



Greenhouse gas emissions from integrated urban drainage systems

Where do we stand?

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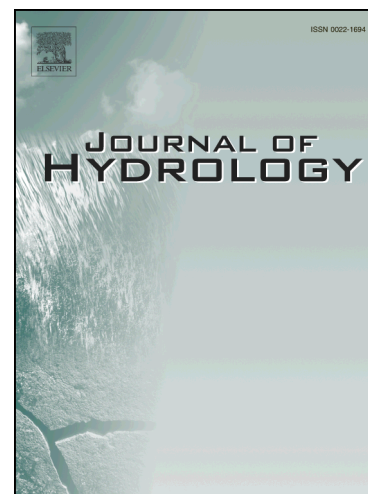
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Greenhouse gas emissions from integrated urban drainage systems: where do we stand?

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Abstract

As sources of greenhouse gas (GHG) emissions, integrated urban drainage systems (IUDSs) (i.e., sewer systems, wastewater treatment plants and receiving water bodies) contribute to climate change. This paper, produced by the International Working Group on Data and Models, which works under the IWA/IAHR Joint Committee on Urban Drainage, reviews the state-of-the-art and modelling tools developed recently to understand and manage GHG emissions from IUDS. Further, open problems and research gaps are discussed and a framework for handling GHG emissions from IUDSs is presented. The literature review reveals that there is a need to strengthen already available mathematical models for IUDS to take GHG into account.

Keywords

Integrated urban drainage modelling, water quality, mathematical modelling, GHG

Introduction: greenhouse gases from integrated urban drainage systems

Climate change can be attributed to greenhouse gas (GHG) emissions and is currently one of the most urgent challenges for humankind. The impacts of climate change are evident worldwide, and scientists predict that these impacts will intensify in the coming decades (IPCC, 2014). Conveyance of water and wastewater in integrated urban drainage systems (IUDSs) contributes to GHG emissions through energy consumption (indirect CO₂ emissions) and fugitive gaseous emissions such as nitrous oxide (N₂O) and methane (CH₄) (direct emissions). CH₄ and N₂O are two potent greenhouse gases with global warming potentials that are 25 and 298 times the global warming potential of CO₂, respectively (when considering a 100-year period) (IPCC, 2014). In addition, CH₄ and N₂O contribute to stratospheric ozone destruction. It is generally accepted that N₂O is produced as an intermediate product in the microbial process of denitrification, which converts nitrogen dinitrogen (an inert gas).

The production of GHGs from water and wastewater occurs throughout integrated urban drainage systems, which are complex systems composed of sewer systems, wastewater treatment plants (WWTP) and receiving water bodies (RWB), as illustrated in Figure 1.

The sewer system drains wastewater (mainly from household and industrial facilities) and rainwater to prevent problems with hygiene and flooding in urban areas. Part of this drainage water is transported to WWTPs and treated for subsequent release into a receiving water body. Remaining water which exceeds the capacity of the sewer system and/or WWTP may be discharged directly into the receiving water body as an overflow. In addition, the receiving water body receives pollutant loads from agricultural activities (i.e., non point pollution) in the catchment (i.e., the surrounding area) that contribute to the quality status of the water body.

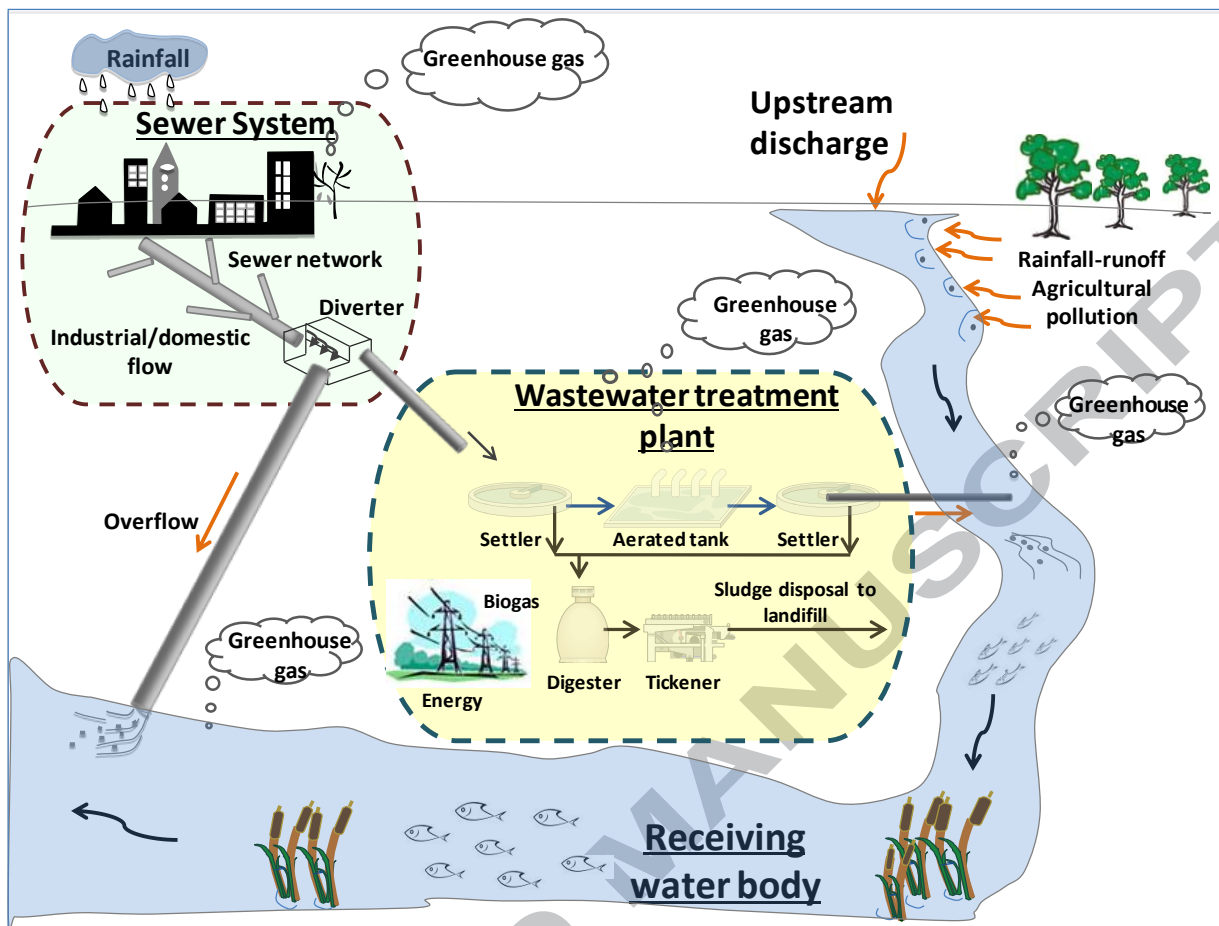


Fig. 1. The integrated urban drainage system

IUDs consider all systems jointly because individual optimisation of the different components will not result in an overall optimisation of the system (Schütze and Alex, 2004; Bach et al., 2014). The Water Framework Directive (WFD) requires strict effluent limits for pollutants and entails the adoption of river basin scale management for water issues and for achieving full cost recovery of water services (Benedetti et al., 2013). Similarly, the Integrate Pollution Prevention and Control (IPPC) Directive requires Member States of the European Union to issue operating permits containing emission limit values based on the best available techniques. The benefits of using integrated system-wide approaches for solving real problems have been demonstrated by modelling pollution indicators required by the WFD (i.e., concentrations of dissolved oxygen, ammonia, nitrate, phosphorus etc.) (Langeveld et al., 2013).

Recently, significant investments have been made by the European Union to improve knowledge regarding each component of the integrated water management systems and to understand how the different components interact (e.g., EU FP6 projects NEPTUNE, INNOWATECH, FP7 project ClimateWater, and FP7 ACQWA aimed at understanding the climate impact of water management). In addition, the EU FP7 project PREPARED and CORFU FP7 projects worked on integration at an urban water level, and the TRUST and SANITAS FP7 projects worked on the deficiencies in European urban water management to develop an integrated technology, knowledge and an action base.

Despite these efforts, governments and researchers are moving towards new integration concepts in water management that consider the inclusion of new environmental quality indicators (including GHG emissions). Therefore, new challenges must be overcome to improve sustainability and protect the environment.

In the same context, there is a growing concern that IUDSs are not sustainably managed with respect to energy consumption. However, climate change is an important driver to increase the use of sustainable energy sources and minimise carbon footprint. This knowledge has pushed researchers to consider new novel targets for preserving the environment, including additional performance indicators that are related to GHG emissions (Flores-Alsina et al., 2014; Mannina et al., 2016). When considering this principle, new novel target indicators have been used to reduce climate change due to GHG emissions from IUDSs (Flores-Alsina et al., 2014). In addition, a theoretical modelling study that quantified the GHG emissions from an IUDS was recently conducted (Guo et al., 2012). Despite strong limitations due to the use of a hypothetical/virtual case study, the potential of using a dynamic system-wide model for balancing water quality, operational costs and GHG emissions was demonstrated. Aside from this study, no other surveys have been conducted to quantify or reduce GHG emissions from IUDSs. One possible reason for this lack of research is the only recent awareness of the relevant contribution of GHGs from IUDSs,

as well as the lack of dedicated research projects that are focused on the goals mentioned above. IUDSs are very complex. In addition, the quantification of GHG emissions can only be pursued at this preliminary stage by dedicated projects with sufficient relevant investments, due to the extensive resources required for monitoring complex systems. Regarding the production and mitigation of GHG emissions from individual sub-systems of the integrated systems (i.e., sewer systems, WWTP and receiving water bodies), studies available in the literature are present but not designed for IUDS related applications (e.g. Campos et al., 2016).

Despite the importance of GHG emissions from IUDSs, as far as the authors are aware, no studies have been carried out that consider GHG emissions from all elements of the system in an integrated manner. In the following sections, the main studies regarding greenhouse gases from the individual sub-systems (sewer system, WWTP and receiving water body) are reported. In the final section, the research needs and efforts beyond the state-of-the-art are discussed.

Greenhouse gases from sewer systems

In a sewer system, GHG emissions occur mainly in sewer conduits, which convey wastewater (mainly from households and industrial facilities) and rainwater. In the sewer conduits, biological processes occur due to the presence of organic substances, nutrients and microorganisms. GHG emissions originate from anaerobic, anoxic or aerobic biological processes that occur in sewer sediments (which can be deposited at the bottom of the sewer conduits due to fluctuations in flow), bulk water and in biofilms that grow on pipe walls (Figure 2). One challenge in evaluating GHG from sewer systems results from limited knowledge regarding the chemical, biological and transport processes that occur in sewers. In addition, uncertainty regarding the characteristics of the system that affect physical-chemical processes such as exact wastewater composition or

sedimentation and resuspension poses further challenge to the quantification of GHG emissions (Bertrand-Krajewski, 2007; Benedetti et al., 2013; Mannina et al., 2012).

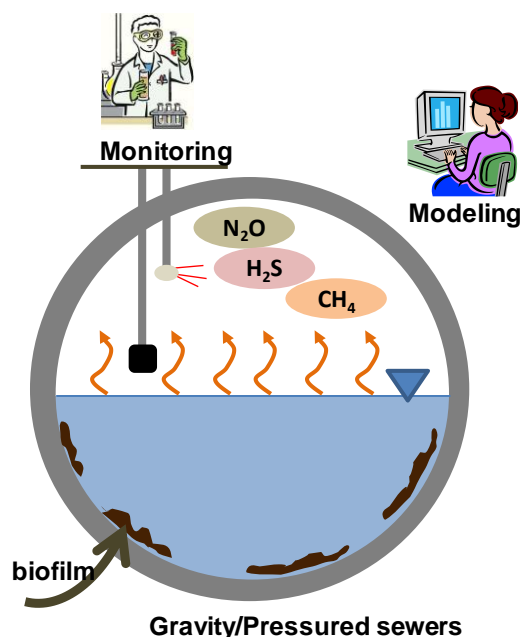


Fig. 2 Main processes in sewers

The first notable study focused on two pressurised sewer systems in the Gold Coast area (Australia) and was conducted in 2008 (Guisasola et al., 2008). The authors of this study found that a significant amount of CH_4 can be produced in sewer systems. In addition, this CH_4 production is positively correlated with the hydraulic retention time of the wastewater in these systems. Guisasola et al. (2008) emphasised the need for understanding and controlling methanogenesis processes because they reduce the wastewater organic carbon that influences the formation of N_2O inside of the wastewater treatment plant due to incomplete denitrification. Gutierrez et al. (2014) found that the rate of CH_4 production decreased during caustic dosing and increased when the pH was above. However, field studies have shown that, in practice, caustic dosing must be increased to achieve the same reduction in CH_4 production rate as was obtained in the laboratory experiments (Gutierrez et al. 2014). Mohanakrishnan et al. (2008) found that nitrite addition could be a promising and effective strategy for controlling CH_4 production in sewers.

However, this finding must be confirmed by conducting actual case studies. Jiang et al. (2013) found a substantial reduction in CH_4 production following the addition of nitrate in a laboratory gravity sewer system. Sudarjanto et al. (2013) evaluated the effectiveness of three bioproducts for controlling CH_4 in laboratory pressurised sewers and suggested that rigorous laboratory system tests should be performed prior to adopting bioproducts in real sewers.

Little information exists regarding the role that sewers play in the production and emission of N_2O (among others, Koh and Shaw, 2016). Contrary to the current international guidance of the Intergovernmental Panel on Climate Change, gravity sewer systems have recently been found to serve as a source of N_2O (Short et al., 2014). These authors stress that research is needed regarding the quantification of GHG emissions from sewers. In addition, the longitudinal N_2O concentrations in sewer networks (both dissolved and in the headspace) should be assessed to capture the spatio-temporal variability of N_2O production under different conditions (Short et al., 2014). Knowledge regarding the biochemical transformations that are responsible for N_2O production in sewers is lacking (Short et al., 2014).

These previously listed results indicate that a consolidated and worldwide approach for effectively reducing such emissions does not exist. Studies have been conducted for mitigating GHG emissions from sewer systems; however, the application of these mitigation strategies is generally limited to the local conditions of the selected and limited case studies.

From a mathematical modelling perspective, very few process models have been published. In addition, the applicability of these studies is generally limited to the local conditions in which they were developed. For example, (1) sulphide control (Sharma et al., 2008; Vollertsen et al., 2011) (2) methanogenesis (Guisasola et al., 2009) and (3) sewer exfiltration (Benedetti et al., 2013) studies have been conducted. To predict sewer water quality, empirical models have been proposed as an alternative to process models (Benedetti et al., 2013). However, a consolidated mathematical

model for simulating CH₄ and N₂O from sewer systems has not been developed (Guo et al., 2012). Indeed, few models have been proposed to assess the formation of CH₄ from pressure sewers (Foley et al., 2009; 2010; Kampschreur et al., 2009; Law et al., 2012). Thus, models for estimating the formation of CH₄ from gravity sewer systems and the formation of N₂O for pressure and gravity systems must be developed. The limited number of mathematical models that are available for simulating GHG emissions from sewer systems has occurred because research was previously lacking. Thus, this knowledge is in its infancy and requires additional research.

Greenhouse gases from wastewater treatment plants

Previous results have shown that the GHG emissions from WWTPs should be controlled and reduced due to their high global warming potential (Kampschreur et al., 2009; Law et al., 2012; Mannina et al., 2016).

The Environmental Protection Agency of the United States (2006) reported that N₂O from WWTPs accounts for approximately 3% of N₂O emissions and represents the sixth largest contributor. Recently, several attempts have been made to understand GHG production processes (Joss et al., 2009; Foley et al., 2009; Daelman et al., 2012, Harper et al., 2015, Ogurek et al., 2016), to quantify and measure GHG emissions (GWRC, 2011) and to predict and control GHG production (Corominas et al., 2012; Ni et al., 2013a; Ni et al., 2013b). Although greenhouse gas emissions from WWTPs are of concern, knowledge regarding their source and magnitude (mainly for N₂O) remains incomplete (Kampschreur et al., 2009). Specifically, the production of N₂O due to the denitrification pathways of nitrifiers remains a subject of debate (Ni et al., 2013b; Mannina et al., 2016; Ogurek et al., 2016; Sperandio et al., 2016). Specifically, N₂O can be produced both during nitrification (only by means of the ammonia oxidizing bacteria - AOB) and denitrification processes

(during both the nitrification/denitrification process, hydroxylamine (NH_2OH) pathways and the heterotrophic denitrification pathway). Indeed, it is well known that N_2O is an intermediate of the heterotrophic denitrification bacteria but it can also be produced during the ammonia oxidation process (nitrification) (Kampschreur et al., 2009). However, the wide range of WWTP N_2O emission factors measured and reported in literature underlines that the mechanisms involved in the N_2O formation are not completely understood (Kampschreur et al., 2009; Law et al., 2012; Mannina et al., 2016).

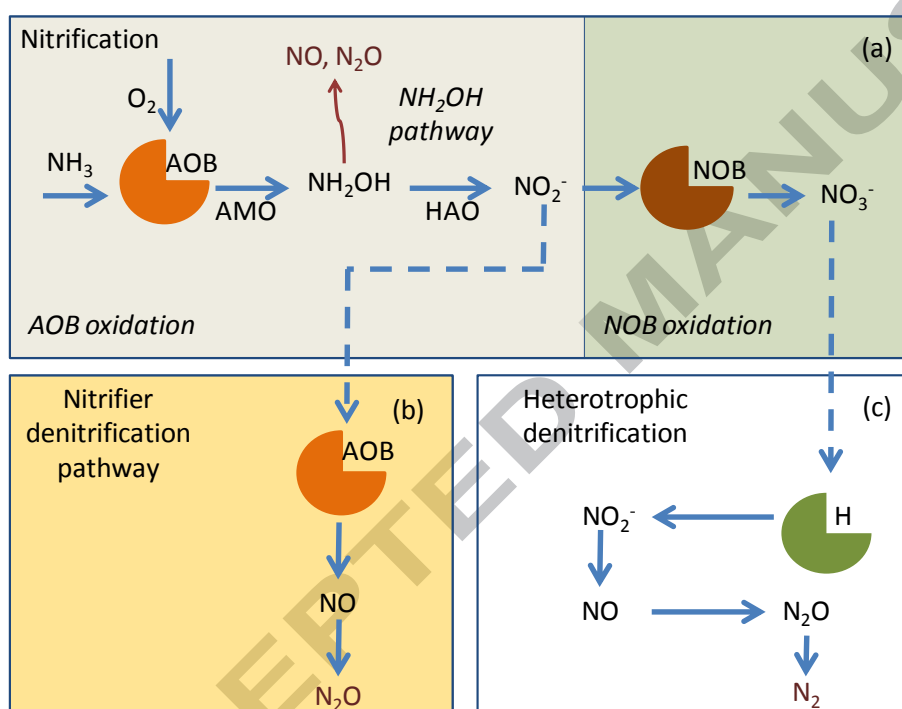


Figure 3. N_2O formation pathways

In Figure 3 the N_2O formation pathways are summarized. The nitrification process is divided into two main steps: In the first step, autotrophic ammonia oxidizing bacteria (X_{AOB}) aerobically oxidize NH_3 or NH_4^+ into NO_2^- ; in the second step, autotrophic nitrite oxidizing bacteria (X_{NOB}) aerobically oxidize NO_2^- into NO_3^- . Denitrification leads to the reduction of NO_3^- into N_2 by means of heterotrophic bacteria growth (X_{H}). N_2O is produced during biological nitrogen removal processes due to both X_{AOB} and X_{H} (Kampschreur et al., 2009; Ni and Yuan, 2015). X_{AOB} can produce N_2O as a

product of the hydroxylamine (NH_2OH) oxidation, identified as one of the major pathways, or nitrite (NO_2) reduction (AOB denitrification) (Ni et al., 2013). Heterotrophic biomass produces N_2O as an obligate intermediate during nitrate (NO_3) reduction (Law et al., 2012).

Regarding the CO_2 , it is directly produced due to aerobic and anaerobic biological processes. During the aerobic biological processes, the cell growth lead to the organic compounds oxidation into CO_2 . While, during the anaerobic biological processes the organic matter is transformed into biogas composed by CO_2 and CH_4 . The amount of the fossil CO_2 emissions from WWTPs can vary with the inlet wastewater composition and the plant configuration (Law et al., 2013).

CH_4 has a GWP of 34 over a 100-year period (IPCC, 2013). It is mainly produced during the decomposition of a wide range of organic matter in anaerobic conditions. A great amount of the volatile matter contained of the sludge entering the anaerobic digester is converted into CH_4 (around 40%). The process of anaerobic digestion consists of four main subsequent steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis (Appels et al., 2008).

Specifically, during the hydrolysis step (first step), both insoluble organic material and high molecular weight compounds such as lipids, polysaccharides, proteins and nucleic acids, are converted into soluble organic substances (e.g. amino acids and fatty acids). The products of the hydrolysis are further degraded during acidogenesis (second step). During the third step (acetogenesis), the organic acids and alcohols produced by acidogenesis are further digested to produce acetic acid as well as CO_2 and H_2 . Finally, during the fourth step (methanogenesis) CH_4 is produced.

WWTPs where anaerobic processes are implemented are often a source of CH_4 (CEC, 2006, <https://www.ncbi.nlm.nih.gov/pubmed/22575155>). CH_4 , produced during the anaerobic decomposition of organic substrate (activated by methanogenic bacteria), can be released to the atmosphere through the surface of the opened tanks (Mannina et al., 2016b), or during storage and handling of the digested sludge. This methane emission can easily set-off the reduced fossil

CO₂ emission associated with biogas energy production

(<https://www.ncbi.nlm.nih.gov/pubmed/22575155>). Biogas, containing 55-65% of CH₄, can be adopted as energy source to reduce the energy footprint (and consequently the GHG emissions) of the WWTP. Large amounts of CH₄ can be also produced due to the disposal of raw sewage sludge to landfill (Czepiel et al., 1993).

Regarding the quantification of GHGs and the different measurement techniques that are used, previous studies have reported a range of measured GHG emissions (mainly N₂O) (Daelman et al., 2012; GWRC, 2011). The existence of a range of GHG measurements has resulted in the conclusion that estimating GHG emissions from WWTPs using emissions factors (e.g. IPCC, 2006; 2014) oversimplifies the process and leads to extremely uncertain results (Law et al., 2012). The emission factor for N₂O, for example, is only based on one field study, in which the WWTP was not designed for nitrogen removal (GWRC, 2011). The detailed mechanisms of N₂O production have not been fully elucidated (Law et al., 2012).

Recently, two international research groups under the umbrella of the International Water Association (IWA) have been set up: on Benchmark Simulation models (TG-IWA-BMWWTP) and on Greenhouse gas emissions (GHG-IWA). These research groups have the objective of deepening the aspects related to the setting up of a standard modelling tool for WWTPs to be used at an international level, and also deepening the knowledge concerning the assessment of GHG emissions from WWTPs. Both groups have highlighted the need to converge research efforts towards the implementation of integrated approaches in the design and management of WWTPs, explicitly considering the minimization of the GHG emissions as one of the objectives.

From a mathematical modelling perspective, WWTPs are generally modelled using the Activated Sludge Models that were proposed by the IWA (Henze et al., 2000). These models are considered standard. Several authors have attempted to use these models (Flores-Alsina et al., 2014; Guo et

al., 2012; Corominas et al., 2012; Hiatt and Grady, 2008); however, most of these mathematical models remain theoretical because they are applied to hypothetical case studies without real data. Recently, a mathematical model was successfully applied to a wastewater treatment plant (Ni et al., 2013a), but no consensus has been reached regarding the mathematical modelling of GHGs from WWTPs. Recently, a mathematical modelling study that was based on a virtual system demonstrated the benefits of mathematical modelling and included GHG emissions among the wastewater treatment plant targets (Flores-Alsina et al., 2014). These authors concluded that the optimal way to simulate GHG emissions from WWTPs is to use a plant-wide approach that identifies all synergies among the different units of the plant (Flores-Alsina et al., 2014; Grau et al., 2007). Sweetapple et al. (2014a-b) developed an extensive uncertainty analysis at plant wide scale taking into account GHG emissions. Such a study, although developed on a theoretical case study, demonstrated the effectiveness of advanced mathematical modelling methods for reducing the emissions and pin down criteria for plant operational strategies. Recent studies on GHG modelling include both conventional (Massara et al., 2018) and advanced treatment systems such as membrane bioreactors (Mannina et al., 2018b). Such models are modifications of the ASM in an attempt to come up with a modelling tools for GHG emissions from WWTPs.

Despite the efforts that have been made at an international level, a simulation platform for the design and/or the management of WWTPs to minimise GHG emissions is still lacking. Moreover, a literature review indicated that some important aspects require additional research (Law et al., 2012). For example, criteria are lacking for the design and management of WWTPs that use integrated approaches including consideration of the emission of GHGs. Furthermore, an extensive database of GHG measurements is lacking in terms of the temporal and spatial distributions for encoding the behaviour of GHGs in the yield process and for assessing the temporal variability of the GHGs throughout the year (Mannina et al., 2018a). These extensive databases are essential for developing and applying robust and reliable mathematical models. In

addition, standard protocols for measuring emissions are lacking. These protocols would allow individuals to compare the data obtained from different WWTPs. Finally, the identification of appropriate mitigation measures, which are based on process control and are aimed at reducing GHG emissions, is lacking. Furthermore, knowledge gaps are present regarding the contributions of autotrophic and heterotrophic biomass during the formation of GHG emissions. Very recently, an extensive Italian national project on greenhouse gas emission from WWTPs (PRIN) has been funded and is studying the production such gases with the final aim to set-up a decision support system for their reduction (Caniani et al., 2015; Mannina, 2017). Such studies are, however, still lacking. There are several projects ongoing that focus on the reduction of the energy consumption in WWTPs (De Gussem et al., 2014), but these projects do not explicitly quantify the impacts on GHG emissions.

Greenhouse gases from receiving water bodies

The issues raised by GHG emissions from receiving water bodies have been thoroughly investigated in recent years. GHGs from receiving water bodies are produced by complex biological processes in the water column (Figure 4). Many efforts have been made by the technical community to accurately quantify GHG emissions from aquatic systems (Beaulieu et al., 2014; Musenze et al., 2014; Chen et al., 2013). Indeed, these studies highlighted the significant contribution of these sources on GHG emissions and climate change. A recent study reported that river and stream networks may contribute at least 10% of the N₂O emissions resulting from anthropogenic activities to the atmosphere (Beaulieu et al., 2011). Beaulieu et al. measured the N₂O production rates of 72 streams and found that they were three times greater than those estimated by the Intergovernmental Panel on Climate Change (IPCC, 2014).

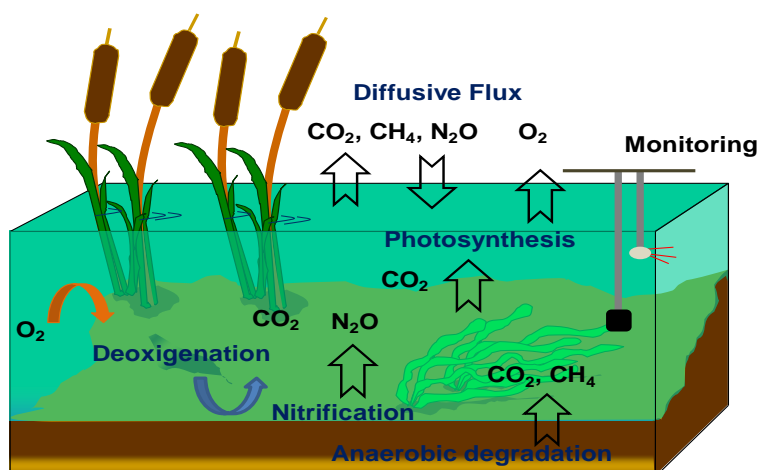


Figure 4. Main biological processes in the receiving water body

Musenze et al. (2014) reported the results of a two-year field data gathering campaign that was conducted in a sub-tropical estuarine system and aimed to quantify CH₄ and N₂O emissions. Musenze et al. (2014) found huge spatial and temporal variability in the CH₄ and N₂O emissions and highlighted the uncertainty due to a lack of accurate estimation methods for gas transfer velocity, which represents a fundamental parameter for estimating CH₄ and N₂O fluxes from water. Beaulieu et al. (2014) analysed the N₂O concentrations in water samples and N₂O emissions from the water surface by using floating chambers. This study focused on the roles of heterotrophic denitrification and chemoautotrophic nitrification, which have not been elucidated, and highlighted the need for further research to understand the mechanisms that are responsible for N₂O production in water systems. Furthermore, despite strong efforts towards building a consensus for assessing the GHG status of aquatic systems, many uncertainties remain. These uncertainties mainly result from the lack of standard measurement techniques and standard tools for assessing GHG emissions and the limited reliable information obtained from a variety of sources (Goldenfum, 2012). From a modelling perspective, previous reports have not consolidated

mathematical models for simulating GHG emissions from receiving water bodies (Guo et al., 2012). Despite a River Water Quality Model (RWQM) has been developed (Shanahan et al., 2001) to assess the influences of both point and non-point pollution sources on water quality (Bach et al., 2014), water quality models have yet to be extended to include N_2O and CH_4 production.

One could even go a step further by including the entire river catchment. It is well known that land use and land management, e.g. urbanization, agricultural practices and forest management, have a strong effect on both the catchment runoff and the carbon balance (Richardson et al., 2013). Catchment runoff directly affects river flows and as a consequence also the river water quality and related impacts of the urban drainage and wastewater system. This again shows the need for a holistic approach, where the development of sustainable, climate-proof approaches should not only address the impacts of climate change but also the feedbacks to the climate system and the potential benefits of the climate change mitigation. In addition to an understanding of the processes occurring, at the technical level such an approach requires holistic modelling methods that are efficient. Due to the multitude of aspects and interactions to be considered and the huge number of scenario simulations required to derive optimal strategies, fast simulation models that describe the essence of the responses and interactions are necessary. Existing detailed, physically-based models have their limitations here. One solution is the use of conceptual models or the option to combine models of different degrees of complexity according to the needs of the particular study (Schütze and Alex, 2004). Wolfs et al. (2015) recently developed an approach for the identification of a simplified surrogate conceptual model based on the results of a limited number of simulations with a state-of-the-art full hydrodynamic river model. Similar approaches were developed for sewer systems (Wolfs and Willems 2017) and for river and sewer water quality (Mannina and Viviani, 2010a-b; Mannina et al., 2012; Vezzaro et al., 2014; Ogurek et al., 2015; Keupers and Willems 2017). Due to their simplicity and modular structure, they allow easy extension with other conceptual model blocks, e.g. to describe GHG emissions and feedbacks.

They moreover allow optimization applications and the derivation of optimal management strategies for urban storm and waste water systems.

Proposal of a new framework for GHG assessment from IUDS

Bearing in mind the considerations discussed above, the working group on Data and Models of the Joint Committee on Urban Drainage of IWA and IAHR proposes a framework for dealing with GHG from IUDSs. The overall idea is to overcome critical issues typical of IUDS modelling – more specifically, to model GHG emissions at an integrated urban drainage scale, the different sources of water and pollution have to be considered by integrating a cascade of sub-models (Freni and Mannina, 2010). In the case of integrated approaches, uncertainties propagate throughout a chain of sub-models and the use of either extremely simplified or extremely detailed approaches can reduce the operator's confidence in the model's robustness (Willems, 2008; Freni et al., 2009a;b; 2010a; Mannina et al., 2017; Mannina and Viviani, 2009). It is thus crucial to have an equal distribution of sub-model complexities (Willems, 2012). Therefore, advanced and innovative methods (e.g. global sensitivity analysis, identifiability analysis, uncertainty analysis, mathematical calibration protocols, etc., (Cosenza et al., 2013; Mannina et al., 2011) should be used to develop and employ the mathematical modelling tools.

An important requirement is to define the boundaries of the integrated system in order to better define the information needed for the integrated model application.

Modelling should be carried-out based on a two step-procedure: first, an in-depth analysis of the different components should be carried out and new detailed mathematical models derived for simulating each sub-system, utilising existing physical-based models from literature which do not currently do not fully take into account greenhouse gases (Bach et al., 2014). To ensure the sub-

models produced are reliable, the development process should be supported by knowledge derived from experimental activities. The experimental data gathered would allow insights to be gained and ensure that phenomena regarding GHG formation and propagation are captured in the models.

Due to their complexity, these new models will not be appropriate for deriving long-term statistical information, which would be useful for mitigation strategies (Willems, 2006). Therefore, the new detailed sub-system models should be simplified by using conceptual simplified mathematical models characterized by a lower number of calibration parameters and reduced calculation times (second step). Such simplified models should be derived for each sub-system, based on the detailed mathematical models and making optimal use of physical interpretation given to the model structure. Moreover, a screening of mitigation measures (e.g. best management practices (Freni et al., 2010b), control strategies for best sewer operation (Kroll et al., 2016), specific bacteria for wastewater treatment integrated control automation, regulation of aerated and non-aerated phases in the wastewater treatment plant, river oxygenation, employment of particular aquatic plants for the receiving water bodies, etc.) should be carried out to gain insight into the potential reduction of GHG emissions at micro/sub-system scales.

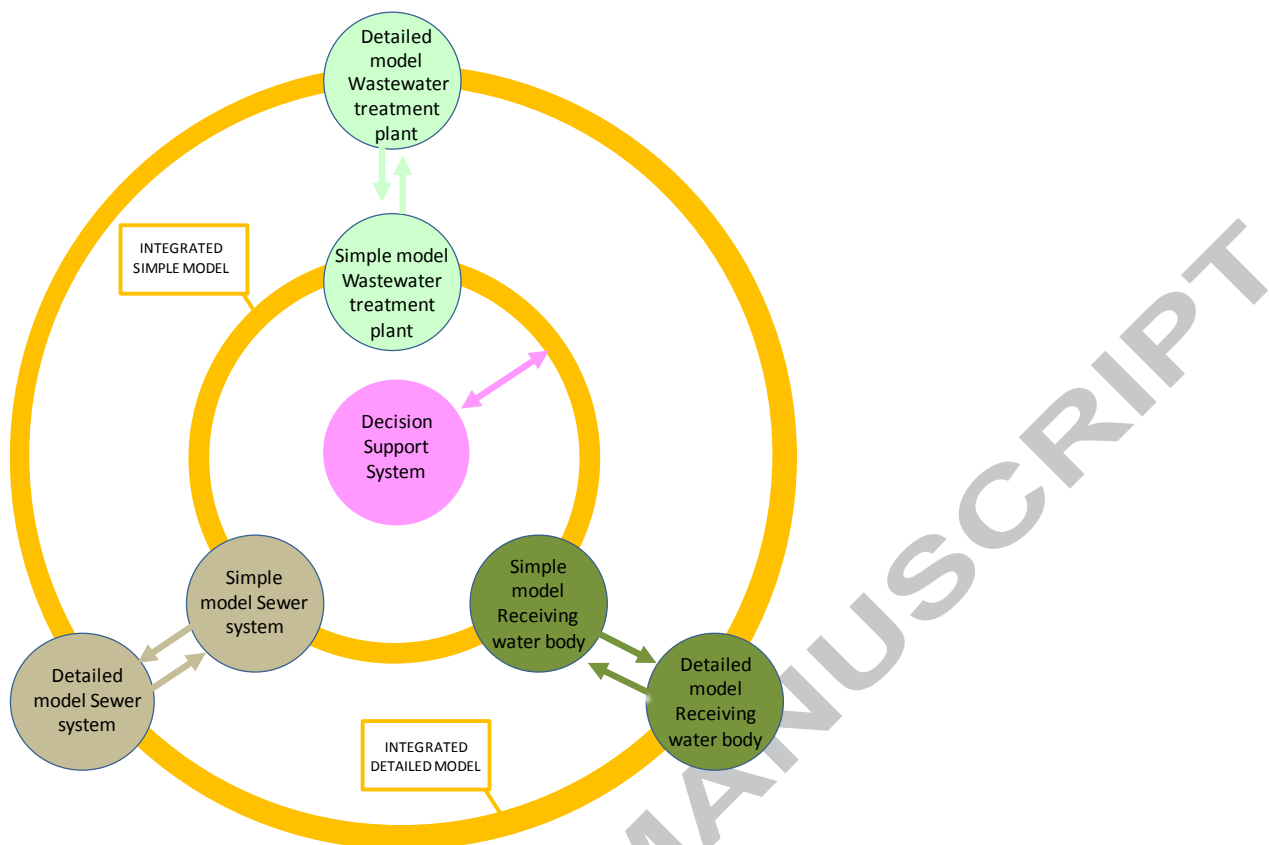


Figure 5. Detailed and simplified integrated model layout of the urban drainage system.

As good modelling strategy, the major goal would be to integrate detailed and simplified models already available in literature to create a model (detailed and simplified) that can simulate GHG emissions from an integrated system under dynamic conditions. Furthermore, beginning with the simplified integrated model, a decision support system must be developed to design, operate and evaluate control strategies for IUDSs (Figure 5). To fulfil this goal, the following activities are required.

1. Setting-up the detailed integrated model. This model should be created by integrating the detailed mathematical models that should be developed for each sub-system. The model should include algorithms that are opportunely developed by upgrading existing algorithms

in the literature based on the knowledge acquired when attempting to understand the GHG emission process and interactions. Model connectors should be developed to link the detailed models (outer circle of Figure 5) developed for each sub-system. The integrated detailed model should be calibrated and validated using a dataset collected during field monitoring campaigns.

2. Setting-up the simplified integrated model. To reduce the computational burden, a simplified integrated model should be developed, utilising simplified mathematical models for each sub-system. With this aim, simple model connectors should be developed to link each sub-model (inner circle of Figure 4).
3. Setting-up the decision support system. The decision support system should utilise the simplified integrated model. It should be usable for general applications and by researchers and managers to optimise the design and operation of IUDSs.

Future perspectives and research needs

The importance of reducing and mitigating GHG emissions from IUDSs has to be highlighted in this review. To achieve such goals, the following key requirements should be addressed:

- Produce a comprehensive data set containing GHG emissions from IUDSs (i.e., sewer systems, wastewater treatment plants and receiving water bodies) and create new methods for collecting this data based on measurement protocols/guidelines.
- Deliver a fundamental understanding of the key processes that are responsible for producing GHG emissions in IUDSs.
- Create mathematical models using data gathered from laboratory experiments and field monitoring to support the development of new tools that are able to quantify the effects of mitigation measures on GHG emissions. The integrated mathematical model will be able

to optimize (in terms of GHG reduction) entire systems while accounting for any interactions.

- Deliver innovative strategies, scenario analyses and guidelines for reducing GHG emissions from IUDSs by means of innovative methods. A comparison of alternative scenarios and solutions in terms of overall performance, risk and cost is warmly recommended.

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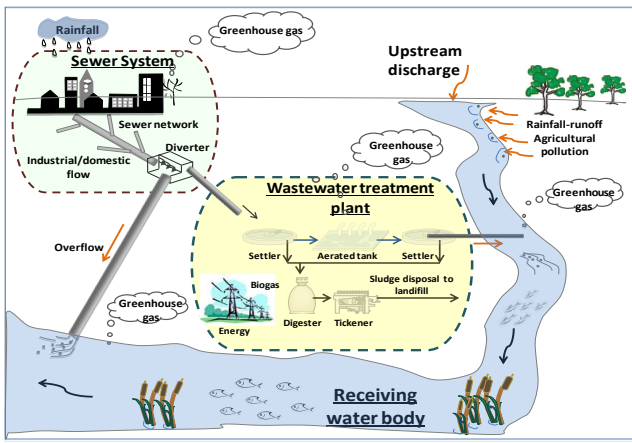
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