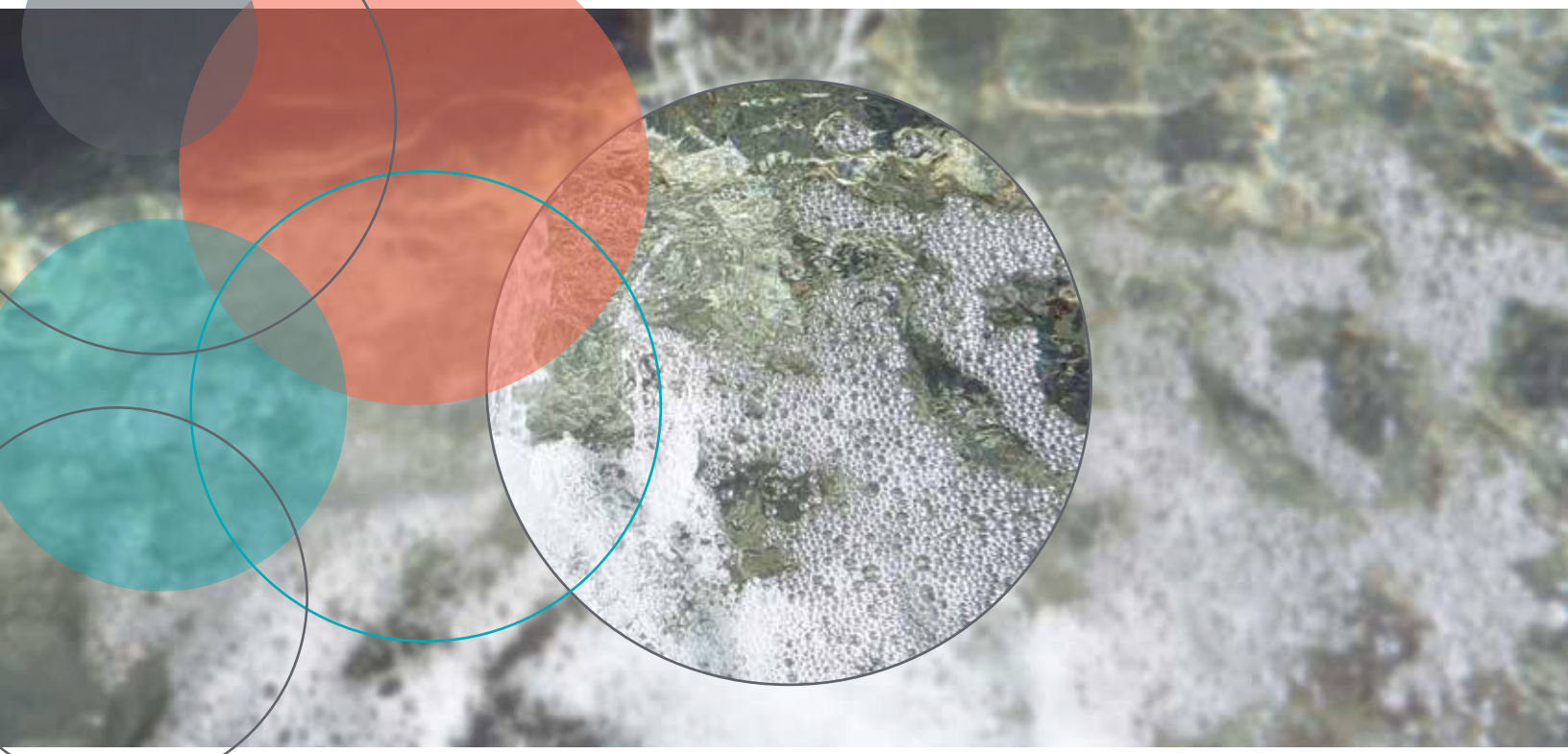

Greenhouse Gas Emissions and Biological Nutrient Removal

MARCH 2019

The 2010 *Greenhouse Gas Emissions and Biological Nutrient Removal Compendium* was written to identify knowledge gaps to be addressed by the Nutrient Removal Challenge. This document contains state-of-the-art knowledge to achieve reliable, cost-effective nutrient removal and reduce GHG emissions. The 2010 compendium included a number of questions and challenges to reduce nutrients in advanced treated wastewater. This 2019 compendium revision contains a summary of the findings presented in reports and documents generated by the researchers and contributors. This updated version is not intended to include a thorough update on the 2010 compendium literature review.

THE Water Research FOUNDATION

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The findings from the Nutrient Removal Challenge were incorporated into this 2019 edition by:

Mike Falk
HDR Inc.

Bryce Figdore
HDR Inc.

JB Neethling
HDR Inc.

David Stensel
University of Washington

The following individuals contributed to earlier versions of this compendium:

Marlies J. Kampschreur
Delft University of Technology

David J. Kinnear
HDR Inc.

Andrew Shaw
Black & Veatch

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1199 North Fairfax Street, Suite 900
Alexandria, VA 22314-1445

6666 West Quincy Avenue
Denver, CO 80235-3098

info@waterrf.org
www.waterrf.org

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DEFINITIONS

Carbon Dioxide Equivalent
The concentration of carbon dioxide that would cause the same level of radiative forcing as a given type and concentration of a greenhouse gas.

Global Warming Potential
A measure of how much of a given mass of a greenhouse gas is expected to contribute to global warming relevant the reference gas, carbon dioxide.

Radiative Forcing
The change in net irradiance (W/m2) at the tropopause due to the pertubance of a parameter known to influence irradiance (greenhouse gases, ozone, albedo, aerosols, etc.).

Tropopause
The atmospheric boundary between the troposphere and the stratosphere characterized by the elevation at which air ceases to cool with height and becomes almost completely dry.

ACRONYMS

ACES	American Clean Energy and Security Act of 2009
AR4	Intergovernmental Panel on Climate Change Fourth Assessment Report
AR5	Intergovernmental Panel on Climate Change Fifth Assessment Report
AR6	Intergovernmental Panel on Climate Change Sixth Assessment Report
BOD	Biochemical Oxygen Demand
CAS	Conventional Activated Sludge
CDM	Clean Development Mechanism
CECs	Constituents of Emerging Concern
CH4	Methane
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
EBPR	Enhanced Biological Phosphorus Removal
EPA	U.S. Environmental Protection Agency
GHG	Greenhouse Gas
GWP	Global Warming Potential

HFC	Hydroflourocarbons
IPCC	Intergovernmental Panel on Climate Change
JI	Joint Implementation
LCA	Life Cycle Assessment
MCF	Methane Correction Factor
N_2O	Nitrous Oxide
PFC	Perflourocarbons
RGG	Regional Greenhouse Gas Initiative
SF_6	Sulfur Hexafluoride
TN	Total Nitrogen
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
WCI	Western Climate Initiative
WMO	World Meteorological Association
WRRF	Water Resource Recovery Facility

ABBREVIATIONS

mt = metric tons (ton = 1000 kg = 2,204 lbs.)

kWh = kilowatt hours

MWh = megawatt hours

CLIMATE CHANGE FUNDAMENTALS

This section provides a brief background on climate change research and introduces greenhouse gases (GHGs) of greatest relevance to water resource recovery facilities (WRRFs).

Why Be Concerned about Climate Change?

The consensus of scientific evidence indicates that human activities, predominately the burning of fossil fuels, increased post-industrial revolution (since 1750) atmospheric concentrations of certain gases that adsorb and emit infrared radiation, known as GHGs. Although atmospheric GHG allows life to exist on Earth by warming the planet, concern mounts that anthropogenically increased GHG concentrations result in excessive temperature increase and unintended climate change.

Mathematical models of the earth's climate systems attempt to account for the factors that influence the earth's climate, including increasing atmospheric GHG concentrations, to predict future climate scenarios. The Nobel-laureate Intergovernmental Panel on Climate Change (www.ipcc.ch), the leading body on climate change under the auspices of the United Nations Environmental Programme (UNEP) and the World Meteorological Association (WMO), reviews these models and other pertinent information to provide a consensus scientific view on the current state of climate change and its potential environmental and socioeconomic consequences. To date, the Intergovernmental Panel on Climate Change (IPCC) has released five assessment reports with the Fourth Assessment Report (AR4) and the Fifth Assessment Report (AR5). AR4, Chapter 8, "Climate Models and Their Evaluation" discusses the details of the climate models, including strengths and weaknesses. Longer-term model-based forecasts of changes in global mean temperature and general climactic conditions from the AR5 Synthesis Report include the following:

- Relative to 1850–1900, global surface temperature change for the end of the 21st century (2081–2100) is projected to likely exceed 1.5°C with high confidence for scenarios with zero, low, or medium efforts to reduce global anthropogenic GHG emissions.
- Warming is likely to exceed 2°C with high confidence for scenarios with zero or low efforts to reduce global anthropogenic GHG emissions, more likely than not to exceed 2°C with medium confidence for the scenario with medium efforts to reduce global anthropogenic GHG emissions; but unlikely to exceed 2°C with medium confidence for the scenario with high efforts to reduce global anthropogenic GHG emissions.
- The Arctic region will continue to warm more rapidly than the global mean.
- It is virtually certain that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal time scales, as global mean surface temperature increases. It is very likely that heat waves will occur with a higher frequency and longer duration. Occasional cold winter extremes will continue to occur.

Although climate science requires continued research, each IPCC AR successively provided more convincing modeling and physical evidence validating climate change concerns. AR5 follows that trend. Some specific concerns of climate change include:

a. Rising sea level due to thermal expansion of water as well as glacier, ice sheet, and snow pack loss.
b. Increased floods and droughts, altered fresh water availability.
c. Changing weather patterns, including stronger hurricanes, temperature variability, and precipitation extremes.
d. Ecosystem threat due to species range modification resulting from temperature increase and resulting climate anomalies.

Debate continues about how governments and policymakers should respond to the threat of climate change. Scientific uncertainty due to climate model complexity creates confusion over the scientific theory and accuracy of model predictions. Additionally, the consequences of climate change on both human and planetary socioeconomic and natural ecosystems make the appropriate political and economical response difficult to determine. *The Stern Review: The Economics of Climate Change* (Stern 2006) provides a widely read source on the alternative courses of action.

Also of interest to water professionals, the IPCC Working Group II – Technical Support Unit released Technical Paper VI: *Climate Change and Water* in June 2008. Although this technical paper focuses on water, it discusses the consequences of climate change more than the sources of GHG and therefore greatly applies to water resources.

How Do Greenhouse Gases Impact Earth's Energy Balance and Temperatures?

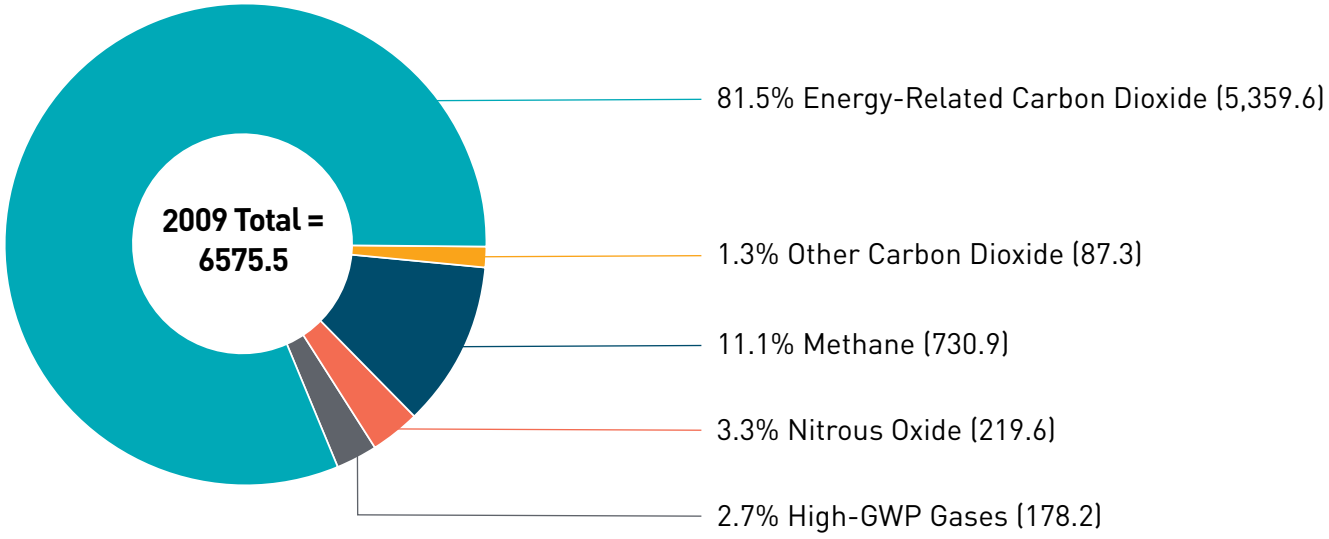
IPCC (2007) summarized Earth's overall energy balance, which demonstrates how increased GHG concentrations lead to increased global temperatures. Of the 342 W/m^2 influent short-wave solar radiation, the atmosphere absorbs 67 W/m^2 and the earth absorbs 168 W/m^2. This translates to absorbing approximately 70 percent of incoming solar radiation. To balance the incoming energy, the earth radiates energy back into space as long-wave infrared radiation (identical to the heat felt emanating from a fire). The natural greenhouse effect (actually a misnomer because nothing similar occurs in a greenhouse) warms the earth by adsorbing this emitted long-wave radiation directed out of the earth's atmosphere. Upon adsorption, GHG molecules become briefly unstable (microseconds) and then stabilize by reemitting infrared radiation. The greenhouse effect occurs because the vectors of the outbound radiation point directly out of the atmosphere while the vectors of the re-emitted radiation point in a random direction, and to some extent back toward the earth. This back-radiation warms the atmosphere beyond the temperature that would occur without the atmospheric GHG concentration.

What Greenhouse Gases Should WRRFs Practicing Biological Nutrient Removal Be Most Concerned About?

Anthropogenic global warming occurs when GHG concentrations increase above natural levels, trapping excessive heat in the atmosphere. Historical concentrations of the GHGs carbon dioxide, methane, and nitrous oxide have increased dramatically since the Industrial Revolution circa 1750 (IPCC 2007). Carbon dioxide, methane, and nitrous oxide are also primary GHGs of concern at WRRFs performing biological nutrient removal. The reader is referred to IPCC (2007) for a more detailed list of anthropogenic GHGs, which include chlorofluorocarbons, hydrofluorocarbons, perflurocarbons, and sulfur hexafluoride.

Data from the U.S. Energy Information Administration indicate that carbon dioxide, methane, and nitrous oxide emissions constituted 97.2 percent of U.S. GHG emissions in 2009 (Figure 1). As a result, the emphasis at WRRFs is on these three GHG emissions. A common approach used in Figure 1 is quantifying GHG emissions as carbon dioxide equivalents (CO_2e). The CO_2e for a given GHG is a measure of the mass of carbon dioxide needed to contribute an equal global warming potential (GWP) as the GHG of interest. As indicated in Table 1, CO_2 equivalents for methane and nitrous oxide at 100-year atmospheric lifetime are 25 and 298 times that of CO_2. Table 1 also indicates that the atmospheric lifetime of a given GHG may vary; thus, the GWP for a given GHG is a function of the time horizon being evaluated. GWP is most often expressed based on a 100-year time horizon.

Figure 1 - 2009 U.S. GHG Emissions by Gas (Emissions in Million Metric Tons of CO_2 Equivalent)



Source: Adapted from EIA 2011

Table 1 - Atmospheric Lifetime and Global Warming Potential for CO_2, Methane, and Nitrous Oxide				
Common Name	Lifetime (Years)	GWP for Given Time Horizon		
		20-Yr	100-Yr	500-Yr
Carbon Dioxide	BCCM	1	1	1
Methane	12	62	23	7
Nitrous Oxide	114	275	296	156

BCCM = Apply Bern Carbon Cycle Model

Source: IPCC 2001

REGULATIONS AND CLIMATE CHANGE LEGISLATION

This section provides an overview of international agreements and U.S. legislation on GHG emissions of greatest relevance to WRRFs.

What Governmental Policies, Laws, and Regulations Concern WRRFs?

The Kyoto Protocol

The Kyoto Protocol, an international environmental treaty and protocol to the United Nations Framework Convention on Climate Change (UNFCCC), attempted to stabilize GHG concentrations at a level that would prevent dangerous anthropogenic interference with the climate system. The treaty requires industrialized countries to reduce GHG emissions to 5.2 percent below 1990 emission levels by reducing four GHGs and two groups of GHG:

- Carbon Dioxide (CO_2)
- Methane (CH_4)
- Nitrous Oxide (N_2O)
- Sulfur Hexafluoride (SF_6)
- Hydroflourocarbons (HFCs)
- Perflourocarbons (PFCs)

Although the United States did not ratify the treaty, many other countries did. It therefore may foreshadow regulations that may affect U.S. municipal WRRFs in the future. Kyoto includes several flexible mechanisms, such as emissions trading, the clean development mechanism (CDM), and joint implementation (JI), that may be incorporated into future GHG environmental treaties the United States ratifies.

Non-ratification of Kyoto led to several U.S. regional mandatory and voluntary climate action initiatives applicable to WRRFs. The Regional Greenhouse Gas Initiative (RGGI) (www.rggi.org) requires ten northeastern and mid-Atlantic states to cap and reduce CO_2e emissions from the power sector by 10 percent by 2018 through an auction process with proceeds funding energy efficiency, renewable energy, and clean energy technologies. Although RGGI does not affect wastewater treatment facilities directly, the program does include offsets due to landfill methane reduction, manure management, and energy efficiency. Energy efficiency directly affects WRRFs while methane management and power production suggests anaerobic digestion offsets would be welcomed.

Western Climate Initiative

The Western Climate Initiative (WCI), a similar cap-and-trade program to RGGI, includes seven U.S. states and four Canadian provinces plus several U.S., Canadian, and Mexican observer

states considering membership. The program includes the six Kyoto GHGs designed to reduce GHG emissions by 15 percent below 2005 levels by 2020. Although not regulated directly, WCI offers WRRFs the potential to develop carbon offsets for trade to WCI.

RGGI and WCI preempted the U.S. Kyoto non-signatory status and initiated programs to reduce GHG initiatives based on the foundation of the Kyoto protocol. Federal legislation discussed below should expand these programs to incorporate the entire country in a similar fashion. These evolving carbon cap-and-trade regulations and markets presently offer more opportunities to WRRF than liabilities. Direct emissions fall several orders of magnitude below the likely regulatory threshold, while indirect power emissions, energy efficiency, and anaerobic digestion methane management offers opportunities for developing carbon offsets for trading in these markets.

The Climate Registry

The Climate Registry is a nonprofit collaboration between North American states, provinces, and native sovereign nations to record and track GHG emissions of businesses, municipalities, and other organizations. This umbrella organization provides data for carbon-reduction initiative, such as the RGGI and WCI.

Mandatory Reporting of Greenhouse Gases (40 CFR Part 98)

On December 29, 2009, the U.S. Environmental Protection Agency (EPA) promulgated a rule for mandatory GHG reporting from large U.S. GHG emissions sources. The Federal Register published the proposed rule October 30, 2009. The rule collects comprehensive emissions data to support future policy decisions as required by the FY2008 Consolidated Appropriations Act that instructed EPA to use existing authority under the Clean Air Act to develop a GHG reporting rule. It does not require emissions control. The rule calls for 41 categories of reporters, including power plants, suppliers of fossil fuels or industrial GHGs, manufacturers of vehicles and engines, and other industrial facilities that emit greater than 25,000 metric tons (mt) CO_2e/yr to submit annual reports to EPA. Additional information can be found from EPA (https://www.epa.gov/ghgreporting).

The rule recognized from the onset that there would be complications in accounting for carbon emissions. In order to delineate clear, consistent boundaries for carbon emitters to avoid the possibility of undercounting or double counting. The rule references the Water Resources Institute/World Business Council for Sustainable Development Document: *The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard* (WRI/WBCSD, 2004), which designates the following three scopes to designate direct and indirect GHG emission sources.

Scope 1 – Direct Greenhouse Gas Emissions

- Production of Electricity, Heat, or Steam
- Physical or Chemical Processing
- Transportation of Materials, Products, Waste, and Employees
- Fugitive Emissions

Scope 2 – Indirect Greenhouse Gas Emissions from Imports of Electricity, Heat, or Steam

Scope 3 – Other Indirect Greenhouse Gas Emissions
Consequences of the activities of the reporting company but occur from sources owned or controlled by another company.

- Employee Business Travel
- Transportation of Products, Materials, and Waste
- Outsources Activities
- Emissions from Waste
- Emissions from Final Product Disposal
- Employee Commuting
- Production of Imported Materials

Municipal WRRFs are not required to report under the GHG reporting program. A Technical Support document published by EPA on February 4, 2009, entitled *Technical Support Document for Wastewater Treatment: Proposed Rule for Mandatory Reporting of Greenhouse Gases,* previously determined that domestic wastewater treatment plants would be below the reporting threshold and therefore would not need to report. However, municipal WRRFs combusting significant quantities of fossil fuels for power production within the WRRF facility itself may exceed this threshold and trigger the need to report GHG emissions. For example, if a WRRF uses waste heat from an incinerator to operate a steam system/microturbine to recover heat then they might be considered a power producer and be susceptible to GHG reporting requirements.

Some industrial WRRFs, including pulp and paper, food processing, ethanol refining, and petroleum refining industries are required to report under Subpart II of the rule. Methane is the only GHG required to be reported for these industrial WRRFs. Additional details are available in a Technical Support Document for Industrial Wastewater Treatment: *Final Rule for Mandatory Reporting of Greenhouse Gases* (EPA 2010).

R 2454 The American Clean Energy and Security Act of 2009 (Waxman-Markey)

The U.S. Congress anticipates passing climate change legislation sometime in the future. The American Clean Energy and Security Act of 2009 (ACES) passed in the House of Representatives on June 26, 2009. The Senate continues debate on a similar bill. The act, when passed, will likely reduce GHG footprints of major U.S. sources by 17 percent by 2020 and 80 percent by 2050.

As with the EPA Mandatory Reporting of GHG Regulation, ACES specifically exempts entities such as WRRFs with emissions less than 25,000 mt CO_2e per year from regulation. The bill does specifically mention WRRFs but mentions "wastewater treatment gas" as a qualifying energy resource in the Combined Efficiency and Renewable Electricity measures. Thus, WRRFs should likely benefit from developing renewable energy credits through combined heat and power (CHP) anaerobic digestion gas and should not likely be regulated for GHG emissions in the near future.

The Paris Agreement

The Paris Agreement (Agreement) is an agreement within the UNFCCC, dealing with GHG-emissions mitigation, adaptation, and finance, beginning in 2020. The Agreement opened for signature on Earth Day on April 22, 2016, at UN Headquarters in New York and to date 185 of 197 parties of the UNFFCCC have ratified the Agreement. The central aim of the Agreement is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels. The Agreement requires all parties to put forward their best efforts through nationally determined contributions (NDCs). As a result, WRRFs and other entities are not required to report on GHG emissions under this Agreement. NDCs embody efforts by each country to reduce national emissions, adapt to the impacts of climate change, and regularly report their emissions and implementation efforts to the UNFCCC. The Agreement also welcomes non-party stakeholders to address and respond to climate change, including those of civil society, the private sector, financial institutions, cities and other sub-national authorities.

For more detailed information on the Agreement, please refer to the UNFCCC website: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

GREENHOUSE GAS EMISSIONS FROM WATER RESOURCE RECOVERY FACILITIES

This section provides general information on methodologies used to estimate GHG emissions from WRRFs and the relative contribution of WRRFs to U.S. GHG emissions. Individual GHGs are covered in subsequent sections in more detail.

What Methodologies to Calculate GHG Emissions Are Used in International Agreements and U.S. Legislation?

Methodologies established by IPCC are widely used or adapted for GHG inventories. The methodologies proposed by the IPCC and GHG accounting standards typically use simple emission factors or coefficients in calculating CO_2, CH_4 and N_2O emissions. IPCC method calculations are structured with minimal understanding of the biochemical pathways and process controls to minimize GHG emissions. The simplistic IPCC methodologies do not incorporate the specific operational factors expected to influence WRRF GHG production. Therefore, these simplistic approaches do not provide accurate estimates when applied to any individual WRRF due to differing effluents, designs, and operating conditions. Emissions factors are covered later in greater detail for specific GHGs.

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories distinguishes between direct GHG emissions from treatment plants and indirect GHG emissions resulting from effluent discharge to receiving waters and GHG formation and emission from receiving waters. Methane or N_2O emissions from treatment processes are examples of direct emissions. An example of indirect GHG emissions is N_2O emissions resulting from nitrogen transformations in the receiving waterbody. The EPA does not consider indirect effluent emissions from effluent discharge as a GHG source in the GHG accounting rule; nevertheless, it provides formulas to estimate such indirect emissions. WRRFs conducting voluntary GHG inventories may consider accounting for both direct and indirect GHG emissions.

What Are EPA Estimates of WRRF Greenhouse Gases?

EPA's U.S. greenhouse gas inventory report (2009b) includes estimates of emissions from WRRFs as of 2007. The EPA estimates from the report pertaining to WRRFs are summarized on the following page in Table 2. The EPA methodology followed the 2006 IPCC Guidelines for National Greenhouse Gas Inventories methodology with some adjustments discussed under the individual GHGs in the following pages. Because the simplistic IPCC (and EPA) methodologies do not incorporate the specific operational factors expected to influence WRRF GHG production, these simplistic approaches do not provide accurate estimates when applied to any individual WRRF due to differing effluents, designs, and operating conditions. Customized GHG footprint calculations could be used if desired or when required. Policy makers use these

methodologies to determine the order of magnitude estimate of WRRF GHG emissions to compare to other sources for economic decision making and to set priorities for reversing climate change.

Table 2 - EPA 2009 Greenhouse Gas Inventory – Wastewater

	U.S. GHG Emissions and Sinks (Tg CO_2e) (M mt)				Change 1990 to 2007	
Gas/Source	**1990**	**2005**	**2006**	**2007**	**Absolute**	**Percent**
National CO_2	5,076.7	6,090.8	6,014.9	6,103.4	1,026.7	20.2
Wastewater Treatment CO_2	—*	—*	—*	—*	—*	—*
% Wastewater Treatment CO_2	—*	—*	—*	—*	—*	—*
National CH_4	616.6	561.7	582.0	585.3	(31.3)	-5.1
Wastewater Treatment CH_4	23.5	24.3	24.5	24.4	0.9	3.8
% Wastewater Treatment CH_4	3.8%	4.3%	4.2%	4.2%		
National N_2O	315.0	315.9	312.1	311.9	(3.1)	-1.0
Wastewater Treatment N_2O	3.7	4.8	4.8	4.9	1.2	32.4
% Wastewater Treatment N_2O	1.2%	1.5%	1.5%	1.6%		
National Others (Sum of HFCs, PFCs, and SF_6)**	90.4	140.2	142.1	149.5	59	65.2
Wastewater Treatment Others	—*	—*	—*	—*	—*	—*
% Wastewater Treatment Others	—*	—*	—*	—*	—*	—*
Total Sources	6,098.7	7,108.6	7,051.1	7,150.1	1,051.4	17.2
Total Sinks	841.4	1,122.7	1,050.5	1,062.6	221.2	26.3
Net Emissions (Sources Minus Sinks)	5,257.3	5,985.9	6,000.6	6,087.5	830.2	15.8
Total Wastewater Treatment	27.2	29.1	29.3	29.3	2.1	7.7
% Wastewater Treatment	0.52%	0.49%	0.49%	0.48%		
% CO_2 of Total Net Emissions	—*	—*	—*	—*		
% CH_4 of Total Net Emissions	11.7%	9.4%	9.7%	9.6%		
% N_2O of Total Net Emissions	6.0%	5.3%	5.2%	5.1%		

* CO_2 emissions explicitly from the biological oxidation of organic matter do not contribute to global warming potential and thus are not considered anthropogenic GHGs

** HFCs = hydrofluorocarbons; PFCs = perfluorocarbons; and SF_6= sulfur hexafluorides

Source: Adapted from EPA 2009b

Based on the EPA methodology, results summarized in Table 2 indicate that WRRFs represented 0.48 percent of U.S. GHG emissions in 2007. This low percentage suggests that WRRFs should avoid GHG emission regulation in the foreseeable future according to current regulations. Methane and nitrous oxide from wastewater treatment comprised 4.2 percent and 1.6 percent of U.S. methane and nitrous oxide emissions, respectively. Of the wastewater-associated GHG emissions, greater than 80 percent are from methane gas emissions; these emissions could be mitigated at municipal WRRFs by flaring or using digester gas in CHP energy recovery systems. Only a small fraction of the methane inventoried is attributed to properly managed methane from centralized WRRFs. Most of the methane in the inventory originates from anaerobic activity in lagoons and other less controlled treatment systems.

While most WRRFs are not required to report GHG emissions, they should still be concerned with minimization of energy consumption from a triple-bottom-line perspective considering cost, environmental, and social benefits. Minimizing energy consumption minimizes indirect GHG emissions from energy production by an outside energy provider serving the WRRF, assuming that electricity is derived from fossil fuels.

CARBON DIOXIDE

What Are the Major Sources of Carbon Dioxide in a Biological Nutrient Removal WRRF?

Major sources of WRRF CO_2 emissions come from biological processes or electricity used in the treatment processes. CO_2 emissions explicitly from the biological oxidation of organic matter do not contribute to global warming potential and thus are not considered anthropogenic GHGs. Such CO_2 emissions are considered "short-cycle" or natural sources of atmospheric CO_2, which cycles from plants to animals to humans as part of the carbon cycle and food chain. For example, photosynthesis-produced short-cycle CO_2 removes an equal mass of CO_2 from the atmosphere that returns during respiration or wastewater treatment. Short-cycle CO_2 emissions attributable to WRRFs include the following:

- Oxidation of organic matter, e.g., CO_2 generated by the biological degradation in the activated sludge process.
- Digestion processes, either aerobic or anaerobic.
- Biological nutrient removal generates comparable quantities of short-cycle CO_2 compared to carbonaceous treatment only or nitrification treatment. Nutrient removal can increase indirect emissions from increased purchased electrical power usage, but the magnitude depends on the level of nutrient removal, aeration efficiency, and other factors. CO_2 emissions in the receiving water from effluent biochemical oxygen demand (BOD) also qualify as short-cycle carbon.

Fossil-fuel-derived electricity imported from outside utilities or produced directly onsite to power WRRF treatment processes would qualify as anthropogenic GHG emissions. The exception is WRRFs that combust significant quantities of fossil fuels for power production within their facility itself may trigger the need to report GHG emissions. The 2006 IPCC methodology assumes that conventional activated sludge (CAS) facilities use approximately 2,000 kWh/million gallon treated and that power production emits 0.564 mt CO_2/MWh. By these metrics, a 10.0 mgd facility emits 4,100 mt CO_2e/yr.

METHANE

What Are the Sources of Methane Gas in a Biological Nutrient Removal WRRF?

Methane gas forms under anaerobic conditions by design or circumstance when the absence of electron acceptors; including oxygen, nitrite, nitrate, and sulfate; permit microorganisms to use organic compounds for both electron donors and acceptors in biochemical reactions, ultimately resulting in methane formation.

Potential methane emissions from a WRRF include:

- Collection System
- Primary Clarifiers
- Anaerobic Selectors
- Aeration Basin: improperly aerated aeration basins could produce methane in small quantities
- Anaerobic Digester: intentional production of methane gas
- Digested Sludge Management in Storage, Dewatering, and Disposal: dissolved methane from anaerobic digestion can be liberated in dewatering equipment or in filtrate return streams
- Effluent Emissions: effluent BOD degraded anaerobically in receiving waters can produce methane gas

How Does the IPCC Methodology Quantify WRRF Methane Emissions?

The IPCC methodology applies an emission factor called the methane correction factor (MCF) dependent on the anaerobic degradation situation, such as:

- Sea, River, and Lake Discharge
- Stagnant Sewer
- Flowing Sewer
- Centralized, Aerobic Treatment Plant (well managed)
- Centralized, Aerobic Treatment Plant (overloaded)
- Aerobic Sludge Digester
- Anaerobic Reactor
- Anaerobic Lagoon, Shallow
- Anaerobic Lagoon, Deep
- Septic Systems
- Latrine, various conditions

Of the listed potential sources of methane emissions, those from anaerobic treatment (including anaerobic digestion) are treated as the most significant source of methane emission from

WRRFs. The IPCC methodology first estimates maximum CH_4 production capacity (B0) for domestic wastewater based on 0.6 kg CH_4/kg BOD. The amount of actual methane emission estimated is a function of different factors such as quantity of methane recovered or flared and combustion efficiency. The methodology agrees well with empirical gas production values in U.S. wastewater treatment facilities.

The IPCC methodology also includes a methane emission estimate associated with effluent BOD, which may be anaerobically degraded in receiving waters.

Sewers are assumed to be fast moving and thus produce minimal methane gas according to the IPCC methodology. This assumption is in agreement with a WERF study that determined that only minor methane production occurs in collection systems (Willis 2012). With the advent of water conservation and low flow fixture, methane production in sewers is something to consider for future research on GHG emissions calculations.

The IPCC methodology does not account for potential differences in methane produced from centralized aerobic treatment processes. Within conventional centralized aerobic secondary treatment processes, CH_4 emissions from nutrient removal processes should not differ significantly from non-nutrient removal conventional activated sludge processes; the majority of CH_4 emission comes from anaerobic digestion. Anaerobic selectors may emit slightly more CH_4 but in insignificant quantities in the overall GHG footprint. Emerging low-temperature mainstream anaerobic treatment processes are not considered in IPCC methodologies and require greater attention with respect to methane emissions potential considering higher methane solubility at lower temperatures.

How Does the EPA Methodology Quantify WRRF Methane Emissions?

The EPA methodology separated methane emissions into four categories:

1. Emissions from Septic Systems
2. Emissions from Centrally-treated Aerobic Systems
3. Emissions from Centrally-treated Anaerobic Systems
4. Emissions from Anaerobic Digesters

The first three categories follow the IPCC MCF methodology. Emissions from centralized anaerobic digesters use a factor for the unit production of digester gas of 1.0 cf/person/day. Methane emissions are determined based on gas production and a flare efficiency factor similar to that previously discussed. Emission estimates agree with the IPCC methodology.

What Process Design and Operational Factors Influence Methane Gas Production and Emissions from Anaerobic Digestion Processes?

Methane gas production varies between WRRFs based on many factors such as:

1. Primary Treatment Presence and Performance
2. Digester Mixing Effectiveness
3. Digester Solids Retention Time
4. Temperature
5. Use of Pretreatment Technologies to Enhance Digestion

Technologies to maximize gas production being developed by physically, chemically, or biologically conditioning of solids prior to or during digestion may offer the ability to improve energy production, minimize GHG production, and minimize solids disposal costs.

The following factors influence methane emissions from anaerobic digestion processes:

1. Gas Utilization Systems (e.g., flare, CHP, etc.) or Lack Thereof
2. Efficiency of Gas Utilization Systems
3. Leakage from Gas Piping or Digester Systems
4. Extent of Volatile Solids Destruction and Fugitive Methane Production Potential in Biosolids
5. Biosolids Storage and Management Practices

NITROUS OXIDE

What Are the Sources of Nitrous Oxide Gas in a Biological Nutrient Removal WRRF?

Nitrous oxide can form during both nitrification and denitrification in nutrient removal WRRFs. (Kampschreur et al. 2008a). Although N_2O can form in either aerated or anoxic bioreactors, more N_2O gas atmospheric transfer occurs in aerated reactors, so that N_2O formed in anoxic reactors may be released to the atmosphere in subsequent aerated reactors. N_2O emissions also result from discharge of nitrogen-laden effluent to receiving waters.

How Does the IPCC Methodology Quantify WRRF Nitrous Oxide Gas Emissions?

The IPCC does not consider direct N_2O emissions from WRRFs to be significant, and thus direct N_2O emissions are not included in IPCC GHG inventories. This is most likely because the IPCC methodology tries to identify the most significant GHG sources to set worldwide priorities for GHG reduction, and direct N_2O emissions from WRRFs are not considered to be significant in this context. The IPCC methodology focus is on indirect N_2O from nitrogen discharged to receiving waters and subsequent transformations in the receiving water.

The IPCC methodology uses an approach whereby indirect N_2O emissions are a function of influent nitrogen load and influent nitrogen load is a function of population size and dietary nitrogen intake. This approach is intended to allow broad applicability worldwide, including undeveloped countries where influent nitrogen sampling does not occur to the degree that it does in developed countries. The indirect N_2O emission factor is also a function of effluent nitrogen concentration achieved.

IPCC provides a default effluent emission factor of 0.005 kg N_2O/kg N with a range of 0.0005–0.25 kg N_2O/kg N. For a 10 mgd WRRF with an effluent total nitrogen (TN) of 20 mg/l, the methodology estimates 670 mt CO_2e/yr. For an identically sized nitrification/denitrification facility with an effluent TN of 5 mg/l the methodology estimates 170 mt CO_2e/yr.

The IPCC considers N_2O originating from nitrogen discharged to receiving waters to be a more significant GHG emission source worldwide than direct N2O emissions from centralized WRRFs with biological nitrogen removal. However, IPCC also notes that this may not be the case in developed countries where biological nitrogen removal is widely practiced.

How Does the EPA Methodology Quantify WRRF Nitrous Oxide Greenhouse Gas Emissions?

A Technical Support document published by EPA on February 4, 2009, entitled "Technical Support Document for Wastewater Treatment: Proposed Rule for Mandatory Reporting of Greenhouse Gases," provides guidelines for estimating direct N_2O emissions from WRRFs (EPA 2009a). Indirect N_2O emissions from nitrogen discharge to receiving waterbodies and subsequent nitrogen transformations are not in-

cluded. The EPA methodology uses a simplistic method based on service population and emission factors depending on whether the WRRF has nitrification-denitrification. The emission factor is 7.0 g N_2O/person-year with nitrification-denitrification and 3.2 g N_2O/person-year without nitrification-denitrification.

The EPA document does not provide a basis for the emissions factors. However, the emissions factors appear to be based on two studies from additional literature search. Czepiel et al. (1995) measured N_2O emissions from a non-BNR activated sludge municipal WRRF in Durham, New Hampshire, and estimated the N_2O emissions were approximately 3.2 g N_2O/person-year. Schön et al. (1993) measured N_2O emissions from municipal WRRFs with nitrification-denitrification and found the average emission factor was 7.0 g N_2O/person-year. The use of these simple emissions factors does not accurately predict N_2O emissions from any specific WRRF.

Using the EPA methodology and taking into account the CO_2e of N_2O, N_2O-associated GHG emissions from 10 mgd WRRFs with and without nitrification-denitrification are 217 and 99 mt CO_2e/year, respectively.

What Is the Variability in N_2O Emissions Measured from Factors from Full-Scale Facilities?

In contrast to IPCC and EPA 'emission factors,' scientific literature focusing on N_2O emissions from WRRFs typically expresses the N_2O emissions as a function of nitrogen load. Table 3 presents N_2O emissions measured from full-scale WRRFs as reported by Kampschreur et al. (2008b) and Ahn et al. (2009). Ahn et al. (2010) presented similar results.

Table 3 - N_2O Emission Factor Variability

Reference	Configuration	Sampling	N_2O Emission Factor	
			% of TKN Influent Load	PE g N_2O/PE Yr
Czepiel et al. 1995	CAS	Weekly (15 Weeks)	0.035	3.2
Wicht and Beier 1995	25 plants	2 Weekly Grabs (1 Year)	0 – 14.6 (avg: 0.6)	
Sümer 1995	Trickling Filter/ Nitrifying Activated Sludge	Weekly Grabs on Alternate Weeks (1 Year)	0.001	
Kimochi et al. 1998	CAS	Online 4 Cycles	0.01 - 0.08	
Kampschreur et al. 2008a	Nitrification Stage of CAS	3 Grab Samples	4.0	
Kampschreur et al. 2008b	Nitritation-Anammox	Online 4 Days	2.3	
Ahn et al. 2009	Separate-Stage Nitrification		0.05	1.3
Ahn et al. 2009	Four-Stage Bardenpho		0.18	9.8
Ahn et al. 2009	Step-Feed BNR		3.2	290
Ahn et al. 2009	Step-Feed		0.26	18
Ahn et al. 2009	Plug Flow		0.6	26
Ahn et al. 2009	Plug Flow		0.1	8.5

Although the magnitude of these emissions factors varies considerably, only the greatest values would make N_2O emissions significant compared to electricity demands at WRRFs. However, the contribution of N_2O emissions to overall WRRF GHG emissions becomes more important as WRRF energy self-sufficiency increases.

What Process Design and Operational Factors Influence Nitrous Oxide Gas Production and Emissions?

Research continues into the factors that influence N_2O production and emissions to confirm that emissions factors provide accurate estimates and to minimize GHG production from nutrient removal WRRFs.

Some investigators now consider variability and the influence of peak loading on emissions and the factors that influence the integrated mass emitted over time to be critical (Ahn et al. 2009, Yu et al. 2010). The importance of ammonia and nitrite peaks and liquid-phase N_2O peaks continues to be determined, particularly in aerobic (nitrification) N_2O generation.

Aerobic (nitrification) bioreactor design and operating parameters under investigation include:

1. Low Dissolved Oxygen (due to either insufficient aeration capacity or diurnal oxygen uptake rate (OUR) peaks (BOD or NH_3))
2. High Nitrite Concentrations
3. Low SRT
4. Toxic Compounds
5. Low Temperature

Researchers have shown that nitrification biochemical pathways generate significantly more N_2O than denitrification biochemical pathways, particularly during the transition from anoxic to aerobic conditions (Yu et al. 2010, Chandran et al. 2011).

Anoxic (denitrification) bioreactor design and operating parameters that have been associated with N2O emissions include:

1. High Dissolved Oxygen Content
2. High Nitrite
3. Low C/N Ratio
4. H_2S Concentration

FACTORING GHG EMISSIONS INTO NUTRIENT REMOVAL DESIGN AND PERMITTING

While foundational in the field and useful for high-level GHG emissions estimates, the IPCC and EPA methodologies described above do not fully capture specific circumstances that vary between WRRFs. A more detailed methodology is necessary for more accurate plant-specific estimates. Further, different levels of nutrient removal may be required for permit compliance and must be considered in GHG emissions estimates as increasingly stringent nutrient removal places increasing demands on energy, chemicals, and other material resources for treatment. Removal of constituents of emerging concern (CECs) present at very low concentrations may also be included with nutrient removal requirements or otherwise be required for water reuse. This section addresses these topics from the lens of GHG emissions and sustainability considerations.

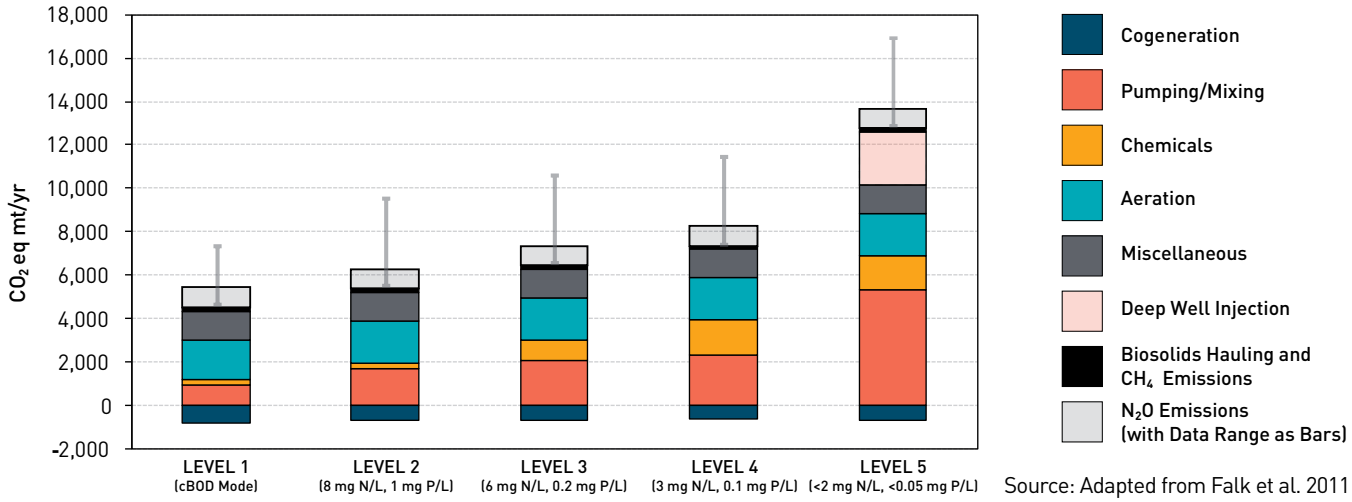
How Do Nutrient Discharge Limits Impact GHG Emissions Potential?

A Nutrient Removal Challenge study (Falk et al. 2011) evaluated GHG emissions in a desktop analysis of five different hypothetical treatment configurations to meet increasingly stringent treatment targets that ranged from cBOD mode (Level 1) to four different nutrient removal targets. The nutrient removal targets ranged from 8 mg N/L; 1 mg P/L (Level 2) to the most stringent at <2 mg N/L; <0.02 mg P/L (Level 5). For consistency, all plants were evaluated at a nominal flow of 10 mgd.

The study concluded, not surprisingly, that as the degree of nutrient removal increased, the impact on sustainability increased significantly. The GHG emissions and cost increased significantly. GHG estimates for the hypothetical 10 mgd facility at different levels of nutrient removal are shown in Figure 2. The reader is referred to the report for full details on basis for GHG emissions calculations and the boundary conditions. Approaches for outside the stated boundary conditions are discussed, such as how to account for hauling distances.

Figure 2 - Combined Liquid and Solids Stream Mass Balance GHG Emissions Estimates

(10 mgd WRRF at Different Levels of Nutrient Removal)



Source: Adapted from Falk et al. 2011

Another Nutrient Removal Challenge study (deBarbadillo et al. 2015) developed GHG emission estimates for WRRFs achieving various levels of effluent phosphorus concentrations. Consistent with findings of Falk et al. (2011), deBarbadillo et al. (2015) pointed out that the GHG emission carbon footprint for phosphorus removal is heavily influenced by the permit limit. The increasing carbon footprint was attributed to the need to add a higher dose of chemicals as well as operation of a tertiary treatment process to achieve lower limits. The study noted that while enhanced biological phosphorus removal can reduce chemical demand and associated GHG emission potential, reduced dewaterability of digested sludge from enhanced biological phosphorus removal (EBPR) processes can increase polymer demand and/or hauling and associated GHG emissions. Tradeoffs in terms of GHG emission potential and methods for mitigating EBPR impacts on solids dewatering must be considered and evaluated on a site-specific basis when selecting a phosphorus removal process.

How Does Removal of Constituents of Emerging Concern Impact GHG Emissions Potential?

Gu et al. (2016) evaluated and compared the environmental impacts associated with different levels of wastewater treatment technologies that have been specifically designed for various degrees of nutrient removal and for potential CEC removal using the life cycle assessment (LCA) method. Sixty-four different treatment scenarios incorporating various secondary and advanced tertiary processes for both nutrient and CEC removal were evaluated. Results showed that implementation of more advanced technologies to achieve higher-level nutrient removal significantly reduced the point-source eutrophication potential because of the further reduction of nutrient discharges. However, the LCA analysis of different nutrient removal technologies indicated that the benefits achieved from the reduction of eutrophication through nutrient removal can be outweighed by the negative impacts caused from the additional chemical and energy usages required in implementing more advanced treatments. Assessment of implementation of advanced tertiary technologies for enhanced CEC removal revealed that treatment scenarios designed for CEC elimination led to relatively small improvements in toxicity reduction associated with CEC removal. In contrast, the high amounts of energy and chemical usage required in the advanced tertiary processes targeting CEC reduction produce higher toxicity levels compared to the benefits achieved. Therefore, management and risk mitigation strategies (i.e., pollution prevention, toxic chemicals control, and regulation) rather than treatment technologies alone for CECs should be considered.

How Would the Introduction of Organics/FOG-Receiving Facilities into WRRF Anaerobic Digesters Impact GHG Emissions?

This topic was not investigated under the Nutrient Removal Challenge. However, it is an area that merits discussion and consideration on future research and thus included. It is well documented that as WRRFs start acceptance of organics/FOG the effluent nutrient levels will likely increase. The impact on GHG emissions is unclear. While the acceptance of such materials typically results

in energy recovery at the WRRF, what is the overall impact on GHG emissions compared to where such material would otherwise end up? For material that would otherwise end up at a landfill, acceptance at a WRRF would likely have a reduced GHG emissions footprint.

How Should GHG Emissions Be Considered in Design and Permitting?

GHG emissions and overall sustainability of a process is significantly impacted by factors external to the plant operation or nutrient removal process. Planners, designers, and managers must understand the balance between process selection, solids handling and disposal practices, facility design, and community and financial impacts. Operators can use the tools given to optimize performance and reduce consumption. Regulators must be cognizant of how effluent limits may impact the design, operations, costs, and overall sustainability of WRRFs and be willing to consider alternatives that can meet water quality needs in a more sustainable manner.

The Nutrient Removal Challenge addressed nutrient permitting frameworks (Clark et al. 2016), including cases where low nutrient limits drive the need for advanced treatment. More advanced levels of point source wastewater treatment come with penalties in terms of additional energy use, chemical use, and both direct and indirect GHG emissions. Nutrient control requirements that call for treatment at or beyond the capabilities of technology may be counterproductive in balancing overall environmental goals.

Nutrient discharge permits that are restrictive in ways unrelated to water quality protection because of the structure of the permit itself should be avoided. Unnecessarily restrictive permits do not enhance water quality protection, but may create circumstances that result in noncompliance. Nutrient permit structures that provide utilities with flexibility foster creative solutions to best meet overall water quality objectives, such as watershed permitting, shared loading capacity, and trading. Flexible permits can be developed to facilitate opportunities for effluent reuse, recharge, and restoration.

CONCLUSIONS

Although many industrial sectors need to take significant action to comply with anticipated global warming initiatives, the municipal wastewater treatment industry can proceed with a few simple activities to evaluate GHG emissions and GHG reduction strategies.

1. Typical municipal WRRFs fall below the 25,000 mt CO_2e/year emissions reporting threshold for the EPA Mandatory Reporting of Greenhouse Gas regulation and therefore do not need to take any action in this regard.
2. Municipal WRRFs combusting significant quantities of fossil fuels for power production within the WRRF facility itself may exceed this threshold and trigger the need to report GHG emissions. For example, if a WRRF uses waste heat from an incinerator to operate a steam system/microturbine to recover heat then they might be considered a power producer and be susceptible to GHG reporting requirements. Biogas from anaerobic digestion is not considered a fossil fuel.
3. Municipal WRRFs may still wish to quantify GHG emission by performing a GHG inventory. This provides documentation of emissions below the reporting threshold, a basis for further voluntary emissions, and information for the public in terms of the impact of WRRF operations on global warming. Reporting values in terms of total emissions and per capita emissions allows more readily comparisons to other GHG sources.
4. Municipal WRRFs should still be concerned with minimization of energy consumption from a triple bottom line perspective considering cost, environmental, and social benefits. Minimizing energy consumption minimizes emission indirect GHG emissions from energy production by an outside energy provider serving the WRRF, assuming that electricity is derived from fossil fuels.
5. Municipal WRRFs may wish to measure bioreactor N_2O emissions to ensure their particular design and operation remains in the lower ranges of measured values to date.
6. Municipal WRRFs should not be emitting digester gas without combustion—either via flaring or energy generation in CHP—or other beneficial use such as gas cleaning and addition to natural gas distribution networks.
7. Municipal WRRFs not presently producing power from digester gas may be able to produce carbon offsets by installing gas utilization systems. In many states, incentives and subsidies may be available to assist in developing such projects. Some regulations require power companies to adopt renewable energy portfolios, motivating power companies to participate in these projects.
8. Municipal WRRFs should engage the regulatory community to foster a discussion of tradeoffs between advanced nutrient and CECs removal, potential GHG emissions, and overall environmental impacts. Innovative and flexible permitting structures for nutrient removal are a preferred outcome when necessary to meet overall water quality objectives from a watershed perspective.

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