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Chapter 1

Introduction

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SUMMARY

The *Introduction* chapter explains the motivation for assessing and reducing greenhouse (GHG) emissions from urban water systems and gives an overview of the design for this book. This chapter also provides a summary for the content of each chapter in terms of the state-of-the-art regarding urban water system GHG emissions sources, inventory protocols, quantification methods, and the existing modelling tools. Finally, this chapter explains the scope and objectives of this book, as well as providing a general guide for the use of this book in GHG assessment and reduction efforts.

Keywords: Greenhouse gas, methane, nitrous oxide, and urban water systems

TERMINOLOGY

Term	Definition
Urban water system	An engineered system to decouple the water used by the human community and the natural water environment
N_2O	Nitrous oxide, a potent GHG, with a global warming potential 265-fold stronger than that of carbon dioxide (CO_2)
CH_4	Methane, a potent GHG, with a global warming potential 25-fold stronger than that of carbon dioxide (CO_2)
Biomass	A clump of organic material consisting of living organisms, which live on the substrates in wastewater, or the dead organism debris.
Greenhouse gas	Gas that absorbs and emits radiant energy within the thermal infrared range and contributes to the global warming effect.
Nutrient	Substances such as nitrogenous compounds, phosphate or organic carbon that can be assimilated by microbes to promote the metabolism and growth of microbes in wastewater.
Organic matter	Organic waste of plant or animal origin from homes or industry, or originated from storm water run-offs, and so on., which mainly contains volatile fraction of solids.

Mathematic model	A system of mathematical equations that describes physical and biological processes. It is a simplified representation of the real process.
Wastewater	The used water including solids discharged from communities, businesses, industry or agriculture that flows into a wastewater treatment plant. Storm water, surface water, and groundwater infiltration also may be included.

1.1 CLIMATE CHANGE, SUSTAINABILITY, AND GHG LEGISLATION IN THE WATER SECTOR

The effects of climate change can have a tremendous impact on almost all facets of life on Earth. In many parts of the world, they are already being felt and, to no surprise, the global position on climate change, as evidenced since COP21, is that we must stand and fight to minimize anthropogenic greenhouse gas (GHG) emissions, and move towards net zero emissions to help mitigate climate change impacts. Although the water sector's overall contribution is small compared to the global GHG emissions, urban water management can make up a significant part of a city's GHG emissions inventory. In New York City, for example, urban water management is second only to the buildings sector in GHG emissions and makes up 20% of the city-wide GHG emissions inventory (Bonczak *et al.* 2020). This is largely due to the low emissions per capita resulting from the mass transit system, and the same results are likely for water utilities in other large cities around the world with extensive mass transit systems. However, even if, as a whole, the water sector represents a small fraction of the total GHG emissions, the effects of climate change can be detrimental to the urban water cycle, prompting problems such as water scarcity and stress from droughts, flooding and disruption of service from extreme weather events, combined sewer overflows, and a variety of water quality issues. Since we cannot live without water, and the sustainability and resilience of the urban water cycle is central to human quality of life, there is a physical need and driver for climate change mitigation and minimizing GHG emissions in the water sector. Therefore, the water sector needs to lead the fight against climate change by example.

The physical effects that climate change has on the urban water cycle have also prompted a cultural change among water utilities. Sustainability and resilience are now widely incorporated into the planning and operations of water utilities and are implemented in varying degrees. Therefore, in addition to addressing economic and social factors, minimizing the environmental impact of urban water systems is at the forefront for water utilities with a wish list of activities to be more environmentally friendly, such as resource recovery, minimizing water, chemical, and energy consumption, including minimizing the GHG emissions related to urban water system management and development. There is this idea of the green utility (Welch, 2010). Therefore, there is also a water utility cultural driver for mitigating GHG emissions.

Although there is no argument among water utilities that we should all be striving for environmental stewardship from a sustainability point of view, there are other specific drivers for reducing GHG emissions in the water sector. These include various types of GHG legislation that implicate some water utilities in different parts of the world, such as in the US, UK, Denmark, Australia, and The Netherlands, as well as general voluntary GHG reduction goals that are incorporated into strategies that are implemented at local, regional, and national levels, which also implicate water utilities in various parts of the world. However, there should be no other driver needed than the real and visible climate-related disasters that are happening much more frequently and led to the Climate Crisis being declared in 2019. Hence, clear drivers exist for water utilities to mitigate climate change and action is either already being taken by leaders in the field, or is planned by water utilities in response to these drivers. These drivers are what makes this book relevant, and they provide the main motivation to equip the water sector with knowledge and tools to start taking climate action now by quantifying, modelling, and mitigating urban wastewater system GHG emissions.

Given the urgency in addressing the Climate Crisis, we know that GHG emissions must be reduced in the next decade to minimize the effects of climate change, as the time left for us to take action has been cut by two-thirds. We cannot wait until the middle of the century to achieve the original target (Höhne *et al*., 2020). This requires efforts from all sectors to reduce the emissions.

The wastewater sector contributes to greenhouse gas emissions not only through its significant energy consumption, but also through direct emissions of fugitive gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). According to the guidelines from the Intergovernmental Panel on Climate Change (IPCC) on national GHG inventories calculation (IPCC, 2006), the GHG emissions are categorized into three scopes:

- Scope 1: direct GHG emissions from the treatment of wastewater;
- Scope 2: indirect emissions from the generation of purchased electricity, heat or steam that is consumed in its owned or controlled equipment or operations;
- Scope 3: indirect GHG emissions from materials and consumables used for the treatment of wastewater – for example chemicals manufacture and transport and the emissions associated with purchased goods and services, including those for capital infrastructure works, waste generated by company operations, as well as employee travel and commuting and so on.

Currently, the wastewater sector is required to report both direct (Scope 1) and indirect (Scope 2) GHG emissions from wastewater systems as part of the waste and energy sectors. The indirect emissions are expected to decrease substantially in the coming decade due to both the increased recovery of energy from wastewaters and the improved energy utilization efficiency for wastewater treatment. Use of onsite wind and solar energy will further reduce Scope 2 emissions. Therefore, the Scope 1 emissions will become the key contributors and are also more difficult to reduce. As most of the CO_2 produced from wastewater treatment processes are biogenic carbon, the majority of the Scope 1 emissions from urban wastewater systems are CH_4 and N_2O. This is because both CH_4 and N_2O are potent GHGs, with global warming potentials 25-fold and 265-fold, respectively, stronger than that of CO_2. N_2O emissions are especially important, contributing up to 80% of the overall carbon footprint of a wastewater treatment plant (WWTP) (Daelman *et al*., 2013). The pathways and factors leading to biological nitrous oxide and methane formation and emissions from wastewater are also highly complex and site-specific. In 2019, IPCC published a refinement to its 2006 GHG inventory guidelines and a substantial increase of the default emission factor for N_2O was used for WWTPs (IPCC, 2019). It is also noted that the national level GHG methodologies lack the level of detail required to properly quantify N_2O emissions at the asset level because they do not account for the site-specific conditions.

As the water industry has a strong stake in improving environmental performance, sustainability and reducing emissions, the objective of this book is to provide a detailed summary of the current state-of-knowledge for both N_2O and CH_4 generation, quantification and modelling from urban wastewater systems, therefore improving the scientific basis used by the water industry in understanding and mitigating the Scope 1 emissions from wastewater processes.

1.2 OVERVIEW OF GHG EMISSION SOURCES IN URBAN WATER SYSTEMS

The urban water cycle is not only intricate and complex by nature, it is also unique for every city, like a fingerprint. It can include a drinking water stage with supply, treatment, and distribution; a wastewater stage with collection, treatment, and discharge; and everything in between, such as water reuse, rainwater harvesting, and urban drainage. The layout and configuration for each part will have varying impacts on the total urban water cycle carbon footprint depending upon various factors, such as elevations, population, climate, water consumption behaviour, electrical grid energy mix, water resource type (e.g., surface water or groundwater), and how everything is managed and further developed by water utilities. Therefore, climate change mitigation by minimizing GHG emissions from urban water systems requires a multi-faceted and holistic approach to address the different issues related to the different stages/systems of the urban water cycle, and the different sources of GHG emissions in each stage. This holistic approach not only requires looking at planning, design,

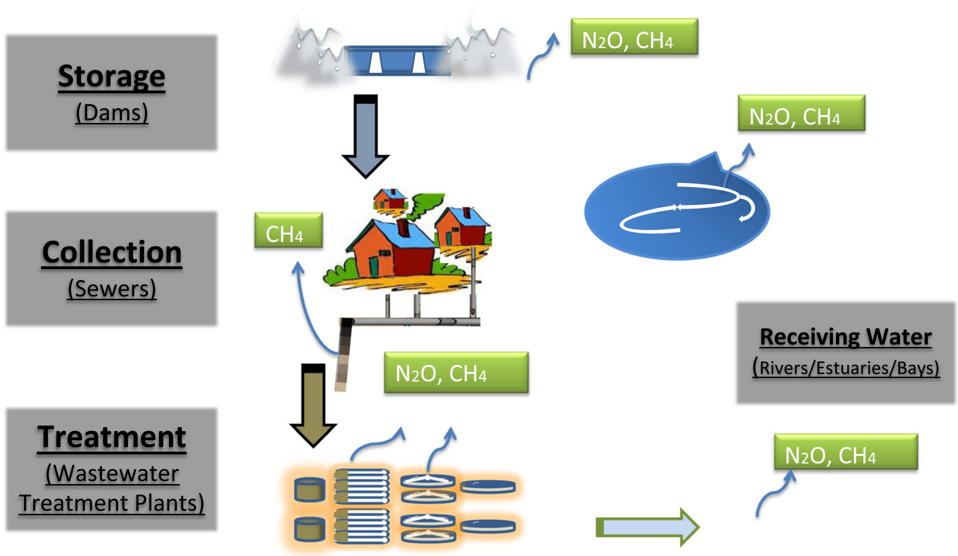

Figure 1.1 Fugitive greenhouse gas (N_2O and CH_4) emissions from urban water systems.

operations, and construction of urban water systems, but also requires consideration of urban water system management and development in an integrated fashion, as the various parts of the urban water cycle are inherently linked and can impact the GHG emissions of each other. However, the focus of this book is on the urban wastewater system.

As a whole, the urban wastewater system is engineered to decouple the water used by the human community and the natural water environment, from water storage to wastewater collection and treatment before the water is safely discharged to receiving water bodies (illustrated in Figure 1.1).

It has been reported that all urban water systems and receiving water bodies (i.e., rivers, estuaries and bays) will produce N_2O and CH_4 (Sturm *et al.*, 2013). This is because N_2O and CH_4 are generated biologically either as a by-product or an obligatory intermediate during the biological nitrogen or carbon cycle (more details can be found in Chapters 2 and 3). Given the amount of nitrogen and carbon inventory in the urban water system, only underground wastewater collection systems (sewers) and the subsequent wastewater treatment plants are within the scope of this book as these are regarded as the key emissions sources of N_2O and CH_4. It should be noted that while the fundamental generation pathways of N_2O and CH_4 are similar in either the natural environment or in urban water systems, the quantification methodologies may vary. This book will focus on the N_2O and CH_4 emission points in sewers and wastewater treatment plants (as shown in Figure 1.2 below) to introduce their associated generation mechanisms and factors (operational or environmental) that may affect their emissions.

Chapter 2 focuses on sources and pathways of N_2O generation. As an environmentally detrimental greenhouse gas, N_2O generated from wastewater treatment systems has attracted a lot of attention due to its important contribution to the overall facility carbon footprint. When aiming for mitigation of N_2O, it is imperative to understand the mechanisms that trigger its formation. Sources and pathways for N_2O production are reviewed and discussed. Despite extensive investigations, the mechanisms for N_2O production continue to undergo extensive academic research because of the complexity of wastewater treatment systems. N_2O generation is influenced by a diversity of interrelated conditions: the different species of microbes with specialized functions, the interactions among these microbes in a mixed system, and the responses of microbes to the different environmental factors and operational

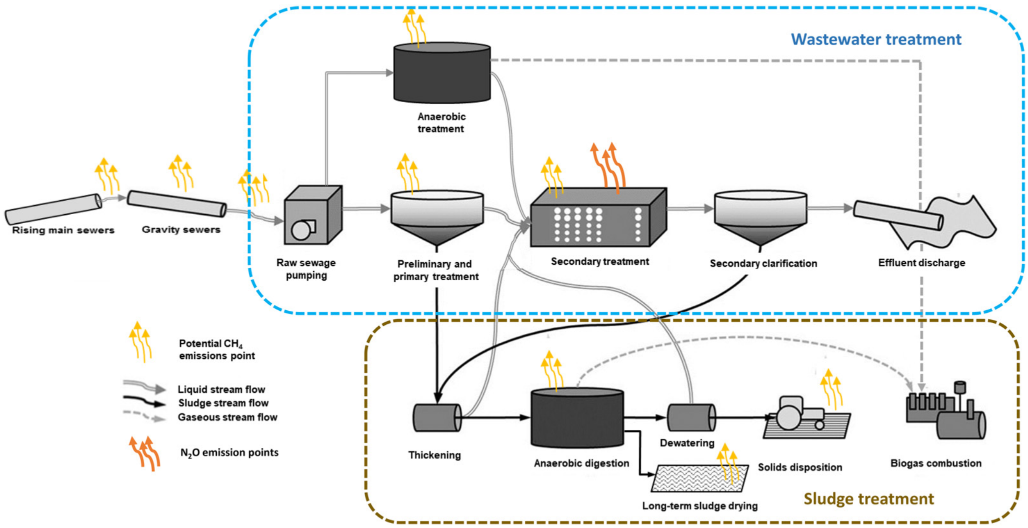

Figure 1.2 Sources of N_2O and CH_4 emission points from wastewater transport and treatment (Adapted from Figure 3.3 in Chapter 3).

conditions. Chapter 2 provides an overview of the N_2O production pathways and mechanisms during the biological nitrogen removal (BNR) process and describes the different factors that have been reported to have an effect on N_2O production.

Chapter 3 provides an overview of the contribution of urban wastewater system methane emissions. CH_4 formation in urban wastewater systems occurs through anaerobic digestion (AD) of organics contained in sewage. AD consists of a sequence of concomitant reactions by which a consortium of microorganisms, in the absence of oxygen, break down biodegradable carbon material producing biogas, a mixture of methane, carbon dioxide and traces of H_2S. In an urban wastewater system, those reactions can occur naturally in sewer systems depleted of oxygen or be artificially promoted in wastewater treatment plants to capture and recover the energy contained in molecules of methane. Specifics of methane generation in sewer biofilms, sewer sediments, anaerobic wastewater treatment and sludge disposal of wastewater treatment plants are presented in this chapter. Identification of CH_4 emission spots in urban wastewater engineered systems represents the initial step for reliable quantification of GHG; this then facilitates development and implementation of effective mitigation strategies.

1.3 GHG EMISSIONS INVENTORY PROTOCOLS

Following a better understanding of N_2O and CH_4 generation for the urban wastewater system, **Chapter 4** provides readers with focused analysis of the accounting methodologies and protocols supporting GHG emissions assessment and reporting of relevance to the urban water system in wastewater treatment of domestic and industrial wastewaters. It summarizes the basis for existing CH_4 and N_2O emission factors, the three-tier approach set out in the internationally accepted IPCC methodology and areas where further work is required. This chapter also summarizes the implications of the 2019 IPCC refinement of top-down emission factors on the magnitude of N_2O emissions from secondary treatment, as well as country-specific emission factors developed through national bottom-up monitoring and reporting guidelines. Finally, this chapter highlights the importance of bottom-up approaches to understand the opportunities to optimize treatment processes and conditions that minimize direct GHG emissions and help move the water industry towards net zero GHG emissions.

1.4 DIRECT MEASUREMENT OF URBAN WATER SYSTEM GHG EMISSIONS

Current reporting guidelines on N_2O and CH_4 emissions from the wastewater sector, whether at international or national level, provide for single emission factors each for N_2O and CH_4 in a top-down approach. Evidence from scientific and industry investigations shows that this is not likely to be accurate as the fixed emissions factor methods are adopted to report all emissions. Therefore, the quantification of direct GHG emissions from sewers and wastewater treatment plants is of great importance to provide science-based emissions baselines and understanding from which mitigation strategies can be developed and emissions reductions can be implemented and sustained in urban water systems.

Chapter 5 provides an overview of the currently available nitrous oxide and methane quantification methods applied at full-scale in sewers and wastewater treatment plants. Since the first measurement campaigns in the early 90 s were based on sporadic grab sampling, quantification methodologies and sampling strategies have evolved significantly, in order to describe the spatial-temporal dynamics of the emissions. The selection of a suitable quantification method is mainly dictated by the objective of the measurement survey and by specific local requirements. Plant-wide quantification methods provide information on the overall emissions of wastewater treatment plants, including unknown sources, which can be used for GHG inventory purposes. To develop on-site mitigation strategies, in-depth analysis of GHG generation pathways and emission patterns is required. In this case, process-unit quantifications can be employed to provide data for developing mechanistic models or to statistically link GHG emissions to operational conditions. With regard to sewers, current available methods are not yet capable of capturing the complexity of these systems, due to their geographical extension and variability of conditions, and only allow monitoring of specific locations where hotspots for GHG formation and emission have been identified.

Chapter 6 reviews and summarizes recent studies from N_2O and CH_4 monitoring campaigns in full-scale WWTPs and sewer networks. The analysis classifies quantified N_2O and CH_4 emissions, triggering operational conditions and formation pathways for different configurations. Control strategies to minimize N_2O emissions are proposed for different process groups. Main reasons for the emission factor (EF) discrepancies in the control strategies (i.e., aeration control), configuration, and operational and environmental conditions that favour the preferred enzymatic pathways are discussed as well.

Compared with N_2O, CH_4 quantification from full-scale WWTPs is less investigated, while it also contributes significantly to the overall plant carbon footprint. The results of full-scale CH_4 quantification studies are summarized in this chapter. Emissions of CH_4 in WWTPs mainly originate from the influent, anaerobic wastewater treatment and anaerobic sludge handling processes. The amount of CH_4 emissions varies greatly with different configurations of WWTPs. For WWTPs without anaerobic sludge handling processes, the CH_4 emissions can mainly be traced back to the CH_4 dissolved in the influent. When anaerobic treatment is applied in WWTPs for wastewater chemical oxygen demand (COD) removal, its CH_4 emissions might substantially increase the overall plant carbon footprint. GHG monitoring campaigns carried out in WWTPs should include the monitoring of fugitive CH_4 emissions. Finally, CH_4 and N_2O emissions reported from sewer networks are also summarized in this chapter.

The last part of the chapter also summarizes some mitigation strategies applied at full-scale to control fugitive CHG emissions from WWTPs and sewers.

1.5 MODELLING TOOLS FOR ASSESSING GHG EMISSIONS FROM URBAN WATER SYSTEMS

Mathematical modelling plays a critical role towards the understanding and the success of mitigation of GHG emissions from urban wastewater systems. Mechanistic models based on biological pathways for both N_2O and CH_4, so called first principle models, have been successfully used to simulate the emissions. Benchmarking has been a useful tool for unbiased comparison of control strategies in wastewater treatment plants in terms of effluent quality, operational cost and risk of suffering microbiology-related total suspended solids (TSS) separation problems. Recently, deep learning has been increasingly applied to urban water management, models based on neural networks and machine learning also develop quickly in this field. In this book, Chapters 7–10 review all the different types of models and their applications in full-scale N_2O and CH_4 simulation and mitigation.

Chapter 7 reviews the current status of the modelling of N_2O emissions from wastewater treatment. The existing mathematical models describing all known microbial pathways for N_2O production are reviewed and discussed. These include N_2O production and consumption by heterotrophic denitrifiers, N_2O production by ammonia-oxidizing bacteria (AOB) through the hydroxylamine oxidation pathway and the AOB denitrification pathway, and the integration of these pathways in single-pathway N_2O models. The two-pathway models are compared to single-pathway models. The calibration and validation of these models using lab-scale and full-scale experimental data is also reviewed. The mathematical modelling of N_2O production, while still being enhanced by new knowledge development, has reached a maturity that facilitates the estimation of site-specific N_2O emissions and the development of mitigation strategies for wastewater treatment plants taking into account the specific design and operational conditions of the plant.

Chapter 8 provides a review of the models available for estimating the production and emission of methane from wastewater collection and treatment systems. The details of a number of mechanistic models as well as the simplified empirical models are summarized. Their limitations are identified and general methods for calibration and validation are presented.

Chapter 9 presents the status of extending the original Benchmark Simulation Model No. 2 (BSM2) towards including greenhouse gas emissions. A mathematical approach based on a set of comprehensive models that estimate all potential on-site and off-site sources of CO_2, CH_4 and N_2O is presented and discussed in detail. Based upon the assumptions built into the model structures, simulation results highlight the potential undesirable effects of increased GHG emissions when carrying out local energy optimization in the activated sludge section and/or energy recovery in the anaerobic digester. Although off-site CO_2 emissions may decrease in such scenarios due to either lower aeration energy requirement or higher heat and electricity production, these effects may be counterbalanced by increased N_2O emissions, especially since N_2O has a 300-fold stronger greenhouse effect than $CO_{2.}$ The reported results emphasize the importance of using integrated approaches when comparing and evaluating (plant-wide) control strategies in wastewater treatment plants for more informed operational decision-making.

In **Chapter 10**, alternatives to mechanistic modelling, such as knowledge-based and data-driven approaches for assessing and mitigating GHG emissions from urban wastewater systems are detailed. Examples include knowledge-based artificial intelligence (AI), integrating mechanistic modelling and computational fluid dynamics (CFD) with AI, and data-driven and machine learning (ML) methods for assessing and mitigating nitrous oxide emissions from wastewater treatment. Using a knowledge-based AI approach, the expert knowledge of N_2O pathways and influencing factors can be represented and applied to generate a dynamic risk score using the process data and identify mitigation actions. Using data-driven methods like principal component analysis (PCA) and machine learning, specifically support vector machines (SVM), patterns in data can be detected to identify mitigation opportunities and to classify process conditions for guiding monitoring campaigns and minimizing the time needed for monitoring to properly represent the full range of emissions for a specific site. Although the focus is on the use of these approaches for assessing and mitigating N_2O emissions, the same general approach can be applied for assessing and mitigating CH_4.

1.6 MITIGATION OF GHG EMISSIONS FROM URBAN WATER SYSTEMS

The final chapter, **Chapter 11**, summarizes the key knowledge presented in this book. It also discusses the issues, knowledge gaps and perspectives in GHG quantification, reporting guidelines and modelling, and provides the perspectives for future work. This gives us the knowledge and tools for starting to monitor and mitigate emissions and begin to contribute towards net zero plants. Further work is needed and will likely also surface while implementing this knowledge in practice. However, it is of great importance that the already available knowledge is put into practice without delay, in order to initiate efforts to reduce the impact of the water sector on climate change now.

1.7 GENERAL GUIDE FOR USE OF THIS BOOK IN GHG ASSESSMENT AND REDUCTION EFFORTS

As mentioned, the goal of this book is to provide practitioners with the knowledge and tools to start taking climate action now by quantifying, modelling, and mitigating urban wastewater system GHG emissions. Therefore, the following use of this book is suggested:

- Read Chapter 1 for understanding the full context and drivers for GHG emissions quantification, modelling, and mitigation, and an overview of the relevant urban wastewater system GHG emission sources, as well as for understanding the contents of each chapter.
- Depending on the GHG of interest, read either Chapters 2 or 3 to understand mechanisms and pathways.
- Assuming the starting point is GHG accounting and reporting and no measurements or mitigation has begun, read Chapter 4 to understand how emissions can be quantified using best use of the protocols until measurement can be performed.
- Read Chapter 5 for quantification methods through direct measurements.
- Read Chapter 6 to understand the results of previous monitoring campaigns, the emission factors that have been derived from different monitoring strategies, and factors affecting monitoring results.
- Read either Chapters 7 or 8 depending on the GHG of focus to understand how mechanistic models can and should be used.
- Read Chapter 9 to understand results of control benchmarking studies and the types of effects different control strategies can have on WWTP GHG emissions for the specific case of the Benchmark Simulation Model platform.
- Read Chapter 10 to understand what AI and data-driven approaches can be taken.
- Read Chapter 11 for perspectives on where we are and where we are going with quantifying, modelling and mitigating urban wastewater system GHG emissions.

It should be noted however that, depending on the specific objectives, not all chapters may need to be read. For example, if there are mechanistic modelling studies planned, then perhaps it makes sense to start with either Chapters 7 or 8. Similarly, if only quantification is needed at the moment, then the focus can be on Chapters 5 and 6.

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NOMENCLATURE

AD	Anaerobic digestion
AI	Artificial intelligence
AOB	Ammonia oxidizing bacteria
BNR	Biological nutrient removal
BSM	Benchmark simulation model
CFD	Computational fluid dynamics
EF	Emission factor
GHG	Greenhouse gas
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
ML	Machine learning
PCA	Principal component analysis
SVM	Support vector machines
TSS	Total suspended solids
UK	United Kingdom
USA	United States of America
WWTP	Wastewater treatment plant