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ICUD-0426 Greenhouse gas emissions from integrated urban drainage systems: where do we stand?

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Summary

Integrated urban drainage systems (IUDS) (i.e., sewer systems, wastewater treatment plants and receiving water bodies) contribute to climate change being sources of greenhouse gas emissions (GHG). 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 the recently developed modelling tools used to understand and manage GHG emissions from IUDS. Further, open problems and research gaps are discussed, while proposing a framework for handling GHG from IUDS. The literature review reveals that there is a need to strengthen and partially adequate already available mathematical models for IUDS to take GHG into account.

Keywords

climate change, greenhouse gases, integrated urban drainage modelling, mathematical modelling

Greenhouse Gases from Integrated Urban Drainage Systems

Climate change is caused by greenhouse gas 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). Water and wastewater conveyed by integrated urban drainage systems contribute to greenhouse gas emissions through energy consumption (indirect CO_2 emissions) and fugitive gas emissions, such as nitrous oxide (N_2O) and methane (CH_4) (direct emissions). CH_4 and N_2O are two potent greenhouse gases with global warming potentials that are 25 and 298 times the global warming potential of CO_2, respectively (when considering a 100-year period). In addition, CH_4 and N_2O contribute to stratospheric ozone destruction. A generally accepted procedure considers, nitrous oxide is produced via a microbial process called denitrification, which converts nitrogen to nitrous oxide and dinitrogen (an inert gas).

The production of greenhouse gases from water and wastewater occurs throughout integrated urban drainage systems, which are complex systems that are composed of three main sub-systems (Fig. 1): sewer systems (SS), wastewater treatment plants (WWTP) and receiving water bodies (RWB).

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 wastewater treatment plants and treated for subsequent release into a receiving water body. The remaining water is generally discharged directly into the receiving water body. In addition, the receiving water body receives pollutant loads from agricultural activities (i.e., no point pollution) in the catchment (i.e., the surrounding area) that contribute to the quality status of the water body.

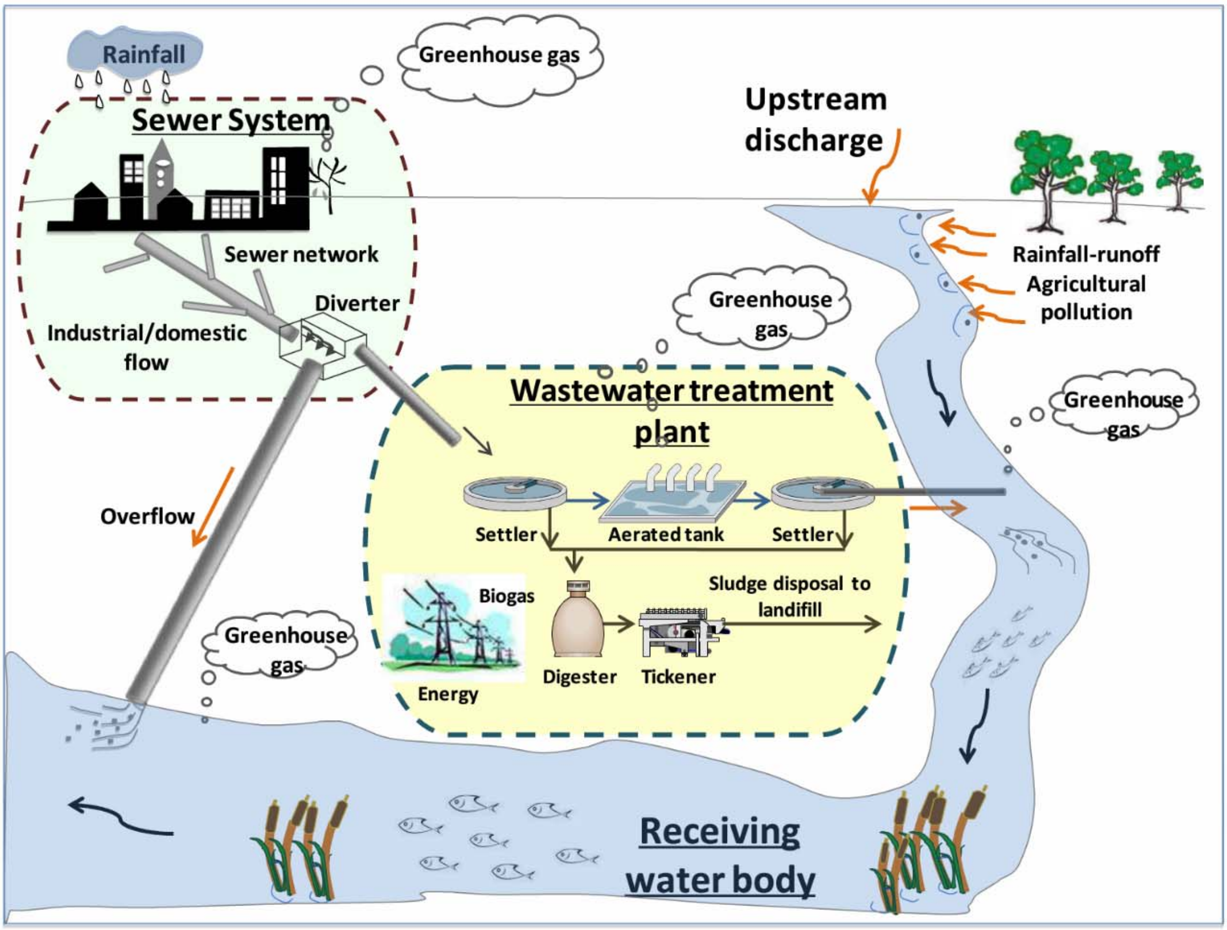

Fig. 1. *The integrated urban drainage system*

Integrated urban drainage systems consider all systems jointly because the individual optimisation of the different components will not result in an overall optimisation of the system (Schütze et al., 2002, Bach et al., 2014). The Water Framework Directive (WFD) requires strict effluent limits for the 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 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 were demonstrated by accounting for the pollution indicators that were required by the WFD (i.e., oxygen concentrations, 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 water management systems and to understand how each component interacts with other components (e.g., FP6 NEPTUNE, INNOWATECH, FP7 ClimateWater, and FP7 ACQWA aimed at understanding the climate impact of water management). In addition, the PREPARED and CORFU FP7 projects worked on integration at an urban water level. Moreover, the TRUST and SANITAS FP7 projects worked on the deficiencies in European urban water management to develop 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 (i.e., greenhouse gas emissions). Therefore, new challenges must be faced to improve sustainability and protect the environment.

There is growing concern that integrated urban drainage systems are not sustainably managed in the face of climate change and energy consumption. However, climate change is important for improving sustainable energy use while minimising the carbon footprint. This knowledge has pushed researchers to include new novel targets for preserving the environment, including additional performance indicators that are related to greenhouse gas emissions (Flores-Alsina et al., 2014; Mannina et al., 2016). When considering this principle, new novel target indicators were used to reduce climate change due to greenhouse gas emissions from integrated urban drainage systems. In addition, a theoretical modelling study that quantified the greenhouse gas emissions from an integrated urban drainage system was recently conducted (Guo et al., 2012). Despite the strong limitations due to the use of hypothetical/virtual case study, it was demonstrated the potential of using a dynamic system-wide model for balancing water quality, operational costs and greenhouse gas emissions. Aside from this study, no other surveys have been conducted to quantify or reduce greenhouse gas emissions from integrated urban drainage systems. One possible reason for this lack of research is the only recent awareness of the relevant contribution of greenhouse gases from integrated urban drainage systems as well as lack of dedicated research projects that are focused on the goals mentioned above. Integrated urban drainage systems are very complex. In addition, the quantification of greenhouse gas emissions can only be pursued at this primary stage by dedicated projects with relevant investments due to the extensive resources that these studies require for monitoring complex systems. Regarding the production and mitigation of greenhouse gas emissions from individual sub-systems of the integrated systems (i.e., sewer systems, wastewater treatment plant and receiving water bodies), in the literature there are only few studies.

Despite the relevant role of greenhouse gas emissions from integrated urban drainage systems, as far as the authors are aware, no studies have been carried out on the whole system. In the following sections, the main studies regarding greenhouse gases from the individual sub-systems (SS, WWTP and RWB) are reported. In a final section, the research needs and efforts beyond the state of the art are discussed.

Greenhouse Gases from Sewer Systems

In a sewer system, greenhouse gas emissions occur mainly in sewer conduits, which convey wastewater (mainly from household, industrial facilities) and rainwater. In the sewer conduits, biological processes occur due to the presence of organic substances, nutrients and microorganisms. Greenhouse gas 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 biofilms that grow on pipe walls (Fig. 2). One drawback of evaluating greenhouse gases from sewer systems results from limited knowledge regarding the chemical, biological and transport processes that occur in sewers. In addition, the characteristics of the system that affect physical–chemical processes, such as sedimentation and resuspension, are problematic (Bertrand-Krajewski, 2007; Benedetti et al., 2013).

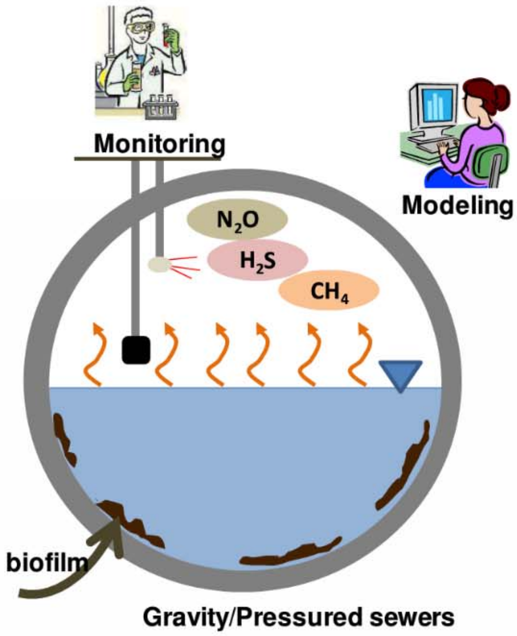

Fig. 2. *Main biological processes in sewer*

The first notable study focused on two pressure sewer systems in the Gold Coast area (Australia) and was conducted in 2008 (Guinasola et al., 2008). The authors of this study indicated that a significant amount of methane can be produced in sewer systems. In addition, this methane production is positively correlated with the hydraulic retention time of the wastewater in these systems. Guinasola 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 the pH to more than 10. However, field studies have shown that caustic dosing must be increased to achieve the same reduction in the CH_4 production rate that was obtained in the laboratory experiments. Mohanakrishnan et al. (2008) found that nitrite addition could be a promising and effective strategy for controlling CH4 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 pressure 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 producing and emitting N_2O. 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 greenhouse gas emissions from sewers. In addition, the longitudinal N_2O concentrations in sewer networks (both dissolved and 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., 2013).

These previously listed results indicated that a consolidated and worldwide approach for effectively reducing such emission does not exist. However, studies have been conducted for mitigating greenhouse gas emissions from sewer systems. Indeed, the application of these mitigation strategies is generally limited to the local conditions that are related to 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 (Guinasola et al., 2009) and (3) sewer exfiltration (Benedetti et al., 2013) studies have been conducted. To predict sewer water quality, empirical models are used as an alternative to process models (Benedetti et al., 2013). However, a consolidated mathematical model for simulating CH_4 and N_2O from sewer systems has not been developed (Guo et al., 2012). Indeed, few models have been proposed to assess the formation of CH_4 from pressure sewers (Foley et al., 2010; Kampschreur et al., 2009; Law et al., 2012). Thus, models for estimating the formation of CH_4 from gravity sewer systems and the formation of N_2O for pressure and gravity systems must be developed. The limited number of mathematical models that are available for simulating greenhouse gas 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 greenhouse gases from wastewater treatment plants should be controlled and reduced due to their high global warming potential (Kampschreur et al., 2009; Law., 2012).

The Environmental Protection Agency of the United States (2006) reported that N2O from wastewater treatment plants accounts for approximately 3% of N_2O contributions and represents the sixth largest contributor. Recently, several attempts have been made to understand greenhouse gas 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 greenhouse gas emissions (GWRC, 2011) and to predict and control greenhouse gas production (Corominas et al., 2012; Ni et al., 2013a; Ni et al., 2013b). Although greenhouse gas emissions from wastewater treatment plants are of concern, knowledge regarding their source and magnitude (mainly for N_2O) remains incomplete (Kampschreur et al., 2009). Specifically, the production of N_2O due to the denitrification pathways of nitrifiers remains unknown and is an object of debate (Ni et al., 2013b; Mannina et al., 2016; Ogurek et al., 2016;Sperandio et al., 2016). Specifically, N_2O 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).

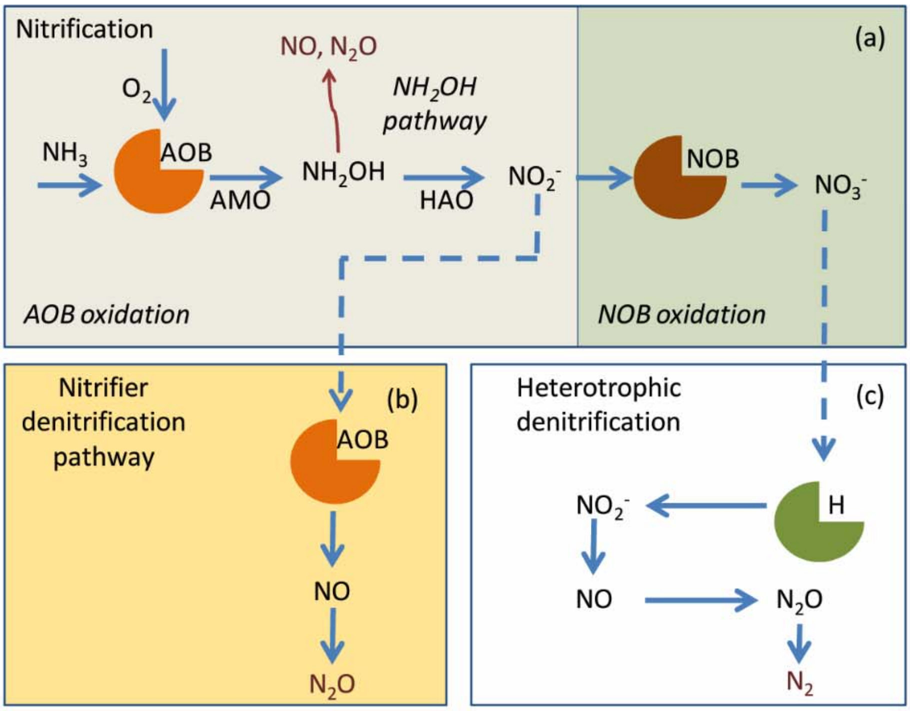

Fig. 3. *pathway of N_2O formation*

In Fig. 3 the pathway of N_2O formation, described in the follows, are summarized. Regarding the quantification of greenhouse gases and the different measurement techniques that are used, previous reports have indicated a range of measured greenhouse gas emissions (mainly N_2O) (Daelman et al., 2012; GWRC, 2011). The existence of a range of greenhouse gas measurements has resulted in the conclusion that estimating greenhouse gases from wastewater treatment plants 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 N_2O is only based on one field study, in which the wastewater treatment plant was not designed for nitrogen removal (GWRC, 2011). The detailed mechanisms of N_2O 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 wastewater treatment plants to be used at an international level and also deepening the knowledge concerning the assessment of greenhouse gas emissions from wastewater treatment plants. Both groups have highlighted the need to converge research efforts towards the implementation of integrated approaches in the design and management of wastewater treatment plants, explicitly considering the minimization of the greenhouse gas emissions as one of the objectives.

From a mathematical modelling perspective, wastewater treatment plants 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). However, no consensus has been reached regarding the mathematical modelling of greenhouse gases from wastewater treatment plants. Recently, a mathematical modelling study that was based on a virtual system demonstrated the benefits of mathematical modelling and included greenhouse gas emissions among the wastewater treatment plant targets (Flores-Alsina et al., 2014, Ogurek et al., 2016). These authors concluded that the optimal way to simulate greenhouse gas emissions from wastewater treatment plants 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). Despite the efforts that have been made at an international level, a simulation platform is lacking for the design and/or the management of wastewater treatment plants for minimising emissions. 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 wastewater treatment plants that use integrated approaches including considerations on the emission of greenhouse gases. Furthermore, an extensive database of greenhouse gas measurements is lacking in terms of the temporal and spatial distributions for encoding the behaviour of greenhouse gases in the yield process and for assessing the temporal variability of the greenhouse gases throughout the year. 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 wastewater treatment plants. Finally, the identification of appropriate mitigation measures, which are based on process control and are aimed at reducing greenhouse gas emissions, is lacking. Furthermore, knowledge gaps are present regarding the contributions of autotrophic and heterotrophic biomass during the formation of greenhouse gas emissions. Very recently, an extensive Italian national project PRIN on greenhouse gas emission from WWTP 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). A German project aimed at modelling GHG emissions from wastewater treatment plants (Ogurek et al., 2016).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 greenhouse gas emissions.

Greenhouse gases from receiving water bodies

The issues raised by greenhouse gas emissions from receiving water bodies have been thoroughly investigated in recent years. Greenhouse gases from RWB are produced by complex biological processes in the water column (Fig. 4). Many efforts have been made by the technical community to accurately budget greenhouse gas emissions from aquatic systems (Beaulieu et al., 2014; Musenze et al., 2014; Chen et al., 2013). Indeed, these studies highlighted the significant impacts of these sources on greenhouse gas emissions and climate change. A recent study reported that river and stream networks may contribute at least 10 percent of the nitrous oxide emissions resulting from anthropogenic activities to the atmosphere (Beaulieu et al; 2011). Beaulieu and co-workers measured the nitrous oxide production rates of 72 streams and found that they were three times greater than the amounts estimated by the Intergovernmental Panel on Climate Change (IPCC, 2014).

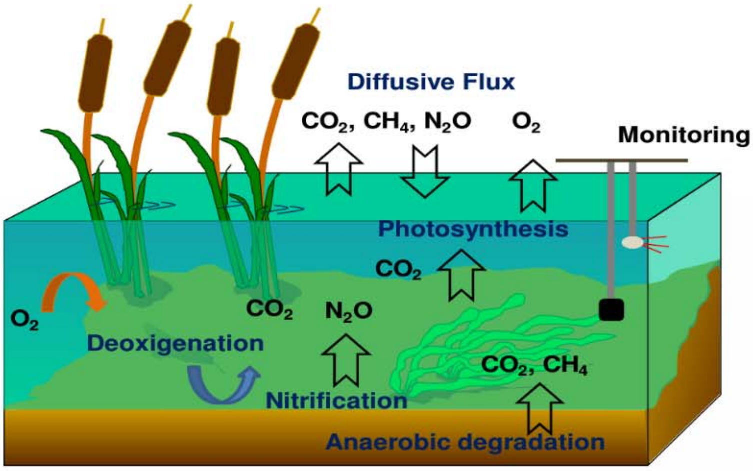

Fig. 4. *Main biological processes in the RWB almost nitrogen-related*

Musenze et al. (2014) reported the results of a two-year field gathering campaign that was conducted in a sub-tropical estuarine system and aimed to quantify CH_4 and N_2O emissions. Musenze and co-workers (2014) found huge spatial and temporal variability in the CH_4 and N_2O emissions that highlighted the uncertainty due to lacking accurate estimation methods for gas transfer velocity, which represents a fundamental parameter for estimating CH_4 and N_2O fluxes from water. Beaulieu et al. (2014) analyzed the nitrous oxide concentrations in the water samples and the nitrous oxide emissions from the water surface by using floating chambers. This research highlighted the need for further research to understand the mechanisms that are responsible for nitrous oxide production in water systems. Specifically, this research focused on the roles of heterotrophic denitrification and chemoautotrophic nitrification, which have not been elucidated. Furthermore, despite strong efforts towards building a consensus for assessing the greenhouse gas status of aquatic systems, many uncertainties remain. These uncertainties mainly result from the lack of standard measurement techniques and standard tools for assessing greenhouse gas 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 greenhouse gas emissions from receiving water bodies (Guo et al., 2012). Despite the developed river water quality model (i.e., RWQM, Rauch et al., 2001) that complements the ASM models that were formerly derived for wastewater treatment plants 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 an holistic approach, where the development of sustainable, climate-proof approaches should not uniquely address the impacts of climate change but also the feedbacks to the climate system and the potential benefits of the climate change mitigation. Next to the process understanding, at the technical level such 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 to derive optimal strategies, fast simulation models are required that describe the essence of the responses and interactions. 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, 2010; 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. describing the greenhouse gas emissions and feedbacks. They moreover allow optimization applications and the derivation of optimal management strategies for our 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 IUDS. The overall idea is to overcome critical issues typical of IUDS modeling. More in details, to model the greenhouse gas 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 the uncertainty basically propagates throughout a chain of sub-models and the use of approaches extremely simplified or detailed can reduce the operator's confidence in the model's robustness (Willems, 2008; Freni et al., 2011). It is thus crucial to have an equal distribution of sub-models complexity (Willems, 2012). Therefore, advanced and innovative methods should be used to build-up and employ the mathematical tools (i.e., global sensitivity analysis, identifiability analysis, uncertainty analysis, mathematical calibration protocols, etc., (Cosenza et al., 2013; Mannina et al., 2011)).

Modelling should be carried-out basing on a two step-procedure: first, an in-depth analysis of the different components should be carried out deriving new detailed mathematical models for simulating each sub-system via existing physical-based literature models which, however, do not fully take into account greenhouse gases (Bach et al., 2014). Therefore, to derive reliable sub-models, knowledge should be exploited from the information derived by experimental activities. The gathered data would allow to gain insights and to encode the phenomena regarding greenhouse gas formation and propagation. Due to their complexity, these new models will not be appropriate for deriving long-term statistical information (Willems, 2006) (useful for mitigation strategies). Thus, the new detailed sub-system models should be simplified by using conceptual simplified mathematical models characterized by a lower number of calibration parameters and limited calculation times. Such simplified models should be derived for each sub-system basing on the detailed mathematical models making optimal use of physical interpretation given to the model structure. Moreover, a screening of the mitigation measures (i.e., best management practices (Freni et al., 2010), 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 about the potential reduction of greenhouse gas emission at microscale/sub-system.

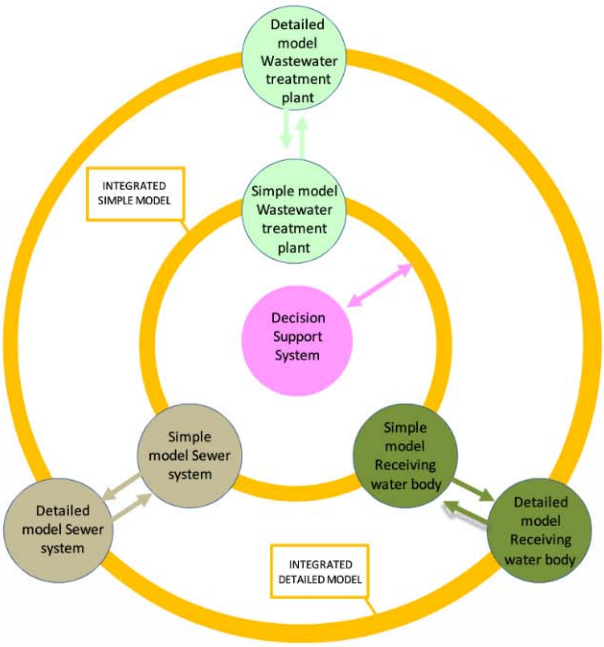

Fig. 5. *Detailed and simplified integrated model layout of the urban drainage system.*

As good modeling strategy, the major goal would be to integrate of the detailed and simplified models already available in literature to create a model (detailed and simplified) that can simulate greenhouse gas 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 the control strategies for integrated urban systems (Fig. 4). To fulfil this goal, the following activities should be performed (some of them already implemented).

(1) Setting-up of the integrated detailed 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 process and interactions. A model connector should be developed to link the detailed models (outer circle of Fig. 4) that should be developed for each sub-system. The integrated detailed model should be calibrated and validated using the dataset that should be collected during field monitoring campaigns.

(2) Setting-up the integrated simplified model. To reduce the computational burden, a simplified integrated model should be developed by investigating the simplified mathematical models that should be developed. With this aim, simple model connectors should be developed to link each sub-model (inner circle of Fig. 4).

(3) Setting-up of the decision support system. The decision support system should be created by using the simplified integrated model. The decision support system should be used for general applications and can be used by researchers and managers to optimise the design and operation of integrated urban drainage systems.

Future Perspectives and Research Needs

The reduction and mitigation of greenhouse gases emissions from integrated urban drainage systems has to be pointed out. To achieve such goals, the following crucial points should be addressed:

- Produce a comprehensive data set on greenhouse gas emissions from integrated urban drainage systems (i.e., sewer systems, wastewater treatment plants and receiving water bodies) and create new methods for assessing this data based on measurement protocols/guidelines.
- Deliver a fundamental understanding of the key processes that are responsible for producing greenhouse gas emissions from integrated urban drainage systems.
- Create mathematical models using data gathered from laboratory experiments and field monitoring to use new tools that are able to quantify the effects of mitigation measures prior to their effective realization by making simulations. The integrated mathematical model will be able to optimize (in terms of greenhouse gas reduction) the entire systems while accounting for any interactions.
- Deliver innovative strategies, scenario analysis and guidelines for reducing greenhouse gas emissions from integrated urban drainage systems by means of also innovative methods. A comparison of alternative scenarios and solutions in terms of overall performance, risk and cost is warmly recommended.

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