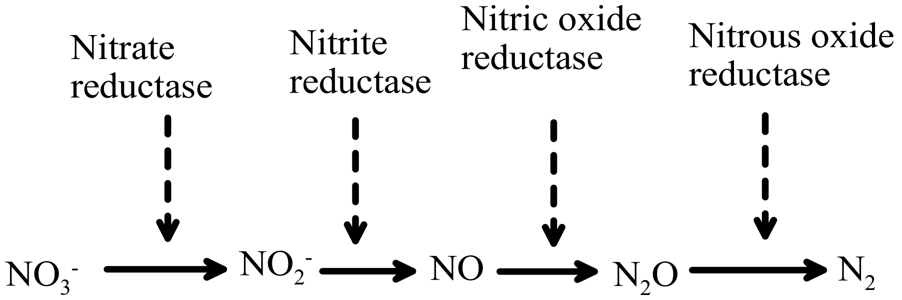


Figure 2.11: Denitrification pathway and enzymes involved (adapted from Hochstein and Tomlinson, 1988)

Overall scheme for N_2O production through nitrification, denitrification and nitrifier-denitrification is shown in Fig. 2.12.

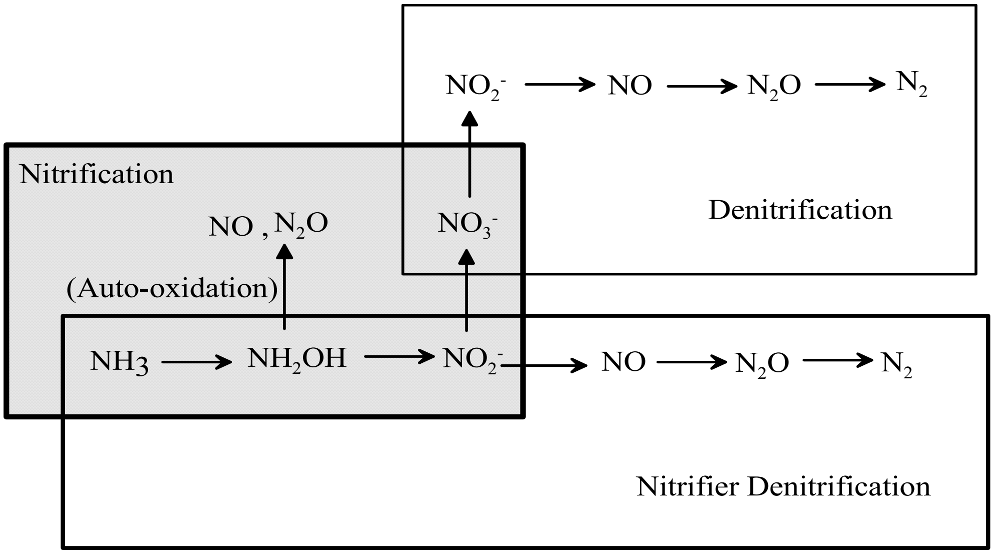


Figure 2.12: Pathways for nitrous oxide production (Wrage et al., 2001; Cantera and Stein, 2007)

2.9 Emission Factors for Nitrous Oxide related to Wastewater Treatment Plant

The IPCC (2006) has changed the standard N_2O emission factor from 1% to 0.5% of the nitrogen content of the effluent of a treatment plant, even though both factors are still used. In 2006, the IPCC guideline assumed that direct emission of N_2O from WWTPs was a minor source but the largest emission of N_2O derived from nitrogen in wastewater by nitrification and denitrification in estuaries and rivers. Therefore, a lower factor was considered for the direct emission from WWTPs which typically contains 3.2 g N_2O/ person/ year (IPCC, 2006). In addition, some pilot scale and field measurements showed that a significant amount of N_2O can be produced in WWTPs during biological nitrogen removal process, which are shown in Table 2.8 (Osada et al., 1995; Tallec et al., 2006; Kampschreur et al., 2008b; Foley et al., 2009).

Table 2.8: Nitrous oxide emissions (% of N-load) in full-scale and lab-scale measurement (Kampschreur et al., 2009a)

N_2O emission (% of N-load)	Type of WWTP	Sample frequency	Remarks	Reference
Full-Scale Measurement				
0.035% *	Activated sludge (11,000 PE)	Weekly grab sample (vented chamber) during 15 weeks		Czepiel et al. (1995)
0–14.6% (0.6% average)	25 activated sludge plants	Single grab samples per WWTP	N_2O emission increased with increasing nitrogen load	Wicht and Beier (1995)
0.001%	Activated sludge plant (60,000 PE)	2-weekly grab samples over 1 year	N_2O emission increased with nitrite and nitrate concentrations	Sümer et al. (1995)
0.02%	Activated sludge plant (60,000 PE)	1 or 2-weekly grab samples during 1.5 years		Sommer et al. (1998)
0.01–0.08%	Activated sludge plant (1000 PE)	On-line measurements during 4 aeration cycles (2 h)	N_2O emission decreased with proportionally shorter aeration periods	Kimochi et al. (1998)
2.3% **	Nitritation – anammox sludge water treatment	On-line measurements during 4 days	N_2O emission increased with decrease in oxygen concentration (aerated stage) and increase of nitrite concentration (anoxic stage)	Kampschreur et al. (2008b)
4%	Nitrification stage (nitrogen removal stage) of activated sludge plant (620,000 PE)	3 grab samples during one day		Kampschreur et al. (2008b)

Table 2.8 (continued)

N_2O emission (% of N-load)	Type of WWTP	Sample frequency	Remarks	Reference
Lab-Scale Measurement				
2.3–16%	Continuous nitrifying activated sludge–artificial wastewater	Daily grab samples	N_2O emission increased with decreasing O_2 concentration and SRT	Zheng et al., (1994)
1–35%	Continuous oxic–anoxic SBR activated sludge – real high strength wastewater (>50 days)	Grab samples	N_2O emission higher with longer aeration period in one SBR cycle, probably linked to increased nitrite levels	Osada et al., (1995)
5–95%	Continuous oxic–anoxic SBR activated sludge –artificial wastewater (380 days)	Grab samples	N_2O emission decreased over time – increased N_2O emission possibly a start-up phenomenon	van Benthum et al., (1998)
0.005–0.5%	Batch tests denitrifying activated sludge-artificial wastewater	Grab samples	N_2O emission increased with decrease of COD/N ratio	Chung and Chung (2000)
0.2–4.5%	Continuous nitrifying and denitrifying activated sludge – real wastewater	Grab samples	N_2O emission decreased upon methanol addition for higher COD/N ratio	Park et al., (2000)
0.08–1.17%	Continuous nitrifying activated sludge – artificial wastewater	On-line measurement	N_2O emission increased with increasing ammonia shock loads and nitrite concentration	Burgess et al., (2002a)
0.2–1.5%	Continuous activated sludge – real wastewater (50 days)	Weekly grab samples	N_2O emission increased with decreasing O_2concentration and decreasing SRT	Noda et al., (2003)
0.2–0.5%	Continuous nitrifying activated sludge – artificial wastewater (30–300 days)	Daily grab samples	N_2O emission ratio increased with increasing salt concentration	Tsuneda et al., (2005)
0.7–13%	Continuous oxic–anoxic activated sludge	Daily grab samples	N_2O emission increased with increasing salt	Tsuneda et al., (2005)

	–artificial wastewater (30–300 days)		concentration	
0.1–0.4%	Batch test (5 h) nitrifying activated sludge – real wastewater	On-line measurement	N_2O emission is largest at 1.0 mg O_2/L and lower above and below this O_2 concentration – emission increases with nitrite concentration	Tallec et al., (2006a)
0.2–1% (0.4% average)	Batch test (1 day) nitrifying biofilter – real wastewater	On-line measurement	N_2O emission ratio increased with decreasing O_2 concentration	Tallec et al., (2006b)
0.4%	Batch test (5 h) nitrifying activated sludge – real wastewater	On-line measurement	N_2O emission is largest at 0.3 mg O_2/L and lower above and below this O_2 concentration	Tallec et al., (2008)
2.8%	Continuous nitrifying SBR activated sludge – artificial wastewater	On-line measurement	N2O emission increased with decreasing O_2 and increasing nitrite concentration	Kampschreur et al., (2008a)

* Based on the assumption of 100 g protein/person/day and 0.16 g N/g protein (FAO-statistics, IPCC, 2006), the value of 3.2 g N_2O/person/year is converted into a ratio.

** Sum of load based N_2O emission of nitritation reactor (1.7%) and anammox reactor (0.6%).

PE = people

2.10 Operational Factors for GHGs Emissions

The methane gas generation from wastewater treatment management depends on degradable organic fraction which is expressed as biochemical oxygen demand (BOD) or chemical oxygen demand (COD). When BOD or COD concentration increases, CH_4 production also increases (EI-Fadel and Massoud, 2001). The other environmental factors are temperature, retention time, pH, degree of wastewater treatment, competition between methanogens and sulfate reducing bacteria, toxicants, and presence of oxygen (DeHollander, 1998; EI-Fadel and Massoud, 2001).

Different operating parameters are responsible for N_2O emissions, such as hydraulic retention time (HRT), dissolved oxygen (DO), pH, water temperature, C/N and so on (Hynes and Knowles, 1984; Brenner and Argaman, 1990; Kishida, et al., 2004). According to Kishida et al., (2004) the total N_2O emissions from influent nitrogen with BOD to TN of 2.6 was 10 times higher than with BOD to TN of 4.5 during biological nitrogen removal process of swine wastewater.

2.11 Control and Reduction Strategies

Greenhouse gases are produced in municipal biological wastewater treatment plant due to different reasons (Stephenson et al., 2007):

1. Using large amounts of energy from electrical and natural gas utilities to operate the plant,
2. Inherently producing CO_2 in cause of organic matter oxidation, which is lost to the atmosphere, and
3. Generating excess microorganisms (biomass) that must be disposed of.

The nitrous oxide is emitted as a byproduct during nitrification and denitrification processes, when ammonia is present in effluent (IPCC, 2001).

According to Monteith et al., (2005) there are two significant steps that can be used to reduce the GHGs production in the WWTPs. The first is the effective conversion of waste activated sludge to biogas in an anaerobic digester and the other is the conversion of biogas to energy. When a WWTP uses biogas to generate heat and electricity, it reduces the use of non-renewable energy and the mass of residual sludge (Stephenson et al., 2007). Mohareb et al., (2008) also suggested that waste incineration and anaerobic digestion of organic wastes can reduce GHGs emissions from waste sector.

CHAPTER III

DESIGN AND METHODOLOGY

3.1 General

Wastewater and biosolids (sewage sludge) are of interest in calculating carbon emissions. The estimation of GHGs emissions from wastewater treatment plant and wastewater solids management is a relatively new attempt. According to the Environment of Canada, the GHGs estimations can be determined by monitoring or direct measurement, mass balance, emission factors, or engineering estimates methods. The emission factors can be derived from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. According to El-Fadel and Massoud (2001), theoretical and experimental approaches are commonly used to estimate the GHGs emissions from the biodegradation of organic fraction in the treatment of municipal wastewater. Theoretical approach is based on overall reaction stoichiometry.

3.2 Emission Factors and Activity Data

Non-CO_2 gases emissions from large industrial plants can be measured directly and/or from the activity data and emission factors, i.e. emissions per unit activity (Rypdal and Winiwarter, 2001). Emission factor is a coefficient which quantifies the emissions or removals per unit activity (Sylvis Environmental, 2009). Based on IPCC (1996) guidelines for National Greenhouse Gas Inventories, the activity data are defined as data on the magnitude of human activity resulting in emissions over a given time period and an emission factor is the average emission rate of a given GHG for a specific source, relative to units of activity. Generally, GHG activity data are related to the amount of energy, fossil fuel consumption, material production and so on.

3.3 Study Area

The Little River Pollution Control Plant (LRPCP) serves the eastern part of Windsor and the surrounding municipality of Tecumseh. Its' capacity is 72 million litter/day (MLD) and average daily flow is 47.5 MLD based on Ontario MOE (2008). It has two separate activated sludge systems (Plant1 and Plant 2) and consists of primary clarifiers, aeration tanks followed by secondary clarifiers to remove the biomass. A completely mix reactor is used in Plant 1 and plug flow reactor is used in Plant 2. The organic load and oxygen concentrations are uniformly distributed in the completely mixed reactor, whereas in the plug flow reactor, higher rate of oxygen is supplied at the beginning and lower rate of oxygen is supplied at the end of the reactor. According to 2009 annual MOE report for the city of Windsor, Plant 1 has a capacity of 36,400 m^3/d and Plant 2 has a capacity of 27,300 m^3/d for a total population of 87,000.

The Lou Romano Water Reclamation Plant (LRWRP) receives wastewater from locations throughout Windsor and Essex County. In 2007, primary treatment, secondary treatment, power supply and disinfection processes were expanded and upgraded. It includes primary clarifiers, 16 biological aerated filter (BAF) cells and dewatering facilities. Based on 2009 annual MOE report, it has a capacity of 272.5 MLD (million litter per day) for primary treatment and 218 MLD for secondary treatment for a total population of 181,000.

3.4 Off-site GHGs Emissions by Emission Factor Technique

Large amount of electricity is needed to operate the biological wastewater treatment plants. It is used in blowers, pumps, motors, heaters, clarifiers, illumination of plants, and other devices. The off-site GHGs emissions result from:

- The electricity production for treatment plant
- The production of natural gas for on-site usage
- The degradation of remaining nutrients (BOD, TKN) in the effluent
- The degradation and transport of biosolids

The provincial electricity generation sources were required to calculate the off-site GHGs emissions during electricity production and are reported in Table 3.1.

Table 3.1: Electricity Generation Mix of Ontario in Canada (Ontario Power Generation Inc., 2009)

Province	Hydroelectric	Nuclear	Coal	Oil
	Fuel Type, %			
Ontario	39	51	6.7	3.3

3.4.1 Hydroelectric Power

According to the World Commission on Dams (WCD) (2000), the reservoirs and catchment areas of large hydroelectric dams are contributors of GHGs emissions. It was identified that the GHGs emissions, especially CH_4 and CO_2 are generated due to rotting vegetation and carbon inflows from the surrounding catchments. The bacterial aerobic and anaerobic decompositions of autochthonous and allochthonous organic matters in power-dam reservoirs produce CO_2 and CH_4 in tropical regions (Rosa et al., 2004). The GHGs emissions rate is wide ranging and controversial, because it depends on several factors such as reservoir size, soil type, water depth, type of vegetation cover, and climate (Weisser, 2007).The World Commission on Dams (2000) suggested a value of 300 to 1320 g CO_2 equivalent/m^2/ year for tropical regions. On the other hand, Rashad and Hammad (2000) estimated an emission factor in the range of 10 – 400 g CO_2 equivalent/kWh from hydropower energy. The lower value was used in this study because of colder climate in Canada.

3.4.2 Nuclear Power

The CO_2 emission from the use of nuclear energy for electricity generation is lower than the other energy sources. Moreover, comparing with other sources, the nuclear power emits less air polluting gases such as NO_X, CH_4, SO_2 and thus has less effect on global warming (Rashad and Hammad, 2000, Weisser, 2007). According to Smith (2004), Ontario is considered to be the largest user of nuclear power in Canada. Hydropower, nuclear and wind energy technologies have lower global warming impact than fossil fuels.

3.4.3 Fossil Fuels (Coal, Oil, Natural Gas)

The GHGs emissions factors depend on the type of fuel used, mode of its operation and its thermal efficiency. The fossil fuel power plants mainly emit the GHGs during the operation of plants (Weisser, 2007). Emission factors of related sources of electricity production for Ontario are presented in Table 3.2 and emissions factors of natural gas productions are included in Table 3.3 based on the Canadian natural gas industry.

Table 3.2: Emission factors of each source of electricity generation (based on CO_2 equiv units and base case scenarios)

	Fuel Type, g CO_2 equiv/kWh			
	Hydroelectric	Nuclear	Coal	Oil
Emission factors	10	9	877	604
Reference	Rashad and Hammad, 2000	Andesta et al., 1998	IPCC, 2001	IPCC, 2001

Table 3.3: Emission factors of natural gas (NG) production (Natural Resources Canada, 1999)

	Emission factor
$EF_{NG,CO2}$	234 g CO_2/m^3 NG
$EF_{NG,CH4}$	83 g CO_2/m^3 NG

The total emissions of off-site GHGs are calculated as below:

STEP 1

For electricity generation, the offsite emissions are (Shahabadi et al., 2009):

P_{CO_2}, electricity = QE*∑ (PF_i*EF_i) ....………………………………….. (Eq. 3.1)

where,

$P_{CO_2,\ electricity}$ = the GHG production due to electricity demands of the plant, (kg CO_2equiv/d)

QE = the quantity of electricity used for the operation of the entire plant, (kWh/d)

PF_i = percentage contribution of fuel i to satisfy electricity generation needs of the WWTPs (Table 3.1).

EF_i = a GHG emission factor of fuel i in producing GHGs (kg CO_2 equiv/kWh) (Table 3.2)

STEP 2

For production and transportation of natural gas (NG), the offsite emissions are (Sahely, 2006):

$P_{CO_2,\ NG}$ = [(Q_G*EF_{NG,CO_2}) /10^3(g/kg)] + 23* [(Q_G*EF_{NG,CH_4})/10^3(g/kg)]…….. (Eq. 3.2)

where,

$P_{CO_2,\ NG}$ = the off-site GHG production because of natural gas consumption for space heating in the plant (kg CO_2 equiv/yr)

Q_G = the quantity of natural gas used for space heating in the plant (m^3/d)

$EF_{NG,\ CO_2}$ and $EF_{NG,\ CH_4}$ = the overall natural gas CO_2 and CH_4 emissions factors (g CO_2/m^3 NG) specific to the Canadian natural gas industry (Table 3.3).

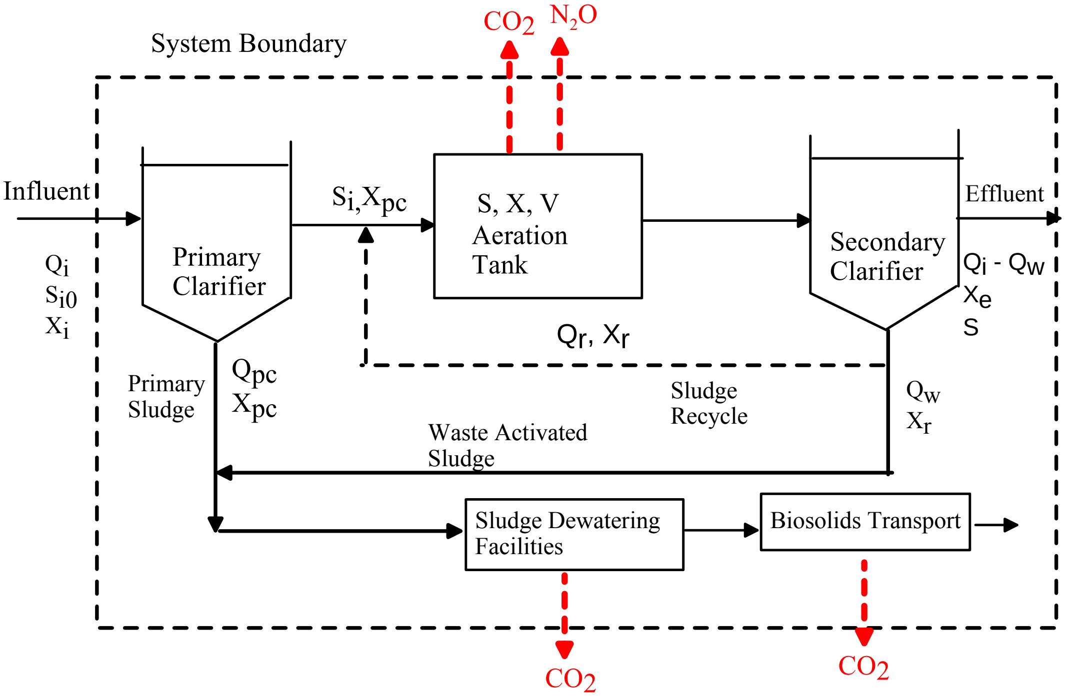
STEP 3

Therefore, the total amount of off-site GHG production is:

$P_{\text{Total CO2, off-site}}$ (kg CO_2 equiv/d) = $P_{\text{CO2,electricity}} + P_{\text{CO2,NG}}$………….……….. (Eq. 3.3)

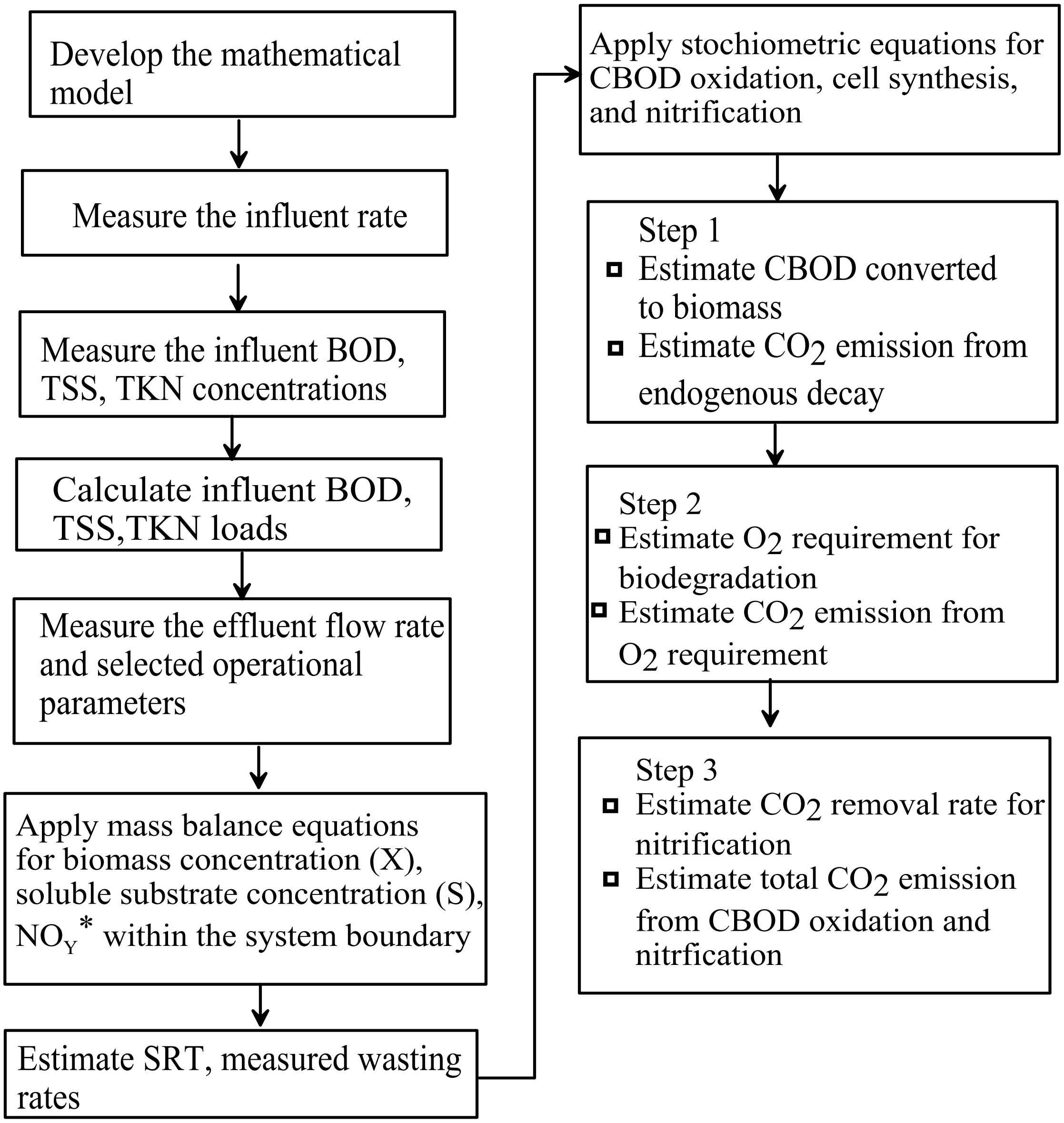
3.5 Estimation of CO_2 Emissions from Aerobic Wastewater Treatment

A typical layout of activated sludge process and the nomenclature are shown in Figure 3.1. The CO_2 emission from aerobic wastewater treatment is estimated according to the procedure shown in Figure 3.2.



Flow is expressed by Q, BOD concentration is expressed by S, and VSS concentration is expressed by X

Figure 3.1: A typical activated sludge process with a system boundary



*NO_Y = the concentration of NH_4^+-N in the influent that is nitrified into the aeration tanks (mg N/L)

Figure 3.2: Flow chart used in estimating on-site GHGs emissions in activated sludge system

3.5.1 Primary Treatment

The settleable suspended solids are removed by the primary sedimentation tank and it is assumed that there is no biological reaction in the clarifier. These settleable solids (primary sludge) are sent to the solids dewatering process. The removal of BOD and TSS in the primary clarifier is a function of the detention time and the concentration of constituents (Metcalf and Eddy, 2004).

The mass of raw suspended solids (SS) removed in the primary clarifiers in LRPCP was calculated by using Equation 3.4 (Monteith et al., 2005).

$R_{ss,\,pc}$ (kg VSS/d) = $Per_{ss,\,pc} * Q_i * X_i$ ………………………………………… (Eq. 3.4)

where,

$Per_{ss,\,pc}$ = the percentage of SS removal in primary clarifier (65% in LRPCP)

Q_i = influent wastewater flow rate (m^3/d)

X_i = influent volatile suspended solids (mg VSS/L)

The mass of BOD removed in primary clarifiers both soluble and insoluble was estimated by using Equation 3.5.

The removal rate of BOD_5 in primary clarifiers:

$R_{BOD,\,pc}$ (kg BOD_5/d) =$Per_{BOD} * Q_i * S_{i0}$ …………………..………………… (Eq. 3.5)

where,

Per_{BOD} = the percentage of BOD_5 removal in primary clarifier (50% in LRPCP)

S_{i0} = the influent BOD_5 (mg /L)

3.5.2 Aerobic Treatment

(a) Mass Balance for Biomass

A mass balance equation for biomass in biological treatment can be expressed as follows:

$V(\frac{dx}{dt})$ = Inflow rate – Outflow rate + Net BOD conversion to microorganisms

$$V(\frac{dx}{dt}) = (Q_i - Q_{pc})*X_{pc} - [Q_wX_r + (Q_i - Q_{pc} - Q_w)*X_e] + V*r'_g \quad \text{.................. (Eq. 3.6)}$$

where,

V = volume of aeration tank (m^3)

$(\frac{dx}{dt})$ = the change rate of biomass concentration with respect to time (g VSS/m^3/d)

X = concentration of biomass in aerobic reactor (mg VSS/L)

Q_{pc} = Primary clarifier sludge flow rate (m^3/d)

X_{pc} = concentration of biomass in primary clarifier effluent (mg VSS/L)

Q_w = wastage biomass flow (m^3/d)

X_r = concentration of recycle biomass (mg VSS/L)

X_e = concentration of effluent biomass (mg VSS/L)

r'_g = net rate of biomass production in the aeration tank (g VSS/m^3/d)

The following assumptions are made:

Under steady state condition, the accumulation of microorganism $(\frac{dx}{dt})$ becomes zero. The microorganisms' concentration in the influent can be considered as negligible compared to their concentration in the aeration tank ($X_{pc} = 0$) and primary underflow rate Q_{pc} is also assumed to be negligible compared to Q_i.

Then, simplified form of Eq. 3.6 becomes,

$V*r'_g = Q_w* X_r + (Q_i - Q_w) *X_e$ …………………………………….............. (Eq. 3.7)

Now,

r'_g = (rate of bacterial growth due to substrate utilization) – (biomass decay)

$= -Y*r_{su} - K_d*X$

where,

Y = cell yield coefficient (g VSS/g BOD_5). It depends on the oxidation state of the carbon source, nutrient elements, and the pathways of metabolism.

r_{su} = substrate utilization rate (g BOD_5/ m^3/d)

K_d = biomass endogenous decay coefficient (d^{-1})

According to the literature (Metcalf and Eddy, 2004),

$r_{su} = KXS/(K_s+S)$ ………………………………………………………….. (Eq. 3.8)

where,

K= maximum substrate utilization rate per unit mass of microorganisms (g BOD_5/g VSS/d)

$= \frac{\mu m}{Y}$.

K_s = the half velocity constant (mg BOD_5/L). It is the value of the soluble substrate concentration at which the specific growth rate is half of the maximum specific growth rate.

S = substrate concentration in aeration tank (mg BOD_5/L)

Therefore, $r'_g = Y * \frac{KXS}{K_s+S} - K_d * X$ ……………………………………… (Eq. 3.9)

Combining the Equations (3.7) and (3.9) gives,

$[Q_w * X_r + (Q_i - Q_w) * X_e] / VX = Y\frac{KS}{K_s+S} - K_d$ ………………………………..... (Eq. 3.10)

The inverse of the left term is known as solid retention time (SRT) or sludge age. The SRT represents the quantity of biomass retained in the aerobic reactor divided by the mass of cells removed from the system per day. The SRT was calculated by using the data obtained from the LRPCP treatment Plant with consideration for seasonal variations of temperature. The Equation 3.10 can be expressed in the following way:

$\text{SRT} = \frac{VX}{Q_w * X_r + (Q_i - Q_w) * X_e}$ ………………………………………………. (Eq. 3.11)

The BOD concentration in the aeration tank was calculated from the following equation and compared with the measured effluent BOD_5 concentration.

$S = \frac{K_s(1+K_d * SRT)}{SRT(YK - K_d) - 1}$ …………………………………………………..…. (Eq. 3.12)

(b) Mass Balance for Substrate

The mass balance equation for soluble substrate (BOD_5) within the system boundary (Fig. 3.1):

$V\left(\frac{ds}{dt}\right) = (Q_i - Q_{pc}) * S_i - [Q_w * S + (Q_i - Q_{pc} - Q_w) * S] + V * r_{su}$ ……………… (Eq. 3.13)

Same assumptions used for the mass balance Equations for biomass were applied in this case also. Under steady state condition, Q_{pc} and $\left(\frac{ds}{dt}\right)$ become equal to zero and Equation 3.13 becomes:

$$(S_i - S) = \frac{V}{Q_i} * \frac{KXS}{K_s + S} \quad \text{(Eq. 3.14)}$$

Therefore, biomass concentration in the aerobic reactor is given by:

$$X = \frac{SRT}{\tau} * \frac{Y(S_i - S)}{1 + K_d * SRT} \quad \text{(Eq. 3.15)}$$

where,

τ = the hydraulic retention time, $\frac{V}{Q_i}$

The heterotrophic biomass concentration in the reactor can be calculated by Eq. 3.15 and the autotrophic biomass concentration can be calculated by the following equation:

$$X_n = \frac{SRT}{\tau} * \frac{Y_n(NO_Y)}{1 + K_{dn} * SRT} \quad \text{(Eq. 3.16)}$$

where,

X_n = autotrophic biomass concentration (mg VSS/L)

Y_n = the synthesis yield co-efficient for nitrifying bacteria (g VSS/g N)

NO_Y = the concentration of NH_4-N in the influent that is nitrified to nitrate (mg N/L)

K_{dn} = the endogenous decay factor for nitrifying micro-organisms (g VSS/g VSS.d)

(c) Sludge Production

For maintaining the biomass concentration in the reactor, the mass of solids must be removed on a daily basis from the aeration tank. The amount of sludge produced each day from activated sludge process can be expressed by the following equation.

$$M_X = \frac{V * X}{SRT} \quad \text{(Eq. 3.17)}$$

M_X = the amount of biomass wasted per day (g VSS/d)

By substituting the value of X in Eq. 3.15 in Eq. 3.17,

$$M_X = \frac{Q_i * Y(S_i - S)}{1 + K_d * SRT} \quad \text{(Eq. 3.18)}$$

The biomass is produced by (i) substrate utilization via heterotrophic bacteria, (ii) substrate utilization via nitrifying bacteria, and (iii) cell debris.

The biomass production due to carbonaceous BOD removal is given by:

$M_{X,\,CBOD}\ (\mathrm{gVSS/d}) = \frac{Q_i * Y(S_i - S)}{1 + K_d * SRT}$ …………………………………………… (Eq. 3.19)

Using a similar approach, biomass production due to nitrogenous BOD consumption is given by:

$M_{X,\,nit}\ (\mathrm{gVSS/d}) = \frac{Q_i * Y_n(NO_Y)}{1 + K_{dn} * SRT}$ ………………………………………………… (Eq. 3.20)

The total biomass production due to BOD utilization is:

Pbiomass (gVSS/d) = $M_{X,\,CBOD} + M_{X,\,nit}$ …………………………………... (Eq. 3.21)

A mass balance equation for nitrogen removal is (Shahabadi, 2008):

$Q_i * NO_Y = Q_i * TKN_i - Q_i * TKN_e - 0.12 * Pbiomass$

where,

TKN_i = influent TKN (mg VSS/L)

TKN_e = effluent TKN (mg VSS/ L)

Pbiomass = the biomass production due to CBOD and NBOD utilization (g VSS/d)

The amount of ammonia oxidized to nitrate is:

$NO_Y\left(\frac{mgN}{L}\right) = TKN_i - TKN_e - \frac{0.12 * Pbiomass}{Q_i}$ ………………………… (Eq. 3.22)

There were not data available for NO_Y but TKN values were known. According to Metcalf and Eddy (2004), the value of NO_Y is equal to about 0.8 TKN. Based on this assumption, $M_{X,\ nit}$ was calculated from Eq. 3.20. Subsequently, trial and error method was applied to find out a new value for NO_Y.

Since, some of the total influent BOD is removed in the primary clarifier, the influent BOD concentration to the aeration tank is given by:

$S_i = S_{i0} - R_{BOD,\ PC}/Q_i$ ………………………………………………………… (Eq. 3.23)

where,

S_i = influent BOD concentration in aerobic reactor (mg BOD/L)

S_{i0} = influent BOD concentration in primary clarifier (mg BOD/L)

$R_{BOD,\ PC}$ = the removal rate of BOD in primary clarifier (g BOD/d)

3.5.3 Stoichiometric Relationships

Aerobic reactions include (i) BOD oxidation to CO_2, (ii) BOD incorporation into new cell, and (iii) nitrification. In this study, $C_{10}H_{19}NO_3$ and $C_5H_7NO_2$ were used to represent the substrate and the biomass, respectively based on Rittmann and McCarty (2001).

Bacterial growth depends on the energy production and the cell synthesis. Microorganism use electron donor for energy production and support to cell synthesis. The complete reaction involves the donor half-reaction, the acceptor half-reaction and the cell half reaction (Rittmann and McCarty, 2001). The stoichiometric relationships have been developed based on the half reactions for the carbonaceous BOD utilization, cell synthesis, and complete nitrification as shown in Equations 3.24, 3.25 and 3.26 (Shahabadi et al., 2010; Sawyer et al., 1994). The derivations of complete equations are illustrated in Appendix D.

$0.02C_{10}H_{19}NO_3 + 0.01\ NH_4^+ + 0.01\ HCO_3^- + 0.1\ O_2 \longrightarrow 0.03\ C_5H_7NO_2 + 0.11H_2O + 0.06CO_2$ ……. (Eq. 3.24)

$0.05\ C_5H_7NO_2 + 0.25\ O_2 \longrightarrow 0.2\ CO_2 + 0.05\ NH_4^+ + 0.05\ HCO_3^- + 0.05\ H_2O$ ……… …………… (Eq. 3.25)

$0.1275\ NH_4^+ + 0.2375\ O_2 + 0.01\ CO_2 + 0.0025\ HCO_3^- \longrightarrow 0.0025\ C_5H_7NO_2 + 0.125\ NO_3^- + 0.25\ H^+ + 0.1225\ H_2O$ ………………. (Eq. 3.26)

The amount of CO_2 production resulting from the carbonaceous BOD removal and nitrification can be expressed as follows:

$P_{CO_2,CBOD}\ \left(\frac{g}{d}\right) = 0.33*[Q_i*(S_i - S) - 1.42*M_{X,CBOD}] - 0.25*NO_Y*Q_i$ ……… (Eq. 3.27)

A fraction of the biomass produced is further converted to CO_2 due to endogenous decay of biomass. The amount of CO_2 production from endogenous respiration is calculated as (Shahabadi, 2008):

$P_{CO_2,endogenous}\ \left(\frac{g}{d}\right) = 1.56\ g\ CO_2/g\ VSS * B_{degraded,\ aeration\ tank}$ …………….. (Eq. 3.28)

where,

$B_{degraded,\ aeration\ tank}$ (g VSS/d) = the amount of biomass (heterotrophic and autotrophic cell tissues) decayed by auto-oxidation process in the aeration tank.

= 0.8 * the biomass decayed

= 0.8 * volume of reactor * ($K_d*X + K_{dn}*X_n$)

$= 0.8 * SRT * Q_i \left[\frac{K_d*Y(S_i - S)}{1 + K_d*SRT} + \frac{K_{dn}*Y_n(NO_Y)}{1 + K_{dn}*SRT}\right]$ …..……. (Eq. 3.29)

By using the Eq. 3.15 and Eq. 3.16 and assuming the biodegradable part of the biomass as 80% (Metcalf and Eddy, 2004).

Total CO_2 emission in the aerobic reactor = $P_{CO_2,CBOD} \left(\frac{g}{d}\right) + P_{CO_2,endogenous} \left(\frac{g}{d}\right)$

……………………… (Eq. 3.30)

3.6 Off-site GHGs Emissions from Remaining BOD in Effluent

The soluble BOD remaining in the effluent is degraded in the receiving water bodies, and contributes to the off-site GHGs emissions. When the organic matter is oxidized, 0.422 g VSS/g BOD and 0.33 g CO_2/g BOD are generated. Furthermore, oxidation of VSS produces 1.56 g CO_2/g VSS based on stoichiometric relationship. Therefore, the resulting CO_2 emissions from the off-site BOD degradation become:

$M_{CO_2,BOD_{eff}}$ (g CO_2/d)

= (0.33 g CO_2/g BOD + 0.422 g VSS/g BOD * 1.56 g CO_2/g VSS) * BODeff * Q_i

= 0.986 * BODeff * Q_i ……………………………………………(Eq. 3.31)

3.7 Off-site GHGs Emissions from Biosolids Disposal and Degradation

The excess sludge production during biological treatment is described in Figure 3.3.

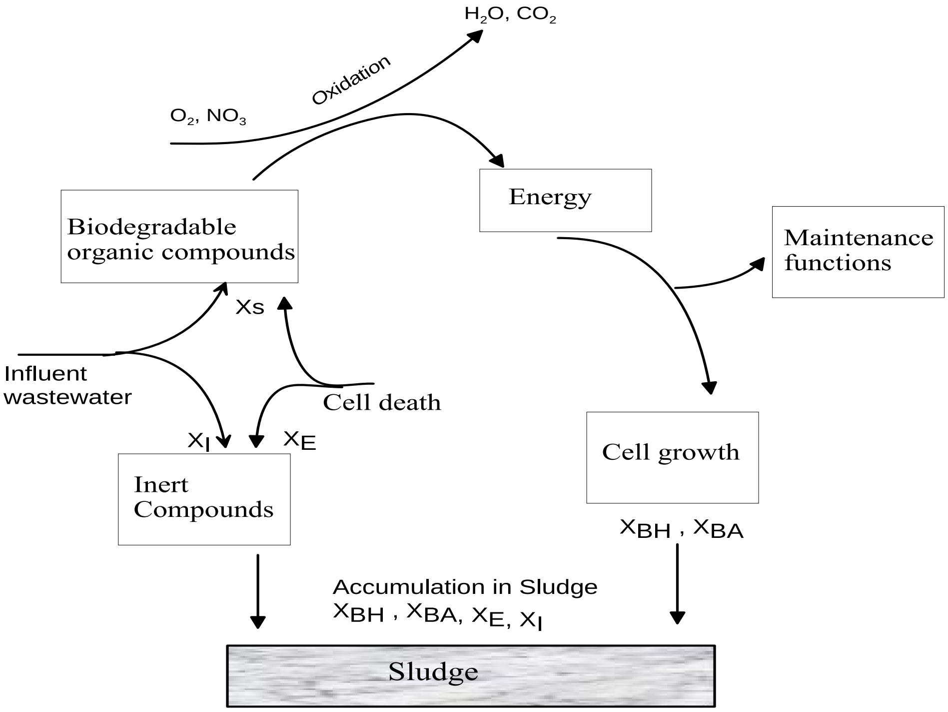


Figure 3.3: The processes leading to sludge production in the biological treatment of influent wastewater (adapted from Foladori et al., 2010)

X_{BH} = heterotrophic biomass, X_{BA} = autotrophic biomass, X_E = endogenous residue,

X_I = inert, X_s = biodegradable.

The biodegradable solids in the sludge also generate GHGs emissions. The remaining biodegradable solids from the aerobic reactor are degraded off-site and contribute GHGs emissions (Shahabadi, 2008). In LRPCP, dewatering facilities receive activated sludge and primary sludge to separate liquid and waste. Most of the biomass comes as secondary sludge and it is assumed that no biomass is produced in primary clarifier. In this study, only biosolids transportation and their off-site degradation are considered. The amount of GHGs generation depends on the biosolids management systems. The GHGs emissions from biosolids include the following conditions (Shahabadi, 2008; Monteth et al., 2005):

- Boisolids transport from WWTP to the disposal sites.
- Disposal methods.
- Travel distance
- Fuel type

The dewatering and thermal drying processes of biosolids have no effect on the carbon content of biosolids because no biodegradation occurs in these processes. According to Torrie Smith Associates (2004), 10 kg CO_2 equivalent is released per tonne of biosolids disposal during short trips. This factor determination depends on the following factors:

- Distance traveled by truck
- The efficiency of the truck operation and routing
- Fuel efficiency of the engines

Therefore, the off-site GHGs emissions from biosolids transport were calculated according to the following equation:

$$P_{CO_2,\text{solid disposal}} \left(\frac{\text{kg}}{\text{d}}\right) = 10 \text{ kg } CO_2 \text{ equiv/tonne waste} * \text{total dried solids} \quad \ldots\ldots \text{(Eq. 3.32)}$$

The data for total dried biosolids transported was obtained from MOE report.

The off-site GHGs emissions due to anaerobic biodegradable solids were calculated according to the following equations:

$$MCO_2,_{\text{remaining biodegradable solids}}\left(\frac{g}{d}\right) = 0.58 \text{ g } CO_2/\text{g VSS} * \text{Degradable Sludge} \ldots \text{(Eq. 3.33)}$$

$$MCH_4,_{\text{remaining biodegradable solids}}\left(\frac{g}{d}\right) = 0.35 \text{ g } CH_4/\text{g VSS} * \text{Degradable Sludge} \ldots \text{(Eq. 3.34)}$$

where,

Degradable Sludge =0.8* Pbiomas (g VSS/d)

The values of 0.58 g CO_2/g VSS and 0.35 g CH_4/g VSS calculation from anaerobic stoichiometric relationship are shown in Appendix D.

Therefore,

$$P_{CO_{2,}\text{equiv,off-site anaerobic sludge degradation}}\left(\frac{g}{d}\right) = MCO_2,_{\text{remaining biodegradable solids}}$$

$$+23*(MCH_4,_{\text{remaining biodegradable solids}}) \ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 3.35)}$$

3.8 Estimation of Nitrous Oxide (N_2O) Production in Wastewater Treatment

When wastewater containing nitrogen comes in/contact with autotrophic ammonia oxidizing bacteria such as Nitrosomonas spp. and heterotrophic bacteria in any kind of environment such as treatment facility bioreactor, water body receiving effluent, biosolids application site, N_2O gas is produced (Shiskowski, 2007). In the present study, the on-site N_2O emissions were estimated during treatment processes and the off-site emissions were estimated from the effluent wastewater for the LRPCP.

Therefore, emissions of N_2O in WWTPs were performed by using emission factor. Czpiel et al., (1995) used conventional activated sludge treatment plant Durham, New Hampshire (NH), U.S. to develop an emission factor. The total estimated N_2O per year (yr) from this plant was 3.5 x 10^4 g of N_2O. A weighting factor was considered due to annual variation of residents. The time weighted average was 10,925 for approximately 12,500 people from September through May and 6200 from June to August. The emission factor of 3.2 g N_2O per year per person was obtained.

Weighted average = $\frac{12500*9+6200*3}{12}$ = 10925 people

Emission factor = $\frac{3.5*10^4}{10925}$ = 3.2 g of N_2O person^{-1} yr^{-1}

The IPCC default methodology uses only annual, per capita protein consumption (kg/yr). Also various researchers have conducted field tests at wastewater treatment plants in order to develop N_2O emission factor and estimates.

N_2O emission from wastewater handling = $E_{N_2O,Direct} + E_{N_2O,Indirect}$ …….. (Eq. 3.36)

N_2O emissions can occur as direct emissions from treatment processes due to nitrification and denitrification and indirect emissions from wastewater after disposal of effluent into aquatic environments (IPCC, 2006).

3.8.1 Direct Emissions from Wastewater Treatment Plant

N_2O emissions from a secondary treatment wastewater facility directly are (EPA, 1997):

$E_{N_2O,Direct}$ (kg N_2O /year) = W_{pop} * EF_1 * CF………………………………. (Eq. 3.37)

where,

$E_{N_2O,Direct}$ = the direct emission from wastewater treatment processes (kg N_2O /year)

W_{pop} = the connected population number

EF_1 = emission factor =3.2 g N_2O / person per year

CF= correction factor

CF= correction factor
= a factor for industrial co-discharge
= 1.14

Correction Factor (CF)

Doorn et al., (1997) provided a range 20 - 50 mg TKN/L (average 35 mg TKN/L) and Metcalf and Eddy (1995) suggested 40 – 50 mg TKN/L for residential wastewater, which includes bathwater, laundry and the food scrap. Also Metcalf and Eddy (1995) provided nitrogen loading range 20 – 85 (assume 40 mg/L) for combined industrial and residential wastewater.

Therefore, $\mathrm{CF} = \frac{40\ \mathrm{mg/L}}{35\ \mathrm{mg/l}}$

$\mathrm{CF} = 1.14$

3.8.2 Indirect Emissions from Wastewater Effluent

The off-site or indirect emission of N_2O was calculated by using Eq. 3.38 (Scheehle and Doorn, 2001).

$$E_{N_2O,Indirect}\ (\text{kg } N_2O\ /\text{year}) = [(P * NP_{frac} * F * W_{pop}) - Nit_{ww} - Nit_{sludge}] * EF_2 * 44/28 \quad \text{......... (Eq. 3.38)}$$

where,

$E_{N_2O,Indirect}$ = the indirect emission from wastewater effluent (kg N_2O /yr)

P = annual per capita protein consumption (kg/ person per year)

= 38 (kg/ person per year) (FAOSTAT data, 2004)

NP_{frac} = fraction of nitrogen in protein =0.16 kg N/kg protein (IPCC, 1996)

F = a factor of non-consumption protein in domestic wastewater (calculation in Appendix D)

= 1.14*1 =1.14

Nit_{ww} = quantity of N in domestic wastewater removed by wastewater treatment processes

$= W_{pop} * EF_1 * CF * 28/44$

Nit_{sludge} = quantity of sludge N not entering the aquatic environments, i.e nitrogen removed with sludge, (kg N/yr) [default value was zero in the IPCC (2006)]

= 0.12* Pbiomass (calculations are shown in Appendix B)

EF_2 = emission factor (kg N_2O-N/ kg sewage-N produced)

= 0.01 kg N_2O-N/kg sewage-N produced (default value from IPCC, 1996) i.e. 1% of the nitrogen in effluent is converted into N_2O. This emission factor is based on limited field data and on specific assumptions regarding the occurrence of nitrification and denitrification in rivers and estuaries and is directly related to nitrification and denitrification, i.e. nitrogen is discharged into the river.

44/28 = the molecular mass ratio of N_2O to N_2

CHAPTER IV

RESULTS AND DISCUSSION

4.1 General

The main purpose of this study was to quantify the GHGs for the Little River Pollution Control Plant (LRPCP) and the Lou Romano Water Reclamation Plant (LRWRP) by using the actual data obtained from these treatment plants. The GHG model was selected to quantify the GHGs and was verified by using the kinetic parameters reported in the literature. These values were compared to the treatment plants reported values. This model was also verified by comparing the results reported in this literature. The onsite GHGs emissions were calculated from the LRPCP activated sludge system. There are two treatment plants, Plant 1 and Plant 2. Plant 1 is completely mixed system and serves the population of 34,800. On the other hand, Plant 2 is plug flow system and serves the population of 52,200.

4.2 Results

4.2.1 Off-site GHGs Emissions

The raw data collected from different sources are presented in Appendix A. The calculated off-site GHGs emissions on daily basis from utility consumption for the Little River Pollution Control Plant (LRPCP) and the Lou Romano Water Reclamation Plant (LRWRP) for consecutive three years are shown in Table 4.1 by using Eq. 3.1 and Eq. 3.2 and Eq. 3.3.

Table 4.1: Off-site GHGs emissions rate from energy consumption

Name of treatment plant	In 2007	In 2008	In 2009
Little River Pollution Control Plant	2.10 (tonnes CO_2equiv/d)	2.04 (tonnes CO_2equiv/d)	2.31 (tonnes CO_2equiv/d)
Lou Romano Water Reclamation Plant	2.74 (tonnes CO_2equiv/d)	4.56 (tonnes CO_2equiv/d)	4.64 (tonnes CO_2equiv/d)

In 2008 and in 2009, the GHGs emissions rates of the LRWRP were significantly higher than in 2007 year, because the treatment plant was expanded after 2007. In the LRPCP, the rates of GHGs emissions were almost similar for three consecutive years.

Figure 4.1 and Figure 4.2 illustrate the contribution of off-site GHGs emissions due to electricity consumption and natural gas consumption for space heating at the LRPCP and LRWRP, respectively (based on Eq. 3.1 and Eq. 3.2).

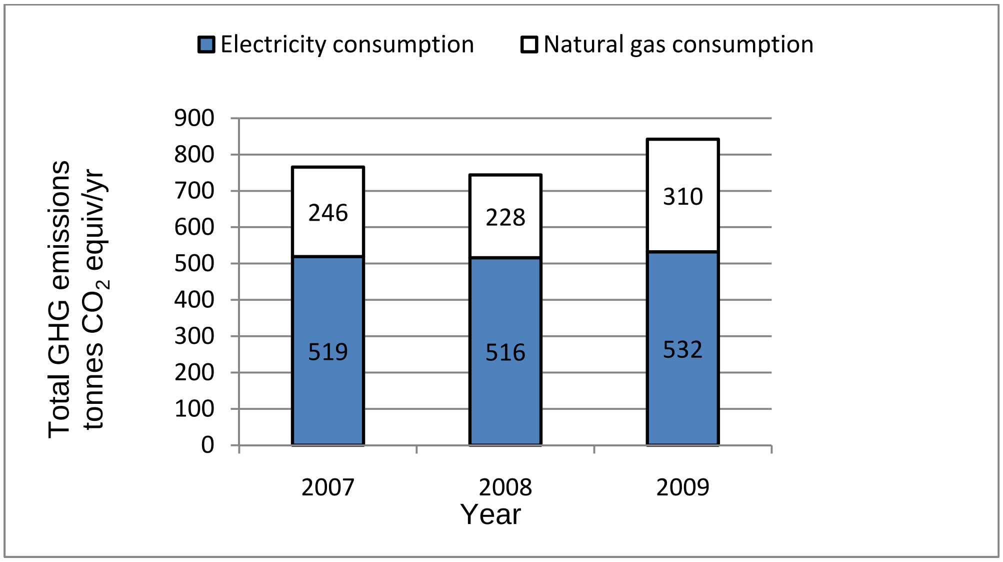


Figure 4.1: Off-site GHGs emissions from electricity and natural gas consumption at the Little River Pollution Control Plant (LRPCP)

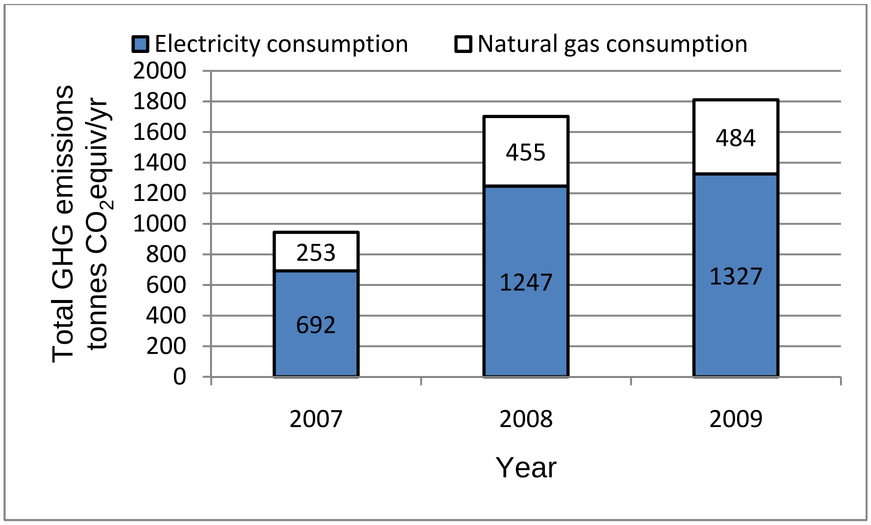
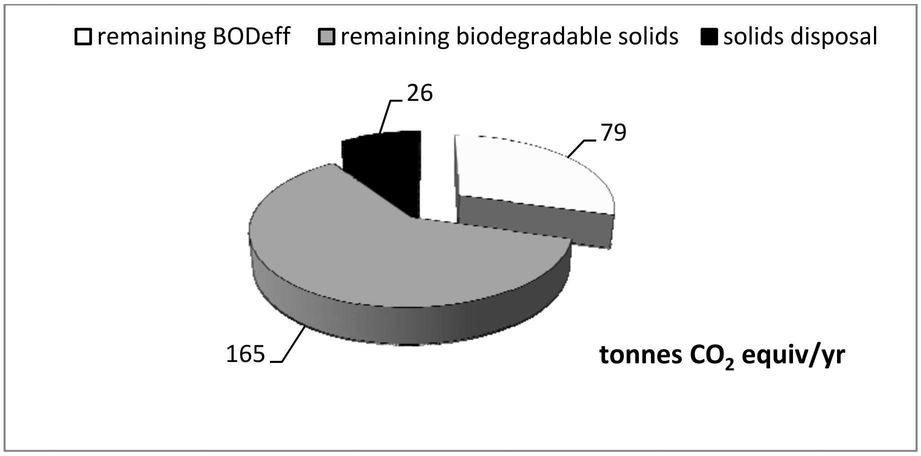


Figure 4.2: Off-site GHGs emissions from electricity and natural gas consumption at the Lou Romano Water Reclamation Plant (LRWRP)

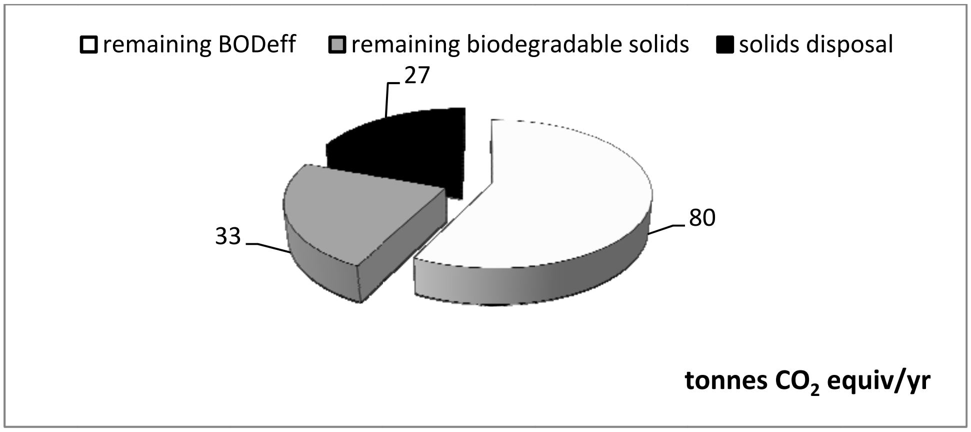
Sahely et al., (2006) have reported the electricity consumption rate of 0.2 kWh/m^3 of wastewater treated in the aerobic processes. In the present study, electricity consumption rate was 0.4 kWh/m^3 for LRPCP and 0.3 kWh/m^3 for LRWRP. It was related to the operation of electrical devices such as pumps, blowers, dewatering system and UV disinfection as well as general lighting.

In the case of off-site GHG emissions, the emission rate was 0.03 kg CO_2/m^3 for activated sludge system in the LRPCP and 0.02 kg CO_2/m^3 for biological aerated filter in LRWRP. Thus, lower amount of electricity was needed to treat wastewater by the BAF system than the conventional activated sludge system.

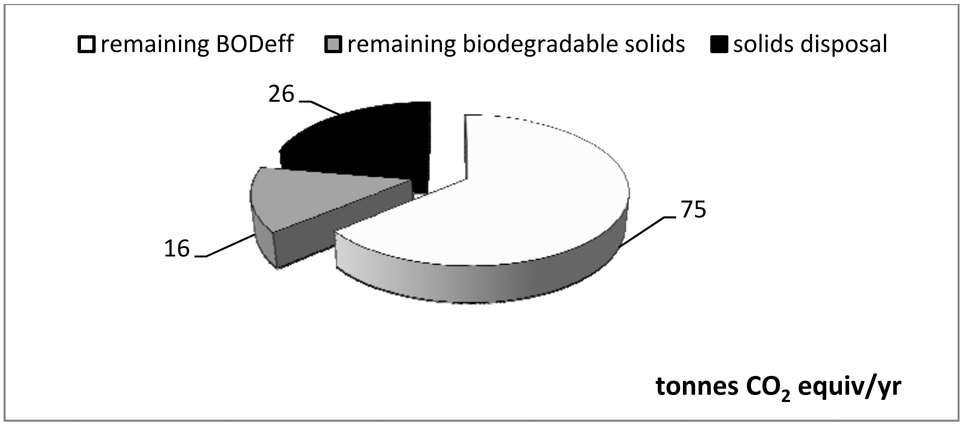
The off-site GHGs emissions from the remaining effluent BOD degradation, biosolids disposal and biosolids degradation were depicted in the following Fig. 4.3 (a), (b), and (c) by using Eq. 3.31, Eq. 3.32, Eq. 3.33 and Eq. 3.34, accordingly. It was assumed that biosolids degraded in landfill sites anaerobically.



(a)



(b)



(c)

Figure 4.3: The off-site GHGs emissions from remaining BOD degradation, biosolids degradation and biosolids disposal at the LRPCP in (a) 2007 (b) 2008 (c) 2009

The results from Fig. 4.3(a) shows that the contribution of GHGs production from biosolids degradation was highest in 2007 compared with the other GHGs production from remaining BOD degradation and biosolids transport. The collected data expressed that 50%, 11% and 5% biosolids disposed to the landfill in 2007, 2008 and 2009, respectively.

4.2.2 On-site GHGs Emissions

In this study, seasonal variations in temperature were considered and the SRT values were calculated for winter (November to April) and summer (May to October) based on the operational parameter of the LRPCP. Figures 4.4 and 4.5 show both the CO_2 emissions due to BOD utilization and endogenous respiration for Plant 1 and Plant 2 in the LRPCP, respectively based on Eq. 3.27 and Eq. 3.28. The SRT values in day are shown also. The on-site CO_2 emissions from plug flow activated sludge system, Plant 2, were higher than the completely mixed activated sludge system, Plant 1. Figure 4.6 shows the total on-site CO_2 emissions trend from microbial processes over the three year time period, 2007 to 2009.

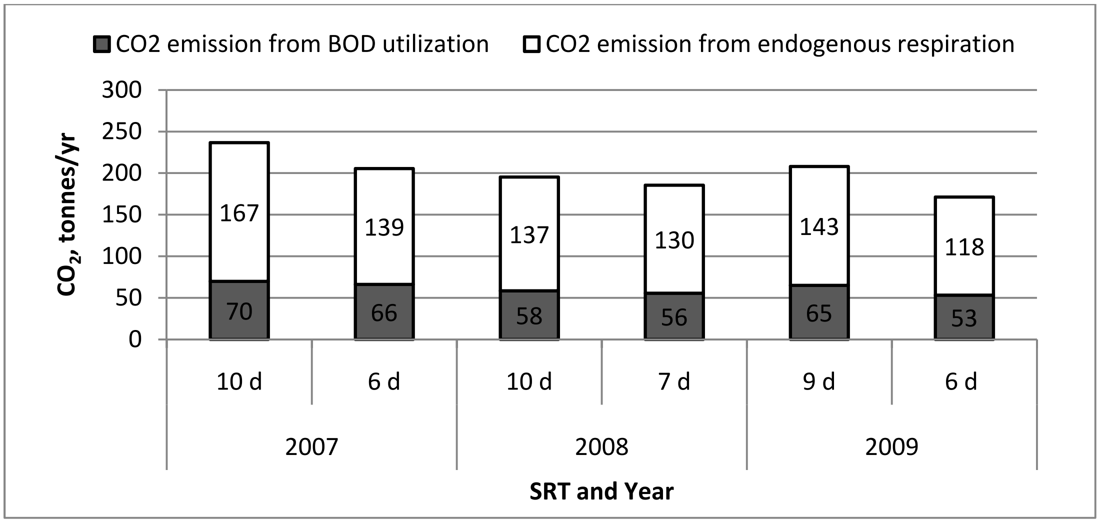


Figure 4.4: On-site GHGs emissions from Plant 1 at the LRPCP

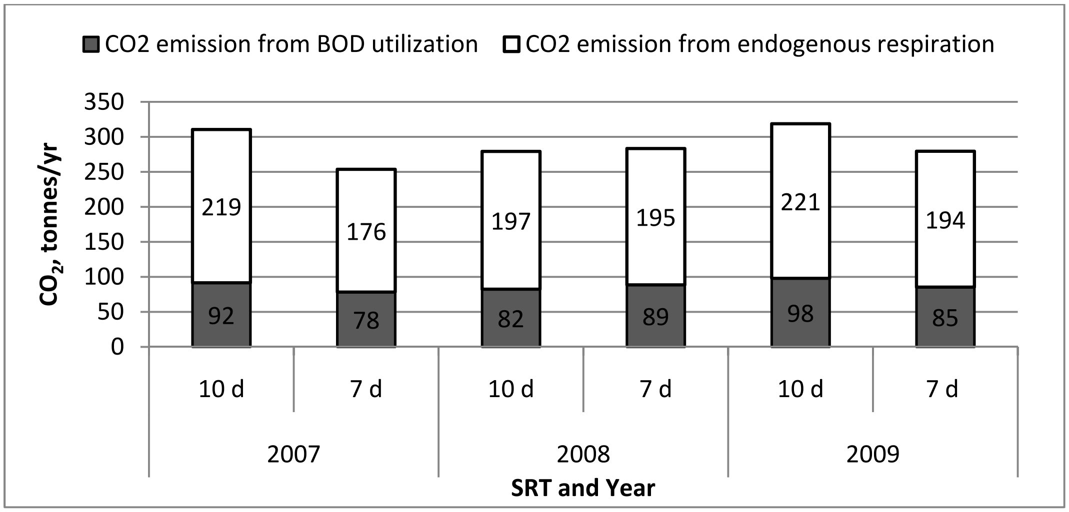


Figure 4.5: On-site GHGs emissions from Plant 2 at the LRPCP

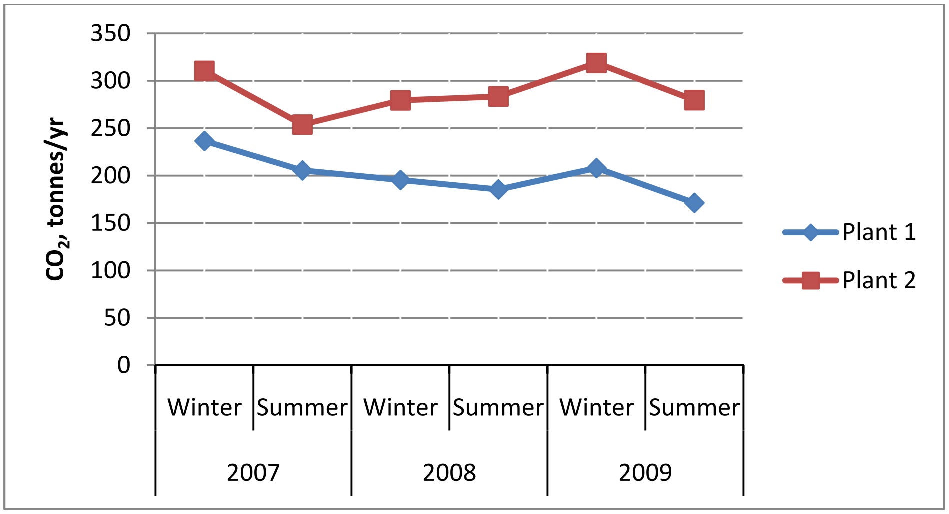


Figure 4.6: On-site GHGs emissions trends for Plant1 and Plant 2 at the LRPCP

In this research, the on-site GHGs emissions model was applied only for LRPCP and was validated by comparing the results with values reported by Monteth et al., (2005) and Shahabadi (2008).

Monteith et al., (2005) found the emission rate to be 0.23 to 0.26 kg CO_2 equiv/m^3 for conventional activated sludge system with anaerobic sludge digestion and 0.168 kg CO_2 equiv/m^3 for conventional activated sludge without anaerobic sludge digestion. On the other hand, Shahabadi (2008) has reported 0.20 kg CO_2 equiv/m^3 emissions from food processing industrial wastewater using conventional activated sludge system with anaerobic sludge digestion. In this research, the emission rate was 0.024 to 0.033 kg CO_2 equiv/m^3 for conventional activated sludge system without sludge digestion. The difference between the present study and those reported by others is very significant and can be explained by the following reasons:

- Biogas production and flaring were considered in both cited studies, but in LRPCP biogas generation does not exist. Moreover, Shabadi (2008), had considered the GHGs emissions from food processing industrial wastewater, whereas, Monteith et al. (2005), considered the GHGs emissions from municipal wastewater during the onsite treatment processes only and the nitrification process was ignored, which can act as a carbon sink. In the present study, nitrification was considered.
- In study by Shabadi (2008), onsite GHGs emissions included the fossil fuel burning for wastewater heating and electric heater was needed for aerobic reactor operation. However, in the present study the specific treatment plant scenario in Windsor, ON, was considered. There was no need fossil fuel burning on site to maintain the wastewater temperature. Natural gas was used for space heating in the both treatment plants. There is no aerobic digester or anaerobic digester to stabilize the sludge.
- The process parameters such as inflow rate, sludge wasting rate, VSS removal rate BOD removal rate were assumed in those in cited studies. On the other hand, the actual process parameters are taken to estimate the GHGs emissions in this study.
- Denitrification and the related material consumption, such as methanol as a carbon source, were considered by Shabadi (2008). However, denitrification is not used in LRPCP and no need for methanol or acetate as a carbon source.

Nitrogenous Matter

Year 2009 was selected for N_2O emissions inventory from LRPCP based on the available data. During on-site treatment, 0.127 tonnes N_2O/yr or 37.59 tonnes CO_2 equiv/yr from Plant 1 and 0.19 tonnes/yr or 56.24 tonnes CO_2 equiv/yr were released from Plants 1 and Plant 2 in that year, subsequently based on Eq. 3.37 (Fig. 4.7). It was found that 3.45 tonnes N_2O/yr and 5.21 tonnes N_2O/yr were emitted from Plants 1 and Plant 2, respectively due to degradation of remaining of nitrogenous matter in the receiving water bodies by using Eq. 3.38 (Fig. 4.8).

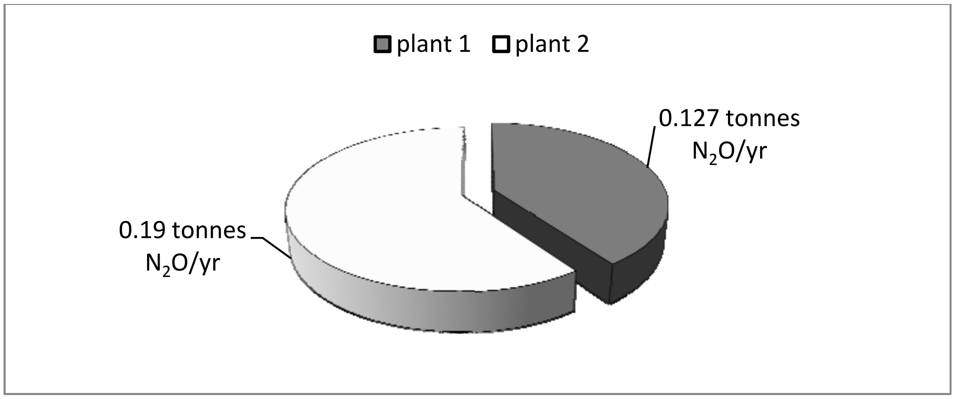


Figure 4.7: On-site N_2O emissions from Little River Pollution Control Plant (LRPCP) in 2009

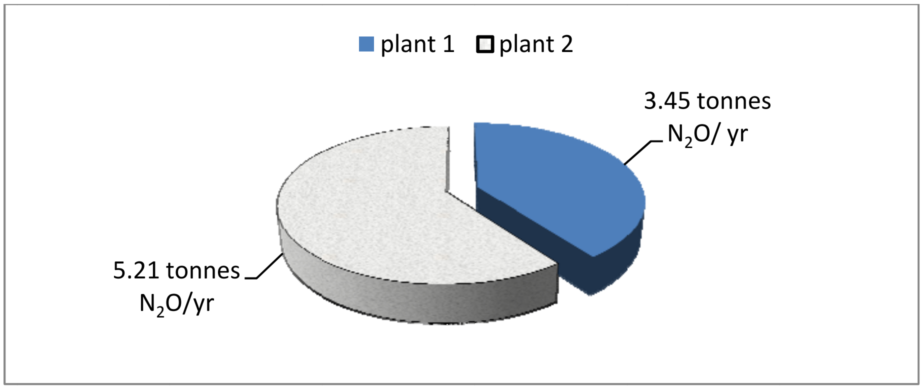


Figure 4.8: Off-site N_2O emissions from Little River Pollution Control Plant (LRPCP) in 2009

4.2.3 Total GHGs Emissions in 2009

Total GHGs emissions from LRPCP in 2009 are summarized in Table 4.2.

Table 4.2: Summary of total GHGs release from LRPCP in 2009

Year	Scope	Source	tonnes CO_2 equiv/yr	% of subtotal	% of total
2009	Off-site	Electricity consumption	532	15.12	11.60
		Natural gas consumption	310	8.81	6.75
		Remaining BOD degradation	75	2.13	1.63
		Biosolids disposal	26	0.74	0.57
		Off-site biosolids degradation	16	0.45	0.35
		Indirect N_2O emissions	2561	72.76	55.81
		Subtotal	3520	100	
	Onsite	BOD utilization	300	28.07	6.54
		Endogenous respiration	675	63.12	14.70
		Direct N_2O emissions	94	8.79	2.05
		Subtotal	1069	100	
		Total	4589		100

4.3 Analysis

4.3.1 Effect of BOD loading on GHGs Emissions in 2009

Figure 4.9 shows that the BOD loading relates well with the GHGs emissions for Plant 1. The coefficient of determination (R^2) is 0.88. Similar relationship between BOD loading and GHGs emissions is also depicted in Figure 4.10, where the data from the Plant 2 has been plotted. The R^2 value for Plant 2 is 0.79. In this analysis two outliers were neglected during the computation of the coefficient of determination. These two points are related to the months of August and February (Appendix B).

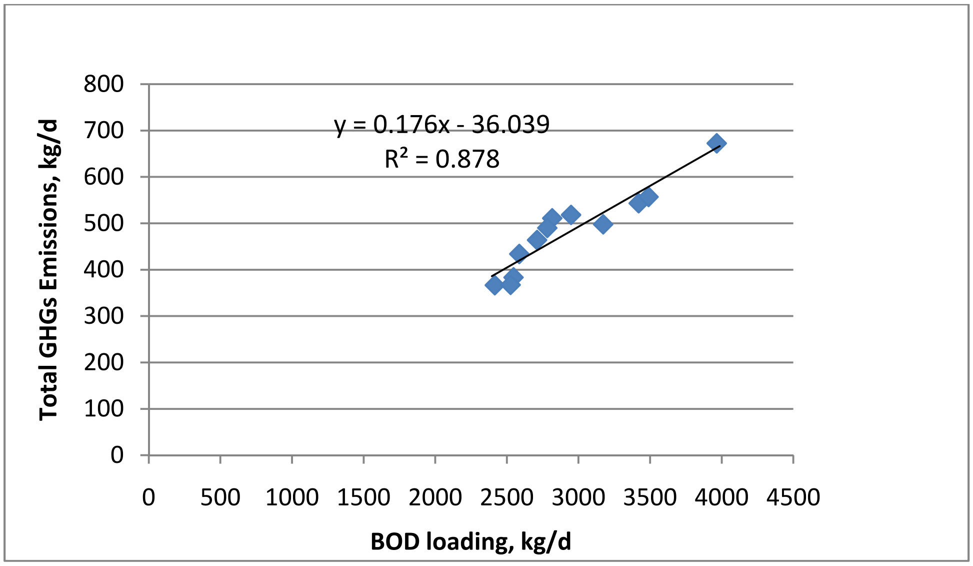


Figure 4.9: Effect of BOD loading on GHGs emissions for Plant 1 in the LRPCP

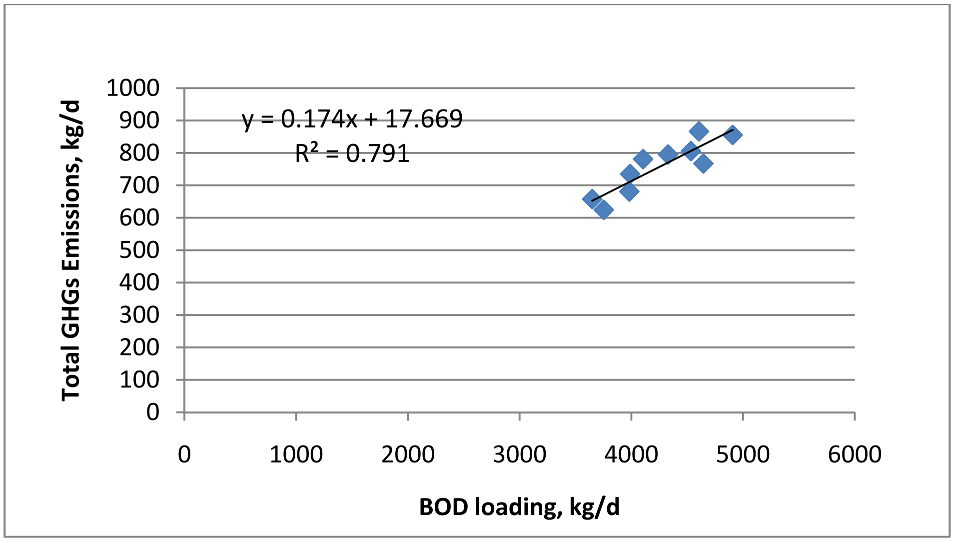


Figure 4.10: Effect of BOD loading on GHGs emissions with ignored some data point for Plant 2 in the LRPCP

4.4 Regression Analysis

In multiple regression analysis, three variables are considered, temperature, SRT and BOD loading rate on GHGs Emissions for mixed flow reactor and plug flow reactor. In that analysis adjusted R^2 values are very similar to the R^2 value. This means that these three variables have strong influence on the GHGs emissions. Summary outputs of Plant1 (mixed flow reactor) and Plant 2 (plug flow reactor) are shown in Appendix B (Tables B.11 and B.12). The adjusted R^2 were also calculated with an additional variable, Q_w/Q_i. With these four variables (temperature, SRT, BOD loading rate and wasting ratio, Q_w/Q_i) the adjusted R^2 values were found to be 0.88, 0.83, in Plant 1 and Plant 2, respectively (Tables B.13 and B14). This indicates that even with the addition of extra variable (Q_w/Q_i), the GHGs emissions (dependent variable) did not change.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The results of this research has indicated that the amounts of GHGs production depend on the incoming wastewater characteristics, loading rate, removal efficiencies, solid retention time, the wastewater temperature, type of processes used in treatment plant and the overall operating procedures. The study has established the following conclusions:

- The indirect emissions were significantly higher than the direct emissions at the LRPCP. The indirect emissions are produced during off-site degradation of the remaining constituents, energy consumptions and hauling activities.
- The GHG emissions per cubic meter of wastewater treated by BAF at the LRWRP accounted for 0.02 kg CO_2/m^3. It was lower than the LRPCP activated sludge system at the LRPCP, which accounted for 0.03 kg CO_2/m^3 based on electricity and natural gas consumptions.
- At the LRPCP, plug flow reactors emitted significantly higher onsite CO_2 than the completely mixed reactors. The emissions from the plug flow reactors were 27%, 48% and 58% higher than the completely mixed reactors in 2007, 2008, and 2009, respectively.
- It was found that wastewater temperature, SRT and BOD loading rate had effect on the overall onsite GHGs emissions at the LRPCP.
- Direct and indirect N_2O emissions from plug flow reactors (Plant 2) were significantly greater than the completely mixed reactors (Plant 1). This is because, inflow rate, influent TKN loading rate and serving population were higher in Plant 2 than that of Plant 1.

5.2 Limitations of the Study

There were some limitations under which this study was undertaken. These included:

- On-site GHGs emissions from biological aerated filters (BAF) processes could not be completed due to the lack of some of the essential data, time and resources constraints. For the same reason, the offsite GHGs emissions from heat drying system could not included.
- Off-site GHGs emissions due to chemical consumption such as polymer and aluminum sulphate production were not considered due to resource constraints.

5.3 Recommendations for Future Study

The results of this study indicate that municipal wastewater treatment plants generate GHGs emissions. The following recommendations should be considered for future research:

- Further research can be done for improving the N_2O estimation model for the LRPCP activated sludge system and the LRWRP biological aerated filter process. Field measurements are needed to determine exact N_2O emission factors for LRPCP.

- The on-site GHG estimation model needs to be developed for LRWRP BAF process for better understanding of the GHGs emissions and contribution to global warming.
- The off-site GHGs emissions for polymer consumptions should be included in the future study.
- The off-site GHGs emissions associated with construction of infrastructure can be measured in the future study.

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APPENDICES

APPENDIX A

Data Sheet

Table A.1: Electricity consumption at the LRPCP for 2007, 2008 and 2009

Year: 2007

From	To	Days	kWh	Daily Usage
12/31/06	01/31/07	31	547943	17675.6
01/31/07	02/28/07	28	474399	16942.8
02/28/07	03/31/07	31	482832	15575.2
03/31/07	04/30/07	30	456310	15210.3
04/30/07	05/31/07	31	507124	16358.8
05/31/07	06/30/07	30	457728	15257.6
06/30/07	07/31/07	31	499870	16124.8
07/31/07	08/31/07	31	522634	16859.2
08/31/07	09/30/07	30	501598	16719.9
09/30/07	10/31/07	31	505435	16304.4
10/31/07	11/30/07	30	459298	15309.9
11/30/07	12/31/07	31	540769	17444.2
Total			5,955,940	

Year: 2008

From	To	Days	kWh	Daily USAGE
12/31/07	01/31/08	31	542431	17497.8
02/01/08	02/29/08	29	522929	18032.0
03/01/08	03/31/08	31	535793	17283.6
04/01/08	04/30/08	30	449362	14978.7
05/01/08	05/31/08	31	477661	15408.4
05/31/08	06/30/08	30	468964	15632.1
06/30/08	07/31/08	31	475742	15346.5
07/31/08	08/31/08	31	457970	14773.2
08/31/08	09/30/08	30	480073	16002.4
09/30/08	10/31/08	31	514861	16608.4
10/31/08	11/30/08	30	457439	15248.0
11/30/08	12/31/08	31	551489	17790.0
Total			5,934,714	

Year: 2009

From	To	Days	kWh	Daily USAGE
12/31/08	01/31/09	31	539970	17418.4
01/31/09	02/28/09	28	513689	18346.0
02/28/09	03/31/09	31	528087	17035.1
03/31/09	04/30/09	30	514070	17135.7
04/30/09	05/31/09	31	514426	16594.4
05/31/09	06/30/09	30	494680	16489.3
06/30/09	07/31/09	31	499242	16104.6
07/31/09	08/31/09	31	506914	16352.1
08/31/09	09/30/09	30	491408	16380.3
09/30/09	10/31/09	31	530984	17128.5
11/01/09	11/30/09	29	436712	15059.0
Total			5,570,181	

Table A.2: Natural Gas consumption (Union Gas) at the LRPCP for 2007, 2008 and 2009

Year 2007

From	To	Days	Meters Used	Daily Usage
12/28/06	01/29/07	32	24757.788	773.7
02/28/07	02/28/07	30	30976.182	1032.5
02/28/07	03/28/07	28	14532.175	519.0
03/28/07	04/27/07	30	11253.54	375.1
04/27/07	05/30/07	33	2535.931	76.8
05/30/07	06/28/07	29	556.322	19.2
07/30/07	07/30/07	32	516.789	16.1
07/30/07	08/29/07	30	403.83	13.5
08/29/07	09/28/07	30	522.853	17.4
10/30/07	10/30/07	32	1304.675	40.8
10/30/07	11/28/07	29	8421.092	290.4
11/28/07	12/27/07	29	18793.554	648.1
Total			114,574.73	

Year 2008

From	To	Days	Meters Used	Daily Usage
12/27/07	01/28/08	32	20242.254	632.6
01/28/08	02/26/08	29	21295.595	734.3
02/26/08	03/27/08	30	16291.512	543.1
03/27/08	04/28/08	32	8104.808	253.3
04/28/08	05/29/08	31	3120.492	100.7
05/29/08	06/27/08	29	590.211	20.4
06/27/08	07/30/08	33	242.861	7.4
08/28/08	08/28/08	29	175.085	6.0
08/28/08	09/30/08	33	217.445	6.6
09/30/08	10/29/08	29	3645.751	125.7
10/29/08	11/27/08	29	10231.263	352.8
11/27/08	12/30/08	33	23342.977	707.4
Total			107,500.25	

Year 2009

From	To	Days	Meters Used	Daily Usage
12/30/08	01/27/09	28	25667.109	916.7
01/27/09	02/26/09	30	26353.334	878.4
02/26/09	03/27/09	29	21165.693	729.9
03/27/09	04/29/09	33	10372.461	314.3
04/29/09	05/29/09	30	1869.47	62.3
05/29/09	07/01/09	32	534.604	16.7
03/27/09	09/29/09	186	24890.514	133.8
09/28/09	10/28/09	30	7929.723	264.3
10/28/09	11/27/09	30	13300.922	443.4
11/27/09	12/29/09	32	25339.529	791.9
Total			157,423.36	

Table A.3: Electricity consumption at the LRWRP for 2007, 2008 and 2009

Year	Electricity consumption, kWh
2007	7,938,998
2008	14,300,548
2009	152,171,48

Table A.4: Natural gas consumption in the LRWRP for 2007, 2008 and 2009

Year	Natural gas consumption, m^3
2007	143,341
2008	194,617
2009	172,041.7

Table A.5: Influent Quality at the LRPCP in 2007, 2008 and 2009 as reported to the Ontario Ministry of the Environment (MOE) (2007, 2008, and 2009)

Plant 1 and Plant 2

in 2009		Influent 1	
	BOD, mg/L	SS,mg/L	TKN,mg/L
November	231	330	42.9
December	196	232	31.9
January	210	232	33.3
February	158	190	25.7
March	138	166	21.2
April	99	121	20.4
Average	**172.00**	**211.83**	**29.23**
May	144	162	25.3
June	159	135	25.4
July	174	244	30.7
August	202	263	29.3
September	204	354	39.3
October	209	319	36.7
Average	**182.00**	**246.17**	**31.12**

Plant 1 and Plant 2

in 2008		Influent 1	
	BOD, mg/L	SS,mg/L	TKN,mg/L
November	160	245	33.19
December	170	281	29.07
January	158	170	24.89
February	114	133	20.65
March	98	129	17.43
April	117	160	23.18
Average	**136.17**	**186.33**	**24.74**
May	195	260	28.87
June	142	235	29.19
July	157	238	25.37
August	199	265	35.49
September	156	232	28.88
October	195	323	40.78
Average	**174.00**	**258.83**	**31.43**

Plant 1 and Plant 2

in 2007		Influent 1	
	BOD, mg/L	SS,mg/L	TKN,mg/L
November	235	465	47.9
December	213	428	31.7
January	124	164	22
February	260	242	46.1
March	105	120	24.4
April	133	154	27.4
Average	**178.33**	**262.17**	**33.25**
May	165	195	29.6
June	164	192	23
July	188	226	34.4
August	147	214	27.8
September	193	314	39.9
October	237	359	37.2
Average	**182.33**	**250.00**	**31.98**

Table A.6: Effluent Quality at the LRPCP in 2007, 2008 and 2009 as reported to the Ontario Ministry of the Environment (MOE) (2007, 2008, and 2009)

	Plant 1			Plant 2		
in 2007		effluent,1			effluent,2	
	BODe, mg/L	SSe,mg/L	TKNe,mg/L	BODe,mg/L	SSe,mg/L	TKNe,mg/L
November	6	6	4.63	5	5	3.47
December	6	7	5.01	11	7	2.5
January	4	6	2.55	7	missing data	5.36
February	6	4	3.52	missing data	7	5.16
March	5	6	3.75	missing data	5	6.48
April	6	6	2.79	11	5	4.81
Average	**5.5**	**5.83**	**3.71**	**8.50**	**5.80**	**4.63**
May	4	8	3.71	4	3.8	3.8
June	5	8	8.02	3	3.2	3.2
July	3	8	3.46	2	2.72	2.72
August	2	6	2.56	1	2.15	2.15
September	2	6	4.22	1	2.25	2.25
October	2	6	6.05	1	2.44	2.44
Average	**3.00**	**7.00**	**4.67**	**2.00**	**2.76**	**2.76**

	Plant 1			Plant 2		
in 2008		effluent,1			effluent,2	
	BODe, mg/L	SSe,mg/L	TKNe,mg/L	BODe,mg/L	SSe,mg/L	TKNe,mg/L
November	6	5	3.36	5	8	2.27
December	5	6	2.66	8	11	2.31
January	7	7	3.03	6	6	2.5
February	4	5	2.46	6	6	2.77
March	5	6	1.8	10	7	3.91
April	3	5	1.91	8	4	4.08
Average	**5.00**	**5.67**	**2.54**	**7.17**	**7.00**	**2.97**
May	3	7	1.79	4	5	2.12
June	2	5	1.78	2	3	1.61
July	1	5	1.9	2	4	1.9
August	2	5	2.22	3	7	2.24
September	2	4	2.35	3	7	1.89
October	2	5	2.81	3	8	2.2
Average	**2.00**	**5.17**	**2.14**	**2.83**	**5.67**	**1.99**

In 2009	Plant 1			Plant 2		
		effluent,1			effluent,2	
	BODe,mg/L	SSe,mg/L	TKNe,mg/L	BODe,mg/L	SSe,mg/L	TKNe,mg/L
November	7	8	2.6	5	6	2.19
December	7	9	2.34	6	7	1.97
January	4	4	2.26	8	8	2.89
February	5	5	1.89	13	9	5.11
March	4	4	1.81	7	5	3.95
April	4	4	1.57	7	3	2.35
Average	**5.17**	**5.67**	**2.08**	**7.67**	**6.33**	**3.08**
May	2	3	1.62	3	3	1.39
June	3	5	1.33	2	4	1.02
July	3	5	2	3	4	1.5
August	2	4	2.36	3	5	2.24
September	3	6	2.18	2	3	1.86
October	2	4	2.11	3	5	2.29
Average	**2.5**	**4.5**	**1.93**	**2.67**	**4.00**	**1.72**

Table A.7: Inflow rate of the LRPCP in 2007, 2008 and 2009

in 2007	Month	Treated volume 1, ML	Q1,m3/d	Treated volume 2, ML	Q2,m3/d
Winter	Nov	455.6	1.52E+04	664.7	2.22E+04
	Dec	639.3	2.06E+04	960.1	3.10E+04
	Jan	815.7	2.63E+04	1016.9	3.28E+04
	Feb	343.5	1.23E+04	599.6	2.14E+04
	Mar	739	2.38E+04	960.2	3.10E+04
	Apr	651.8	2.17E+04	742.4	2.47E+04
	Total	3644.9	2.00E+04	4943.9	2.72E+04
Summer	May	711.3	2.29E+04	706.7	2.28E+04
	Jun	667.4	2.22E+04	495.2	1.65E+04
	Jul	428.4	1.38E+04	615.6	1.99E+04
	Aug	658.3	2.12E+04	778.4	2.51E+04
	Sep	471	1.57E+04	642.1	2.14E+04
	Oct	487	1.57E+04	652.1	2.10E+04
	Total	3423.4	1.86E+04	3890.1	2.11E+04

in 2008	Month	Treated volume 1, ML	Q1,m3/d	Treated volume 2, ML	Q2,m3/d
Winter	Nov	539.3	1.80E+04	784	2.61E+04
	Dec	749.1	2.42E+04	1070.5	3.45E+04
	Jan	591.9	1.91E+04	923.1	2.98E+04
	Feb	669.9	2.39E+04	963.5	3.44E+04
	Mar	874.9	2.82E+04	1205.9	3.89E+04
	Apr	544.3	1.81E+04	912.5	3.04E+04
	Total	3969.4	2.19E+04	5859.5	3.24E+04
Summer	May	442.7	1.43E+04	719.9	2.32E+04
	Jun	664.9	2.22E+04	890.3	2.97E+04
	Jul	569.2	1.84E+04	830	2.77E+04
	Aug	361.2	1.17E+04	672.2	2.17E+04
	Sep	545.3	1.82E+04	750.1	2.50E+04
	Oct	398.4	1.29E+04	652.1	2.10E+04
	Total	2981.7	1.62E+04	4514.6	2.47E+04

		Plant 1		Plant 2	
in 2009	Month	Treated volume 1, ML	Q1,m3/d	Treated volume 2, ML	Q2,m3/d
Winter	Nov	352.1	1.17E+04	533.2	1.78E+04
	Dec	551.9	1.78E+04	734.7	2.37E+04
	Jan	415.8	1.34E+04	669.3	2.16E+04
	Feb	702.8	2.51E+04	1001.3	3.58E+04
	Mar	662.3	2.14E+04	1034.6	3.34E+04
	Apr	771.8	2.57E+04	1137.2	3.79E+04
	Total	3456.7	1.92E+04	5110.3	2.84E+04
Summer	May	556.9	1.80E+04	857.3	2.77E+04
	Jun	525	1.75E+04	752.7	2.51E+04
	Jul	430.4	1.39E+04	650.2	2.10E+04
	Aug	486.9	1.57E+04	705.7	2.28E+04
	Sep	371.5	1.24E+04	636.6	2.12E+04
	Oct	507.3	1.64E+04	728	2.35E+04
	Total	2878	1.56E+04	4330.5	2.35E+04

Table A.8: Assumed % removal of BOD and TSS Value from primary clarifier of Plant 1 and Plant 2 and assumed VSS/TSS in based on reported values from LRPCP and literature.

Parameter	**Value**
Primary Clarifier BOD removal rate	50%
Primary Clarifier TSS removal rate	65%
VSS/TSS in influent of Primary Clarifier	0.5 (Henze et al., 2008)
VSS/TSS in effluent of secondary Clarifier	0.85 (Metcalf and Eddy, 2004)
Aeration HRT	8 hrs

Table A.9: Reported Temperature Values of Plant 1 and Plant 2 (LRPCP, 2008 and 2009)

2008	temp,°C	**2009**	temp, °C
November	13.70	November	14.22
December	13.30	December	11.10
January	9.28	January	8.27
February	7.83	February	7.70
March	7.68	March	8.15
April	10.50	April	9.77
Average	**10.38**	**Average**	**9.87**
May	13.24	May	13.07
June	15.90	June	15.68
July	18.30	July	17.70
August	19.70	August	18.98
September	19.10	September	18.83
October	16.50	October	15.63
Average	**17.12**	**Average**	**16.65**

Appendix B

Calculations

Off-site GHG emissions from utility consumption

P_{CO_2} , electricity = QE*∑ (PF_i*EF_i) .... (Eq. 3.1)

For the Little River Pollution Control Plant (LRPCP) in 2008,

QE = 16216.76 kWh/d

PF_i from Table 3.1 and EFi from Table 3.2

Therefore, P_{CO_2} , electricity = 16216.76 kWh/d*

*[(0.39*10)+(0.51*9)+(0.067*877)+(0.033*604)] g CO_2 equiv/kWh

=1.41*10^6 (g CO_2 equiv/d)

= **1.41*10^3 (kg CO_2 equiv/d)**

$P_{CO2,\ NG} = [(Q_G*EF_{NG,CO2}) /10^3(g/kg)] + 23* [(Q_G*EF_{NG,CH4})/10^3(g/kg)]$........ (Eq. 3.2)

$Q_G = 290.86\ m^3/d$

$EF_{NG,\ CO2}$ = 234 g CO_2/m^3 NG and $EF_{NG,\ CH4}$ = 83 g CH_4/m^3 NG (Table3.3)

Therefore, $P_{CO2,\ NG}$ = 623312.98 (g CO_2 equiv/d)

= 623.31(kg CO_2 equiv /d)

$P_{Total\ CO2,\ off\text{-}site}$ (kg CO_2equiv/d) = $P_{CO2,\ electricity} + P_{CO2,NG}$..................... (Eq. 3.3)

= 1.41*10^3 + 623.31(kg CO_2e/d)

= 2.04*10^3 (kg CO_2 equiv/d)

Table B.1: Calculation of the GHGs Emissions from utility consumption by using Eq. 3.1 and Eq. 3.2

PF	EF g CO_2 equiv/kWh
0.39	10
0.51	9
0.067	877
0.033	604
∑ (PFi*EFi) =	87.18

For LRPCP

Year	$P_{CO2,\ electricity}$ kg CO_2 equiv/d	$P_{CO2,\ NG}$ kg CO_2 equiv/d	$P_{CO2,\ electricity}$ tonnes CO_2 equiv/yr	$P_{CO2,\ NG}$ tonnes CO_2 equiv/yr	$P_{Total\ CO2,\ off\text{-}site}$ kg CO_2 equiv/d	$P_{Total\ CO2,\ off\text{-}site}$ tonnes CO_2 equiv/yr
2007	1422.59	674.55	519	246	2097.14	765
2008	1413.65	624.32	516	228	2037.97	744
2009	1458.30	849.25	532	310	2307.55	842

For LRWRP

Year	$P_{CO2\ ,\ electricity}$ kg CO_2 equiv/d	$P_{CO2,\ NG}$ kg CO_2 equiv/d	$P_{CO2,\ electricity}$ tonnes CO_2equiv/yr	$P_{CO2,\ NG}$ tonnes CO_2 equiv/yr	$P_{Total\ CO2,\ off\text{-}site}$ kg CO_2 equiv/d	$P_{Total\ CO2,\ off\text{-}site}$ tonnes CO_2 equiv/yr
2007	1896.25	841.59	692	253	2737.83	945
2008	3415.72	1142.64	1247	455	4558.36	1702
2009	3634.65	1010.10	1327	484	4644.74	1811

Table B.2: Calculation of the BOD removal rate and SS removal rate from LRPCP

Year:2008

Plant 1	Inf BOD	Inf SS	Pri eff BOD	Pri eff SS	% BOD removal	% SS removal
Nov	159.52	244.60	69.05	65.00	56.71	73.43
Dec	169.55	280.50	72.70	66.29	57.12	76.37
Jan	157.57	170.13	63.78	72.39	59.52	57.45
Feb	113.90	133.10	53.33	56.76	53.18	57.36
Mar	98.40	129.47	43.45	51.87	55.84	59.94
Apr	117.43	159.87	54.59	62.27	53.51	61.05
Average	**136.06**	**186.28**	**59.48**	**62.43**	**56**	**64**
May	194.62	259.59	72.55	73.00	62.72	71.88
Jun	142.38	235.13	54.29	60.80	61.87	74.14
Jul	156.68	237.81	53.95	53.29	65.57	77.59
Aug	198.62	265.16	99.30	66.32	50.00	74.99
Sep	155.77	231.73	85.23	74.41	45.29	67.89
Oct	194.70	322.84	99.74	68.06	48.77	78.92
Average	**173.79**	**258.71**	**77.51**	**65.98**	**56**	**74**

Year:2008

Plant 2	Inf BOD	Inf SS	Pri eff BOD	Pri eff SS	% BOD removal	% SS removal
Nov	159.52	244.60	66.81	67.53	58.12	72.39
Dec	169.55	280.50	74.35	68.00	56.15	75.76
Jan	157.57	170.13	71.78	66.32	54.44	61.02
Feb	113.90	133.10	59.68	55.72	47.60	58.13
Mar	98.40	129.47	48.60	55.73	50.61	56.95
Apr	117.43	159.87	54.55	56.60	53.55	64.60
Average	**136.06**	**186.28**	**62.63**	**61.65**	**54**	**67**
May	194.62	259.59	70.68	71.00	63.68	72.65
Jun	142.38	235.13	45.05	47.27	68.36	79.90
Jul	156.68	237.81	53.00	50.52	66.17	78.76
Aug	198.62	265.16	84.67	54.97	57.37	79.27
Sep	155.77	231.73	73.91	63.37	52.55	72.66
Oct	194.70	322.84	81.39	60.26	58.20	81.33
Average	**173.79**	**258.71**	**68.12**	**57.90**	**61**	**78**

Year:2009

Plant 1	Inf BOD	Inf SS	Pri eff BOD	Pri eff SS	% BOD removal	% SS removal
Nov	231	330	97.29	75.60	57.88	77.09
Dec	196	232	109.42	66.38	44.17	71.39
Jan	210	232	99.65	90.27	52.55	61.09
Feb	158	190	68.80	60.93	56.46	67.93
Mar	138	166	60.59	59.42	56.09	64.21
Apr	99	121	43.00	50.67	56.57	58.13
Average	**172**	**211**	**79.79**	**67.21**	**54**	**67**
May	144	162	data missing	data missing	data missing	data missing
Jun	159	135	data missing	data missing	data missing	data missing
Jul	174	244	79.40	65.43	54.37	73.19
Aug	202	263	72.52	53.74	64.10	79.57
Sep	204	354	75.71	54.90	62.89	84.49
Oct	209	319	84.41	60.84	59.61	80.93
Average	**182**	**246**	**78.01**	**58.73**	**60**	**80**

Year:2009

Plant 2	Inf BOD	Inf SS	Pri eff BOD	Pri eff SS	% BOD removal	% SS removal
Nov	231	330	109.57	72.60	52.57	78.00
Dec	196	232	105.35	77.04	46.25	66.79
Jan	210	232	91.60	80.34	56.38	65.37
Feb	158	190	70.60	65.21	55.32	65.68
Mar	138	166	54.87	48.87	60.24	70.56
Apr	99	121	60.00	53.00	39.39	56.20
Average	**172**	**211**	**82.00**	**66.18**	**51.69**	**67.10**
May	144	162	data missing	data missing	data missing	data missing
Jun	159	135	data missing	data missing	data missing	data missing
Jul	174	244	85.00	67.33	51.15	72.40
Aug	202	263	76.50	55.73	62.13	78.81
Sep	204	354	82.52	64.83	59.55	81.69
Oct	209	319	91.09	65.03	56.42	79.61
Average	**182**	**246**	**83.78**	**63.23**	**57.31**	**78.13**

Table B.3: Calculation of SRT based on reported value from LRPCP

$$\text{SRT} = \frac{VX}{[Qw * Xr + (Qi - Qw) * Xe]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 3.11)}$$

Assumed, $(VSS/TSS)_e = 0.85$ and MLVSS/MLSS = 0.80 (Metcalf and Eddy, 2004)

Plant 1		Q1,m^3/d	Waste1, m^3/d	RAS 1, Xr, mg/L	MLSS 1,mg/L	MLVSS 1 (X),mg/L	TSSe1, mg/L	Xe1, mg/L
Winter 2007	Nov	1.52E+04	249.47	5444.03	2761.03	2208.83	6	5.10
	Dec	2.06E+04	196.81	6016.52	3121.10	2496.88	7	5.95
	Jan	2.63E+04	246.39	5900.16	2549.10	2039.28	6	5.10
	Feb	1.23E+04	251.43	5002.25	2687.82	2150.26	4	3.40
	Mar	2.38E+04	185.61	6771.74	3046.29	2437.03	6	5.10
	Apr	2.17E+04	220.60	6529.10	2960.43	2368.35	6	5.10
	average	2.00E+04	**225.05**	**5943.97**	**2854.30**	2283.44	5.83	4.96
Summer 2007	May	2.29E+04	215.90	6621.55	2986.19	2388.95	8	6.80
	Jun	2.22E+04	314.21	5986.20	3254.40	2603.52	8	6.80
	Jul	1.38E+04	332.81	4219.87	2219.84	1775.87	8	6.80
	Aug	2.12E+04	278.68	4361.03	1897.71	1518.17	6	5.10
	Sep	1.57E+04	261.03	4552.23	2259.57	1807.65	6	5.10
	Oct	1.57E+04	250.64	5343.26	2729.45	2183.56	6	5.10
	average	1.86E+04	**275.54**	**5180.69**	**2557.86**	2046.29	7.00	5.95

Plant 2		Q2,m^3/d	Waste 2, m^3/d	RAS 2, Xr, mg/L	MLSS 2, mg/L	MLVSS 2 (X), mg/L	TSSe 2, mg/L	Xe2, mg/L
Winter 2007	Nov	2.22E+04	302.23	4634.33	2351.07	1880.85	5	4.25
	Dec	3.10E+04	267.94	5656.32	2631.45	2105.16	7	5.95
	Jan	3.28E+04	365.55	5024.45	2153.87	1723.10	missing data	missing data
	Feb	2.14E+04	370.89	4849.82	2553.89	2043.11	7	5.95
	Mar	3.10E+04	271.26	6005.71	2606.06	2084.85	5	4.25
	Apr	2.47E+04	292.27	5750.27	2672.67	2138.13	5	4.25
	average	2.72E+04	**311.69**	**5320.15**	**2494.84**	1995.87	5.80	4.93
Summer 2007	May	2.28E+04	293.84	4872.74	2206.26	1765.01	3.8	3.23
	Jun	1.65E+04	259.15	4604.00	2394.63	1915.71	3.2	2.72
	Jul	1.99E+04	448.10	3995.32	2002.13	1601.70	2.72	2.31
	Aug	2.51E+04	429.21	3623.10	1612.06	1289.65	2.15	1.83
	Sep	2.14E+04	414.63	3990.37	1982.00	1585.60	2.25	1.91
	Oct	2.10E+04	389.48	4153.87	2195.00	1756.00	2.44	2.07
	average	2.11E+04	**372.40**	**4206.57**	**2065.35**	1652.28	2.76	2.35

Plant 1		Q1,m^3/d	Waste1, m^3/d	RAS 1, Xr, mg/L	MLSS 1,mg/L	MLVSS 1 (X),mg/L	TSSe1, mg/L	Xe1, mg/L
Winter 2008	Nov	1.80E+04	181.37	4823.77	2233.87	1787.09	5	4.25
	Dec	2.42E+04	199.48	5669.90	2668.13	2134.50	6	4.50
	Jan	1.91E+04	198.90	5946.48	3031.03	2424.83	7	5.25
	Feb	2.39E+04	176.86	6369.93	2987.05	2389.64	5	3.75
	Mar	2.82E+04	175.26	6771.68	2993.03	2394.43	6	4.50
	Apr	1.81E+04	179.30	6231.97	3008.87	2407.09	5	3.75
	average	2.19E+04	**185.20**	**5968.95**	**2820.33**	**2256.26**	**5.67**	**4.33**
Summer 2008	May	1.43E+04	223.90	5778.42	2958.68	2366.94	7	5.25
	Jun	2.22E+04	256.70	5350.17	2228.40	1782.72	5	3.75
	Jul	1.84E+04	267.68	4141.48	1797.87	1438.30	5	3.75
	Aug	1.17E+04	299.35	3735.74	1823.35	1458.68	5	3.75
	Sep	1.82E+04	284.77	4234.07	1983.03	1586.43	4	3.00
	Oct	1.29E+04	317.19	3814.61	2005.84	1604.67	5	3.75
	average	1.62E+04	**274.93**	**4509.08**	**2132.86**	**1706.29**	**5.17**	**3.88**

Plant 2		Q2,m^3/d	Waste 2, m^3/d	RAS 2, Xr, mg/L	MLSS 2, mg/L	MLVSS 2 (X), mg/L	TSSe 2, mg/L	Xe2, mg/L
Winter 2008	Nov	2.61E+04	345.57	4052.53	1868.10	1494.48	8.00	6.80
	Dec	3.45E+04	296.58	5121.65	2293.74	1834.99	11.00	9.35
	Jan	2.98E+04	277.48	5851.16	2803.71	2242.97	6.00	5.10
	Feb	3.44E+04	241.28	6405.72	2868.26	2294.61	6.00	5.10
	Mar	3.89E+04	251.58	6645.23	2833.19	2266.55	7.00	5.95
	Apr	3.04E+04	221.63	6653.47	3202.57	2562.05	4.00	3.40
	average	3.24E+04	**272.35**	**5788.29**	**2644.93**	**2115.94**	**7.00**	5.95
Summer 2008	May	2.32E+04	359.65	5529.29	2804.87	2243.90	5.00	4.25
	Jun	2.97E+04	373.30	4803.33	1925.97	1540.77	3.00	2.55
	Jul	2.77E+04	365.42	4239.00	1673.61	1338.89	4.00	3.40
	Aug	2.17E+04	398.16	4283.90	1851.29	1481.03	7.00	5.95
	Sep	2.50E+04	358.83	4391.27	1898.63	1518.91	7.00	5.95
	Oct	2.10E+04	467.52	3635.06	1875.77	1500.62	8.00	6.80
	average	2.47E+04	**387.15**	**4480.31**	**2005.02**	**1604.02**	**5.67**	4.82

PLANT 1 2008	V1 = m3 5300	V1*X	Qw* Xr + (Qi - Qw) *Xe	SRT,d
	Winter	11958197.41	1.20E+06	10
	Summer	9043337.19	1301587.487	7

PLANT 2 2008	V2 = m3 8400	V2*X	Qw* Xr + (Qi - Qw) *Xe	SRT,d
	Winter	17773917.29	1.77E+06	10
	Summer	13473766.19	1.85E+06	7

Plant 1		Q1,m3/d	Waste1, m^3/d	RAS 1, Xr, mg/L	MLSS 1, mg/L	MLVSS1 (X),mg/L	TSSe1, mg/L	Xe1, mg/L
Winter 2009	Nov	1.17E+04	294.13	3652.50	2167.83	1734.27	8	6.80
	Dec	1.78E+04	275.06	4368.19	2461.58	1969.26	9	7.65
	Jan	1.34E+04	216.19	5650.19	3013.77	2411.02	4	3.40
	Feb	2.51E+04	180.00	6871.04	3082.11	2465.69	5	4.25
	Mar	2.14E+04	192.00	6562.55	3099.10	2479.28	4	3.40
	Apr	2.57E+04	230.90	5990.63	2875.30	2300.24	4	3.40
	average	1.92E+04	231.38	5515.85	2783.28	2226.63	5.67	4.82
Summer 2009	May	1.80E+04	243.45	5363.81	2349.87	1879.90	3	2.55
	Jun	1.75E+04	259.13	4409.38	2066.83	1653.47	5	4.25
	Jul	1.39E+04	366.68	3316.29	1588.87	1271.10	5	4.25
	Aug	1.57E+04	376.48	3239.81	1444.71	1155.77	4	3.40
	Sep	1.24E+04	370.93	2966.93	1331.03	1064.83	6	5.10
	Oct	1.64E+04	342.87	3314.10	1684.58	1347.66	4	3.40
	average	1.56E+04	326.59	3768.39	1744.32	1395.45	4.5	3.83

Plant 2		Q2,m^3/d	Waste 2, m^3/d	RAS 2, Xr, mg/L	MLSS 2, mg/L	MLVSS 2 (X), mg/L	TSSe 2, mg/L	Xe2, mg/L
Winter 2009	Nov	1.78E+04	396.97	3705.97	2156.80	1725.44	6	5.10
	Dec	2.37E+04	404.45	4035.68	2144.84	1715.87	7	5.95
	Jan	2.16E+04	335.90	5147.03	2933.81	2347.05	8	6.80
	Feb	3.58E+04	279.57	6069.39	2696.68	2157.34	9	7.65
	Mar	3.34E+04	249.65	6234.77	3032.87	2426.30	5	4.25
	Apr	3.79E+04	248.07	6823.43	2951.20	2360.96	3	2.55
	average	2.84E+04	319.10	5336.05	2652.70	2122.16	6.33	5.38
Summer 2009	May	2.77E+04	333.26	6341.00	2557.35	2045.88	3	2.55
	Jun	2.51E+04	394.80	4228.87	1990.30	1592.24	4	3.40
	Jul	2.10E+04	469.94	3276.29	1701.16	1360.93	4	3.40
	Aug	2.28E+04	350.45	2892.35	1484.94	1187.95	5	4.25
	Sep	2.12E+04	503.87	3089.77	1679.80	1343.84	3	2.55
	Oct	2.35E+04	465.26	3239.13	1705.52	1364.41	5	4.25
	average	2.35E+04	419.59	3844.57	1853.18	1482.54	4	3.40

Plant 1	V1 = m^3	V1*X	Qw* Xr + (Qi - Qw) *Xe	SRT, d
2009	5300			
	winter	11801115.74	1.37E+06	9
	summer	7395901.907	1.29E+06	6

Plant 2	V2 = m^3	V2*X	Qw* Xr + (Qi - Qw) *Xe	SRT, d
2009	8400			
	winter	17826138.06	1.85E+06	10
	summer	12453355.87	1.69E+06	7

Table B.4: Calculation of biomass production $M_{X,\ CBOD}$ due to carbonaceous BOD utilization by using Eq. 3.19

$$M_{X,CBOD}\ (gVSS/d) = \frac{Qi*Y(Si-S)}{1+Kd*SRT} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 3.19)}$$

		Qi, m^3/d	S_{io},inf BOD_5,mg/L	$Per_{BOD,PC}$, %	R_{BOD},pc, g/d	Si= Sio-$R_{BOD,pc}$/Qi, mg/L	S, mg/L, test value	Y	K_d	SRT, d	M_x,CBOD, g VSS/d	M_x,CBOD, kg VSS/d
2007												
at 10 ^{0}C	Plant 1	2.00E+04	178.33	0.50	1.78E+06	89.17	5.50	0.5	0.070	10	491469.19	491.47
at 10 ^{0}C	Plant 2	2.72E+04	178.33	0.50	2.42E+06	89.17	8.50	0.5	0.070	10	644803.49	644.80
at 17^{0}C	Plant 1	1.86E+04	182.33	0.50	1.70E+06	91.17	3.00	0.5	0.090	6	532703.88	532.70
at 17^{0}C	Plant 2	2.11E+04	182.33	0.50	1.93E+06	91.17	2.00	0.5	0.090	7	577623.13	577.62
2008												
at 10 ^{0}C	Plant 1	2.19E+04	136.17	0.50	1.49E+06	68.08	5.00	0.5	0.070	10	406719.42	406.72
at 10 ^{0}C	Plant 2	3.24E+04	136.17	0.50	2.20E+06	68.08	7.17	0.5	0.070	10	579814.36	579.81
at 17^{0}C	Plant 1	1.62E+04	174.00	0.50	1.41E+06	87.00	2.00	0.5	0.090	7	423631.84	423.63
at 17^{0}C	Plant 2	2.47E+04	174.00	0.50	2.15E+06	87.00	2.83	0.5	0.090	7	638085.75	638.09
2009												
at 10 ^{0}C	Plant 1	1.92E+04	172.00	0.50	1.65E+06	86.00	5.17	0.5	0.070	9	475842.11	475.84
at 10 ^{0}C	Plant 2	2.84E+04	172.00	0.50	2.44E+06	86.00	7.67	0.5	0.070	10	653181.85	653.18
at 17^{0}C	Plant 1	1.56E+04	182.00	0.50	1.42E+06	91.00	2.50	0.5	0.090	6	449217.42	449.22
at 17^{0}C	Plant 2	2.35E+04	182.00	0.50	2.14E+06	91.00	2.67	0.5	0.090	7	637605.08	637.61

Table B.5: Calculation of NO_X by using Eq. 3.22 and iteration process and $M_{X,\ nit}$ due to nitrogenous BOD utilization by using Eq. 3.20

$$NO_Y\ (gN/m^3) = TKN_i - TKN_e - \frac{0.12*Pbiomass}{Qi} \text{ ………………………………. (Eq. 3.22)}$$

$$M_{X,\ nit}\ (gVSS/d) = \frac{Q_i*Y_n(NO_Y)}{1+K_{dn}*SRT} \text{ ………………………………………………. (Eq. 3.20)}$$

2007		Q_i, m^3/d	Y_n	K_{dn}	SRT, d	TKNi, mg/L	TKNe, mg/L	$M_{X,CBOD}$, g VSS/d	$NO_{Y,}$ mgN/L
at 10 ^{0}C	plant1	2.00E+04	0.12	0.05	10	33.25	3.71	491469.19	26.34
	plant2	2.72E+04	0.12	0.05	10	33.25	4.63	642720.28	25.54
at 17^{0}C	plant1	1.86E+04	0.12	0.07	6	31.98	4.67	536968.10	23.61
	plant2	2.11E+04	0.12	0.07	7	31.98	2.76	583019.16	25.66
2008									
at 10 ^{0}C	plant1	2.19E+04	0.12	0.05	10	24.74	2.54	403550.34	19.80
	plant2	3.24E+04	0.12	0.05	10	24.74	2.97	575247.72	19.45
at 17^{0}C	plant1	1.62E+04	0.12	0.07	7	31.43	2.14	425992.94	25.89
	plant2	2.47E+04	0.12	0.07	7	31.43	1.99	605254.59	26.25
2009									
at 10 ^{0}C	plant1	1.92E+04	0.12	0.05	9	29.23	2.08	469647.17	23.99
	plant2	2.84E+04	0.12	0.05	10	29.23	3.08	645135.91	23.21
at 17^{0}C	plant1	1.56E+04	0.12	0.07	6	31.12	1.93	453127.56	25.45
	plant2	2.35E+04	0.12	0.07	7	31.12	1.72	642957.39	25.87

In 2007	NO_Y (0.8*TKNi)	Mx,nit, g/d	Pbiomass, g/d	$NO_{Y,}$ mgN/L
trial for plant 1 at 10 °C	26.6	41384.49	532853.69	26.34
		40980.09	532449.29	26.34
trial for plant 2 at 10 °C	25.59	56315.39	699035.67	25.53
		54057.45	696777.73	25.54
		54078.56	696798.83	25.54
trial for plant 1 at 17 °C	25.59	40048.74	577016.84	23.59
		36927.47	573895.57	23.61
		36958.97	573927.07	23.61
trial for plant 2 at 17 °C	25.59	43290.22	626309.38	25.66
		43421.86	626441.03	25.66
		43420.6	626439.76	25.66

In 2008	NO_Y (0.8*TKNi)	Mx,nit, g/d	Pbiomass, g/d	$NO_{Y,}$ mgN/L
trial for plant 1 at 10 °C	19.79	33790.48	437340.82	19.80
		33818.2	437368.54	19.80
trial for plant 2 at 10 °C	19.79	49884.65	625132.37	19.44
		49016.49	624264.21	19.45
trial for plant 1 at 17 °C	25.14	32729.4	458722.34	25.90
		33713.9	459706.84	25.89
trial for plant 2 at 17 °C	25.14	49786.01	655040.60	26.26
		51988.17	657242.77	26.25

In 2009	NO_Y (0.8*TKNi)	Mx,nit, g/d	Pbiomass, g/d	$NO_{Y,}$ mgN/L
trial for plant 1 at 10 °C	23.39	36232.81	505879.98	23.99
		37170.2	506817.37	23.99
trial for plant 2 at 10 °C	23.39	51649.72	696785.64	23.21
		51253.81	696389.72	23.21
trial for plant 1 at 17 °C	24.89	32733.32	485860.88	25.45
		33470.59	486598.15	25.45
trial for plant 2 at 17 °C	24.89	46929.32	689886.71	25.88
		48792.88	691750.28	25.87

Table B.6: Calculation of CO_2 production from the carbonaceous BOD removal and nitrification by using Eq. 3.27 and from endogenous respiration by using Eq. 3.28.

$P_{CO2, CBOD}$ (g/d) = $0.33*[Q_i*(S_i - S) – 1.42* P_{X,CBOD}] – 0.25* NO_Y* Q_i$ …… (Eq. 3.27)

P_{CO2}, endogenous (g/d) = 1.56 g CO_2/ gVSS * $B_{degraded, aeration tank}$ ……….. (Eq. 3.28)

$B_{degraded, aeration tank}$ (g VSS/d) = $0.8 * SRT * Q_i \left[\frac{K_d*Y(S_i-S)}{1+K_d*SRT} + \frac{K_{dn}*Y_n(NO_Y)}{1+K_{dn}*SRT}\right]$ ……. (Eq. 3.29)

		Qi, m^3/d	Mx,CBOD , g vss/d	NO_Y, mgN/L	Si= Sio-RBOD,pc/Qi, mg/L	S, mg/L, test value	(Si-S), mg/L	P_{CO2}, CBOD (g/d)	P_{CO2}, CBOD (kg/d)	P_{CO2}, CBOD (kg/yr)
2007										
at 10 ^{0}C	plant1	2.00E+04	491469.19	26.34	89.17	5.50	83.67	1.91E+05	191.18	6.98E+04
	plant2	2.72E+04	642720.28	25.54	89.17	8.50	80.67	2.51E+05	250.82	9.15E+04
at 17^{0}C	plant1	1.86E+04	536968.10	23.61	91.17	3.00	88.17	1.81E+05	181.28	6.62E+04
	plant2	2.11E+04	583019.16	25.66	91.17	2.00	89.17	2.14E+05	214.34	7.82E+04
2008										
at 10 ^{0}C	plant1	2.19E+04	403550.34	19.80	68.08	5.00	63.08	1.60E+05	160.03	5.84E+04
	plant2	3.24E+04	575247.72	19.45	68.08	7.17	60.92	2.26E+05	225.52	8.23E+04
at 17^{0}C	plant1	1.62E+04	425992.94	25.89	87.00	2.00	85.00	1.52E+05	152.22	5.56E+04
	plant2	2.47E+04	605254.59	26.25	87.00	2.83	84.17	2.43E+05	242.59	8.85E+04
2009										
at 10 ^{0}C	plant1	1.92E+04	469647.17	23.99	86.00	5.17	80.83	1.78E+05	178.14	6.50E+04
	plant2	2.84E+04	645135.91	23.21	86.00	7.67	78.33	2.68E+05	268.03	9.78E+04
at 17^{0}C	plant1	1.56E+04	453127.56	25.45	91.00	2.50	88.50	1.46E+05	145.98	5.33E+04
	plant2	2.35E+04	642957.39	25.87	91.00	2.67	88.33	2.34E+05	234.27	8.55E+04

		(K_d*Y*(Si-S))/(1+K_d*SRT)	(K_{dn}*Yn*NO_Y)/(1+K_{dn}*SRT)	$B_{degraded, aeration\ tank}$, g VSS/d	Pco_2,end, g/d	Pco_2,end, kg/d	Pco_2,end, ,kg/yr
2007							
at 10 °C	plant1	1.72	0.11	2.93E+05	4.57E+05	4.57E+02	1.67E+05
	plant2	1.66	0.11	3.84E+05	6.00E+05	6.00E+02	2.19E+05
at 17°C	plant1	2.58	0.14	2.43E+05	3.79E+05	3.79E+02	1.38E+05
	plant2	2.46	0.15	3.08E+05	4.81E+05	4.81E+02	1.76E+05
2008							
at 10 °C	plant1	1.30	0.08	2.42E+05	3.78E+05	3.78E+02	1.38E+05
	plant2	1.25	0.08	3.46E+05	5.40E+05	5.40E+02	1.97E+05
at 17°C	plant1	2.35	0.15	2.27E+05	3.54E+05	3.54E+02	1.29E+05
	plant2	2.32	0.15	3.42E+05	5.34E+05	5.34E+02	1.95E+05
2009							
at 10 °C	plant1	1.74	0.10	2.54E+05	3.97E+05	3.97E+02	1.45E+05
	plant2	1.61	0.10	3.88E+05	6.05E+05	6.05E+02	2.21E+05
at 17°C	plant1	2.59	0.15	2.05E+05	3.21E+05	3.21E+02	1.17E+05
	plant2	2.44	0.15	3.41E+05	5.32E+05	5.32E+02	1.94E+05

Table B.7: Calculation of emission rate from LRPCP

		$P_{CO2,end}$, kg/d	$P_{CO2, CBOD}$ kg/d	total GHG, kg/d	Qi, m^3/d	emission rate, kg/m^3
2007						
at 10 °C	plant1	456.99	191.18	648.17	2.00E+04	0.032
at 17°C	plant1	599.76	250.88	850.64	2.72E+04	0.031
at 10 °C	plant2	378.70	181.16	559.86	1.86E+04	0.030
at 17°C	plant2	481.16	214.18	695.34	2.11E+04	0.033
2008						
at 10 °C	plant1	378.10	160.10	538.20	2.19E+04	0.025
at 17°C	plant1	539.56	225.68	765.24	3.24E+04	0.024
at 10 °C	plant2	354.03	152.14	506.17	1.62E+04	0.031
at 17°C	plant2	533.99	242.53	776.52	2.47E+04	0.031
2009						
at 10 °C	plant1	396.65	178.32	574.97	1.92E+04	0.030
at 17°C	plant1	605.14	268.27	873.41	2.84E+04	0.031
at 10 °C	plant2	320.58	145.86	466.44	1.56E+04	0.030
at 17°C	plant2	531.65	234.11	765.76	2.35E+04	0.033

Table B.8: Calculation of GHGs emissions from remaining effluent BOD in Off-site, biosolids diposal and sludge degradation by using Eq. 3.31, Eq. 3.32 and Eq. 3.35.

0.986 * BODeff * Qi ………………………………………….. (Eq. 3.31)

		BODeff, mg/L	Qi, m^3/d	$M_{CO2,BODeff}$, (gCO_2/d)	$M_{CO2,BODeff}$, ($kgCO_2/d$)	$M_{CO2,BODeff}$, (tonnesCO_2/yr)	Average $M_{CO2,BODeff}$ from Plant 1 and Plant 2, (tonnesCO_2/yr)	Total $M_{CO2,BODeff}$ from Plant 1 and Plant 2, (tonnesCO_2/yr)
In 2007	Plant1							
	10^0 C	5.5	2.00E+04	108308.45	108.31	39.53	29.81	78.98
	17^0 C	3	1.86E+04	55046.58	55.05	20.09		
	Plant2							
	10^0 C	8.5	2.72E+04	227776.03	227.78	83.14	49.17	
	17^0 C	2	2.11E+04	41645.35	41.65	15.20		
In 2008	Plant1							
	10^0 C	5	2.19E+04	108070.24	108.07	39.45	25.57	79.90
	17^0 C	2	1.62E+04	32040.12	32.04	11.69		
	Plant2							
	10^0 C	7.17	3.24E+04	228678.79	228.68	83.47	54.33	
	17^0 C	2.83	2.47E+04	69044.82	69.04	25.20		
In 2009	Plant1							
	10^0 C	5.17	1.92E+04	97763.63	97.76	35.68	24.87	75.28
	17^0 C	2.50	1.56E+04	38537.27	38.54	14.07		
	Plant2							
	10^0 C	7.67	2.84E+04	214313.69	214.31	78.22	50.40	
	17^0 C	2.67	2.35E+04	61871.46	61.87	22.58		

$P_{CO2\text{, solids disposal}}$ =10kg CO_2equiv/tonne waste * total dried solids …….. (Eq. 3.32)

Year	Total dried solids (tonnes/yr)	M CO_2, solids disposal (kg/yr)	M CO_2, solids disposal (tonnes/yr)
2007	2594	25940	25.94
2008	2747	27470	27.47
2009	2607	26070	26.07

$P_{CO_2\ equiv,\ off\text{-}site\ sludge\ degradation} = MCO_{2,\ remaining\ biodegradable\ solids} + 23*(MCH_{4,\ remaining\ biodegradable\ solids})$ ………… (Eq. 3.35)

	Pbiomass, kg VSS/yr	Pbiomass, g VSS/yr	Landfilled, g VSS/yr	Degradable sludge g VSS/yr	MCO_2, remaining biodegradable solids, g CO_2/ yr	MCO_2, remaining biodegradable solids, tonne CO_2/ yr	MCH_4, g CO2/ yr	MCH_4, tonne CO_2/ yr	P CO_2, offsite sludge degradation tonne CO2/ yr
In 2007	4.43E+05	4.43E+08	2.22E+08	1.77E+08	1.03E+08	103	6.21E+07	62	165
					0.00E+00				
In 2008	3.98E+05	3.98E+08	4.37E+07	3.50E+07	2.03E+07	20	1.22E+07	12	33
					0.00E+00				
In 2009	4.35E+05	4.35E+08	2.17E+07	1.74E+07	1.01E+07	10	6.08E+06	6	16

Table B.9: Calculation of N_2O emissions from on-site and off-site sources by using Eq. 3.37 and Eq. 3.38

	E N_2O, Direct1, g/yr	E N_2O, Direct1, kg N2O /yr	tonnes N2O /yr	tonnes CO_2 equiv/yr
plant 1	126950.40	126.95	0.13	37.58
plant 2	190425.60	190.43	0.19	56.37

Year		Pbiomass, g/d	Average, Pbiomass, g/d	Average, Pbiomass, kg/yr	Total biomass, kg/yr	Average, Nit sludge, kg/yr (0.12 * avg Pbiomass)
2009	Plant 1 at 10 °C	506817.37	496707.76	181298.33	434633.88	21755.80
	Plant 1 at 17 °C	486598.15				
	Plant 2 at 10 °C	696389.72	694070.00	253335.55		30400.27
	Plant 2 at 17 °C	691750.28				

	EF_1, g N_2O/p/yr	CF	Pro,kg/p/yr	Np frac	F	Nit $_{ww}$, g/yr	Nit $_{ww}$, kg/yr	Nit sludge,kg/yr	EF_2
2009									
Plant 1	3.2	1.14	38	0.16	1.14	80787	81	21756	0.01
Plant 2	3.2	1.14	38	0.16	1.14	121180	121	30400	0.01

2009	E N_2O, Indirect kg N2O /yr	tonnes N_2O /yr	tonnes CO_2 equiv/yr
Plant 1	3447	3.45	1020.38
Plant 2	5206	5.21	1540.96

Table B.10: Calculation of BOD loading for LRPCP in 2009

plant1	BOD loading, kg/d	Total GHGs Emissions, kg/d	plant 2	BOD loading, kg/d	Total GHGs Emissions, kg/d
Jan	2817	511	Jan	4534	806
Feb	3966	672	Feb	5650	832
Mar	2948	518	Mar	4606	866
Apr	2547	383	Apr	3753	624
May	2587	434	May	3982	681
Jun	2783	490	Jun	3989	735
Jul	2416	366	Jul	3650	657
Aug	3173	498	Aug	4598	1001
Sep	2526	367	Sep	4329	795
Oct	3420	543	Oct	4908	855
Nov	2711	464	Nov	4106	781
Dec	3489	557	Dec	4645	767

Table B.11: Multiple regression analysis output for Plant 1(considering variables: temperature, SRT, and BOD loading)

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.961063937
R Square	0.923643891
Adjusted R Square	0.895010351
Standard Error	27.27167124
Observations	12

Table B.12: Multiple regression analysis output for Plant 2(considering variables: temperature, SRT, and BOD loading)

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.942872035
R Square	0.889007674
Adjusted R Square	0.847385551
Standard Error	40.27144245
Observations	12

Table B.13: Multiple regression analysis output for Plant 1(considering variables: temperature, SRT, BOD loading, and Q_w/Q_i)

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.962085437
R Square	0.925608388
Adjusted R Square	0.883098896
Standard Error	28.77715237
Observations	12

Table B.14: Multiple regression analysis output for Plant 2(considering variables: temperature, SRT, BOD loading, and Q_w/Q_i)

SUMMARY
OUTPUT

Regression Statistics	
Multiple R	0.945211351
R Square	0.893424498
Adjusted R Square	0.832524211
Standard Error	42.18668268
Observations	12

Appendix C

Kinetic Parameters Values

Table C.1: The kinetic coefficients of heterotrophic and autotrophic bacteria for substrate utilization from domestic wastewater in the activated-sludge process (Metcalf and Eddy, 2004)

Coefficient	**Symbol**	**Unit**	**Standard Value (at 20ºC)**
Maximum specific bacterial growth rate	μ_m	g VSS/g VSS-d	4
Maximum specific substrate utilization rate	$k = \mu_m/Y$	g BOD/g VSS-d	8
Substrate half saturation coefficient	K_s	mg BOD /L	60
Endogenous decay rate	k_d	g VSS/g VSS-d	0.1
Synthesis yield coefficient or True yield coefficient	Y	g VSS/g BOD_5	0.5
Synthesis yield coefficient for nitrifying bacteria	Y_n	g VSS/ g NH_4-N	0.12
Endogenous decay factor for nitrifying bacteria	k_{dn}	g VSS/g VSS-d	0.08

Table C.2: Measured wastewater temperature of Plant 1 and Plant 2 of the LRPCP

	Temperature, ºC (Average)
Summer (May to Oct)	17
Winter (Nov to Apr)	10

Effect of Temperature

$K_T = K_{20} * \theta^{(T-20)}$ ………………………… Eq. C 1

Where,

K_T = Reaction rate coefficient at temperature T, ºC

K_{20} = Reaction rate coefficient at 20 ºC

θ = Temperature activity coefficient

T = Temperature, ºC

Table C.3: Temperature activity coefficient, θ (Metcalf and Eddy, 2004)

Coefficient	θ values
μ_m	1.07
K_s	1.00
k_d	1.04
k_{dn}	1.04

Table C.4: The kinetic coefficients for substrate utilization at corrected temperature

Coefficient	Symbol	Unit	Value (at 10ºC)	Value (at 17ºC)
Maximum specific bacterial growth rate	μ_m	g VSS/g VSS-d	2.03	3.27
Maximum specific substrate utilization rate	$k = \mu_m/Y$	g BOD/g VSS-d	4.07	6.53
Substrate half saturation coefficient	K_s	mg BOD /L or g BOD /m^3	60	60
Endogenous decay rate	k_d	g VSS/g VSS-d	0.07	0.09
Endogenous decay factor for nitrifying bacteria	k_{dn}	g VSS/g VSS-d	0.05	0.07

Table C.5: The kinetic coefficients for substrate utilization at corrected temperature in 2009

Year 2009	Y	k = μ_m/Y
January	0.5	3.62
February	0.5	3.48
March	0.5	3.59
April	0.5	4.00
May	0.5	5.01
June	0.5	5.97
July	0.5	6.85
August	0.5	7.47
September	0.5	7.39
October	0.5	5.95
November	0.5	5.41
December	0.5	4.38

Year 2009	Temperature, °C	θ values	Standard Value (at 20ºC)	μ_m at corrected temperature
January	8.27	1.07	4	1.81
February	7.70	1.07	4	1.74
March	8.15	1.07	4	1.79
April	9.77	1.07	4	2.00
May	13.07	1.07	4	2.50
June	15.68	1.07	4	2.99
July	17.70	1.07	4	3.42
August	18.98	1.07	4	3.73
September	18.83	1.07	4	3.70
October	15.63	1.07	4	2.98
November	14.22	1.07	4	2.71
December	11.10	1.07	4	2.19

θ values	K_s
1	60
1	60
1	60
1	60
1	60
1	60
1	60
1	60
1	60
1	60
1	60
1	60

θ values	Standard Value (at 20ºC)	k_d
1.04	0.1	0.06
1.04	0.1	0.06
1.04	0.1	0.06
1.04	0.1	0.07
1.04	0.1	0.08
1.04	0.1	0.08
1.04	0.1	0.09
1.04	0.1	0.10
1.04	0.1	0.10
1.04	0.1	0.08
1.04	0.1	0.08
1.04	0.1	0.07

θ values	Standard Value (at 20ºC)	k_{dn}
1.04	0.08	0.05
1.04	0.08	0.05
1.04	0.08	0.05
1.04	0.08	0.05
1.04	0.08	0.06
1.04	0.08	0.07
1.04	0.08	0.07
1.04	0.08	0.08
1.04	0.08	0.08
1.04	0.08	0.07
1.04	0.08	0.06
1.04	0.08	0.06

Table C.6: Effluent BOD calculation based on kinetic coefficients for substrate utilization at corrected temperature in 2009

$$S = \frac{Ks(1+Kd*SRT)}{SRT(YK-Kd)-1} \quad \text{(Eq. 3.12)}$$

	Temp.	K_s	K_d	Y	k	SRT, d
2008, plant1	at 10 °C	60	0.07	0.5	4.07	10
	at 17 °C	60	0.09	0.5	6.53	7
2009, plant1	at 10 °C	60	0.07	0.5	4.07	9
	at 17 °C	60	0.09	0.5	6.53	6
2008, plant2	at 10 °C	60	0.07	0.5	4.07	10
	at 17 °C	60	0.09	0.5	6.53	8
2009, plant2	at 10 °C	60	0.07	0.5	4.07	10
	at 17 °C	60	0.09	0.5	6.53	7

A	B	Effluent BOD	
$K_s(1+K_d*SRT)$	[SRT(YK-K_d)-1]	S, mg/L, calculated value, (A/B)	S, mg/L, test result
102.00	18.63	5.47	5.00
97.34	21.23	4.58	2.00
97.80	16.67	5.87	5.17
92.00	18.06	5.09	2.50
102.00	18.63	5.47	7.17
102.67	24.41	4.21	2.83
102.00	18.63	5.47	7.67
97.34	21.23	4.58	2.67

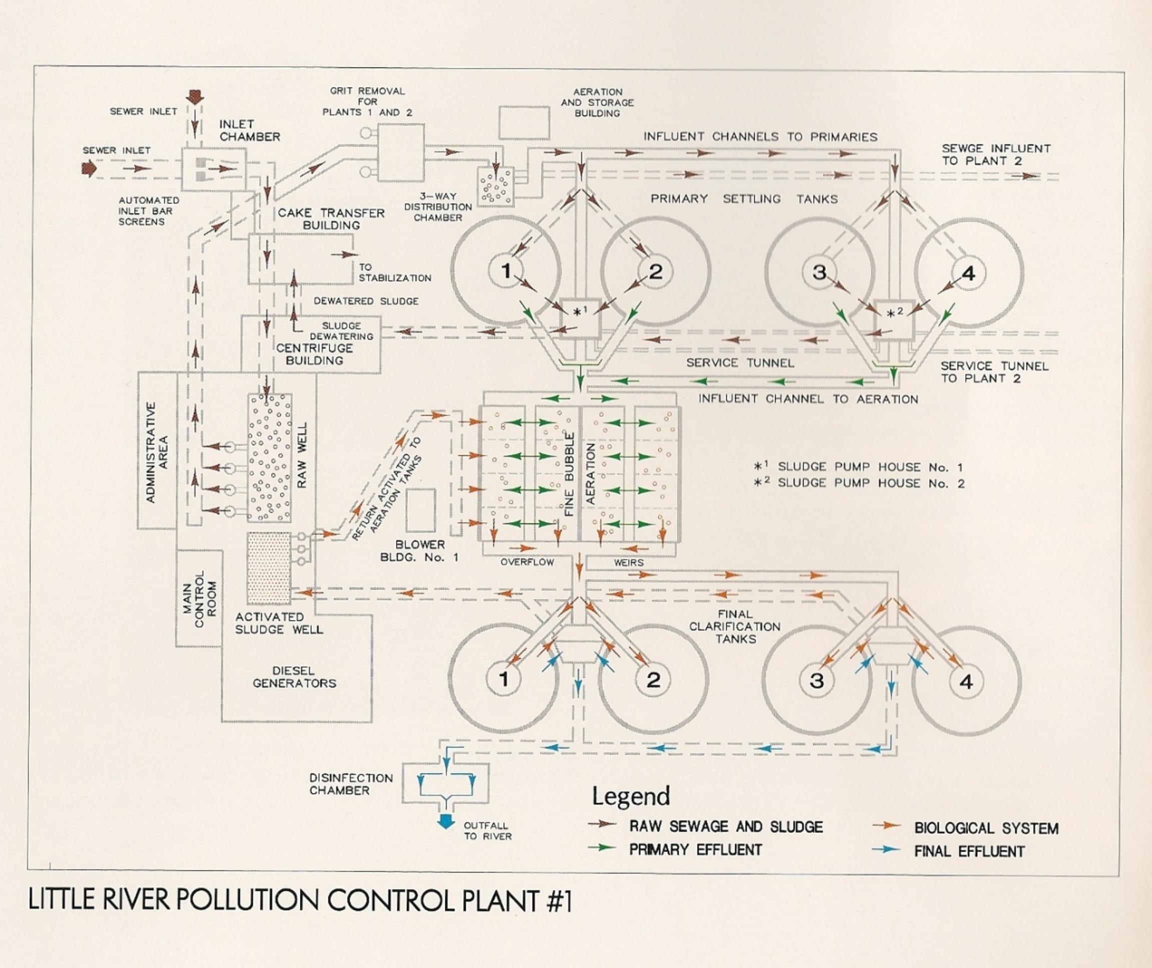

Figure C.1: Layout of the Little River Pollution Control Plant-1

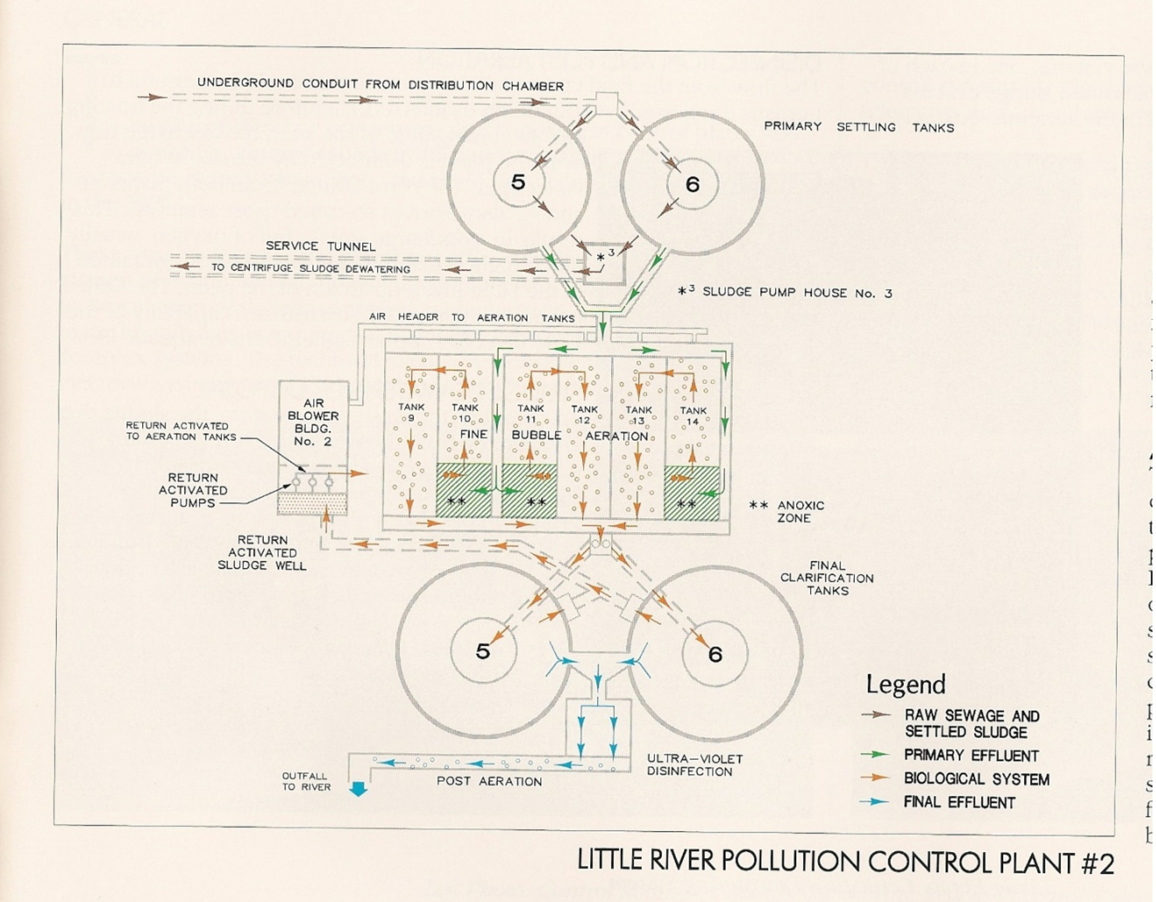

Figure C.2: Layout of the Little River Pollution Control Plant-2

Appendix D

Stoichiometric and Emission Factor Calculations

BOD Oxidation to CO_2

The electron donor is an organic compound and the electron acceptor is oxygen and ammonia is considered as nitrogen source.

(1) Energy production half reactions

Forty percent carbon removed by energy production

$Re = Ra - Rd$

where,

Re = energy reaction

Ra = electron acceptor half reactions

Rd = electron donor half reactions

(2) Cell synthesis half reactions

Sixty percent carbon removed by cell synthesis

$Rs = Rc - Rd$

Complete reaction, $R = Re + Rs$

$$R = fe(Ra - Rd) + fs(Rc - Rd)$$

$$R = feRa + fsRc - Rd$$

Where,

$fe + fs = 1$

fe = a part of electrons is transferred to the electron acceptor

fs = a part of electrons transferred to biomass

according to Rittman and McCarty (2001), fs = 0.6 and fe =0.4

acceptor reaction (Ra):

$$\frac{1}{4}O_2 + H^+ + e^- = \frac{1}{2}H_2O$$

synthesis reaction (Rc):

$$\frac{1}{5}CO_2 + \frac{1}{20}\ HCO_3^- + \frac{1}{20}\ NH_4^+ + H^+ + e^- \ \longrightarrow \ \frac{1}{20}C_5H_7NO_2 + \frac{9}{20}\ H_2O$$

$$f_eR_a: 0.1O_2 + 0.4H^+ + 0.4e^- \ \longrightarrow 0.2H_2O$$

$$f_sR_c: 0.12CO_2 \ + \ 0.03HCO_3^- + \ 0.03NH_4^+ + 0.6H^+ + 0.6e^-$$

$$\longrightarrow \ 0.03C_5H_7NO_2 + \ 0.27H_2O$$

$$-R_d: \ 0.02C_{10}H_{19}NO_3 + 0.36H_2O \longrightarrow \ 0.18CO_2 \ + \ 0.02HCO_3^- + \ 0.02NH_4^+ + H^+ + e^-$$

$$0.02C_{10}H_{19}NO_3 + \ 0.01NH_4^+ + 0.01HCO_3^- + 0.1O_2 \longrightarrow \ 0.03C_5H_7NO_2 + \ 0.11H_2O +$$

$$(201) \qquad\qquad (113) \qquad\qquad 0.06CO_2$$

Based on Monteith et al. (2005), complete oxidation of soluble BOD to produce energy for growth can be expressed as:

$$2C_{10}H_{19}NO_3 + \ 25O_2 \longrightarrow 20CO_2 \ + \ 16H_2O + \ \ 2NH_3$$

every mole substrate required oxygen:

$$\text{BOD of substrate } = \frac{25 \times 32 \text{ g BOD}}{2 \times 201 \text{ g substrate}}$$

$$= 2\ \mathrm{g\ BOD/\ g\ substrate}$$

$$\mathrm{CO_2\ produced} = \frac{0.06 \times 44\ \mathrm{g\ CO_2}}{0.02 \times 201\mathrm{g\ substrate}\ \times 2\ \mathrm{g\ BOD/g\ substrate}}$$

$$= 0.33\ \mathrm{gCO_2\ /g\ BOD}$$

$$\mathrm{VSS\ produced} = \frac{0.03 \times 113\ \mathrm{g\ VSS}}{0.02 \times 201\mathrm{g\ substrate}\ \times 2\ \mathrm{g\ BOD/g\ substrate}}$$

$$= 0.422\ \mathrm{gVSS/\ g\ BOD}$$

$$\mathrm{O_2\ required} = \frac{0.1 \times 32\ \mathrm{g\ O_2}}{0.02 \times 201\mathrm{g\ substrate}\ \times 2\ \mathrm{g\ BOD/g\ substrate}}$$

$$= 0.40\ \mathrm{g\ O_2/\ g\ BOD}$$

Endogenous Decay Reactions

Biomass is considered as electron donor and oxygen as electron acceptor. There is no new cell production in endogenous decay.

The overall reaction, $R = R_a - R_d$

$$R_a\mathrm{:}\ 0.25O_2 + H^+ + e^- \longrightarrow 0.5\ H_2O$$

$$-R_d\mathrm{:}\ 0.05C_5H_7NO_2 + 0.45H_2O \longrightarrow 0.2CO_2 + 0.05HCO_3^- + 0.05NH_4^+ + H^+ + e^-$$

$$0.05C_5H_7NO_2 + 0.25O_2 \longrightarrow 0.2CO_2 + 0.05NH_4^+ + 0.05HCO_3^- + 0.5\ H_2O$$

$$\mathrm{O_2\ required} = \frac{0.25 \times 32\ \mathrm{g\ O_2}}{0.05 \times 113\mathrm{g\ VSS}}$$

$$= 1.42\ \mathrm{gO_2/\ g\ VSS}$$

$$\mathrm{CO_2\ produced} = \frac{0.2 \times 44\ \mathrm{g\ CO_2}}{0.05 \times 113\mathrm{g\ VSS}}$$

$$= 1.56\ \mathrm{gCO_2\ /g\ VSS}$$

Nitrification

Ammonia is considered as electron donor and oxygen as electron acceptor.

according to Rittman and McCarty (2001), fs = 0.05 and fe =0.95

$$\mathrm{f_eR_a}: 0.24\mathrm{O_2} + 0.95\mathrm{H^+} + 0.95\mathrm{e^-} \longrightarrow 0.47\ \mathrm{H_2O}$$

$$\mathrm{f_sR_c}: 0.01\mathrm{CO_2} + 0.0025\mathrm{HCO_3^-} + 0.0025\mathrm{NH_4^+} + 0.05\mathrm{H^+} + 0.05\mathrm{e^-}$$
$$\longrightarrow 0.0025\mathrm{C_5H_7NO_2} + 0.0225\mathrm{H_2O}$$

$$-\mathrm{R_d}: 0.125\mathrm{NH_4^+} + 0.375\mathrm{H_2O} \longrightarrow 0.125\mathrm{NO_3^-} + 1.25\mathrm{H^+} + \mathrm{e^-}$$

$$0.1275\mathrm{NH_4^+} + 0.24\mathrm{O_2} + 0.01\mathrm{CO_2} + 0.0025\mathrm{HCO_3^-}$$
$$\longrightarrow 0.0025\mathrm{C_5H_7NO_2} + 0.125\mathrm{NO_3^-} + 0.25\mathrm{H^+} + 0.1225\mathrm{H_2O}$$

$$\mathrm{O_2\ required} = \frac{0.24 \times 32\ \mathrm{g\ O_2}}{0.1275 \times 14\ \mathrm{g\ N}}$$

$$= 4.32\ \mathrm{gO_2/\ g\ N}$$

$$\mathrm{CO_2\ required} = \frac{0.01 \times 44\ \mathrm{g\ CO_2}}{0.1275 \times 14\mathrm{g\ N}}$$

$$= 0.247\ g\ CO_2/\ g\ N$$

Biosolids Degradation in Anaerobic Environment

In the anaerobic environment, the endogenous decay reaction of biomass is illustrated in the following equation. CO_2 is reduced to CH_4 in acceptor half reaction (Ra) and biomass is decayed to CO_2 in donor half reaction (Rd). There is no cell synthesis due to endogenous decay.

$$R_a: 0.125CO_2 + H^+ + e^- \longrightarrow 0.125\,CH_4 + 0.25H_2O$$

$$-R_d: 0.05C_5H_7NO_2 + 0.45H_2O \longrightarrow 0.2CO_2 + 0.05HCO_3^- + 0.05NH_4^+ + H^+ + e^-$$

$$0.05C_5H_7NO_2 + 0.2H_2O \longrightarrow 0.075CO_2 + 0.125CH_4 + 0.05NH_4^+ + 0.05HCO_3^-$$

$$CO_2\,produced = \frac{0.075 \times 44\,g\,CO_2}{0.05 \times 113g\,VSS}$$

$$= 0.58\,gCO_2/g\,VSS$$

$$\mathrm{CH_4\ produced} = \frac{0.125 \times 16\ \mathrm{g\ CH_4}}{0.05 \times 113\mathrm{g\ VSS}}$$

$$= 0.35\ \mathrm{gCH_4\,/g\ VSS}$$

Calculation of Emission Factor (F)

The average protein consumption, P = 38 kg/person per year (FAOSTAT data, 2004)

Fraction of Nitrogen in Protein, NP_{frac} = 16% by weight (Default value, IPCC, 1996)

Protein conversion in nitrogen = 38* 0.16

= 6 kg N/person per year

Per capita TKN loading = (TKN value from residence* Flow)/ Population………………

(i)

TKN for wastewater from residence = 35 mg/L (Doorn et al., 1997)

From equation (i)

35 mg/L * 10.5 MG/d * 10^6 Gal/ MG *3.78 L/gal * 365 d/yr *1/87000 *1/10^6 kg/mg

= 5.83 kg TKN/person per year = 6 kg TKN/person per year

where,

Flow = 10.5 MIGD (LRPCP, 2008)

Serving Population = 87000

Therefore, a factor is related to the discharged from residence per person,

$$= \frac{\text{Per capita TKN loading}}{\text{Protein conversion in nitrogen}}$$

$= \frac{6}{6} = 1$, introduced for accounting the extra nitrogen discharge from kitchen, bath and laundry wastes.

A factor to account for industrial co-discharge, CF = 40/35 = 1.14

Now, F = CF *extra nitrogen discharge from kitchen, bath and laundry

=1.14*1

= 1.14 = A factor of non-consumption protein in domestic wastewater

Table D.1: summary of emission factor calculation

year	Flow, MLD	Flow, gal/d	Population
2007	43.2	9600000	87000
2008	47.2	10500000	87000
2009	42.7	9500000	87000

year	CF calculation	Per Capita TKN loading , Kg TKN/person/yr
2007	1.14	5.33
2008	1.14	5.83
2009	1.14	5.27

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