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Global Perspective

Toward Enhancing Wastewater Treatment with Resource Recovery in Integrated Assessment and Computable General Equilibrium Models

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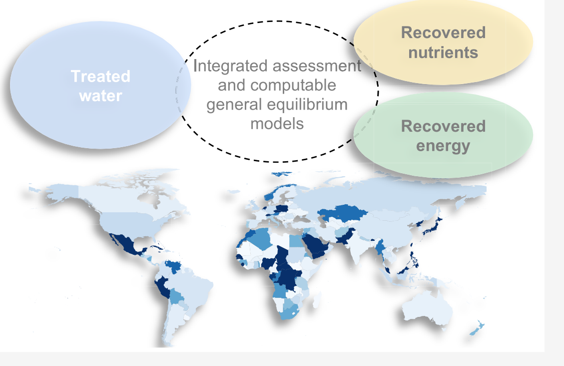

ABSTRACT: Sustainable water management is essential to increasing water availability and decreasing water pollution. The wastewater sector is expanding globally and beginning to incorporate technologies that recover nutrients from wastewater. Nutrient recovery increases energy consumption but may reduce the demand for nutrients from virgin sources. We estimate the increase in annual global energy consumption (1,100 million GJ) and greenhouse gas emissions (84 million t CO_2e) for wastewater treatment in the year 2030 compared to today's levels to meet sustainable development goals. To capture these trends, integrated assessment and computable general equilibrium models that address the energy-water nexus must evolve. We reviewed 16 of these models to assess how well they capture wastewater treatment plant energy consumption and GHG emissions. Only three models include biogas production from the wastewater organic content. Four explicitly represent energy demand for wastewater treatment, and eight include explicit representation of wastewater treatment plant greenhouse gas emissions. Of those eight models, six models quantify methane emissions from treatment, five include representation of emissions of nitrous oxide, and two include representation of emissions of carbon dioxide. Our review concludes with proposals to improve these models to better capture the energy-water nexus associated with the evolving wastewater treatment sector.

KEYWORDS: *water, climate change, nutrient recovery, energy, systems modeling*

1. INTRODUCTION

Numerous analyses have characterized present and future water scarcity, with an emphasis on urban populations.[1,2] Recently, He et al.[3] estimated that 933 million (or 32.5%) of global urban residents experienced water scarcity in 2016. They project that, depending on technical, policy, and social factors, urban residents that experience water scarcity could reach between 1.7 billion and 2.4 billion in 2050.

Recognizing these challenges and that access to clean water is an essential human right, the United Nation's (UN) Sustainable Development Goal (SDG) 6 addresses the need to sustainably manage water and sanitation.[4] Achieving this aim, however, will increase the energy consumed in the water sector.[5] It will require building new wastewater treatment plants (WWTP) that will need to achieve increasingly stringent effluent and drinking water standards. The water sector is already a major energy consumer and source of greenhouse gas (GHG) emissions (Table S1) at levels similar to fertilizer manufacturing[6] and aviation.[7] Per capita emissions vary among regions because of various levels and types of technologies in use, the percent of wastewater treated, and the composition of the electric grid (Table S1). U.S. per capita emissions for the wastewater sector are 0.09 t of CO_2e. This level is 30% greater than European Union (EU) per capita emissions for the wastewater sector and double that of Tunisia's, an exemplar developing country.

Notably, exceedances of water quality thresholds for total dissolved solids, biological oxygen demand, and chemical oxygen demand occur frequently and globally.[8] Furthermore, regions and nations including the EU and the U.S. are considering and advancing policies and regulations that will require lower nutrient (nitrogen and phosphorus) concentrations in WWTP effluents.[9,10] Without intervention,

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addressing the need for more extensive wastewater treatment to address these challenges will increase WWTP energy consumption and GHG emissions.

Identifying technology to achieve lower amounts of nutrients and pollutants in treated wastewater while limiting energy consumption and GHG emissions from WWTP is essential, given the urgency of the climate crisis. In fact, it is possible (and likely to be required in the EU) that, through adjusting operational strategies and adopting new technologies such as anaerobic digestion (AD) with biogas capture and use, WWTP become energy producers.[11] Moreover, recovered nutrients from WWTP can be used as fertilizers or as feedstocks for chemicals or other value-added products that could displace conventional fossil-fuel-based supply chains for these products.

Integrated assessment and computable general equilibrium models (IAM, CGE) are valuable tools that can evaluate the effects of WWTP growth as an energy consumer and GHG emissions source and its interlinkages with energy systems and the chemical and agricultural sectors. Applying these models could help spur the WWTP sector to grow and change in ways that reduce its energy and environmental effects while providing clean water and sanitation. In particular, they can help identify viable and impactful strategies to achieving water-related SDG targets including target 6.3: "By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally."[4]

To explore this application of IAMs and CGEs, we first (Section 2) summarize energy consumption and GHG emissions from WWTPs and how these effects might change in the future, given social and technical drivers. Next, we describe the state of the art of IAMs and CGEs in addressing the WWTP sector (Section 3) and then conclude (Section 4) with recommendations for further development of these models to address tightening standards for WWTP effluent streams, advances in technology, the effects of climate change, and the influence of increasing urbanization.

2. CURRENT AND FUTURE STATUS OF THE WWTP SECTOR

2.1. WWTP State of Technology, Energy Consumption, and Emissions. Wastewater treatment plants typically include primary and secondary treatment steps, followed by disinfection prior to releasing treated water.[10] These treatment trains are summarized in the Supporting Information, Section 1. The combination and order of treatment steps, however, vary from plant-to-plant. Determining the energy consumption and GHG emissions of WWTPs requires overcoming two challenges. First, given the diversity of WWTP configurations, adopting a one-size-fits-all number belies the range of GHG emissions from these facilities. Second, WWTPs also include multiple direct sources of non-CO_2 GHGs emissions such as from anaerobic digesters (Figure S1).[12] Yet, estimating these emissions is challenging because these emissions can vary widely[13,14] and may be underestimated.[15]

2.2. The Wastewater Sector Will Grow in Importance and in Energy Consumption. Currently, global annual wastewater production has reached approximately 360 billion m^3.[16] High-income countries, home to only 16% of the world's population, produce 41% of this wastewater. Only about half of wastewater is treated, and 40 billion $m^3\ yr^{-1}$ is reused, notably in the Middle East, North Africa, and Western Europe.

Undoubtedly, as less-developed world regions urbanize and expand wastewater generation (e.g., from increased use of wastewater-generating appliances), the wastewater sector will grow in importance as an energy consumer. Tightening water purity standards[8] and the effects of climate change and mitigating water scarcity[5] will likely drive up energy consumption as well.

Several studies have evaluated the influence of these changes. For example, van Vliet et al. evaluated the ability of treated wastewater reuse to reduce water scarcity on a regional basis.[17] Their analysis, however, did not account for the increased amounts of energy consumption and GHG emissions that additional treatment for reuse would entail. Kyle et al. evaluated the additional amount of energy that would be consumed to increase the volumes of wastewater treated but do not account for non-CO_2 GHGs or differences among regions in wastewater treatment technology.[5] Neither study accounted for the potential of new wastewater technology to improve water quality, recover nutrients, and to change—hopefully reduce—the amount of energy consumed to treat wastewater.

To begin to develop a holistic assessment of how future demands and technologies will influence global energy consumption and GHG emissions from this sector, it is important to assess regional differences in wastewater treatment technology and effluent standards. Moreover, it is important to consider how technology in the wastewater treatment sector is evolving and may allow developing regions to "leapfrog" energy- and emissions-intensive technologies that are used today.

2.2.1. Regional Wastewater Treatment Standards. Nations and regions take different approaches to WWTP effluent requirements and how they are dictated or enforced (Supplementary Table 2). Our discussion addresses major global economies given their outsized influence on the sector along with an exemplar developing country, Tunisia, that has documented water quality regulations, including for reuse. For example, while the U.S. Environmental Protection Agency (EPA) sets national standards, authorized states can administer their own programs that may place more stringent requirements on WWTP. China requires different treatment standards depending on the type of water that will receive the WWTP effluent. E.U. member states develop country-specific approaches to meeting the requirements of water-related directives. Tunisia's water code includes water quality standards for reuse[18] and wastewater disposal standards in receiving waters.[19] Overall, the aim of setting and enforcing standards is to protect the water quality and human health.

There are many indications that the energy consumption (Supplementary Table 1) of the WWTP sector will increase. For example, the U.S. is exploring introducing standards for nitrogen levels in effluent that will increase energy consumption and GHG emissions at WWTP.[10] In the EU, proposed revisions[9] to the Urban Wastewater Treatment Directive are putting forward more stringent effluent standard for nitrogen and phosphorus. At the same time, efforts in the EU aim to decrease energy consumption in WWTP. The Energy Efficiency Directive requires Member States to carry out energy audits at WWTP and evaluate opportunities to reduce energy consumption without compromising the quality of the treatment, and the proposed revisions to the Urban

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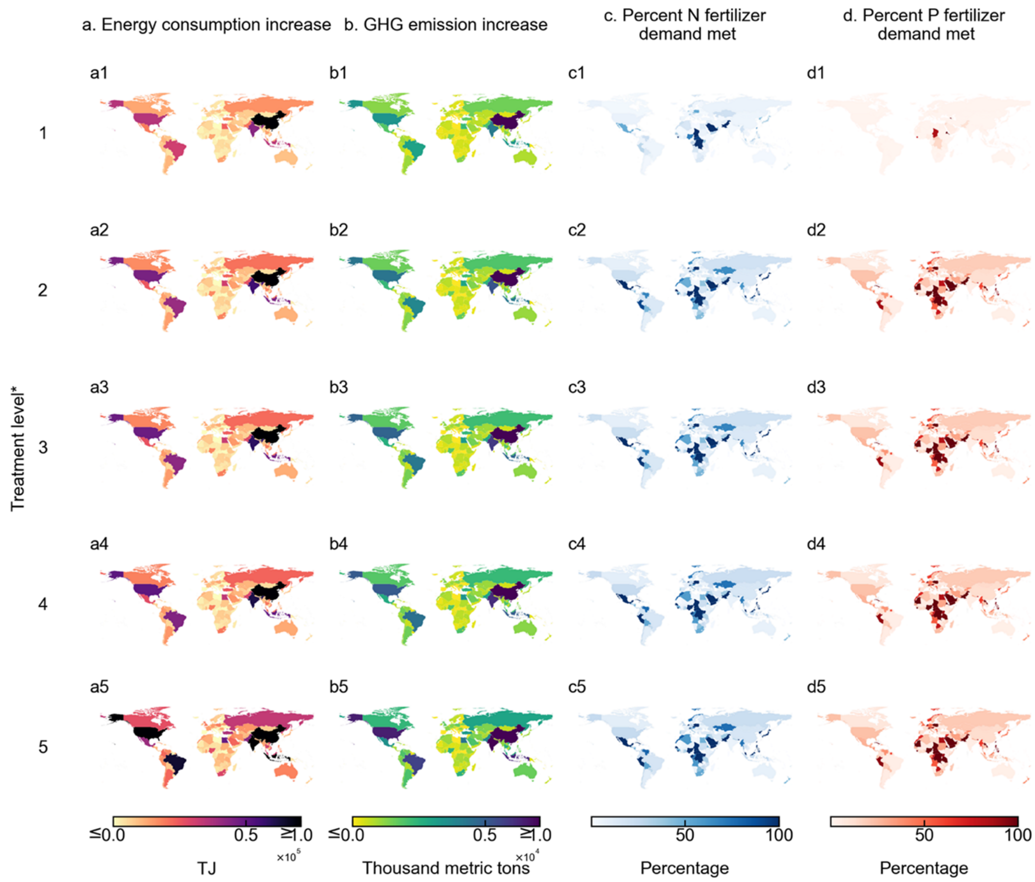

Figure 1. Estimated changes in energy consumption (panel a), GHG emissions (panel b), percent of national N recovery (panel c), and percent of national P (as P_2O_5) recovery (panel d) of achieving SDG 6.3 at five levels of nutrient recovery (Supplementary Table 3).

Wastewater Treatment Directive require WWTPs to produce enough energy from biogas to operate without use of externally provided heat or power. In addition, the European directive on the reuse of water[20] targets direct use of WWTP effluent for irrigation and other uses basing water quality requirements[21] on international collaborations[22] to standardize the water sector. These efforts are critical for irrigated crops that are sold internationally.

In China, the municipal wastewater treatment fleet has grown significantly over the past 40 years. Between 2017 and 2019 alone, the number of WWTP grew from 1,096 to 5,333.[23] China has the world's largest wastewater treatment capacity at around 200 million m^3/day.[24] The rapid growth in capacity of China's wastewater treatment sector caused treatment standards and technologies to lag behind for some time. As standards and technology catch up to capacity, energy consumption associated with wastewater treatment is expected to increase, although efforts to increase energy efficiency and resource recovery may temper the rise in energy consumption.

In Tunisia, the number of WWTPs increased from 60 to 123 between 2000 and 2020.[25] Even though WWTPs treated around 290×10^6 m^3 wastewater in 2020 (99% of wastewater volume collected by the sewage system), 80% of this treated wastewater ended up in water bodies.[26] Meanwhile, only 25 plants of 123 employ tertiary treatment. The others only eliminate organic pollution. Moreover, the average concentration of biological oxygen demand exceeded the 30 mg/L limit for over half of WWTPs.[26]

3. INFLUENCE OF SDG 6.3 ON ENERGY CONSUMPTION AT WWTP AND POTENTIAL FOR NUTRIENT RECOVERY

Jones et al.[8] estimated increased volumes of WWTP required to meet SDG 6.3. As described in Supporting Information Section 3, we build on those estimates for years 2023 and 2030 to quantify the increased energy consumption and GHG emissions associated with meeting this SDG along with considering how nutrient recovery at five levels (Supplementary Table 3) might meet nitrogen and phosphorus fertilizer demand. Figure 1 displays the results of our analysis.

Energy consumption globally for wastewater treatment grows by between 350,000 and 1,480,000 TJ between 2023 and 2030 if wastewater treatment expanded to meet SDG6.3 targets. The countries exhibiting the greatest increases in energy consumption are China and India. The U.S., however, also exhibits a rise in energy consumption of between 25,000 and 107,000 TJ. Correspondingly, GHG emissions rise between 32,000 and 116,000 thousand t CO_2e. Encouragingly, however, the potential for nutrient recovery is high when technologies are in place to extract these valuable resources from wastewater. Increased energy and GHG emissions associated with incorporating more technologies for nutrient recovery have a payoff, however, in increased nutrient recovery. Notably, many African nations may be able to meet a large share (approaching 100%) of their nutrient demand through recovering N and P from WWTPs at level 5. Without nutrient recovery targets (Level 1), the ability to meet national nutrient demand from WWTP is minimal (Figure 1c and d, level 1).

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Ideally, IAMs and CGEs would capture the interplay between the WW sector and other sectors that use nutrients, in particular agriculture, to help assess the trade-offs between the energy and GHG cost of nutrient recovery with potentially decreased demand for nutrient manufacturing (e.g., the high-emitting Haber−Bosch process for ammonia).

4. STATE OF THE ART IN IAM AND CGE MODELING OF THE WASTEWATER SECTOR

The representation of the wastewater treatment sector in 17 existing models was investigated (see the acronym table for an explanation of model names). Of the 17 models considered, Table 1 summarizes the 11 that addressed the WWTP sector in some detail. Of the 17, only three models included biogas production from wastewater organic content. Four models explicitly included representations of energy demand for wastewater treatment, and eight models included explicit representation of the on-site GHG emissions produced by wastewater treatment. Of these eight models, six include representation of methane emissions from treatment, five models include representation of emissions of nitrous oxide, and two models include representation of emissions of carbon dioxide. The following models were investigated but did not explicitly include any of the categories of interest for the wastewater treatment sector, and so are not included in Table 1: E3ME, IGSM, IMAGE, AIM, EUCalc, and REMIND-MAGPIE.

Table 1. Summary of WWTP Treatment in IAMs and CGEs

Model	Energy Demand of WWTP Included	WWTP Biogas Production Included	GHG Emissions of WWTP Included
ANEMI[27]	Y	Y	N
COFFEE[28,29]	N	N	Y (CO_2, CH_4, N_2O)
GAINS[30]	N	Y	Y (CH_4, N_2O)
GCAM[5]	Y	N	Y
MESSAGEix-GLOBIOM[31]	Y	N	Y (CH_4, N_2O)
POLES-JRC[32,33]	N	N	Y (CH_4, N_2O)
WITCH[34,35]	N	N	Y
BET-GLUE[6,7]	N	Y	N
BLUES (Brazil)[36,37]	Y	N	Y (CO_2, CH_4, N_2O)
GEM-E3[38,39]	N	N	Y (CH_4)
IGEM[40]	Y	N	Y (CO_2)

In the following sections, we summarize how five of these models (GAINS, GCAM, MESSAGEix-GLOBIOM, IGEM, and BLUES) estimate activity associated with the wastewater treatment sector which dictates the volume of water that must be treated, quantify energy consumption at WWTP, and quantify GHG emissions from these facilities as applicable. Two additional models, the Intertemporal General Equilibrium System (ICES), which is of note given its detailed treatment of Tunisia as a developing country that is expanding its WWTP sector, and the Global Trade Analysis Project − Agriculture Water (GTAP-AW) model, are described in Supplementary Section 4.

4.1. Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS). *Background.* The Greenhouse gas and Air Pollution Interactions and Synergies (GAINS) model explores cost-effective strategies to simultaneously reduce emissions of air pollutants and GHGs to meet specified environmental targets.[41]

Activity Data. The model includes domestic wastewater and industrial wastewater from manufacturing industries (food and beverage, pulp and paper, and other manufacturing industries with high organic load). The activity data used for estimation of methane emissions from domestic wastewater are the number of people connected to centralized or decentralized collection of wastewater. This essentially refers to wastewater from urban and rural populations, except for most industrialized countries where wastewater collection services often include some rural areas as well.

Energy Consumption Approach. The GAINS model does not currently account for energy consumption at WWTP.

GHG Emissions Estimation Approach. The GAINS model does not estimate CO_2 emissions because it does not include energy consumption at WWTP or emissions of non-combustion CO_2 from degradation of compounds in wastewater. The activity data to derive methane emissions from industrial wastewater is the amount of chemical oxygen demand content in untreated wastewater derived from combining data on production volumes, wastewater generated, and COD generation factors. Methane emission factors are derived following the Intergovernmental Panel on Climate Change guidelines (2006, Vol. 5, eqs 6.1 to 6.3). Treatment technologies applied to domestic and industrial wastewater are incorporated from scientific articles, UN and EU statistics and other country-level information.[42]

4.2. Global Change Analysis Model (GCAM). *Background.* GCAM is an open-source equilibrium model that evaluates connections among energy, water, land, climate, and economic systems between 1990 and 2100.

Activity Data. The quantity of wastewater treated in each region (global) is estimated from the total municipal and industrial water withdrawals minus consumptive use and multiplied by an exogenous fraction of wastewater that is assumed to be treated in treatment plants. Municipal water withdrawals are from AQUASTAT, and the portion that is consumed is from Shiklomanov (2000).[43] Industrial water withdrawals are estimated bottom-up with reference to AQUASTAT;[44] the values from AQUASTAT include the electric power sector, so are not usable as-is. The portion of manufacturing water consumed is from Vassolo and Doll (2005).[45] The share treated in the base year comes from Liu et al. 2016,[46] and is increased over time as a function of per-capita gross domestic product; the relationship between the two is based on the country-level data set in Liu et al. 2016.

Energy Consumption Approach. The energy requirements are indicated as electricity requirements per unit of wastewater treated. The energy intensities are from Liu et al. 2016,[46] and are not varied by region or over time.

GHG Emissions Estimation Approach. The model contains a full representation of the energy system, so the CO_2 emissions from wastewater treatment are all in the upstream sectors (electricity and the production of the fuels used to generate electricity). The energy intensities of wastewater treatment are differentiated between municipal and industrial sectors. They are constant over time.

CH_4 and N_2O emissions are taken from the Community Emissions Data System inventory[47] in the base year. At present, this inventory does not disaggregate emissions from treatment plants as opposed to septic tanks, pit latrines, etc. As

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such, the GHG emissions in the model are driven by the population and not by the wastewater treatment sector. The emission factors (e.g., kg of CH_4 per capita per year) are held constant over time, with the exception that exogenous US EPA marginal abatement cost curves are used. These curves describe the reduction in emission factors as a function of CO_2 prices over time; as many regions have zero-cost abatement, some degree of abatement is seen in the reference scenarios.

4.3. Israeli General Equilibrium Model (IGEM). *Background.* IGEM is a CGE-type model for the entire Israeli economy with representation for multiple water types, characterized by different qualities. It is a structural, real, static model of a small open economy with five sectors, natural freshwater, desalinated freshwater, brackish water, secondary- and tertiary-treated wastewater, five energy commodities, 14 other commodities, government, an investment agent, a foreign agent, and a single representative household. In the IGEM, water sectors are conceptualized as distinct industries. The different qualities characterizing the five water types, which account for constraints associated with crop salinity-tolerance and food-safety regulations, are reflected in the model by the constant elasticity of substitution (CES) rates between different irrigation water types (Supplementary Figure 2).

Activity Data. Introducing marginal water sources into IGEM required adjustment of the social accounting matrix (SAM) − a multisector data set, recording and combining the transactions between different industries, consumers, and government agents. The SAM for the Israeli economy represents the year 2004 and contains information on 18 sectors of the economy, including the water sector. The water sector in the SAM aggregates information on the value of water sales to the remaining 17 sectors, households, government, water import and export, and the value of the input factors purchased by the water sector from the other activities. To adjust the SAM, we divided and allocated the aggregated data for the water sector across the various water types based on the Satellite Account of Water in Israel.[48] This report contains a comprehensive nationwide characterization of the economic value of the flows of different types of water across the economic sectors. In addition, the characterization of the inputs used for the production of the different water types was performed based on Dreizin et al. (2008)[49] and Israeli Water Authority (2011).[50] This includes the assessment of the values of production factors such as energy and labor as well as the values of inputs purchased from other economic sectors for the purpose of desalination and purification of effluents.

Energy Consumption Approach. The energy consumption patterns for water industries are governed by the general functional form specified in the model. Importantly, the relative energy intensity of these sectors is embedded in the underlying database.[51]

GHG Emissions Estimation Approach. The model incorporates energy-related greenhouse gas (mainly CO_2) emissions but not on-site emissions at the WWTP.

4.4. Brazilian Land-Use and Energy Systems (BLUES). *Background.* The Brazilian Land-Use and Energy Systems model (BLUES) is a perfect foresight and mixed-integer linear optimization model, with analysis available up to 2060. It minimizes the total cost of expanding the energy system to meet the expected demand for energy and land use systems.[52−55] This IAM national model represents Brazil in five macroregions and the whole of Brazil. BLUES has been developed to increasingly incorporate new key elements for understanding the possible futures of Brazilian energy demand and supply and land use change, assuming different combinations of mitigation policies or impacts of climate change. Moreover, the model considers environmental constraints such as low carbon economy, air pollution limits, and water security issues.[56,57]

The water resources module contains endogenous and exogenous data. The municipal drinking water (urban and rural users) and its effluents are exogenous data in the model. BLUES built this sector on the national historical data from Brazil's National Sanitation Information System.[58] Future projections are based on the gross domestic product trajectory. Urban water coefficients account for the total supply service, meaning water demand for the urban population and water losses in the distribution. Losses by drinking water distribution are significant in Brazil, around 40% of losses before reaching homes.[58] On the other hand, sewage can be sent to a WWTP or go directly to a waterbody receptor. Then, BLUES calculates the water consumption coefficient as the sum of the average population consumption (20% of demand water) and the amount of domestic effluents without treatment that go directly to a waterbody receptor. All of these data are detailed by region/basin spatial scale identified in BLUES.

Energy Consumption Approach. BLUES considers historical electricity consumption data exogenously from SNISS data (2022) on a national scale.

GHG Emissions Estimation Approach. GHG (CO_2, CH_4, and N_2O) emissions are also exogenous data and are considered at a national scale. They are calculated from historical municipal WWTP emissions.[59] Brazilian wastewater emissions accounted for around 25% of the waste sector emissions by 2020.[60] The GHG emissions are correlated with the population and the treatment routes adopted (or not adopted in the case of uncollected sewage).

Furthermore, BLUES considers future projections of GHG emission and electricity consumption by wastewater treatment technologies based on national studies and the marginal abatement cost curves of Harmsen et al.[61] In Brazil, 43% of the population has collected and treated sewage.[62] This statistic suggests that the WWTPs' capacity will be in constant growth, in which treatment methods must go hand in hand with GHG mitigation measures and reductions in energy consumption. Improvements in the BLUES model seek to link the volume of sewage treated with the technologies identified in BLUES.

4.5. MESSAGEix-GLOBIOM.[31,63] *Background.* The MESSAGEix-GLOBIOM framework is an IAM that evaluates the interconnected global systems of energy, agriculture, land use, climate, and economy, optimizing total system costs across sectors to guide sustainable transition and socioeconomic development.[64] The nexus module within this framework provides a detailed representation of energy, land use, and water requirements, incorporating spatially and temporally explicit climate impact constraints and water allocation algorithms to simulate the complex interlinkages and feedbacks across these sectors.[63]

Activity Data. In MESSAGEix-GLOBIOM, wastewater treatment rates are calculated using historical estimates of the population with access to sanitation and connected infrastructure facilities in urban and rural areas in conjunction with projections of per capita income, governance, and water stress in various regions for various shared socioeconomic pathways at the grid level. The geographical resolution of these

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estimates is then altered to meet the requirements of the water basins. The model receives wastewater collection as an exogenous demand, which is determined as the treatment rate of urban and rural return flows. Although there are several wastewater treatment technologies, the model is parametrized to fulfill potable criteria for a typical secondary-level treatment plant found in a midsized city for urban system and a common septic tank for rural systems. Using estimated recycling penetration rates, the maximum available wastewater reuse per time and basin is determined as the intake to wastewater treatment facilities. The decision to use wastewater as a water source is influenced by the related capital costs and energy footprints of the wastewater treatment procedures.

Energy Consumption Approach. Estimates of energy consumption at WWTP are from Liu et al. (2016).[46]

GHG Emissions Estimation Approach. Emissions stemming from providing energy to WWTP (e.g., from electricity or natural gas systems) are tracked in the energy sector, where the total energy consumed within the wastewater system is computed as a model output. The optimization framework accounts for energy use in water infrastructure estimates, thus connecting the water and energy sectors. MESSAGE's initial energy needs are top-down forecasts that incorporate the water sector and are calibrated using estimated historical water infrastructure capacity and expected energy intensities. This integrated approach ensures a precise quantification of emissions, including CO_2 from fossil fuels and biomass, with the MESSAGE model's detailed representation of energy-related emissions and mitigation strategies, as well as non-CO_2 GHGs from various sources.[64]

IAMs and CGEs represent the wastewater treatment sector with widely varying levels of detail. We have identified several areas that need improvement. These advances will enable these models to guide the development of new technologies that will best reduce the energy consumption and GHG emission from wastewater treatment.

First, there is a need to understand the influence of *activity data* methodology on the modeling results. In the models we surveyed, activity data was either based on population connected to wastewater infrastructure or on top-down data regarding water use in a country or region with assumptions made about how much of that water was treated. One potential weakness of the population-based approach is that per capita water consumption, which is directly related to wastewater treatment volumes, varies regionally and changes over time.[65] For example, between 1985 and 2010, water consumption per person increased by between 90 and 300 L/day in Louisiana and South Carolina but decreased by this same range in Utah and Colorado. Recent efforts[66] to develop highly spatially resolved estimates of wastewater generation still use national statistics at their core or use private databases and data that are several years old.[17] Use of top-down data can require many high-level assumptions. For example, Liu et al. (2016)[46] assume that the ratio of withdrawn water to treated water is identical across sectors (e.g., industrial and municipal).

Second, the energy consumption associated with WWTP in IAMs must be included and updated to capture a range of technologies that recover nutrients and energy from wastewater. This type of expansion would permit a deep analysis of the trade-offs between increased energy expenditure to recover nutrients and energy and ripple effects on markets and industries that would be affected by increased recovery of nutrients (e.g., fertilizer manufacturing, agriculture). Furthermore, the potential of WWTP to produce more energy than they consume could allow for more low-carbon electricity on the grid to power electric vehicles or any number of technologies that achieve only greenhouse gas reductions when the grid is decarbonized (e.g., green hydrogen). Several models rely on the compilation of energy consumption in Liu et al. 2016.[46] This analysis used a robust compilation of data from high-quality data sources, but the most recent data source employed in the analysis is from 2015. The wastewater sector does not necessarily experience dramatic changes in technology, but re-evaluation of the energy intensity of processes used in the sector deserves revisiting at least every decade. Furthermore, the diversity of technologies in use at WWTP and the associated variations in energy consumption and emissions[13,14,67] merit a close look at how these technologies are modeled in IAMs. It is important to note that climate conditions affect direct emissions of CH_4 and N_2O at WWTP and the combined effects of technology advances and climate change on WWTP emissions should be investigated in tandem. Several recent inventories of the wastewater sector could be used to update energy intensity for the United States, for example.[67] A review of WWTP technologies in use around the globe will also be important to inform IAMs.

Box 1. Key Messages

The wastewater treatment sector is an important and growing source of greenhouse gas emissions and energy consumption as effluent standards tighten and more wastewater is treated globally.

Opportunities exist to increase recovery of nutrients and energy from wastewater, which could reduce energy consumption and greenhouse gas emissions in other sectors, including energy and agriculture.

Economic and integrated assessment models can help technology developers and policy makers identify strategies to pursue these opportunities by capturing the interlinkages between wastewater and other sectors.

The modeling community should collaborate to enhance and refine economic and integrated assessment models, boosting their ability to aid decision making and precipitating a decline in energy consumption and greenhouse gas emissions in these interlinked sectors.

Finally, IAMs and CGEs can explore the environmental implications of not treating additional wastewater as water scarcity rises, untreated wastewater continues to emit methane and nitrous oxide, and societies grapple with substandard water quality. Moreover, these models are ideal tools to probe the benefits of water reuse in communities or industrial processes rather than release to surface or groundwater. Additionally, they can evaluate the macroeconomic implications of increased amounts and stringency of wastewater treatment, including the effect on prices, production activities, and households' expenditure and welfare.

To achieve these goals, continued investments in enhancing baseline data for water consumption, wastewater production, and wastewater treatment in these models is essential. For example, to improve water consumption estimates, models could calculate water consumption in domestic buildings based on appliance inventories and standard assumptions about levels of water consumed in appliances like dishwashers. In addition, advancing modeling techniques, in particular,

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characterization of the physical and economic interlinkages among sectors that consume water and generate wastewater, is critical. Together, the modeling and water technology development communities can build and expand modeling tools to guide policy and research and development investments toward more sustainable use and treatment of wastewater (Box 1).

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.4c00280.

> Wastewater sector characteristics for selected countries and regions, a description of wastewater treatment plant technology, methods for modeling results in Figure 1, and information about selected additional models (PDF)

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Notes

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ABBREVIATIONS

AIM	Asia Pacific Integrated Model
ANEMI	ANEMI is not an acronym but a name
BET-GLUE	Basic Energy Systems, Economy, Environment, and End-use Technology − Global land use and energy
BLUES	Brazilian Land-Use and Energy Systems Model
CES	Constant Elasticity of Substitution
CGE	Computable general equilibrium
COFFEE	Computable Framework for Energy and the Environment
E3ME	Energy-Environment-Economy Macro-Econometric Model
EPA	Environmental Protection Agency
EU	European Union
EUCalc	European-Calculator
FAO	Food and Agriculture Organization
GCAM	Global Change Analysis Model
GAINS	Greenhouse gas and Air Pollution Interactions and Synergies
GEM-E3	Global Equilibrium Model- Energy-Environment-Economy
IAM	Integrated assessment model
IGEM	Israeli General Equilibrium model
IGSM	Integrated Global System Modeling
IMAGE	Integrated Model to Assess the Global Environment
MESSAGE-GLOBIOM	Model for Energy Supply Systems and their General Environmental Impact − Global Biosphere Management
POLES-JRC	Prospective Outlook on Long-term Energy Systems − Joint Research Center

REMIND-MAGPIE	REgional Model of Investment and Development- Model of Agricultural Production and its Impact on the Environment
SAM	Social accounting matrix
SDG	Sustainable development goal
UN	United Nations
WITCH	World Induced Technical Change Hybrid
WWTP	Wastewater treatment plant

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