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Making waves: Rethinking our mission for N_2O emissions at WRRFs

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ABSTRACT

Nitrous oxide (N_2O) is a potent greenhouse gas with a global warming potential 273 times that of CO_2, and it is a significant contributor to ozone depletion. Water resource recovery facilities (WRRFs) have been identified as a major source of N_2O emissions, leading to significant research and policy efforts to mitigate these emissions. As WRRFs undertake these N_2O mitigation efforts, important questions remain regarding the impact of more intensive nitrogen removal for pollution prevention and public health protection and how reactive nitrogen discharges are emitted as N_2O in receiving waterways. To answer these questions, this perspective highlights the importance of balancing facility-scale emission factors to estimate N_2O emissions from wastewater while considering the impacts of nitrogen if discharged to receiving water bodies. This perspective suggests more comprehensive approaches to manage N_2O emissions, emphasizing the need to account for the reduction in N_2O emissions achieved through nitrogen removal at WRRFs compared to direct discharge into receiving water bodies. By considering the overall impact of nitrogen from wastewater on N_2O emissions from both WRRFs and receiving water bodies, WRRFs can reduce their impact on the environment while maintaining their important role in removing nitrogen from wastewater.

Nitrous oxide emissions from WRRFs

Nitrous oxide (N_2O) is a potent greenhouse gas (GHG) with an atmospheric lifespan over 100 years and a global warming potential 273 times that of CO_2, and is a contributor to ozone depletion (Forster et al., 2021). Since 1980, global N_2O emissions have increased 40 % (Tian et al., 2024), with N_2O concentrations in the atmosphere now higher than at any other time in the last 800,000 years, based on the latest report from the Intergovernmental Panel on Climate Change, IPCC (Gulev et al., 2021). This unprecedented growth is leading to significant research and policy efforts to identify major sources of anthropogenic N_2O emissions and mitigate these emissions as effectively as possible (Tian et al., 2020; Forster et al., 2021; U.S. Department of State, 2023). Water resource recovery facilities (WRRFs) have been identified as an anthropogenic N_2O source, however they accounted for only ~4 % of total US N_2O emissions in 2022 (EPA, 2024). More concerningly, N_2O emissions attributed to domestic wastewater treatment have increased by 66 % since the 1990s, a larger increase on a percentage basis than other key anthropogenic N_2O sources such as agricultural soils and stationary combustion with 0.7 % and 11 % increases over the same time period, respectively (EPA, 2024). N_2O emissions from WRRFs are expected to increase as wastewater management becomes more accessible in developing countries worldwide (Winiwarter et al., 2018) and we improve nitrogen removal from wastewater to protect our waterways. Considering these emission trends, many WRRFs are exploring approaches to mitigate their N_2O emissions.

While the growth in N_2O emissions attributed to WRRFs appears alarming, it is important to consider the main driver behind this growth: the widespread adoption of nitrogen removal practices for pollution prevention and public health protection. N_2O is produced as an unintended by-product of nitrification and denitrification, biological pathways that are key to the removal of reactive nitrogen from wastewater (Duan et al., 2021). As utilities consider expanding their stewardship of water quality and public health to include local and global sustainability, it is important to consider the following questions: does nitrogen removal at WRRFs from wastewater have a net reduction on N_2O

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emissions through better management of anthropogenically produced nitrogen, or do N_2O emissions from WRRFs result in net production of anthropogenic emissions? Beyond the level of nitrogen removal required to maintain receiving water quality, is the additional nitrogen removal justified when considering the associated increase in N_2O emissions from WRRFs? Are we too focused on emissions at the WRRF, when these emissions may reduce overall N_2O emissions when we consider production in the sewer system transporting this wastewater and N_2O production rates in receiving water bodies if we discharged the nitrogen from wastewater? This perspective paper will address these questions by highlighting shortcomings in methods to estimate N_2O emission factors (EFs) from WRRFs, discussing the potential production of N_2O from nitrogen in wastewater if not treated at a WRRF, and providing suggestions to minimize N_2O production from wastewater treatment and associated infrastructure in the watershed.

Beyond wastewater treatment: the complexities of estimating appropriate emissions factors

EFs, expressed as a percentage of N input, serve as a tool to estimate N_2O released to the atmosphere when direct measurement is not feasible. EFs are used as the basis of regional or global estimates of N_2O emissions from anthropogenically produced nitrogen (Tian et al., 2024), but have serious limitations on a facility-scale as noted by De Haas and Andrews (2022) and Song et al. (2024). For example, N_2O emissions from secondary treatment, typically considered the main contributor to wastewater-associated N_2O emissions, are highly dependent on reactor configuration, seasonal shifts in temperatures and flows, and nitrogen speciation (Duan et al., 2021; Hausherr et al., 2022). Other process units such as primary treatment and dewatering also contribute to N_2O emissions, but less data is available to estimate EFs (Song et al., 2024). Moreover, these EFs only consider direct emissions from the WRRFs, excluding indirect N_2O emissions from energy sources (i.e., natural gas and coal combustion) and downstream operations (i.e., biosolids land application) that contribute to the total N_2O emitted during wastewater treatment. These limitations of WRRF-associated EFs lead to a restricted perspective that focuses mainly on secondary treatment in N_2O mitigation research and does not consider the potential of WRRFs to reduce total anthropogenic N_2O emissions.

Rather than limiting our perspective to the current viewpoint, it is crucial to comprehend the broader picture of anthropogenic nitrogen management from wastewater. Consider an important hypothetical scenario: how much N_2O would be emitted if reactive nitrogen was directly discharged to receiving waters? Based on current IPCC guidelines, nitrogen discharged to nutrient-impacted waters (EF = 0.019 kgN_2O kgN^{-1}) would produce approximately 20 % more N_2O than treating the same amount of nitrogen at the WRRF (EF = 0.016 kgN_2O kgN^{-1}) (IPCC, 2019). In this scenario, maximizing nitrogen removal at WRRFs would be a logical step towards reducing net N_2O emissions from human and industrial wastewater, rather than contributing to anthropogenic N_2O emissions at uncontrolled ecosystems in nutrient-impaired water bodies. To better understand overall N_2O emissions, our baseline should be that which results from direct discharge of untreated wastewater into a waterbody. As we achieve more nitrogen removal at the WRRF, the net EF for wastewater would then decrease more for every pound of nitrogen removed at the WRRF. This would be a beneficial approach, even without considering the other immense benefits of nitrogen removal for aquatic ecosystems and public health (Fig. 1).

The reality of estimating N_2O emissions from waterways is more complicated. The potential for effluent nitrogen in inorganic and organic forms to be transformed and subsequently released to the atmosphere as N_2O is highly complex, depending on various factors such as the quality of the receiving water body, organic carbon availability, turbulence and mixing characteristics, seasonal variations, and influence of groundwater (Beaulieu et al., 2011; Yao et al., 2020). Many studies have evaluated N_2O upstream and downstream of WRRFs, generally finding that N_2O concentrations are higher downstream of effluent WRRF discharge than the background concentration upstream (Masuda et al., 2018; Tang et al., 2024). However, as Tang and colleagues noted, the change between downstream and upstream N_2O measurements is highly variable, with the average fold change of downstream to upstream N_2O ranging from 0.59 (i.e., lower N_2O downstream than upstream) up to 374. This does not consider the level of nitrogen removal from the wastewater in the WRRF, and as noted above, the higher the nitrogen

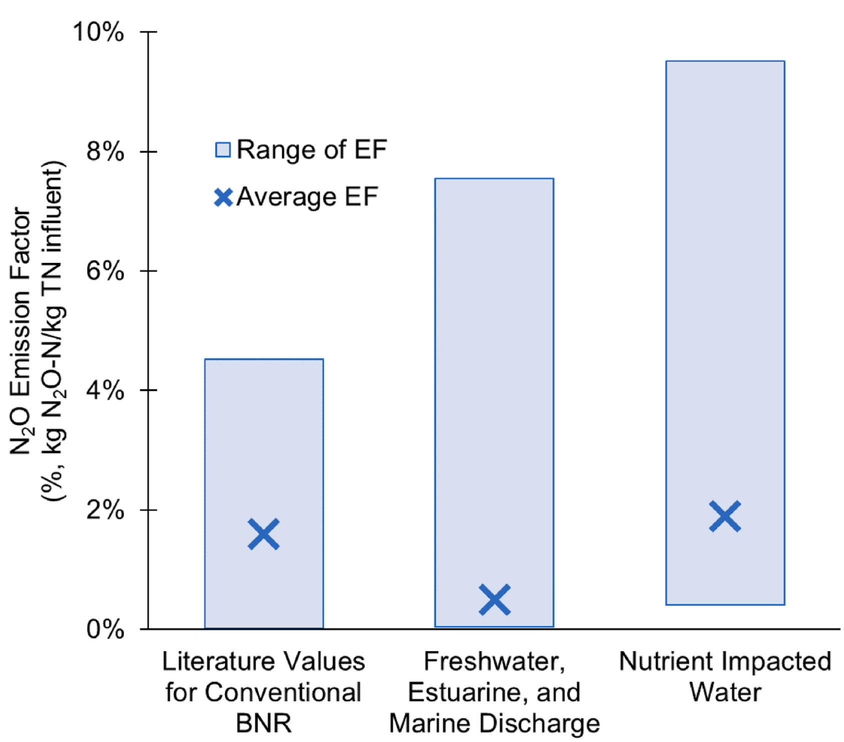

Fig. 1. IPCC guidelines for N_2O emissions from biological nitrogen removal (BNR) at a WRRF versus nitrogen discharged into waterways (IPCC 2019).

removal rate at the WRRF, the lower the expected emissions from the receiving water. Returning to our simple hypothetical scenario, the tradeoffs between maximizing nitrogen removal and minimizing N_2O emissions becomes more complicated if a waterway has significantly lower N_2O EFs compared to a WRRF which discharges to it. However, if all the nitrogen treated by the WRRF was discharged to the waterbody, how much higher would the net EFs become in that system?

Are WRRFs really an anthropogenic source of N_2O?

Estimating N_2O emissions directly produced by WRRFs compared to potential emissions from receiving waters provides perspective on the actual benefits of nitrogen removal for net N_2O emissions. N_2O is an inevitable by-product of the anthropogenic nitrogen cycle, whether at the WRRF or in the receiving body. How we can best control and minimize this N_2O production from this wastewater should be our focus, even if we cannot completely eliminate emissions. This does not imply that the wastewater sector should stop attempting to reduce N_2O emissions. Rather, we should continue long-term investigations into N_2O emissions at the watershed-scale, identify opportunities for co-benefits of N_2O mitigation while removing reactive nitrogen from our receiving water bodies, and utilize N_2O emission data for better process control, optimization, and operation.

One framework to consider wastewater associated N_2O emissions would be to estimate the total N_2O emissions that are produced from the WRRF, the N_2O produced in the receiving water body, and the reactive nitrogen used in the area introduced from anthropogenic activity, and seek to minimize the total N_2O emissions. Implementing this type of regional planning is no small endeavor, particularly considering the N_2O EFs estimating challenges described previously. However, it would bring us closer to our objective of reducing total global anthropogenic N_2O emissions than the current approach, which focuses solely on facility-level emissions. Furthermore, this type of framework would emphasize that human activity is ultimately the source of reactive nitrogen rather than the WRRFs themselves. This shift in our understanding can lead to more ambitious and innovative solutions for reducing total reactive nitrogen loads that end up at the WRRF and increasing the circularity of reactive nitrogen, such as urine source-separation (Hilton et al., 2021).

Whether or not a regional framework exists to manage N_2O emissions, the wastewater industry should continue to identify opportunities to reduce total N_2O emissions that also provide co-benefits for other aspects of WRRF operation. This is particularly important for process units or utility assets beyond the secondary treatment system where N_2O is emitted but has not been the focus of most research. One overlooked but fortuitous example is managing N_2O originating from the wastewater collection system (Fries et al., 2018; Short et al., 2014). In collection systems, N_2O is produced from microbial activity within the sewer itself and could exfiltrate from the sewer to groundwater during periods of no infiltration and inflow. The presence of dissolved N_2O in the collection system can lead to local emissions in the sewer network and downstream emissions at the WRRF (Yuan et al., 2024). In this scenario, reducing biological activity in the sewer and sewer/groundwater interactions would have multiple co-benefits for WRRFs besides N_2O mitigation: better management of the collection system through sewer line cleaning, pipe repair and replacement; decoupling storm sewers from sanitary sewers providing WRRFs with greater hydraulic capacity and reduces chances of flooding or sewer overflows during wet periods; and reduced groundwater contamination during dry periods. Identifying similar opportunities where N_2O can be reduced while achieving multiple shared benefits can help increase adoption and recognition of N_2O mitigation strategies. This example of reducing N_2O production in sewers also highlights challenges of moving beyond facility-level N_2O mitigation, as many utilities do not own the entire collection system within their service area and instead rely on municipalities to maintain local sewers. Quantifying and reducing these emissions would require collaborative monitoring and maintenance efforts at a utility or regional level.

As some N_2O will inevitably be produced at WRRFs, even with the best mitigation strategies, N_2O can also be considered an operational tool rather than simply an undesired output. Long-term monitoring campaigns reveal that N_2O can serve as an indicator of process transitions or upsets and biomass “health.” For instance, Butler et al. (2009) utilized N_2O as a non-invasive early warning indicator for nitrification failure, linking increases in ammonia, DO depletion, pH changes, and toxic shock loads to a rise in N_2O off-gas concentrations. In facilities treating industrial effluents like landfill leachate or pharmaceutical wastewaters, where ammonia levels can be high, N_2O peak warning is even more critical. Recent developments in WRRFs have aimed to leverage the physiological variations within nitrifying bacteria to improve effluent quality while reducing chemical use and aeration energy. A promising approach is the implementation of low DO nitrification, which can effectively cut energy and aeration expenses during secondary treatment while reducing operational costs (Sabba et al., 2024). However, if low DO is implemented suddenly in the process, a spike in N_2O production is likely to occur. Therefore, it is essential to provide the process sufficient time to stabilize, allowing the biomass to gradually adapt and avoid over-production of N_2O (Liu et al., 2021).

Based on the discussion above, tracking N_2O as an early warning indicator and focusing on control strategies to further reduce net anthropogenic emissions from nitrogen should continue. It is worth noting that many WRRFs are already reducing net anthropogenic emission rates (Duan et al., 2020; Unisense, 2022), and we can further enhance this reduction with better process control. Therefore, our industry should take credit for this reduction instead of framing it as a potentially negative impact of WRRFs operation.

Conclusions

- The current approach for estimating N_2O emissions from WRRFs and water bodies with EFs has major limitations. More tailored EFs for WRRFs and natural waters are needed to serve as the basis for informed N_2O mitigation decision-making.
- The wastewater industry should identify new opportunities for N_2O mitigation with co-benefits for other aspects of WRRFs operation, such as managing N_2O originating from the wastewater collection system and utilizing N_2O as a biomonitoring tool.
- Regardless of uncertainties in estimating N_2O emissions, WRRFs still provide a net benefit by preventing nutrient pollution and further impairing water bodies, and many WRRFs are taking active steps to reduce their N_2O emissions. The wastewater industry should take credit for this reduction instead of framing N_2O emission as a potentially negative impact of WRRF operation.

CRediT authorship contribution statement

Leon Downing: Writing – original draft, Visualization, Supervision, Project administration, Conceptualization. **McKenna Farmer:** Writing – review & editing, Writing – original draft, Conceptualization. **Bishav Bhattarai:** Writing – review & editing, Visualization, Data curation. **Michael Penn:** Writing – review & editing, Methodology, Conceptualization. **Joseph Kozak:** Writing – review & editing, Validation. **Jonathan Grabowy:** Writing – review & editing, Conceptualization. **Fabrizio Sabba:** Writing – review & editing, Writing – original draft, Visualization, Validation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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