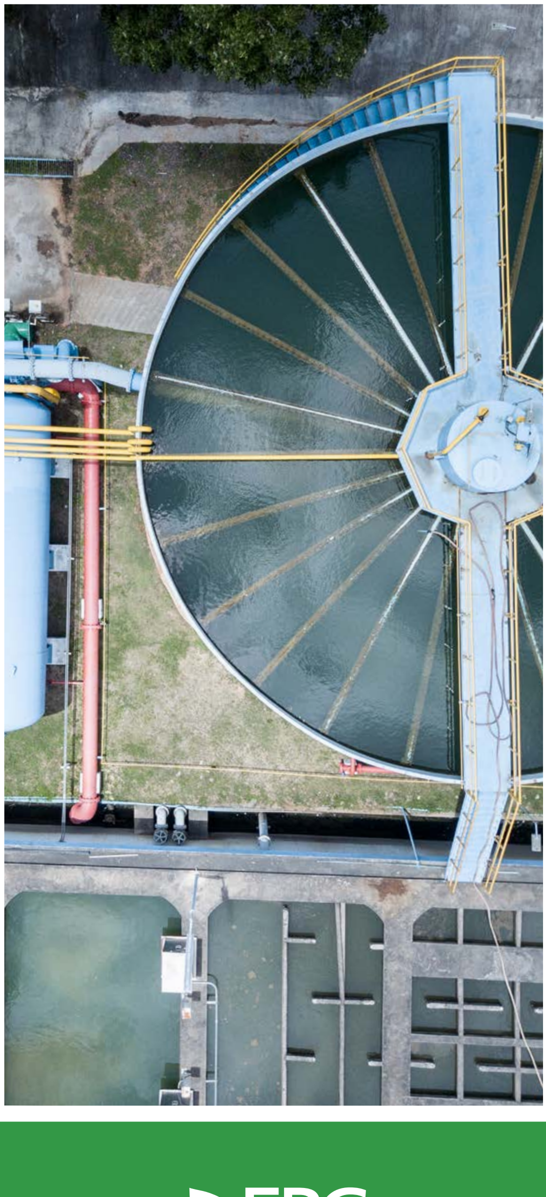
Assessment of Current and Future Sewage Management: Opportunities for Changes in Greenhouse Gases and Other Impacts



ERG

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Abstract

The United Nations Sustainable Development Goal (SDG) 6 seeks to provide access to adequate and equitable sanitation and hygiene for all, with an end to open defecation, by 2030. To achieve this goal, decision-makers may consider a range of sewage management approaches. Each of these approaches have trade-offs related to public health and safety, climate change, and other environmental impacts. It is important to understand and balance these trade-offs when evaluating future plans for sewage management infrastructure; once these infrastructure decisions are adopted, they are often long-lived.

By using existing data together in a new modeling framework, this study assessed the potential environmental impact from ten different sewage management pathways. These pathways are either currently implemented or emerging solutions, and include open defection, pit latrines (dry and wet, and unlined and lined), septic systems, container-based sanitation, and sewered systems (with levels of treatment varying from none to tertiary treatment). The assessment took a life cycle perspective and incorporated all stages from collection through storage, transport, treatment (of both liquid and solid streams if applicable), and eventual discharge to the environment (land or water). The model uses the highest geographic resolution where possible, and results are aggregated based on United Nations SDG Regions and World Bank income levels, with results being further aggregated to global averages. Results are presented for seven different environmental metrics, but the assessment focused on greenhouse gas (GHG) emissions resulting from the sewage management, given the current research and policy focus on GHG emissions. Other local and regional environmental impacts such as eutrophication and particulate matter formation were integrated to understand the potential tradeoffs between different impact categories.

Results indicate that some of the poorer-performing (e.g., higher GHG emitting and nutrient discharging) sewage management types are latrines, open sewers, and (for certain impact categories) primary wastewater treatment. Some of the better-performing (e.g., lower GHG emitting) management archetypes are container-based systems and advanced (secondary and tertiary) wastewater treatment. While primary treatment was found to be beneficial from a climate change perspective, it may have negative implications for eutrophication. We calculated current global GHG emissions from sewage management to be 660 million metric tons of CO_2 equivalents. Sixty percent of these emissions were calculated to be driven by latrine systems, so moving away from latrines is generally desirable from a GHG perspective.

Considering both GHG emissions (global impact) and eutrophication (local impact) suggests that shifting to a combination of container-based systems and secondary and tertiary treatment may be the best solution, provided each system can be improved in key areas. Such shifts are necessary to both move towards safe sanitation and to reduce the future environmental impact of sewage management that will otherwise continue to grow as the global population increases. Since container-based systems are not widely implemented, additional research is needed to understand the environmental impacts of this option.

Executive Summary

Study Background

Sanitation Development Goals

To help address global disparities in access to basic human needs, the United Nations (UN) has set Sustainable Development Goals (SDGs). The sixth of these SDGs focuses on water and sanitation; within it, Goal 6.2 states the aim to provide "access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations" by 2030 (UN General Assembly 2015). To evaluate progress toward this goal, the World Health Organization (WHO) and UNICEF[1] manage the Joint Monitoring Programme (JMP) for Water Supply, Sanitation, and Hygiene, which provides a global database of sanitation practices, among other things (WHO and UNICEF 2020b). The JMP has developed a sanitation ladder as a metaphor and management tool to describe progress towards improved sanitation (moving up the rungs of the ladder). Open defecation is at the bottom of the ladder, followed by unimproved, limited, and basic sanitation (WHO and UNICEF 2017). The top of the JMP sanitation ladder represent the SDG goal of safely managed sewage.

Environmental Concerns With Sanitation

Concurrent with these development needs, there is an understanding of the immediacy of a variety of environmental concerns, as they affect both ecosystems and human health. Changing climate has the potential to bring unexpected and unprecedented changes to the way that ecosystems function and the way humans interact with them. Other environmental concerns, too, threaten similar changes. Alterations to ocean chemistry and biology are at the forefront of these issues. The planetary boundaries framework (Steffen et al. 2015) was developed to estimate the degree to which a suite of environmental issues may be exceeding the ability of global ecosystems to adapt to changes; directly relevant for sanitation are climate change, nutrients (biochemical flows), biosphere integrity, and ocean acidification. All but the latter have exceeded acceptable limits; ocean acidification has nearly done so.

Provision of sanitation services is resource-intensive; if not carried out properly, sanitation can exacerbate the environmental concerns noted above. For example, based on the findings of this assessment, greenhouse gas (GHG) emissions from current sanitation practices exceeds 660 million metric tons of CO_2 equivalents. There is a need to understand the contributions of sanitation to environmental issues, the potential for mitigation, and tradeoffs associated with public health and other ecosystem concerns.

Study Purpose

The primary purpose of this assessment is to synthesize data and models for sewage management to increase understanding of regional and global challenges and opportunities associated with different sewage management solutions. This study addresses a critical information gap, as sanitation decisions are also environmental decisions. Non-governmental organizations, national governments, and regional decision-makers will need to consider further impacts to climate change, as well as a host of other environmental impacts, when selecting approaches to improved sanitation. This report explores inherent environmental tradeoffs associated with these decisions, while setting decisions in the context of the UN SDGs. Specific study goals are described in the subsequent section.

Research Challenges

The goal of this analysis is to understand how current sanitation management practices affect the environment, and to understand how future changes in management, energy supply, and population could play out with

[1] "UNICEF" was formerly an acronym for "United Nations International Children's Emergency Fund"; the organization is now called the United Nations Children's Fund, but still uses "UNICEF" as its name.

respect to environmental issues. Wastewater systems can affect the environment in multiple ways: some global (e.g., climate change), others highly local (e.g., nutrient inputs to water bodies or human health impacts from pathogens or particulate matter).

Ultimately, sanitation decisions are made at a local, or perhaps regional, level, although national or supranational bodies may influence those decisions. The balancing of multiple environmental concerns is likewise local and subjective, but this analysis helps to identify themes and questions to consider. Thus, it aims to bridge the gap between local decisions and impacts and global applicability.

Indeed, this research effort largely draws on local data: for example, the depth to groundwater, which can affect the emission profile of a latrine, can vary at spatial scales of the order of kilometers, if not smaller. Data collected by the JMP are at the country level. In some cases, the best data are available at a regional level: for example, the fraction of the urban population living below a poverty threshold.

A second research challenge is the need to cover a host of environmental and human health impacts. To consider only climate change, or to consider only pathogen transmission, is to neglect a holistic perspective on potential impacts—or benefits.

This study has met these challenges with a spatially flexible modeling approach, prioritizing higher-resolution data to build up country profiles for environmental conditions (e.g., groundwater depth, trophic status of receiving waters) and management practices (e.g., use of communal versus private latrines, frequency of sending sewage solids to anaerobic digestion). We define a set of sewage management archetypes in order to model some of the most commonly used systems. We use life cycle assessment (LCA) approaches (e.g., Frischknecht and Jolliet 2016; ISO 2006) to efficiently build estimates of emissions of a variety of substances, which can then be connected to human health and ecosystem impacts, allowing comparison across the environmental and human health issues. Where LCA approaches are lacking—as they are for pathogens or ocean acidification—we build custom impact models to provide a holistic perspective on impacts.

In total, this analysis includes the following environmental and human health metrics:

- **Climate change** (as global warming potential [GWP] and as human health impacts): During storage and treatment, sewage may release methane (CH_4) and nitrous oxide (N_2O); energy used for transport and treatment releases fossil-based carbon dioxide (CO_2). These and other GHG emissions contribute to global climate change. This analysis focuses on GHG emissions across a 100-year time period.
- **Ocean acidification**: CO_2 emissions from sewage treatment may dissolve in the ocean and change its pH, which may negatively affect marine life.
- **Eutrophication** (both marine and freshwater): Eutrophication is the process in which ecosystems receive surplus amounts of limiting nutrients (typically phosphorus in freshwater or nitrogen in marine systems), which results in excessive growth of algae, reducing available oxygen and causing changes in species composition, biomass, or productivity.
- **Terrestrial acidification**: Emissions such as sulfur oxides and nitrogen oxides lead to acid rain, which can detrimentally affect terrestrial plant life and infrastructure.
- **Particulate matter** (as a human health impact): Particulate matter can affect breathing and respiratory systems, damage lung tissue, and cause other human health concerns.
- **Pathogen transmission:** Human pathogens can cause a host of acute human health issues with both short and long-term effects; reducing pathogen transmission exposure is one central components of the JMP Sanitation Ladder.

One of the challenges for the reader of this report—the decision-maker or stakeholder—is to consider these environmental and human health metrics holistically. While there are some better or poorer performers, no one sewage management option mitigates all environmental or human health metrics. Therefore, this report can provide additional insight about regional or local decisions, as environmental and human health priorities might vary from one region to the next.

Sewage Management Archetypes

This study assessed five general systems for sewage management, producing a total of 10 "archetypes":

- **Open defecation:** Excreta are deposited directly onto land or into water, without any collection system or treatment. Excreta may also be washed into water through storm events or flooding. (Open defecation is included in the analysis to provide an understanding of baseline conditions; this analysis does not recommend the use of open defecation.)
- **Latrine (three archetypes):** Excreta are deposited into a collection system, generally an excavated pit. As described by Orner et al. (2018), latrines may be unimproved—meaning an open pit or dry pit latrine without a slab—or improved, and may be communal (shared across households) or serve one household. A latrine may have one pit or two alternating pits, and the pits may be above or below the water table, lined or unlined, and ventilated or unventilated. Pit latrines may be waterless or used with flush or pour flush systems. Pits can take a few years to decades to be filled. Once the pit has filled, the contents are either emptied or covered with soil. Pits may be emptied manually (by hand) or mechanically.
- **Septic system:** Excreta are deposited in a flush or pour flush toilet and run through a drainage pipe to a septic tank—an underground water-tight container. As described by Diaz-Valbuena et al. (2011), septic tanks may also receive other household waste, such as drainage from showers, sinks, and laundries. The septic tank allows solids to settle out of the wastewater and form a sludge, where anaerobic digestion provides some reduction in solids volume. The liquid exits the tank, typically into a drain field or soil dispersal system, and percolates through the soil, ultimately discharging to groundwater. Septic tanks need periodic removal of the sludge, or septage.
- **Container-based sanitation (CBS):** Excreta are deposited into toilets with removable containers (Russel et al. 2019). The containers are collected, stored, transported, and then emptied in a CBS facility that sends the liquids to centralized treatment and composts the solids for eventual land application. Other emerging opportunities are available for CBS such as urine diversion and conversion of the solids to briquettes for heating; however, this report does not discuss those specific pathways. (Of the sewage management systems, CBS is the least widely-adopted and therefore is considered to be in developmental stages.)
- **Sewer collection (four archetypes):** Excreta are deposited in a flush or pour flush toilet and run through a drainage pipe, where they are collected into a system of pipes. Sewer collection systems may also collect household waste, such as drainage from showers, sinks, and laundries, as well as wastewater from businesses or industries. Sewer systems collect and transport sewage but do not actively treat it, although some biological processes may occur in transit. Sewer systems can be open or closed; open sewers may be stagnant (i.e., fully flushed during rain events) or flowing. Sewer systems may discharge sewage directly without treatment or deliver it to a wastewater treatment facility, where treatment may remove pathogens, organic matter, and nutrients.

Findings

Table ES 1 shows a comparison of all impact metrics and sewage management archetypes. In this table, the poorest-performing sewage management archetype for each environmental metric is assigned a value of 1; other management options (in the same row) are scaled relative to this value. Cells of the table are shaded on a spectrum from 0 to 1, with higher values shown as red, moderate values shown as yellow and lower values shown as green. The shading is meant to indicate relative differences, and does not signify statistically significant differences. The archetypes in Table ES 1 are organized based on position relative to the JMP sanitation ladder, starting with unsafe open defecation and ending with secondary and tertiary treatment systems that are safely managed.

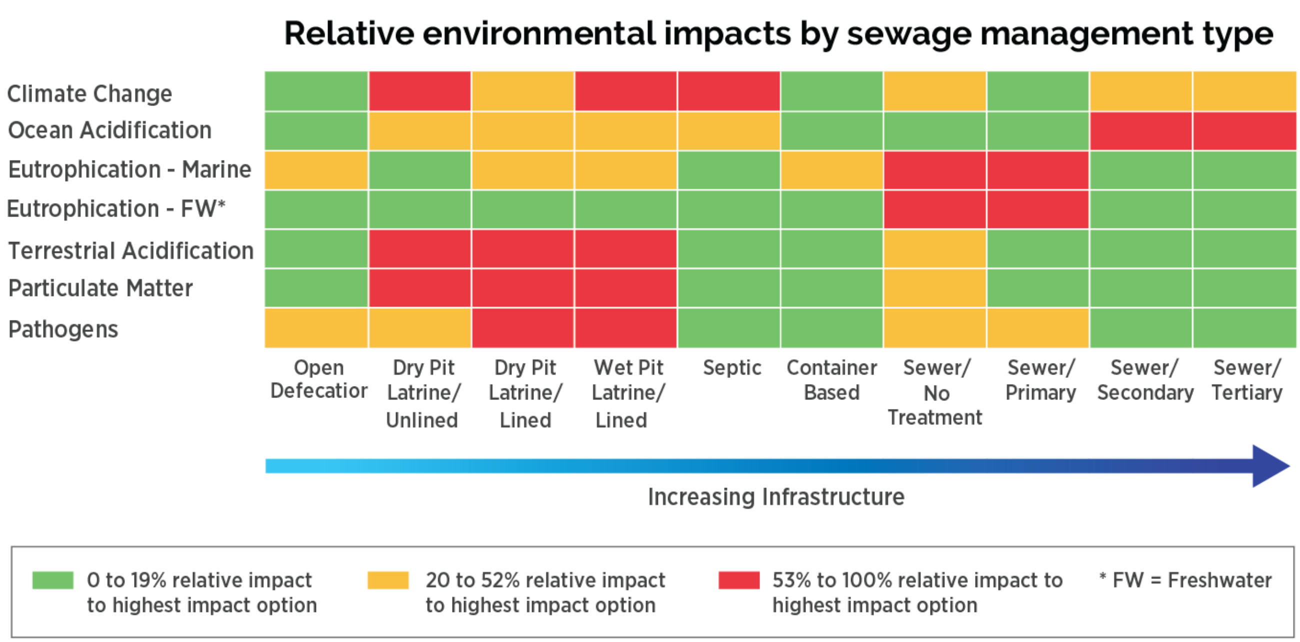
The rows show sewage management archetypes that perform poorly for a given impact category. Specifically, they show the following trends:

- For climate change (GHG/GWP), latrines and septic systems perform poorly; untreated sewers or advanced (secondary and tertiary) wastewater treatment plants (WWTPs) have about a quarter or a third of the impacts of latrines. Latrine, septic, and untreated sewer emissions are driven by CH_4 emissions from stagnant human excreta. The secondary and tertiary wastewater treatment emissions are driven by N_2O emissions during processing, as well as electricity demands.

- For ocean acidification, secondary and tertiary wastewater treatment are the poorest performers, with high emissions of CO_2 related to using the electrical grid.
- For eutrophication, both marine and freshwater, primary wastewater treatment is the poorest performer. Primary WWTPs collect waste (and its nutrients), provide relatively little nutrient removal, and then discharge those nutrients to receiving water bodies. Open defecation and untreated sewers also tend to deliver nutrients directly to water bodies (though less "efficiently" than the primary WWTPs), and thus tend to have impacts that are about 40% of the primary treatment system.
- For both acidification and particulate matter, ammonia emitted from excreta is a contributor to acidification and a precursor for particulate matter. For particulate matter, the energy demands of the advanced treatment systems (secondary and tertiary) also lead to particulate matter emissions during energy production.
- For pathogens, as expected, the systems that keep excreta on site, or do not provide much treatment, have higher potential for pathogen transmission.

The columns show impact metrics that are problematic for a given sewage management archetype. The container-based system is among those with the lowest overall impact (i.e., better performance). It has the advantage of processing excreta (as opposed to letting it decompose on site, as with the latrines); the advantage of processing solids into beneficial products such as compost with relatively little energy input (as opposed to wastewater treatment); and the disadvantage of not handling urine well, resulting in relatively high marine eutrophication impacts. As noted above, CBS systems are still in development, and these results should be considered in the context of ongoing research on CBS systems. The advanced wastewater treatment (secondary and tertiary) systems also tend to have lower impacts. These systems can have tight controls on process emissions and tend to have low nutrient emissions. However, these low emissions can come at the cost of higher energy demands; to the extent that wastewater systems use a carbon-intensive energy source, they tend to have higher GWP emissions and high ocean acidification impacts. These results should be considered in the context of the sanitation ladder, with movement away from open defecation necessary for human safety and dignity.

Table ES 1: Relative impact of each management archetype and environmental metric, scaled to maximum impact by archetype.



Detailed Findings for Climate, Ocean Acidification, and Marine Eutrophication

The following figures show a more detailed perspective on climate change, ocean acidification, and marine eutrophication. These three impact metrics illustrate the variability of performance shown in Table ES 1, as no one management archetype is the best performer across all three.

In these figures, values are presented on a "per archetype user" basis. That is, these are the expected emissions for a single user of each archetype, using global, population-weighted averages for both environmental and management practices. An advantage of assigning one user to each management archetype is that the archetype's inherent performance is evident, while its prevalence is set aside. (Indeed, CBS is relatively uncommon at present, so any presentation of data that accounts for adoption practices will not include the CBS system).

Management archetypes make up the x-axes of these figures. The different-colored parts of each bar (which add up to the archetype's total value) are related to the stages of sewage management, from collection and storage of excreta to ultimate discharge to a groundwater, soil, freshwater, or marine system.

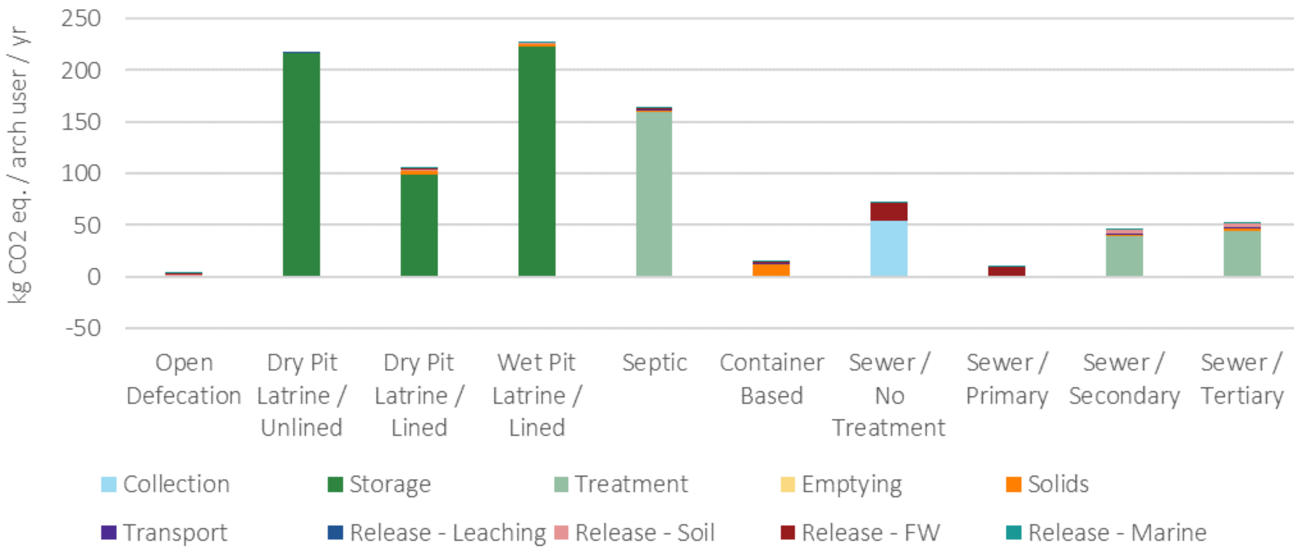


Figure ES 1: Current GHG/GWP impacts for a single archetype user with global environmental and management practices (FW = Freshwater).

In the case of climate change (Figure ES 1), it is the storage of excreta that leads to high emissions for latrines, septic systems, and sewers without treatment. Although these management types have emissions classified as storage, treatment, and collection, emissions are driven by excreta being stored in stagnant conditions. The container-based system has minimal emissions associated with the production, transport, and application of compost. The primary sewer system has limited emissions, generally associated with the discharge of nitrogen to eutrophied water bodies. The secondary and tertiary systems have relatively modest emissions that are driven by N_2O released during biological treatment and, to a lesser extent, upstream electricity demands. Fertilizer, and thus CO_2, is avoided in the case of septic and latrine systems through land application of sludge, digestate, and compost. Wastewater treatment systems can also recover energy (and thus avoid CO_2 emissions) through the use of anaerobic digestion. However, these avoided emissions are negligible in comparison to the scale of emissions from the pit latrines.

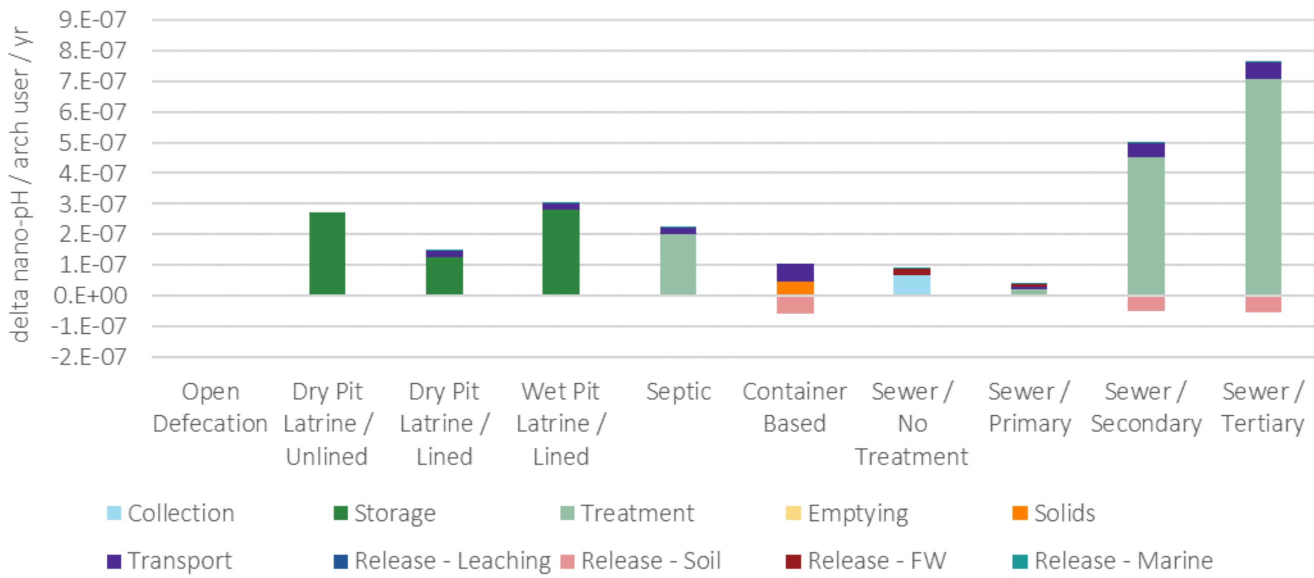


Figure ES 2: Current ocean acidification impacts for a single archetype user with global environmental and management practices (FW = Freshwater).

Ocean acidification impacts are shown in Figure ES 2. Although this metric and GWP share CO_2 and CH_4 as contributing emissions, the two substances have similar ocean acidification characterization factors (in contrast to GWP, for which CH_4 has a factor 20–30 times higher than that of CO_2). CO_2 emissions therefore play a much larger role for ocean acidification than they do for GWP. In general, ocean acidification impacts are driven both by upstream electricity and fuel use, which generate CO_2 emissions, and by CH_4 emissions. Latrine and sewer impacts are driven by CH_4; the container system has emissions related to transport, caused by the frequent emptying and collection of containers. The container system also has small negative emissions that result from the avoided production of synthetic fertilizer. Finally, the advanced treatment systems have high energy demands and thus high CO_2 emissions, causing these two archetypes to have the largest impact on ocean acidification.

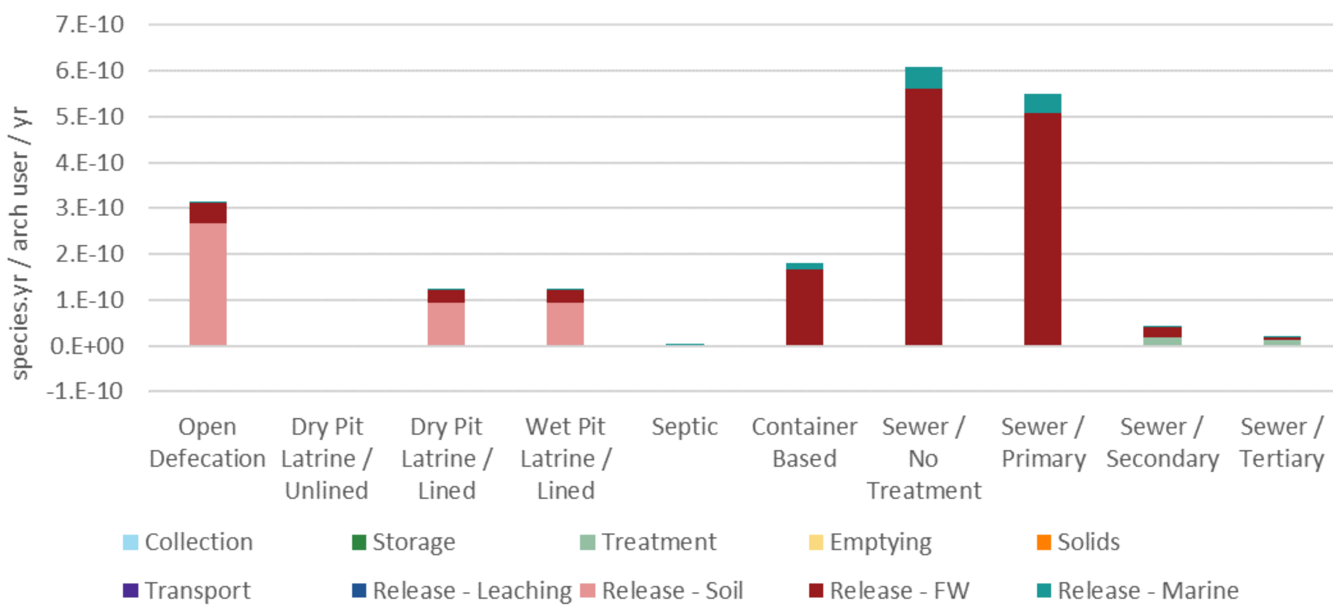


Figure ES 3: Current marine eutrophication impacts for a single archetype user with global environmental and management practices (FW = Freshwater).

Figure ES 3 shows marine eutrophication impacts associated with emissions of nitrogen. Here, uncontrolled release of nutrients to water bodies, and to a lesser degree soil, is problematic. Therefore, open defecation has a relatively high impact in this category. Lined pit latrines, which are emptied, have their collected material directly released to soil or water or emptied into sewers, giving these management archetypes restricted impacts. For CBSs, we model the fate of diverted urine similarly to the fate of collected material from latrines: it can be directly released to the environment or put into a sewer, which may be connected to a treatment plant or not. Therefore, both the container system and the sewer system without treatment allow nitrogen to be released directly to the environment. Among the treatment systems, primary sewer systems have the highest impacts per user, also due to the collection and discharge of nutrients. In the case of primary treatment, very little nitrogen is removed in treatment, and the discharge of the treatment plant is generally to a water body (rather than to soil, as with CBSs). Therefore, the primary treatment system serves as an efficient collector of nutrients, as well as an efficient funnel of nutrients directly to water bodies.

Sewage Management in the Global Context

While this analysis focuses on assessing relative changes in environmental impacts across a variety of scenarios, it is also useful to compare some of the values calculated to other sources. Using the baseline GWP factors in this analysis, we calculate current global GHG emissions from sewage to be 660 million metric tons of CO_2 equivalents. Differences between this value and other estimates include the following:

- We use IPCC Fifth Assessment Report (AR5) GWP values, with climate-carbon feedback, as the baseline GWP factors.
- We use the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas* (Bartram et al. 2019) for estimating sewage management emissions.
- We only account for domestic sewage, not emissions associated with food waste and household chemicals that may be present in some countries' wastewater streams; we do not account for treatment of industrial and commercial wastewater. This approach results in lower emissions than in other estimates for the entire wastewater sector.
- We include the full global population, regardless of whether they are parties to the United Nations Framework on Climate Change (UNFCCC).
- We use global datasets and assumptions to estimate sewage management systems in use and operational conditions.
- We include GHG emissions associated with energy use, transportation, chemical production, and other LCA emission sources.

Considering these differences, our assessment is consistent with other global GHG estimates, as shown in Table ES 2. Background on the other global sources assessed is provided in Appendix H.

Table ES 2: Comparison of ERG global sewage GHG results to other studies.

Source	Wastewater GHG Emissions (Million Metric Tons CO_2e)	Wastewater Emissions as % of Total GHG Emissions[1]	GWP Values (100-Year)
ERG analysis (this study; sewage only)	660	NA	AR5[2]
	505	NA	AR4
PIK PRIMAP-2018 [3]	649	1.34%	AR4
CAIT 2018	636	1.34%	SAR
UNFCCC 2019	449	1.07%	AR4
Annex I countries	123	0.75%	
Non-annex-I countries	326	1.27%	

[1] Excludes emissions from land use, land use change, and forestry (LULUCF).
[2] AR5 GWP values with climate-carbon feedback.
[3] PIK PRIMAP-2018 provided an estimate of GHG emissions from waste, but not specifically wastewater; ERG calculated wastewater emissions using the % of wastewater emissions to total GHG emissions from CAIT 2018.

Future Scenarios

With respect to impact metrics in the future, the analysis focused on the carbon intensity of the energy grid, population, and potential changes in adoption of sewer management archetypes. The carbon intensity of the energy grid is important for ocean acidification (dominated by CO_2), particulate matter, and terrestrial acidification (dominated by oxides of sulfur and nitrogen). For the other impact metrics, the energy grid had a relatively restricted impact. Therefore, in this brief discussion, we focus on population and the management adoption scenarios. For the former, we bracket possibilities using UN high and low estimates (UN DESA 2019a). For the latter, we created a base "2050 Trend" scenario from the asymptotic growth or decay based on JMP 2000 and 2017 data. The "2050 Trend, Safe Sanitation" scenario involved further modifications by proportionately shifting all populations to JMP ladder categories that are "safely managed": septic and WWTP.

Using the "2050 Trend" as a starting point, three other scenarios explore possible changes. One assumes CBS use increases from 0% to 50% between 2017 to 2050, decreasing all other management archetypes proportionately. This scenario is meant to demonstrate the potential for mitigation of environmental impacts; it is not designed to be representative of a specific policy. The "Safe Sanitation" scenario alters the 2050 trend such that only septic and WWTP systems are used. Other scenarios shift all predicted WWTP increases (across primary, secondary, and tertiary) to one type of WWTP; all other sanitation management categories remain at "2050 Trend" levels. These archetype adoption scenarios were developed for urban and rural populations; the urban fraction was further subdivided into low and high income based on regional urban income.

Figure ES 4 shows projections for total global emissions of GHGs based on archetype adoption scenarios and population. Archetype and population are key drivers for total emissions of not just GHGs but all impacts considered: for certain archetypes, there are significant differences in emissions, and population scales these differences directly. Figure ES 4 shows that even high population growth could be offset by changes towards low-GHG sewage management, as demonstrated by the notional scenario of high CBS adoption. Overall, there is a factor of four range between the lowest and highest future projections at 2100, demonstrating the potential for mitigation: even with high population growth, shifting significant population fractions away from high impact management archetypes could keep overall emissions close to present day levels.

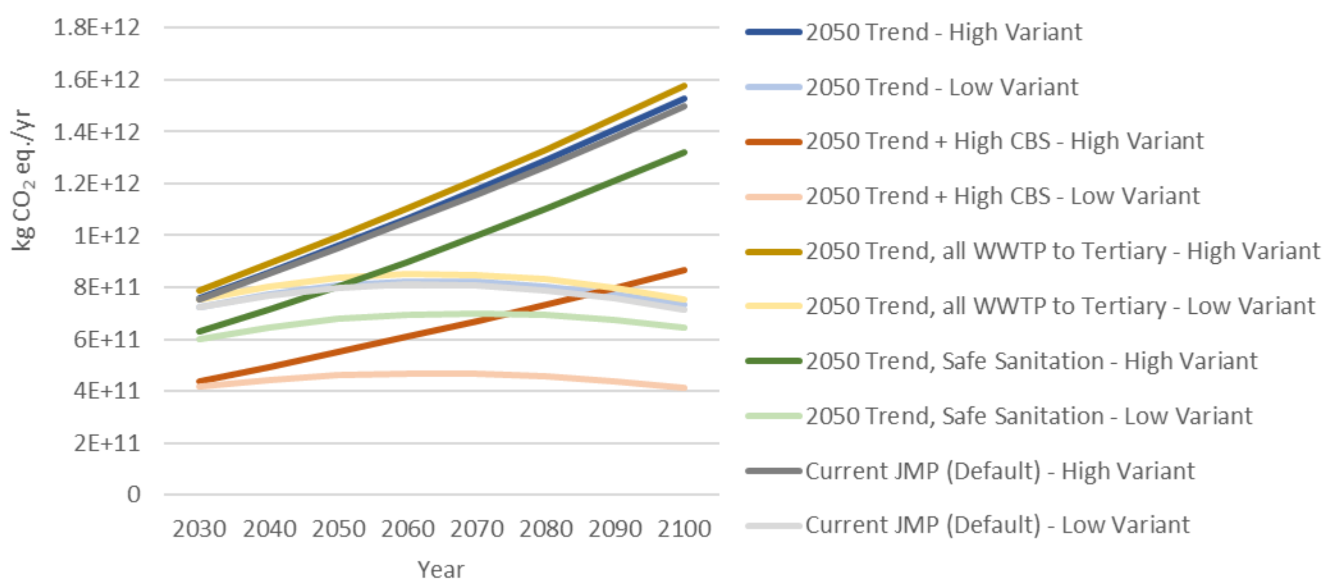


Figure ES 4: Potential GHG emissions under different archetype adoption scenarios and different population scenarios (high and low population variants).

Recommendations and Next Steps

Policy Recommendations

This analysis has focused on forward-looking planning decisions: that is, which sewage management options should policy or funding organizations promote?

From the policy perspective, we unequivocally support the SDG aims of increasing access to safe sanitation in order to reduce acute illness and improve human dignity (the latter being beyond the scope of this study, but being an explicitly stated part of the SDGs). This research shows that each sewage management option, including those that meet the SDG definition of safe sanitation, has areas of poor or better environmental performance. Therefore, we also highlight the need for including environmental and other concerns in policy objectives that aim to improve sanitation.

Some of the poorer-performing management archetypes are latrines, open sewers, and (for certain impact categories) primary wastewater treatment. Some of the better-performing management archetypes are CBS and advanced (secondary and tertiary) wastewater treatment. This suggests that moving users away from latrines to other systems is generally desirable. Moving to primary treatment can be beneficial from a climate change perspective, but it may have negative impacts for eutrophication. Such decisions should be considered at the scale and context of individual localities or regions. Moving directly to advanced treatment (i.e., bypassing primary treatment) would be beneficial from a eutrophication perspective, but has a slight negative climate consequence, and does have negative ocean acidification impacts. Improvements to wastewater treatment operation, including operational changes to increase nutrient removal while lowering electricity requirements and recovering biogas from sludge digestion to offset electricity needs, could mitigate impacts to ocean acidification. CBS appears to perform well across most environmental metrics; in cases where marine eutrophication is not a concern, it could be a useful endpoint on the sanitation ladder. However, there is a lack of information on the overall impacts associated with this archetype due to its low implementation to date. The study indicates that more research is needed on CBS's operational impacts, but CBS may be a promising option if urine can be managed appropriately. Options for using the solids from CBS should also be further explored. This study modeled CBS solids as being composted, but other resource recovery opportunities—such as briquetting the solids for heating, thus reducing demand for other solid fuel heating—should be explored.

Sewage Management Research and Technology Transfer Needs

In addition to policy recommendations, this analysis has highlighted issues with the sewer management archetypes, both in understanding and in operation.

As CBS is not commonly implemented, it is the most poorly understood of the archetypes considered here. More research on container-based systems, and the variety of their implementation practices, is needed. CBS has not yet fully addressed the problem of urine, and thus nitrogen, management. Advancements in urine diversion could improve the performance of this option.

The advanced treatment systems (secondary and tertiary) appear to perform relatively well across impact categories that are not sensitive to the energy grid. Therefore, when renewable sources can be used for these systems, they will be high performers across all impact categories. Although this work did not focus on these systems' range of performance, the operational efficiency of these systems can vary greatly, with corresponding influence on energy use. To the extent that the causes for these efficiencies can be identified and disseminated to operators of the advanced wastewater systems, these systems could be improved in place, without radical changes to the energy grid.

For those situations where a suite of management archetypes is already locked in, disseminating knowledge and continuing research about how to mitigate the environmental impacts identified in this work will be valuable in reducing impacts. For example, where it is still impractical to move beyond latrine use, future research might identify culturally appropriate solutions to reduce CH_4 release from latrines.

General Research Needs and Limitations

This work has demonstrated a flexible framework to evaluate a range of sewage management archetypes across a suite of environmental impacts. Although we report data at a global or regional scale, the spatially flexible data inputs and the structure of the model are amenable to higher-resolution outputs. The model could be augmented to provide high-level, ancillary estimates of country-level GHG emissions for wastewater treatment, which could be of use to organizations such as the JMP.

Any analysis that attempts to be holistic is also inherently limited. The degree to which environmental and human health metrics could be added to this framework is limited by available models. The results of this study should be interpreted in the context of the underlying assumptions and parameters used to generate results.

1 Introduction and Background

The development of technologies and infrastructure to safely remove and treat sewage, especially in urban centers, was a major milestone for public health in the 20th century. At present, concern about the changing climate means that a comprehensive analysis of all sectors, including sewage, is necessary to understand contributions to greenhouse gas (GHG) emissions, the potential for mitigation, and tradeoffs associated with public health and other ecosystem issues.

The primary purpose of this assessment is to synthesize data and models for sewage management to increase understanding of global opportunities for GHG mitigation and the high-level tradeoffs associated with different sewage management solutions that may benefit the climate, environment, and public health. We have developed sewage management archetypes that span the range of sewage treatment globally, and mapped the archetypes to global regions where applicable. For this report, we have used the archetypes to estimate total life cycle global GHG emissions from sewage management, both at present and under various future scenarios. Life cycle assessment (LCA), as defined in ISO 14040/44, is a systems-level (e.g., “collection through grave”) approach that can help decision-makers choose the most environmentally preferable option while minimizing tradeoffs (ISO 2006). Process-based GHG emissions based on estimation methodologies from sources such as the Intergovernmental Panel on Climate Change (IPCC) are coupled with emissions associated with additional sewage management life cycle stages and data sources to form a comprehensive dataset for GHG emissions (IPCC 2015). Other environmental and human health metrics such as pathogen reduction, particulate matter formation, and eutrophication are assessed to understand whether reductions in GHG emissions can lead to increases in other impact areas.

The rest of Section 1 describes the relationship of this work to the World Health Organization (WHO) and the UNICEF[2] Joint Monitoring Programme (JMP), then describes sewage management systems in general and defines broad archetypes for sewage management. Section 2 provides details on collection, treatment, and discharge for each archetype. Section 3 describes how this work evaluates these archetypes: the basis of comparison (functional unit), the metrics to be used, and some preliminary discussion of drivers for differences between the archetypes. Section 4 reviews the data sources used for the full evaluation. Section 5 presents the results of the assessment and a discussion of uncertainty; Section 6 presents conclusions; and Section 7 presents references used.

1.1 Overview of the JMP Sanitation Ladder

In 2015, the United Nations set Sustainable Development Goals (SDGs) to achieve “peace and prosperity for people and the planet now and into the future” (UN General Assembly 2015). Goal 6 is “Ensure availability and sustainable management of water and sanitation for all”; Goal 6.2 states a specific aim to, “by 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations.” To evaluate progress toward this goal, the United Nations looks at the proportion of population using safely managed sanitation services, among other things.

The WHO and UNICEF manage the JMP for Water Supply, Sanitation, and Hygiene, which provides a global database of sanitation practices, among other things (WHO and UNICEF 2020b). The JMP conducts surveys of sanitation annually, but not all countries provide updated data annually. Sanitation services are generally classed into five service levels: the JMP sanitation ladder, shown in Table 1.1.

[2] “UNICEF” was formerly an acronym for “United Nations International Children's Emergency Fund”; the organization is now called the United Nations Children’s Fund, but still uses “UNICEF” as its name.

Table 1.1: The JMP sanitation ladder.

	Safely Managed	Use of improved facilities that are not shared with other households and where excreta are safely disposed of in situ or removed and treated off site
	Basic	Use of improved facilities which are not shared with other households
	Limited	Use of improved facilities shared between two or more households
	Unimproved	Use of pit latrines without a slab or platform, hanging latrines or bucket latrines
	Open Defecation	Disposal of human faeces in fields, forests, open bodies of water, beaches and other open spaces or with solid waste

Improved facilities are those that separate excreta from human contact. They include flush/pour flush toilets connected to piped sewer systems, septic tanks, or pit latrines; ventilated improved pit latrines; composting toilets; or pit latrines with slabs.

(WHO and UNICEF 2020a)

Meeting the SDGs without exacerbating environmental issues is not trivial. For example, In the specific case of urban water and wastewater management, there will be challenges in meeting SDG 6 without further damaging certain ecosystem functions (Sørup et al. 2020). Therefore, this study provides important information to decision-makers and stakeholders alike, as decisions about sewage management are also environmental decisions.

1.2 Sewage Management Archetypes

The most recent global JMP data include information by country and region on the percent of population falling into each of the five levels on the sanitation ladder, broken out by populations in rural versus urban areas. Country-level data are also available on the specific types of sanitation system in use and the method of waste management, though this information is incomplete or partially populated, depending on the country. For example, a 2021 country-level file may have data from 2016 as the most recent (this is the case for Angola) (WHO and UNICEF 2021). Appendix A shows a sample of these data.

ERG used the sanitation systems covered in the JMP data to inform 10 proposed archetypes, based on five general systems for sewage management:

- **Open defecation:** Excreta are deposited directly onto land or into water, without any collection system or treatment. Excreta may also be washed into water through storm events or flooding. (Open defecation is included in the analysis to provide an understanding of baseline conditions; this analysis does not recommend the use of open defecation.)
- **Latrine (three archetypes):** Excreta are deposited into a collection system, generally an excavated pit. Latrines may be unimproved—meaning an open pit or dry pit latrine without a slab—or improved[3], and may be communal (shared across households) or serve one household. A latrine may have one pit or two alternating pits, and the pits may be above or below the water table, lined or unlined, and ventilated or unventilated. Pit latrines may be waterless or used with flush or pour flush systems. Pits can take a few years to decades to be filled. Once the pit has filled, the contents are either emptied or covered with soil (i.e., buried). Pits may be emptied manually (by hand) or mechanically (Orner, Naughton, and Stenstrom 2018). There have been efforts to generate biogas from latrines (Kulak et al. 2017; Mutai et al. 2016). While biogas capture is promising for reducing GHG emissions from these

[3] Improved means that humans are separated from contacting the sewage (e.g., slabs to defecate over which prevent falling into the pit).

systems, we assume that widespread installation and operation of latrine biogas systems is unlikely and therefore model latrines without biogas capture.

- **Septic system:** Excreta are deposited in a flush or pour flush toilet and run through a drainage pipe to a septic tank—an underground water-tight container. Septic tanks may also receive other household waste, such as drainage from showers, sinks, and laundries. The septic tank allows solids to settle out of the wastewater and form a sludge, where anaerobic digestion provides some reduction in solids volume. The liquid exits the tank, typically into a drain field or soil dispersal system, and percolates through the soil, ultimately discharging to groundwater. Septic tanks require periodic removal of the sludge, or septage (Diaz-Valbuena et al. 2011).
- **Container-based sanitation (CBS):** Excreta are deposited into toilets with removable containers (Russel et al. 2019). The containers are collected, stored, transported, and then emptied in a CBS facility that sends the liquids to centralized treatment and composts the solids for eventual land application. Other emerging opportunities are available for CBS, such as urine diversion and conversion of the solids to briquettes for heating (Mijthab, Anisie, and Crespo 2021). As many CBS systems are still in development and operational characteristics may be uncertain, this report assumes all CBS systems produce compost. (Of the sewage management systems, CBS is the least widely-adopted and therefore is considered to be in developmental stages.)
- **Sewer collection (four archetypes):** Excreta are deposited in a flush or pour flush toilet and run through a drainage pipe, where they are collected into a system of pipes. Sewer collection systems may also collect household waste, such as drainage from showers, sinks, and laundries, as well as wastewater from businesses or industries. Sewer systems collect and transport sewage but do not actively treat it, although some biological processes may occur in transit. Sewer systems can be open or closed; open sewers may be stagnant (i.e., fully flushed during rain events) or flowing. Sewer systems may discharge sewage directly without treatment or deliver it to a wastewater treatment facility, where treatment may reduce pathogens, organic matter, and nutrients prior to discharge or reuse.

1.3 Sewage Management Stages

For the purposes of this assessment, sewage management methods are evaluated and presented in terms of five general stages of management:

- **Collection:** Method of collection of human excreta (i.e., feces and urine), as well as any contributions from household waste. Typical methods include flush toilets, pour-flush toilets, pit toilets, and sewer systems[4].
- **Storage/emptying:** Method and duration of storing human excreta and/or household waste, including activities to empty waste from the storage location. Typical storage methods include pits and tanks; emptying frequency can range from daily to never and can be manual or mechanical.
- **Transport:** Method of transporting human excreta and associated household waste to other locations for treatment and/or disposal. Typical methods include sewer systems (which are also used for collection), vehicles, or manual methods.
- **Treatment:** Method used to remove or stabilize contaminants, and possibly pathogens, from wastewater or sewage sludge. Typical methods to treat wastewater include septic tanks; composting; or physical, biological, and/or chemical treatment at centralized wastewater treatment plants (WWTPs). WWTPs may perform physical separation of material that readily settles out (typically referred to as primary treatment); biological processes to convert and remove contaminants (typically referred to as secondary treatment); and advanced biological and/or chemical treatment for removal of targeted pollutants, such as nutrients (typically referred to as tertiary treatment). Human excreta removed from pits, septage removed from septic tanks, or sewage sludge from WWTPs may be stabilized, composted, or anaerobically digested. Note that sewage sludge is also transported to its final disposal or reuse site.

[4] Sewer systems could also be categorized under transport stage, but are presented under the collection stage for the purposes of this assessment.

- **Disposal:** Method used to dispose of human excreta, including wastewater effluent and sludge. Typical disposal methods include land disposal (open defecation, pits, septic dispersal fields), land application (as fertilizer to fields), and subsurface or surface discharge to water.

In some cases, variations in archetypes may be simplified because data are not available to properly quantify differences in GHG emissions associated with those variations. For example, many countries use pit latrines—some may be open pits, while others may be improved with slabs and/or ventilation. However, there is little actual measurement data on the variation in GHG emissions from these systems.

2 Sewage Management Archetypes

ERG constructed the 10 archetypes described in this section to estimate total life cycle global GHG emissions from sewage management, both at present and under various future scenarios. These archetypes are based on the five sewage management systems described in Section 1.2 and the five management stages described in Section 1.3.

While the archetypes describe broad groups of sewage management, generally based on collection system, storage, and level of sewage treatment, we note that there are a number of operational alternatives possible for each. These alternatives influence the stages modeled and the calculation of emissions (via emission factors) for the systems. Operational alternatives considered in this analysis include:

- **System use:** Whether systems are communal or used by a household.
- **Ventilation:** For latrines, whether the collection area is ventilated. (Note that the GHG emission factors used in the assessment do not differentiate whether latrines are ventilated; thus, this analysis does not differentiate between ventilated and non-ventilated latrines.)
- **Emptying:** How solids are emptied from collection. Methods may include manual (e.g., shovel and bucket to remove excreta from a pit) and mechanical (e.g., vacuum trucks to remove septage from a septic tank) options.
- **Transport:** How sewage is transported following collection. Methods may include manual (e.g., hand cart) or vehicular (e.g., truck) options.
- **Treatment:** How sewage is treated in an engineered wastewater treatment system (e.g., septic treatment, primary/secondary/tertiary treatment at wastewater facility).
- **Groundwater depth:** For latrines, whether the collected sewage is submerged by the groundwater table. Note that the GHG emission factors used in this assessment vary by whether the pit latrine sewage is submerged or not.
- **Solids/sludge treatment:** Whether, after sewage treatment, sludge is anaerobically digested, composted, or incinerated.
- **Sludge destination:** Whether, after sludge treatment, stabilized sludge is land applied or landfilled.
- **Discharge:** What type and condition of the water body receives the excreta, solids (latrine, septic), or wastewater effluent (relevant for the emission factor). This assessment includes discharge to soil, freshwater (river or lake, which also depends on trophic status), and marine water.

Options for the final destination of untreated excreta, treated solids, or treated effluent are shown in Table 2.1. When evaluating GHG emissions associated with each of these archetypes, ERG applies a percentage of global population to each of these various options that may be used to develop a weighted average representation.

Figure 2.1 shows the relationship between archetypes, the shared stages described above, and management options. Figure 2.2 and Figure 2.3 show an example of the shared stages and final destinations for a particular sewage management system. In the appendices, Appendix Figure B.1 provides a network diagram of all pathways and lists the ultimate fate for releases from the different pathways (e.g., to burial or the marine environment); Appendix Table B.1 briefly describes the network nodes and maps nodes to stages (which are used for reporting results).

Starting in Section 2.1, each archetype is defined along with the color or range of colors representing where it falls on the JMP sanitation ladder and a summary of what stages of sewage management it includes. Each archetype is described, along with several "sub-archetypes" or "pathways" that represent the typically used combinations of management stages. Due to the number of variations of sewage pathways in use throughout the world, the archetypes assessed in the analysis are a subset of those deemed to be most commonly in use, based on JMP data.

Table 2.1: Summary of final destinations modeled.

Sewage Management System	Nature of Solids Material	Solids End Destinations	Nature of Liquid Material	Liquids End Destinations
Open defecation	Feces	▪ Soil ▪ Water	▪ Urine	▪ Same as solids
Latrine	Solids remaining in latrine	▪ Soil ▪ Water ▪ Stabilization ▪ WWTP	▪ Urine ▪ Anal cleansing water ▪ Flush water	▪ Groundwater ▪ Same as solids
CBS	Feces	▪ Compost land application	▪ Urine ▪ Treated effluent	▪ Sewer—no treatment ▪ WWTP
Septic	Septage	▪ Soil ▪ Water ▪ Stabilization ▪ WWTP	▪ Treated effluent	▪ Soil ▪ Groundwater
Sewer—no treatment	Feces	▪ Soil ▪ Water	▪ Urine ▪ Flush water	▪ Same as solids
Sewer—treatment	Biosolids (sludge)	▪ Landfill ▪ Land application ▪ Incineration ▪ Anaerobic digestion ▪ Compost	▪ Treated effluent	▪ Water ▪ Soil

Notes:

- "Soil" implies disposal on land surface; "land application" implies intentional (re)use of material on land surface (e.g., as a soil amendment or fertilizer); "landfill" implies burial, possibly in an engineered landfill. Water destinations include river, lake, and marine systems.
- Material deposited on soil may be transferred to water, if in a wet climates and if within a certain distance of a water body.
- Stabilization (for latrine and septic) includes either compost or anaerobic digestion.
- Composted material is land applied.
- Anaerobically digested material (digestate) may be land applied, landfilled, or incinerated.

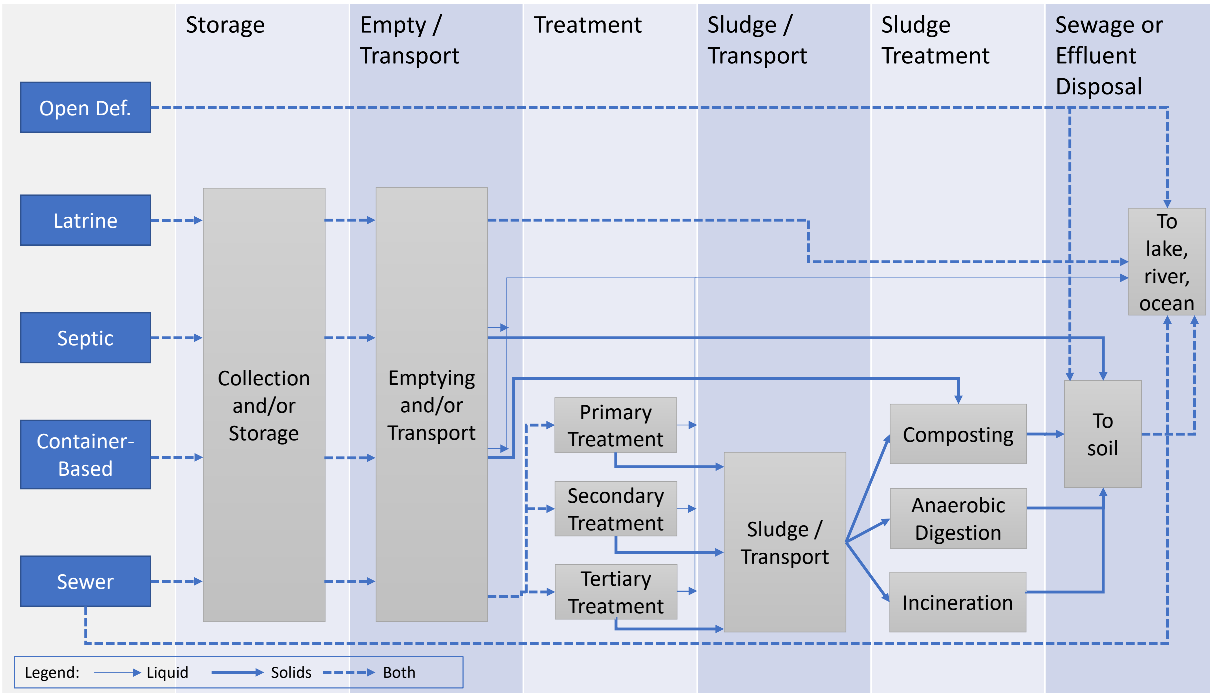


Figure 2.1: Overview of archetypes: relationship to emptying, transport, treatment, and discharge.

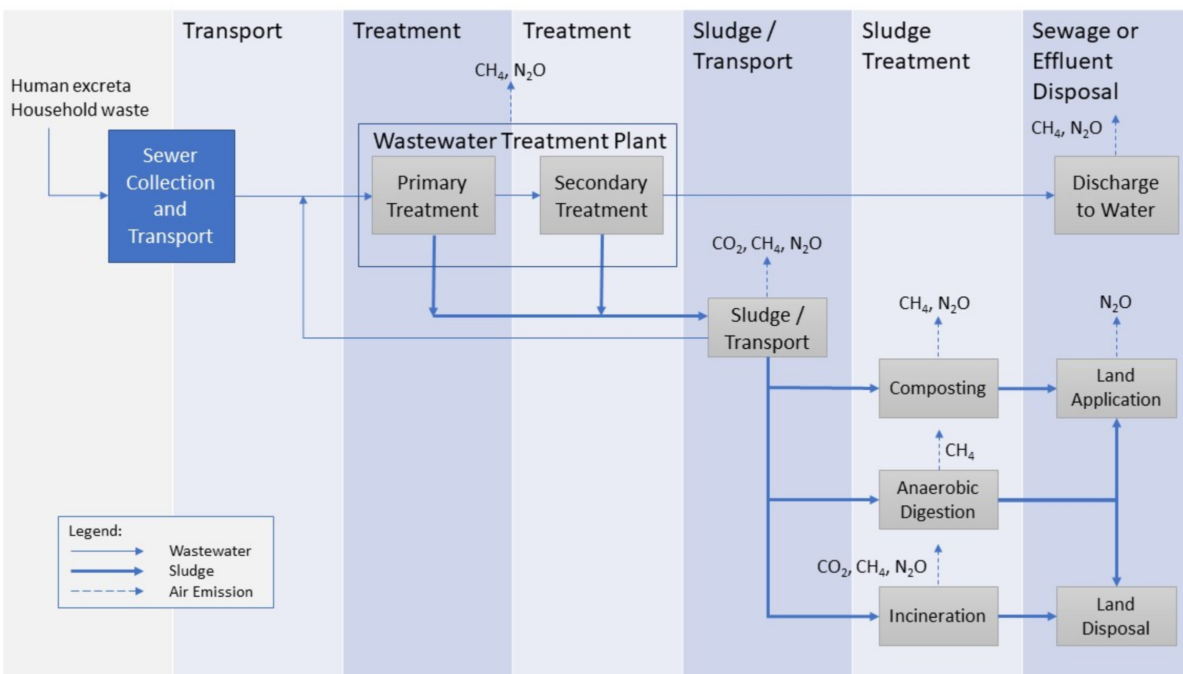


Figure 2.2: Example process diagram indicating GHG emissions by stage for sewer collection with secondary treatment.

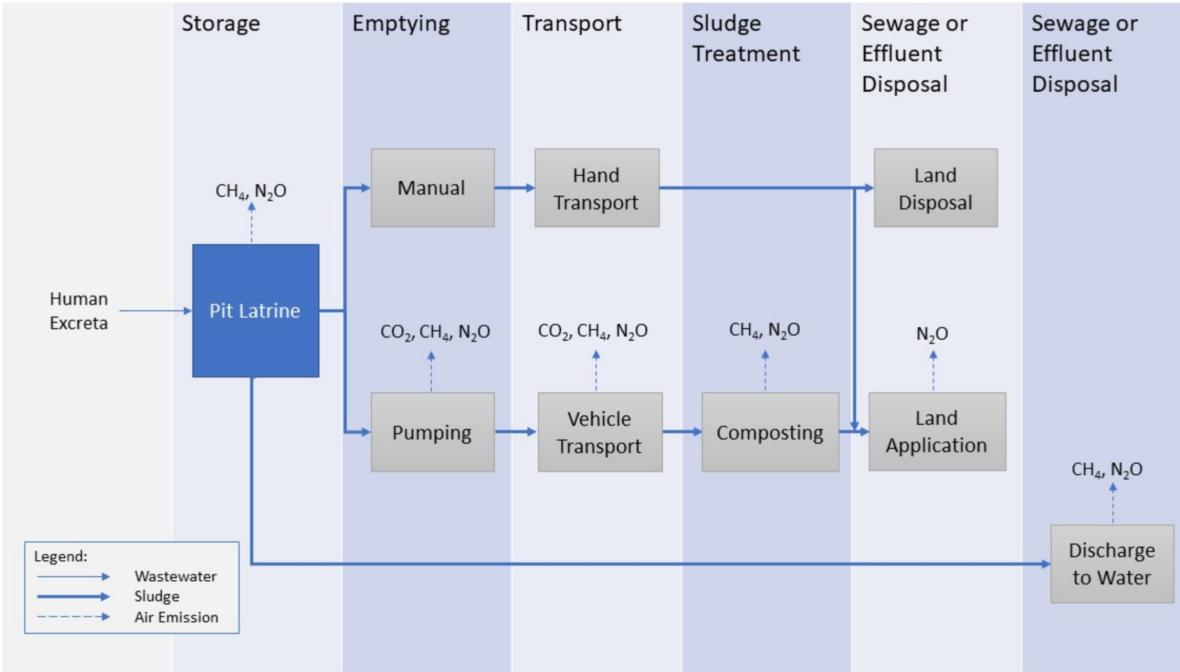


Figure 2.3: Example process diagram indicating GHG emissions by stage for dry pit latrine.

2.1 Archetype 1: Open Defecation

Archetype	Collection	Storage/Emptying	Transport	Treatment	Disposal
Open defecation					✓

1

WHO defines open defecation as "human faeces are disposed of in the fields, forests, bushes, open bodies of water, beaches, and other open spaces." The practice of open defecation is considered unsafe, causing serious security and privacy issues. It can also contaminate water sources and infect humans and animals with disease.

We evaluated one pathway for this archetype:

- Archetype 1.1: Open defecation on land or to open water

2.2 Archetype 2: Dry Pit Latrine (Unlined)

Archetype	Collection	Storage/Emptying	Transport	Treatment	Disposal
Dry pit latrine (unlined)	✓	✓			✓

2
2
2

A dry pit latrine is defined as one that is not connected to a flush or pour flush toilet. It may have one pit or two alternating pits, which may be above or below the water table, and may be used by a household or be a communal latrine for larger groups of people (Orner, Naughton, and Stenstrom 2018). Liquid infiltrates into the ground, leaving solids to accumulate in the pit. For this archetype, the pit is unlined. Unlined latrines can be difficult to empty; therefore, we assume burial of contents.

We evaluated five pathways for this archetype:

- Archetype 2.1: Unlined dry pit latrine, communal use, with groundwater table lower than the latrine and burial of pit contents.
- Archetype 2.2: Unlined dry pit latrine, communal use, with groundwater table higher than the latrine and burial of pit contents.

- Archetype 2.3: Unlined dry pit latrine, household use, with groundwater table lower than the latrine and burial of pit contents.
- Archetype 2.4: Unlined dry pit latrine, household use, with groundwater table higher than the latrine and burial of pit contents.
- Archetype 2.5: Ventilated unlined dry pit latrine.

2.3 Archetype 3: Dry Pit Latrine (Lined)

Archetype	Collection	Storage/Emptying	Transport	Treatment	Disposal
Dry pit latrine (lined)	✓	✓	✓		✓

3

3

3

The archetype is similar to Archetype 2, but the latrine is either partially or fully lined. Liquid infiltrates into the ground, leaving solids to accumulate in the pit. Various materials may be used to line a pit latrine, including bricks, concrete blocks, and wood (Orner, Naughton, and Stenstrom 2018). Lined latrines are easier to empty than unlined ones and can minimize contamination to groundwater. Some improved pit latrines are ventilated, where a vent pipe is installed into the pit and is used to exhaust odor and to control flies (Orner, Naughton, and Stenstrom 2018).

We evaluated five pathways for this archetype:

- Archetype 3.1: Lined dry pit latrine, communal use, with groundwater table lower than the latrine and manual emptying of pit contents and transfer of sludge to end destination.
- Archetype 3.2: Lined dry pit latrine, communal use, with groundwater table higher than the latrine and manual emptying of pit contents and transfer of sludge to end destination.
- Archetype 3.3: Lined dry pit latrine, household use, with groundwater table lower than the latrine and manual emptying of pit contents and transfer of sludge to end destination.
- Archetype 3.4: Lined dry pit latrine, household use, with groundwater table higher than the latrine and manual emptying of pit contents and transfer of sludge to end destination.
- Archetype 3.5: Ventilated lined dry pit latrine with manual emptying of pit contents and transfer of sludge to end destination.

2.4 Archetype 4: Wet Pit Latrine (Lined)

Archetype	Collection	Storage/Emptying	Transport	Treatment	Disposal
Wet pit latrine	✓	✓	✓		✓

4

4

A wet pit latrine is one that is connected to a flush or pour flush toilet, such that water and excreta enter the pit. These latrines are constructed with a cover slab or floor above the hole. The pits are lined, similar to Archetype 3, which facilitates the water to infiltrate into the ground, leaving solids to accumulate in the pit. Often, the latrine is located on a mound to prevent water from entering the pit. Some improved pit latrines are ventilated: a vent pipe runs the pit and is used to exhaust odor and control flies (Tilley et al. 2014; Orner, Naughton, and Stenstrom 2018).

We evaluated five pathways for this archetype:

- Archetype 4.1: Lined wet pit latrine, communal use, with groundwater table lower than the latrine and emptying of pit contents via pumping and transfer of sludge to end destination.
- Archetype 4.2: Lined wet pit latrine, communal use, with groundwater table higher than the latrine and emptying of pit contents via pumping and transfer of sludge to end destination.
- Archetype 4.3: Lined wet pit latrine, household use, with groundwater table lower than the latrine and emptying of pit contents via pumping and transfer of sludge to end destination.
- Archetype 4.4: Lined wet pit latrine, household use, with groundwater table higher than the latrine and emptying of pit contents via pumping and transfer of sludge to end destination.

- Archetype 4.5: Ventilated lined wet pit latrine with emptying of pit contents via pumping and transfer of sludge to end destination.

2.5 Archetype 5: CBS

Archetype	Collection	Storage/Emptying	Transport	Treatment	Disposal
CBS	✓	✓	✓	✓	✓

5

In a container-based system, excreta are deposited into toilets with removable containers.

We evaluated one pathway for this archetype:

- Archetype 5.1: CBS with emptying, transport, and composting. Urine is separated and sent to centralized treatment or open sewers.

2.6 Archetype 6: Flush or Pour Flush Toilet with Septic System

Archetype	Collection	Storage/Emptying	Transport	Treatment	Disposal
Septic system	✓	✓	✓	✓	✓

6

Septic systems are used in combination with flush or pour flush toilets. Septage removed from the tanks can then be transported to a wastewater treatment system, or further digested at an offsite facility to create fertilizer for agricultural use.

We evaluated two pathways for this archetype:

- Archetype 6.1: Flush toilet with septic tank and soil dispersal system, with emptying of tank contents via pumping and transfer of septage via vehicle to a WWTP.
- Archetype 6.2: Flush toilet with septic tank and soil dispersal system, with emptying of tank contents via pumping and transfer of septage via vehicle to a sludge treatment plant followed by land application.

2.7 Archetype 7: Sewer Collection with No Treatment

Archetype	Collection	Storage/Emptying	Transport	Treatment	Disposal
Sewer collection with no treatment	✓		✓		✓

7

In this archetype, sewer systems are assumed to be open and can be stagnant during dry periods or flowing during wet periods. The analysis does not include contributions from businesses or industries. Wastewater is assumed to be discharged to surface water or to soil.

We evaluated two pathways for this archetype:

- Archetype 7.1: Flush toilet with sewer collection, stagnant sewer conditions, and wastewater discharged.
- Archetype 7.2: Flush toilet with sewer collection, flowing sewer conditions, and wastewater discharged.

2.8 Archetype 8: Sewer Collection with Primary Treatment

Archetype	Collection	Storage/Emptying	Transport	Treatment	Disposal
Sewer collection with primary treatment	✓		✓	✓	✓

8

In this archetype, sewer systems are assumed to be closed and typically underground. Primary treatment consists of physical treatment steps to remove readily settleable solids and floating material from the wastewater through primary sedimentation. Wastewater effluent is discharged to surface water or to soil. Primary sludge is treated (either stabilized or digested) and ultimately transported to its final destination: land applied as fertilizer, landfilled, or incinerated.

We evaluated two pathways for this archetype:

- Archetype 8.1: Flush toilet with sewer collection to a centralized WWTP that conducts primary treatment (i.e., settling). Wastewater effluent is discharged; wastewater treatment sludge is stabilized, then transported via truck to its final destination.
- Archetype 8.2: Flush toilet with sewer collection to a centralized WWTP that conducts primary treatment (i.e., settling). Wastewater effluent is discharged; wastewater treatment sludge is anaerobically digested with biogas recovery, then transported via truck to its final destination.

2.9 Archetype 9: Sewer Collection with Secondary Treatment

Archetype	Collection	Storage/Emptying	Transport	Treatment	Disposal
Sewer collection with secondary treatment	✓		✓	✓	✓

9

In this archetype, sewer systems are assumed to be closed and typically underground pipes. Secondary treatment includes the primary processes described above, with the addition of biological treatment, in which various bacteria consume the organic portions of the waste. For this analysis, secondary treatment is assumed to be a conventional plug flow activated sludge system. Wastewater effluent is discharged to surface water or to soil. Primary and secondary sludge is treated (either stabilized or digested) and ultimately transported to its final destination: land applied as fertilizer, landfilled, or incinerated.

We evaluated two pathways for this archetype:

- Archetype 9.1: Flush toilet with sewer collection to a centralized WWTP that conducts secondary treatment (i.e., biological treatment). Wastewater effluent is discharged; wastewater treatment sludge is stabilized, then transported via truck to its final destination.
- Archetype 9.2: Flush toilet with sewer collection to a centralized WWTP that conducts secondary treatment (i.e., biological treatment). Wastewater effluent is discharged; wastewater treatment sludge is anaerobically digested with biogas recovery, then transported via truck to its final destination.

2.10 Archetype 10: Sewer Collection with Tertiary Treatment (Nutrient Removal)

Archetype	Collection	Storage/Emptying	Transport	Treatment	Disposal
Sewer collection with tertiary treatment	✓		✓	✓	✓

10

In this archetype, sewer systems are assumed to be closed and typically underground pipes. Tertiary treatment includes primary and secondary processes; it is focused on the biological removal of nitrogen and phosphorus. Wastewater effluent is discharged to surface water or to soil. Primary and secondary sludge is treated (either stabilized or digested) and ultimately transported to its final destination: land applied as fertilizer, landfilled, or incinerated.

A variety of treatment operations can be used for nutrient removal. Which operation is carried out does not affect the emission factor for GHG emissions; however, different operations can use significantly different amounts of energy, which directly relates to the amount of GHG emissions associated with the treatment step. ERG used a combination of advanced processes (Bardenpho, membrane bioreactor, membrane bioreactor + reverse osmosis) to represent this archetype, and included an electricity demand sensitivity analysis.

We evaluated two pathways for this archetype:

- Archetype 10.1: Flush toilet with sewer collection to a centralized WWTP that conducts tertiary treatment (i.e., nutrient removal). Wastewater effluent is discharged; wastewater treatment sludge is stabilized, then transported via truck to its final destination.
- Archetype 10.2: Flush toilet with sewer collection to a centralized WWTP that conducts tertiary treatment (i.e., nutrient removal). Wastewater effluent is discharged; wastewater treatment sludge is anaerobically digested with biogas recovery, then transported via truck to its final destination.

3 Comparing Archetypes

3.1 Functional Unit

A functional unit provides the basis for comparing results in an LCA. The key consideration in choosing a functional unit is to ensure the sewage management pathways are compared on the basis of equivalent performance. In other words, an appropriate functional unit allows for an apples-to-apples comparison. The functional unit for this study is the management of human excreta produced by one person annually. The assessment only accounts for domestic sewage from humans, and industrial and commercial sewage as well as impacts from household food waste and chemical usage are excluded.

Results from this assessment can be scaled up to management of excreta at a regional or global level, based on the adoption of management archetypes. Therefore, the analysis also has a complementary functional unit: the annual management of regional and global human excreta.

3.2 Metrics

GHGs are the main focus of the analysis, but other environmental impacts are assessed as well, in order to provide a broader evaluation of potential issues associated with sewage treatment archetypes. These additional impacts are included as part of a recognition that wastewater systems can affect the environment in multiple ways. The balancing of such impacts is ultimately a local decision, but this analysis helps to identify themes and questions to consider. The following impact areas are included.

3.2.1 Climate/Climate Change

During storage and treatment, sewage may release methane (CH_4) and nitrous oxide (N_2O); energy used for transport and treatment releases carbon dioxide (CO_2). These and other GHG emissions contribute to global climate change. Following convention, we only account for fossil CO_2, excluding biogenic CO_2 (e.g., CO_2 derived from carbon in food consumed and excreted). The assessment does not account for non-biogenic sources of carbon that may contribute to the sewage management system (i.e., from industrial or commercial waste streams).

We quantify GHG emissions in terms of global warming potential (GWP) over a 100-year horizon and present the results of all emissions as kg CO_2-equivalents. The GWP of a GHG is its ability to trap extra heat in the atmosphere over time relative to CO_2. GWP values are taken from the IPCC Fifth Assessment Report using the GWPs that include climate-carbon feedback (IPCC 2013). These GWP values were also used in the Hierarchist version of the ReCiPe 2016 model (Huijbregts et al. 2017), from which other metric characterization factors were taken.

3.2.2 Other Metrics

This work focuses on climate effects, but we recognize the multi-faceted nature of sewage and related policy decisions. Therefore, to complement the analysis, we use the following additional metrics to provide perspectives on climate, health, and ecosystem issues.

3.2.2.1 Ecosystem/Eutrophication and Acidification

Human perturbations to nutrient cycling, especially of phosphorus and nitrogen, is one of the key threats identified in planetary boundary modeling. Eutrophication refers to the process in which ecosystems receive surplus amounts of limiting nutrients (typically phosphorus in freshwater or nitrogen in marine systems), which results in excessive growth of algae, reducing available oxygen and causing changes in species composition, biomass, or productivity (Mogollón, Beusen, et al. 2018; Mogollón, Lassaletta, et al. 2018). Acidification is the result of inputs with acid-basic chemistries—such as nitrogen oxides (NO_x) and sulfur oxides (SO_x)–inducing changes to terrestrial or aquatic systems that reduce base cations supply or increase proton (H+) supply (Irvine et al. 2017). We use globally applicable factors from ReCiPe 2016 for both impacts, expressed in terms of a species disappearance (Huijbregts et al. 2017).

3.2.2.2 Ecosystem/Ocean Acidification

Ocean acidification is directly related to the increase of CO_2 concentration in the atmosphere. As CO_2 dissolves into ocean water, it undergoes acid-base reactions, resulting in a pH decrease (Cao, Caldeira, and Jain 2007; Zeebe 2012). Small changes in ocean pH have consequences for many forms of marine life (and marine trophic systems), as many species rely on calcium carbonate for biological structures and pH directly affects the stability of calcium carbonate (Ishimatsu et al. 2005; Seibel and Walsh 2001). Ocean acidification is presented as a change in ocean pH; see Appendix D for a full discussion of this approach.

3.2.2.3 Human Health/Climate

In addition to assessing climate change impacts in terms of climate, as described above, we can relate GHG emissions to human health, via modeled changes in malnutrition, heat stress, disease vectors, etc. Recent global consensus efforts have judged these factors to be mature enough for inclusion in modeling studies (Frischknecht and Jolliet 2016). We use such factors to quantify disability adjusted life years (DALYs) associated with GHG emissions (Huijbregts et al. 2017).

3.2.2.4 Human Health/Particulate Matter

Sewage treatment is an energy-intensive process. Combustion-based energy sources, such as coal and biomass, emit particulate matter (fine particulates, especially those smaller than 2.5 µm, known as $PM_{2.5}$). In addition, particulate matter can be formed from secondary particulates (ammonium nitrates and ammonium sulfates) associated with ammonia (NH_3) emissions. Epidemiological studies have shown a clear relationship between particulate matter and human respiratory conditions (Apte et al. 2015; Jolliet et al. 2018). In many LCAs, particulate matter is one of the dominant human health issues associated with energy use. We quantify $PM_{2.5}$ equivalents emitted across systems, focusing on energy use; we include NH_3 emissions, as they are precursors to particulate matter formation. For comparison with other metrics, we also present these human health impacts as DALYs, using factors from ReCiPe 2016 (Huijbregts et al. 2017).

3.2.2.5 Human Health/Pathogens

Many pathogens rely on excreta as a means of transmission. Therefore, improving sewage handling and treatment is a key concern for WHO and UNICEF, which focus on safely managed sanitation in their data collection and advocacy efforts (WHO and UNICEF 2019). Pathogen management is critical to meeting the SDGs (Mraz et al. 2021). Although pathogen transmission is a highly localized phenomenon, the Global Water Pathogen Project describe an approach for modeling global pathogen burdens, based on population information, pathogen shedding rates, sanitation adoption, and pathogen survival during containment and treatment (Okaali et al. 2019), drawing on work for cryptosporidium (Hofstra et al. 2013) and rotavirus (Kiulia et al. 2015). We adopt this modeling approach to estimate pathogen burdens as a proxy for disease transmission and human health impacts. Pathogen impacts are presented as DALYs, in order to facilitate comparison to other metrics. See Appendix C for a detailed description of the calculation of this metric. Note that the approach used in this work excludes risks from other pathogens or exposure routes, such as helminths in land-applied sludge (Gyawali 2017).

3.3 Geographic Scope

3.3.1 Coverage and Representativeness

The analysis covers the entire world, focusing on global trends and global implications for sewage management with respect to GHGs and other impacts. To strike a balance between complexity and representativeness, we use a set of regions defined by both UN regional groupings,[5] and country income (World Bank 2019). The combination of geographic region (Figure 3.1) and income (Figure 3.2) leads to a total of 19 distinct calculation regions used in this assessment (Figure 3.3). The fundamental data unit is the country level; the data sources described in the following section and in Section 4 are either upscaled or downscaled to that level. Those country-level values are translated to the calculation regions based on population weighting.

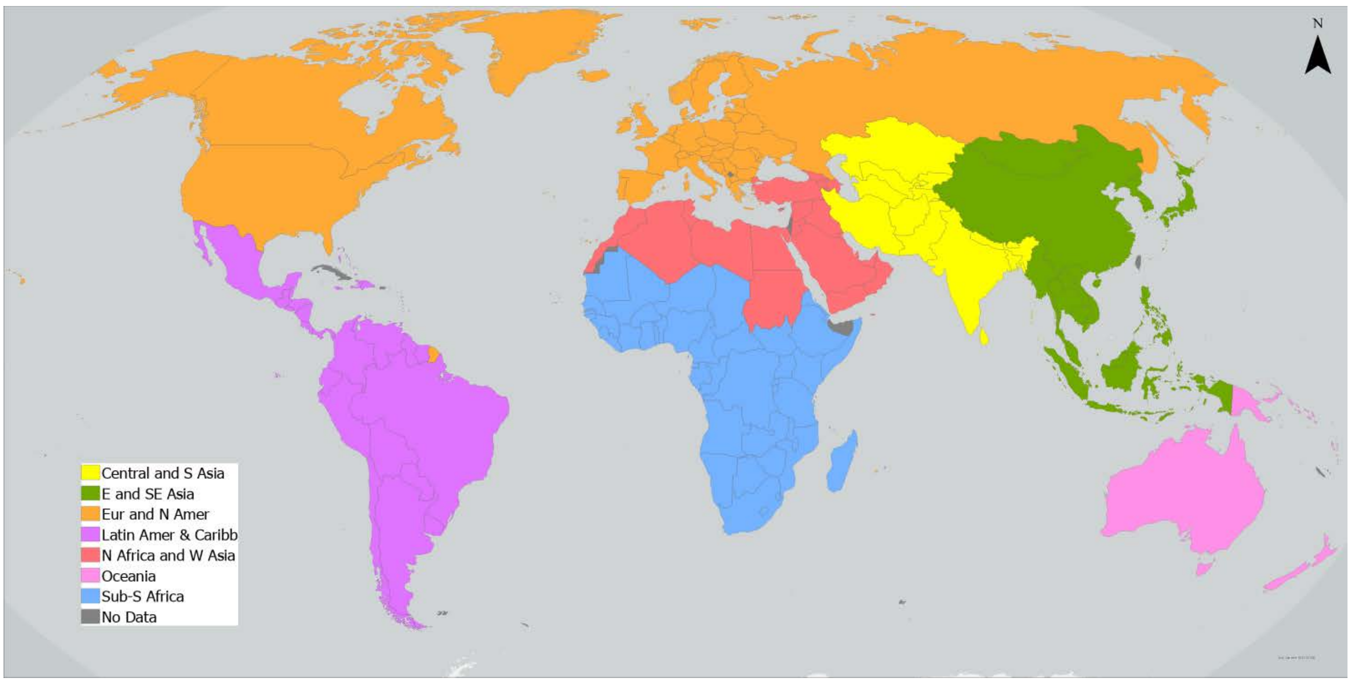


Figure 3.1: UN SDG geographic regions.

[5] United Nations SDG Indicators Regional Groupings: https://unstats.un.org/sdgs/indicators/regional-groups (accessed 2/1/22)

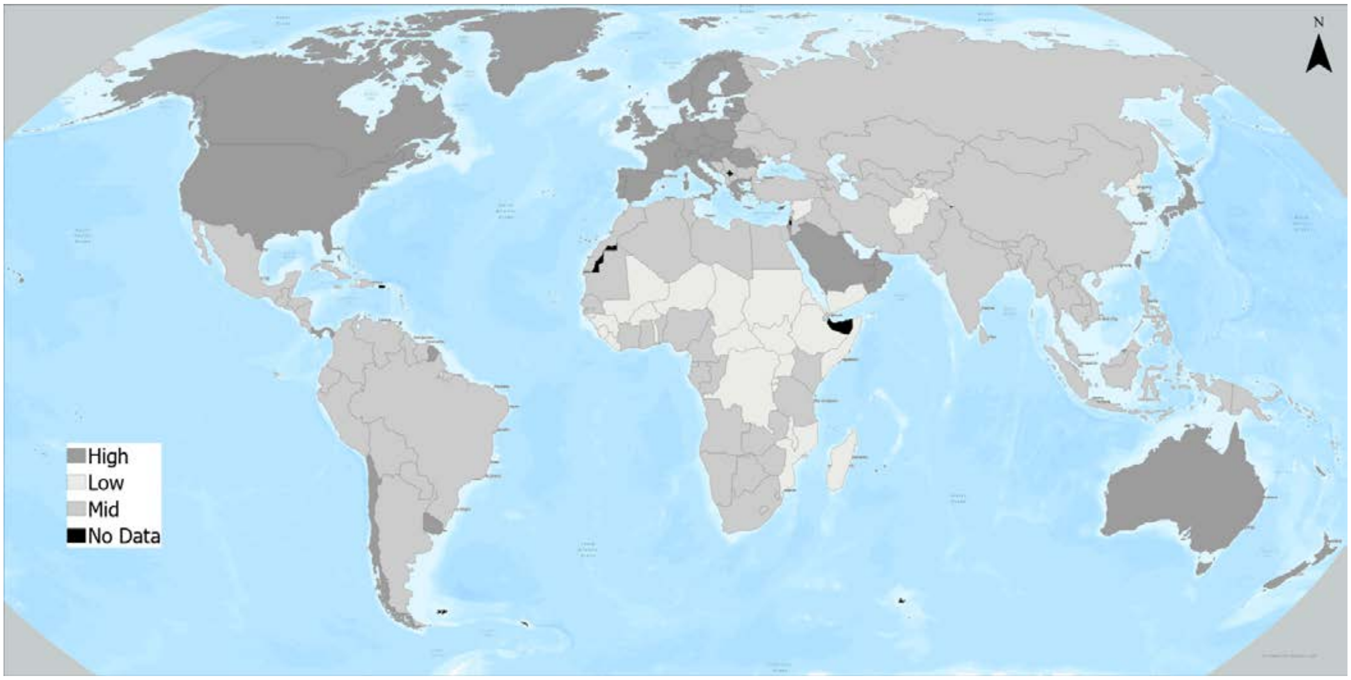


Figure 3.2: World Bank income levels (medium-high and medium-low are combined).

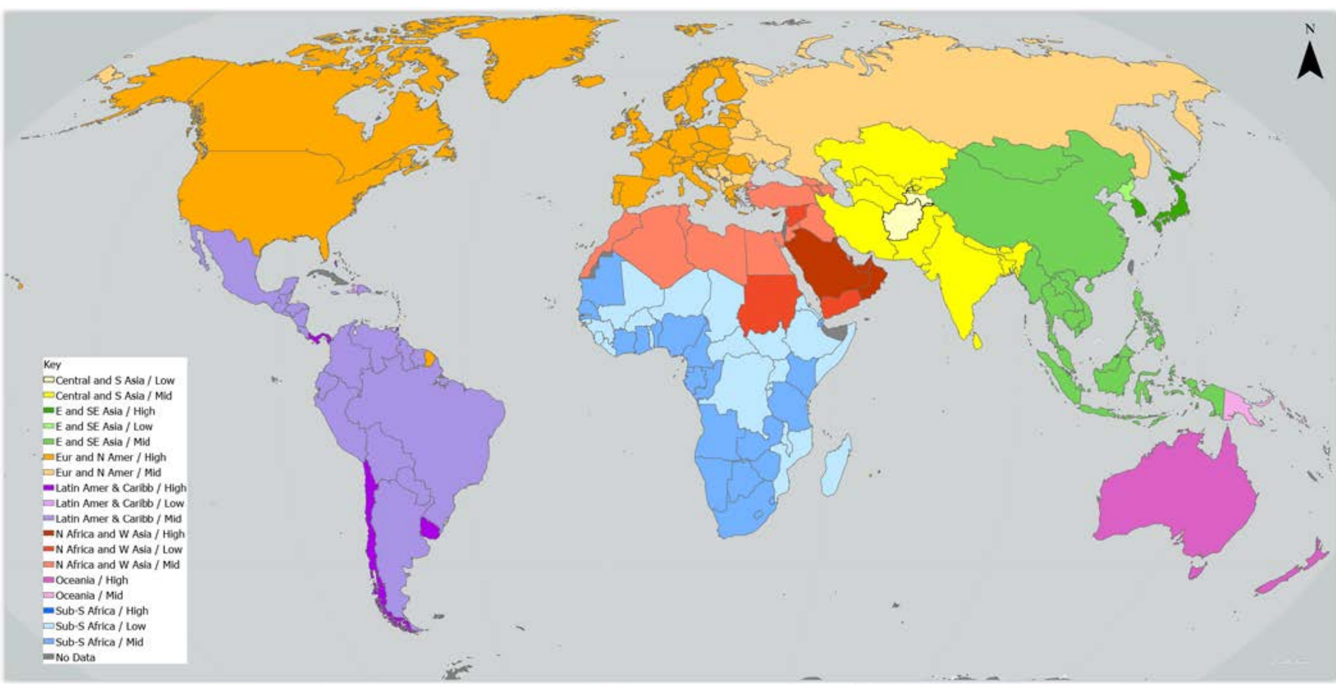


Figure 3.3: Calculation regions, combining UN SDG and World Bank groupings.

3.3.2 Geographic Data Sources and Assumptions

The data sources used in the project represent a range of spatial resolutions:

- Groundwater depth, at 30 arcseconds (~1 km at mid-latitudes) (Fan, Li, and Miguez-Macho 2013).
- Population, at 1/8° (~12 km) (B. Jones and O'Neill 2020; 2016).
- Country data, e.g., JMP sanitation statistics (WHO and UNICEF 2021).
- Regional data based on geographic or economic groups of countries, e.g., the shared socioeconomic pathways used for future scenarios (van Puijenbroek et al. 2014).

- Global values for emission factors, e.g., from IPCC (Bartram et al. 2019).

These disparate spatial scales are dealt with in two ways. For the intersection of datasets, we perform spatial overlays. For reported or estimated data at the country resolution (or lower, e.g., continent), we choose data from the highest resolution data available.

One of the key distinctions for modeling the distribution of sewage archetypes is demographics—the combination of population density and population income. The three demographic groups that are modeled are rural, urban low-income, and urban high-income. These groups are connected to JMP data, and they also have bearing on the likelihood of archetype or pathway adoption (e.g., flush latrines are more prevalent in urban settings than rural; septic tanks are more likely to be emptied in high-income than low-income settings).

Another set of distinctions necessary for estimating emission factors and discharge pathways are physical: depth to groundwater, distance to marine ecosystems, distance to freshwater, trophic state of freshwater, etc. These physical parameters need to be related to the demographic parameters. To estimate the fraction of a given demographic with a given physical parameter (e.g., rural population with depth to groundwater less than 2 meters), we overlay datasets in a geographic information system (GIS). Each data set is transformed to a consistent coordinate system (e.g., Mollweide), and each data set is overlaid with demographic groups. Within each country, each demographic group is assigned a fraction of the physical parameter of interest, such as depth to groundwater or distance to coast.

In the case of reported or estimated data, these data are available at country, regional, or global levels. We use higher-resolution data when available (i.e., we use country-level data if they are available, regional data if country data are not available, and global data by default if country- and region-level data are unavailable).

3.4 Drivers

This section discusses anticipated drivers for the impacts and archetypes discussed above. These anticipated drivers informed the initial efforts for data collection.

3.4.1 GHGs (Climate, Human Health, and Ocean Acidification)

Uncontrolled anaerobic processes are problematic for GHG emissions. Carbon is converted to CH_4, and nitrogen releases N_2O as it is nitrified and denitrified; both of these gases are potent GHGs. While N_2O is emitted during aerobic processes, too, sewage management systems that allow for anaerobic conditions but do not control the anaerobic processes or do not capture gases will be problematic from a GHG perspective. Anaerobic digesters are an example of a controlled process, in which aerobically oxidized organic matter is further digested under anaerobic conditions and biogas is captured and used for energy production or flared.

Energy use and energy source are also of concern for GHGs. Depending on the carbon intensity of the energy grid, energy-intensive processes, such as tertiary treatment, may have non-negligible CO_2 contributions. Such CO_2 contributions will also directly affect ocean acidification.

3.4.2 Particulate Matter (Human Health)

Energy use is also of concern for particulate matter, but transport may be as well. The importance of transport for particulate matter (and also for GHGs) is proportional to the distances traveled, as well the modeled vehicle types.

Ammonia (NH_3) is a precursor to particulate matter formation. There can be off-gassing of NH_3 due to biological processes that occur during storage or treatment. Therefore, management options that involve collection and holding of excreta may have higher particulate matter impacts.

3.4.3 Eutrophication and Acidification (Ecosystem)

Terrestrial acidification is typically driven by NO_x, SO_x, and NH_3 emissions. Combustion processes are typically the main sources of the oxides; NH_3 can be emitted from some sewage containment systems.

With respect to marine eutrophication, NO_x and NH_3 may be emitted to air and subsequently deposit on marine systems, or inland, where they can be transported to marine systems. Therefore, combustion can be of concern for marine eutrophication as well.

One of the key drivers for freshwater and marine eutrophication is the level of treatment, which relates to the concentration of nutrients and location of discharge. When there is no treatment, the degree to which emissions are directly discharged to receiving water bodies (both freshwater and marine) likely control overall eutrophication impacts.

4 Data Sources and Modeling Methods

This section provides a summary of datasets and modeling methods used for the analysis. Data are broadly grouped into categories for demographics, sanitation statistics, physical parameters, and emission factors. Appendix F provides global values for many of the demographic, adoption, and physical parameters.

4.1 Overview of Modeling Approach

All calculations in the assessment are global or regionally-based. The model uses the following inputs to determine the weighted average environmental and human health impacts at these different geographic scales:

- Excretion of nitrogen and BOD per person per region.
- The split of the rural and urban fractions of the population with the following characteristics:
  - Proximity to water (coastal or fresh).
  - Groundwater level.
  - Use of communal versus household sanitation.
  - Directly releasing versus further treating emptied solids.
  - Handling of wastewater treatment sludge through different options such as anaerobic digestion, landfill, and incineration.

These combinations of characteristics result in a large number of possible pathways, as shown in Appendix B. The assumptions and data sources used to identify the characteristics listed above are further described in the subsequent sections (Section 4.2 through 4.6). Section 4.7 describes data sources used to track the initial waste input through these pathways. Emission factors are developed for both process emissions (i.e., emissions resulting from direct activities associated with the sewage) and for life cycle factors associated with upstream processes or avoided processes. Section 4.8 describes the development of key process emission factors, while 4.9 describes the modeling approach for incorporating life cycle emission factors.

4.2 Geography

Basic definitions of countries and their geographic and economic groupings are from the UN classification of sustainable development regional groups,[6] and development indicators are from the World Bank (2019). Human Development Indices (HDI) for each country are from the UN Human Development Reports.[7]

4.3 Demographics

4.3.1 Population

This assessment uses UN projections for current and projected total population (UN DESA 2019a).

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[6] United Nations SDG Indicators Regional Groupings: https://unstats.un.org/sdgs/indicators/regional-groups (accessed 7/1/21)

[7] United Nations Human Development Data Center: http://hdr.undp.org/en/data (accessed 7/1/21)

4.3.2 Rural/Urban

The distinction between urban and rural populations is complex, with many countries and statistical agencies applying unique definitions. For example, the UN Urbanization Prospects report notes that "the urban and city estimates presented in this report are based on the definitions used for statistical purposes by the countries and areas themselves… [and] the lower limit above which a settlement is considered to be urban varies considerably, ranging between 200 and 50,000 inhabitants." (UN DESA 2019b). The U.S. National Aeronautics and Space Administration Socioeconomic Data and Applications Center used population counts and nighttime lighting to define urban areas (CIESIN 2012). Therefore, for consistency in this work, we use the national urban/rural estimates provided by the JMP, which are ultimately based on individual countries' definitions of urban and rural. While these urban and rural fractions will change with time, we hold them constant for consistency of modeling and to standardize the interpretation of future emissions estimates.

4.3.3 Urban Poverty

Within the population that is urban, we model fractions that are low- and high-income. This distinction is necessary to capture the different sanitation practices that can be adopted in the same city. Some spatially explicit GDP data sets start from GDP at a national or subnational level and then distribute it spatially based on population (e.g., Kummu, Taka, and Guillaume 2018). While this approach captures the GDP distribution associated with cities versus rural areas, it does not distinguish between the high-GDP and low-GDP zones of a city. (The concept of low- and high-GDP zones of a city is something of an artifact for a sewage analysis, as human commuting patterns mean that certain populations, especially the urban-high-income group, may distribute sewage generation among urban centers and suburban areas. Tracking the movements of people is beyond the scope of this analysis, which only requires capturing the types of sewage management options available to the different demographic groups.)

The best available approach, therefore, is to use estimates for urban poverty in order to divide the urban population according to these country or regional estimates. The World Bank provides estimates for regional (i.e., Latin America, Eastern Europe, Sub-Saharan Africa, South Asia, Middle East and North Africa, and East Asia-Pacific) urban poverty fractions up to 2002, based on income levels of $1 and $2 per day, adjusted for 1993 purchasing parity (Ravallion, Chen, and Sangraula 2007). In addition, the World Bank World Development Indicators provide country-level data for urban poverty through 2015 with a range of reporting frequencies that vary by country (e.g., Eritrea last reported data in 1993) (World Bank 2019). Neither data set provides estimates for high-income countries. For the purposes of this analysis, however, we assume that while there are many socioeconomic differences between the urban-low-income and urban-high-income groups, sewage management is not significantly different between these urban income groups for high-income countries.

4.4 Sanitation Practices

Unless stated otherwise, adoption fractions are based on the assumptions listed in the sections below.

4.4.1 Communal/Household Latrine Use

We assume that rural use of latrines is communal (except in high-income countries), that urban low income is split 50:50 between communal and household income, and that urban high income is household. There are exceptions to this assumption, such as Swachh Bharat Mission in India, which aims to provide all rural households with individual household latrines (Mehta 2018). The distinction is important: in the case of dry latrines with low groundwater, the CH_4 emission factor for household latrines is 0.06 kg CH_4/kg BOD, while that for communal latrines is 0.3 kg CH_4/kg BOD, so the model may overestimate the emissions from dry latrines. With the assumption described above, the emissions for a single global user of dry pit latrines are 220 kg CO_2eq/user/year for unlined latrines and 100 kg CO_2eq/user/year for lined latrines. With the opposite assumption—that all rural latrines are household—the emissions for a single user drop to 210 and 60 kg CO_2eq/user/year, respectively. These are changes of 3% and 40%. While the latter is significant, the actual adoption of household latrines in rural settings is likely lower (closer to modeling assumptions) rather than higher.

4.4.2 Flowing/Stagnant Sewers

We assume that sewer flow is a function of income, with low-income areas having stagnant flow, high-income areas having flowing sewers, and mid-income areas split 50:50. The research team is unaware of a data set that consistently captures whether sewers are flowing or stagnant. We acknowledge that topography or other conditions might also be used to estimate the flow regime. In the absence of these data, however, the team has used a straightforward assumption that can be evaluated in future work.

4.4.3 Collection and Stabilization

The sewage management chain has numerous decision points for handling fecal matter. We make the following assumptions in our modeling approach:

- Is emptied fecal matter directly released (discharged) to the environment or transported for some type of treatment? Rural: low-income releases, mid-income 50:50, and high-income treats; urban low-income tends to release (50:50 in high-income countries); urban high-income tends to treat (50:50 in low-income countries).
- Is treated fecal matter sent to landfill, stabilization, or to WWTP? Rural is 75% landfill, 25% stabilization; urban is 50% WWTP, 30% stabilization, 20% landfill.
- Is stabilized material composted or anaerobically digested? Anaerobic digestion (AD) is used in high-income urban areas; otherwise, material is composted.

4.4.4 Sewer Water Discharge

The ultimate discharge of water collected in sewers, both with or without treatment, varies by region and by country. While the majority of water collected in sewers is discharged to aquatic systems, some areas do use it for irrigation (Singh, Deshbhratar, and Ramteke 2012; Tzanakakis, Paranychianaki, and Angelakis 2007), and others practice direct potable reuse (H. Lee and Tan 2016). In this model, we use country-level estimates for wastewater reuse (E. R. Jones et al. 2021) as a proxy for the extent to which wastewater is discharged to soil, rather than to aquatic systems. Note that the model does not account for direct potable reuse, but rather assumes all reused wastewater is used for irrigation. While individual country reuse practices vary from 0% to 100%, the global, population-weighted value is approximately 3%. We assume that the discharge of wastewater to water and to soil is the same for both treated and untreated sewer systems.

4.4.5 WWTP Sludge

There are two main decision points when managing WWTP sludge. We make the following assumptions in our modeling approach:

- Is sludge released (discharged) or subject to further treatment? Rural: low-income releases, mid-income 50:50, and high-income treats; urban low-income tends to release (50:50 in high-income countries); urban high-income tends to treat (50:50 in low-income countries).
- When sludge is treated, is it anaerobically digested, composted, incinerated, landfilled, or land applied?[8] These data are based on a survey of (mostly) European countries that includes data for agricultural use, compost, landfill, dumping at sea, and incineration (Rorat et al. 2019). We adjust for country income, resulting in the following table of sludge handling practices (Table 4.1).

Table 4.1: Summary of WWTP sludge handling practices by demographic group and regional income.

Demographic Group	Sludge Handling	Regional Income Level		
		Low	Mid	High
Rural	AD	0%	0%	0%
	Compost	0%	25%	50%

[8] Digestate from anaerobic digestion has different destinations such as incineration, landfill, land application and compost.

Demographic Group	Sludge Handling	Regional Income Level		
		Low	Mid	High
	Incineration	0%	0%	0%
	Landfill	50%	25%	25%
	Land apply	50%	50%	25%
Urban low-income	AD	0%	0%	19%
	Compost	0%	18%	15%
	Incineration	0%	30%	25%
	Landfill	100%	7%	6%
	Land apply	0%	44%	36%
Urban high-income	AD	0%	19%	28%
	Compost	18%	15%	13%
	Incineration	30%	25%	22%
	Landfill	7%	6%	5%
	Land apply	44%	36%	32%

4.4.6 Emptying of Latrines

Thye et al. (2011) and Tilley et al. (Tilley et al. 2014) describe the range of methods for emptying pit latrines, which range from manual excavation to manual pumping to vacuum trucks. A number of factors affect the choice of latrine emptying techniques. Certainly, higher income areas are more likely to use vacuums. However, The UN-HABITAT Vacutug has an emptying speed of 4300 L/min.[9] With typical pit latrines ranging from 2–7 m^3 (Chowdhry and Koné 2012), the operation of the vacuum will be quick relative to the time spent driving the vacuum truck. Therefore, it is appropriate to exclude the operation of the vacuum itself, while modeling the transport and disposition of extracted materials.

In surveys, emptying of latrines can be relatively infrequent. For example, in Dar Es Salaam, Tanzania (Jenkins, Cumming, and Cairncross 2015), typical emptying times are as follows: 8.2 years (unlined), 6.5 years (partially lined), 8.5 years (fully lined), 4.7 years (drum/tire), 5.5 years (other, mainly septic and sewer). Data for a variety of countries are shown below in Table 4.2, from Chowdhry and Koné (2012).

Table 4.2: Frequency of latrine emptying in surveyed countries.

Continent	Country	≥3 Times per Year	Twice per Year	Once per Year	Every 2 Years	Every 3–5 Years	Every 6–10 Years	>10 Years	Average Period (Years)
Asia	Bangladesh	3%	4%	13%	37%	23%	11%	10%	3.9
Asia	Cambodia	2%	2%	14%	13%	34%	21%	15%	5.3
Asia	India		16%	23%	23%	17%	18%	2%	3.1
Asia	Malaysia		6%	16%	42%	19%	14%	2%	3.2
Asia	Vietnam		7%	18%	0%	39%	35%	0%	4.6
Africa	Burkina Faso		13%	19%	26%	20%	15%	7%	3.6
Africa	Ethiopia	3%	18%	30%	48%	1%	0%	0%	1.4
Africa	Kenya		30%	29%	41%	0%	0%	0%	1.3
Africa	Nigeria		11%	32%	57%	0%	0%	0%	1.5
Africa	Senegal	5%	30%	39%	16%	7%	1%	2%	1.5

[9] Engineering for Change: https://www.engineeringforchange.org/solutions/product/the-vacutug/ (accessed 2/1/22)

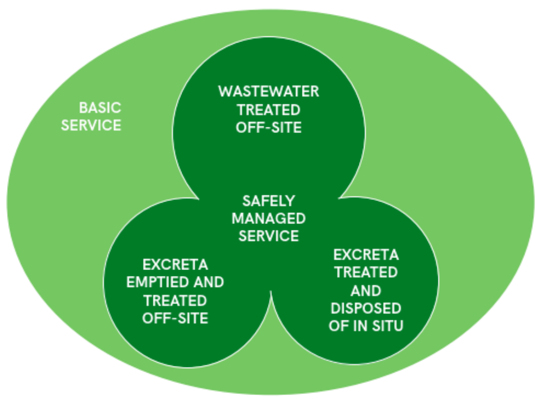
Table notes: Data from Table 6 of Chowdhry and Koné (2012). The last column is an unweighted average of emptying periods for each country; the unweighted averages are 4.0 and 1.9 years for Asia and Africa, respectively.

Taken together, Table 4.2 suggests that emptying the latrines is relatively infrequent, and the preceding discussion shows the process may be relatively quick (if performed mechanically), with any energy use insignificant. Therefore, energy required to empty latrines is excluded from the modelled impacts. The process of emptying excreta is, however, a point of exposure to human pathogens, and this exposure is accounted for in the model.

4.5 Archetype Scenarios

The JMP provides annual updates to country-specific information on sewage management, as well as definitions of categories of their sanitation ladder, shown in Figure 4.1 (WHO and UNICEF 2017). This JMP data is used to define the current implementation of archetypes globally.

The Global Water Pathogen Project includes collated JMP data up to 2020.[10] The authors of this data set have also published work cited here regarding pathogen modeling (Hofstra et al. 2013; Kiulia et al. 2015).



SERVICE LEVEL	DEFINITION
SAFELY MANAGED	Use of improved facilities that are not shared with other households and where excreta are safely disposed of in situ or transported and treated offsite
BASIC	Use of improved facilities that are not shared with other households
LIMITED	Use of improved facilities shared between two or more households
UNIMPROVED	Use of pit latrines without a slab or platform, hanging latrines or bucket latrines
OPEN DEFECATION	Disposal of human faeces in fields, forests, bushes, open bodies of water, beaches or other open spaces, or with solid waste

***Note:** improved facilities include flush/pour flush to piped sewer systems, septic tanks or pit latrines; ventilated improved pit latrines, composting toilets or pit latrines with slabs.*

Figure 4.1: JMP sanitation ladder definitions (WHO and UNICEF 2017).

In addition to the current JMP-reported archetype adoption, we developed six notional scenarios to model potential changes in global sanitation management. The first of these scenarios, "No Open Defecation," starts

[10] Global Water Pathogen Project: https://data.waterpathogens.org/dataset/world-countries (accessed 2/1/22)

from the current JMP data, and within each region, moves half of the fraction of the population practicing open defecation to the CBS system, while the other half is distributed proportionally among the remaining archetypes. The remaining five scenarios are based on regional trends in JMP data from 2000 and 2017 across the five categories of the sanitation ladder (Open Defecation, Unimproved, Limited, Basic, and Safely Managed) (WHO and UNICEF 2019). Using average sanitation management values for urban and rural populations in each region as a starting point, we calculated 2050 adoption values for sanitation ladder categories based on asymptotic exponential growth or decrease.

Sanitation ladder changes were translated to changes in the archetypes for this study using the mapping shown in Table 4.3. Combinations of sanitation ladder categories indicated by "+" in the table were averaged to estimate rates of change for archetypes in this study.

Table 4.3: Mapping between ERG archetypes and JMP sanitation ladder.

ERG Archetypes	UNICEF Categories
Open Defecation	Open Defecation
Sewer—No treatment	Open Defecation
Dry Pit Latrine—Unlined	Unimproved
Dry Pit Latrine—Lined	Limited + Unimproved
Wet Pit Latrine—Lined	Limited + Basic
Container Based	N/A
Septic	Safely Managed
Sewer—Primary Treatment	Safely Managed
Sewer—Secondary Treatment	Safely Managed
Sewer—Tertiary Treatment	Safely Managed

We created the "2050 Trend" scenario from the asymptotic growth or decay based on 2000 and 2017 data. "2050 Trend, Safe Sanitation" involved further modifications by proportionately shifting all populations to "Safely Managed" categories: septic and WWTP.

Using the "2050 Trend" as a starting point, three other scenarios explore possible changes. These just represent theoretical scenarios with the aim to understand how certain management changes impact environmental and health findings. The "2050 Trend + High CBS" assumes CBS increased from 0% to 50% between 2017–2050, decreasing all other archetypes proportionately. "2050 Trend, all WWTP to Primary" and "2050 Trend, all WWTP to Tertiary" shift all predicted WWTP increases (for wastewater not currently managed in a wastewater facility) to one type of WWTP; all other sanitation management categories remain at "2050 Trend" levels. We developed these archetype adoption scenarios for urban and rural populations, and the urban fraction was further subdivided into low and high income based on regional urban income. Table 4.4 and Figure 4.2 present these archetype scenarios. Figure 4.3 shows the current archetype adoption across all study regions.

Note that the comparison of scenarios helps to highlight certain points or address research questions. For example, there are cases in which advanced treatment systems for wastewater may fail or may be operated inefficiently. In this case, the predicted effluent discharges are not met, and the system may perform more like a primary treatment plant than a secondary or tertiary treatment plant. Rather than modeling a failure rate for such WWTPs, we compared the scenarios of high tertiary treatment and high primary treatment; the latter is similar to the situation in which a large fraction of advanced treatment plants are not operated properly. Likewise, rather than explicitly modeling an upgrade from primary to tertiary treatment plants, the scenario "2050 Trend, all WWTP to Tertiary" could represent the situation in which primary plants are upgraded to tertiary and new primary plants are built to replace those that were upgraded.

Table 4.4: Summary of archetype adoption used in this study, by scenario.

Management Archetype	Current JMP (Default)		No Open Defecation		2050 Trend		2050 Trend, Safe Sanitation		2050 Trend + High CBS		2050 Trend, All WWTP to Primary		2050 Trend, All WWTP to Tertiary	
	Rural	Urban	Rural	Urban	Rural	Urban	Rural	Urban	Rural	Urban	Rural	Urban	Rural	Urban
Open defecation	15%	3%	0%	0%	5%	1%	0%	0%	2%	0%	5%	1%	5%	1%
Dry pit latrine/ unlined	9%	6%	23%	15%	7%	5%	0%	0%	3%	2%	7%	5%	7%	5%
Dry pit latrine/ lined	33%	35%	35%	32%	34%	32%	0%	0%	17%	16%	34%	32%	34%	32%
Wet pit latrine/ lined	2%	3%	2%	3%	2%	3%	0%	0%	1%	1%	2%	3%	2%	3%
Septic	12%	16%	8%	18%	16%	17%	40%	38%	8%	9%	16%	17%	16%	17%
CBS	0%	0%	8%	1%	0%	0%	0%	0%	50%	50%	0%	0%	0%	0%
Sewer/no Treatment	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Sewer/ primary	15%	19%	17%	22%	21%	24%	40%	41%	10%	12%	24%	25%	11%	17%
Sewer/ secondary	8%	10%	5%	7%	10%	11%	13%	14%	5%	5%	7%	9%	7%	9%
Sewer/ tertiary	6%	7%	2%	2%	6%	7%	6%	7%	3%	4%	6%	7%	19%	15%

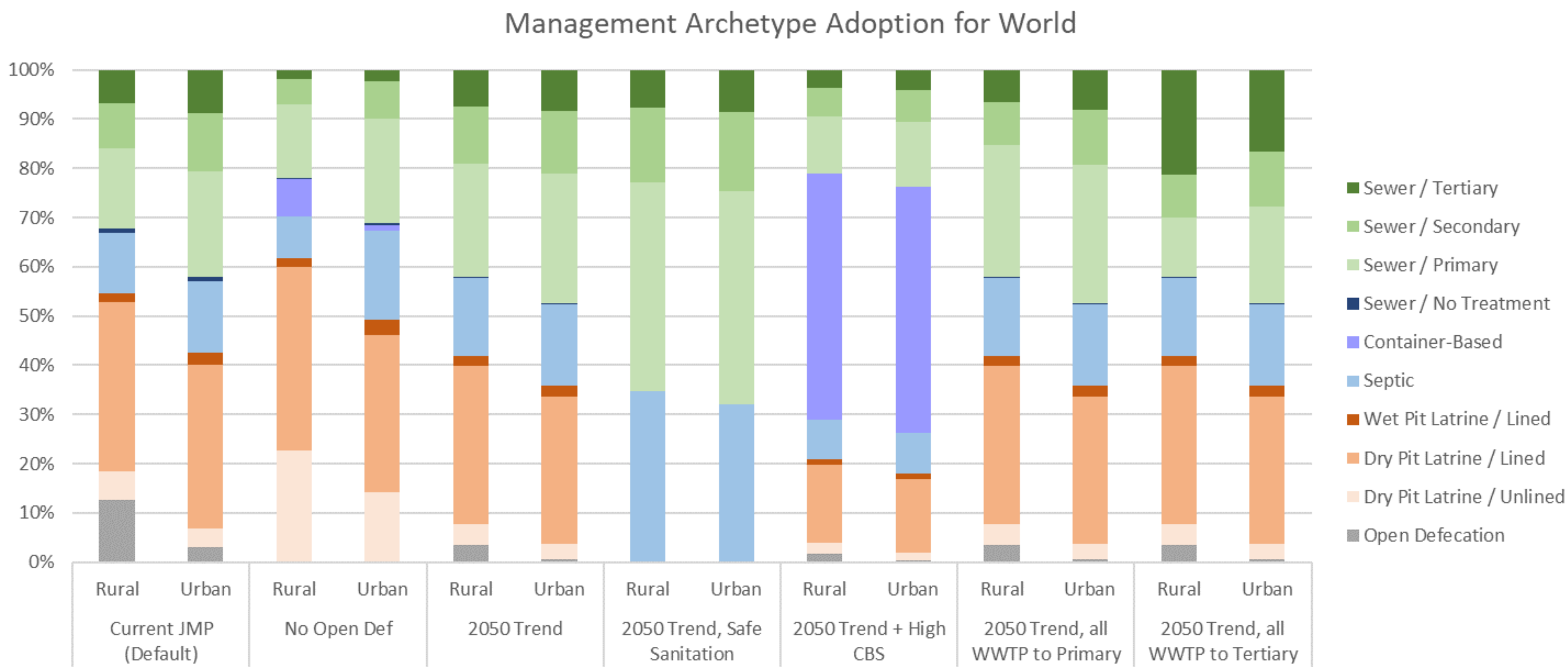


Figure 4.2: Summary of adoption archetypes used in this study, with rural and urban breakout shown.

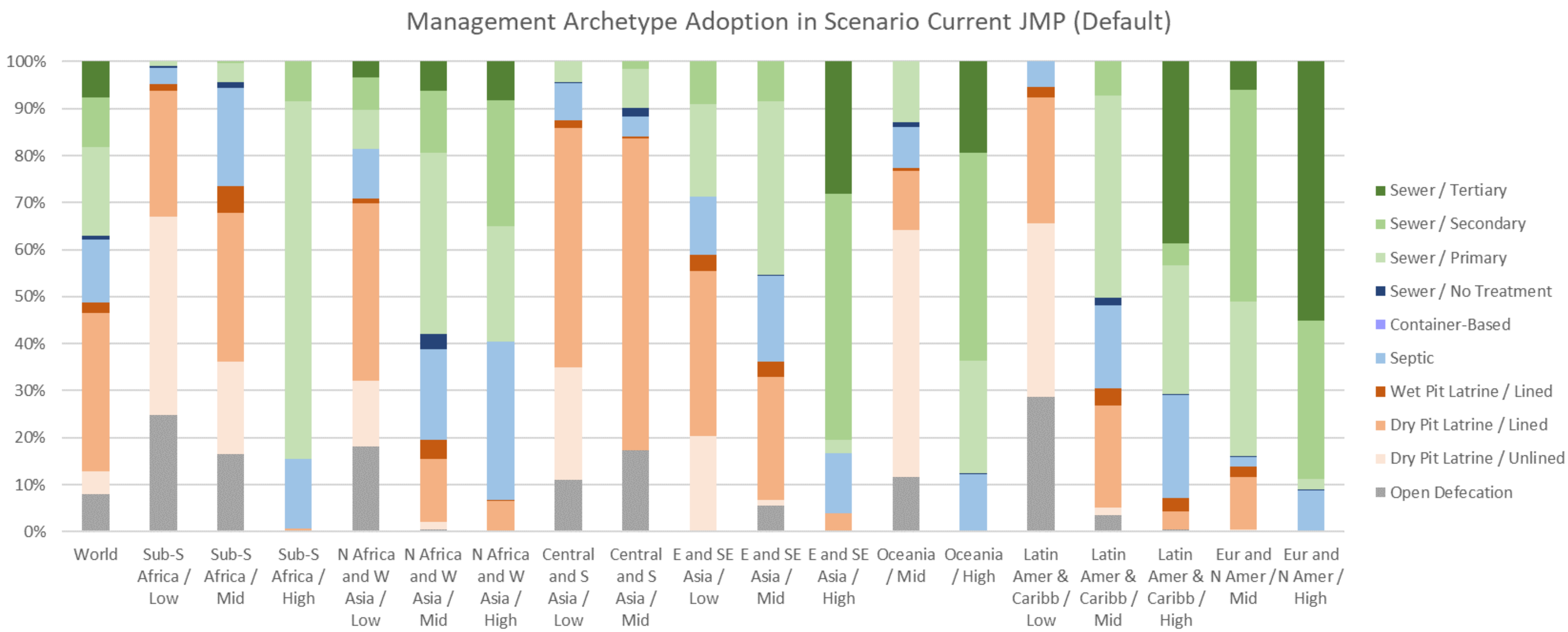


Figure 4.3: Summary of adoption archetypes used in this study (as combination of rural and urban) across study regions.

4.6 Landscape

In addition to political or cultural practices related to sewage management, the physical landscape provides important context as well, as climate may influence emission factors and local hydrology influences the fate of discharge material.

4.6.1 Distance to Marine Water

The Center for International Earth Science Information Network (CIESIN) provides information about rural and urban fractions of countries in the following categories: coastal distance (5, 10, 100, 200 km), climate zones (observed 1976–2000 and 2001–2025), population density, elevation, and biomes (CIESIN 2012). The 5-km coastal distance is used to estimate the fraction of the population for which either direct deposit or runoff (e.g., from open defection, pit latrines, sewer without treatment) from could reach marine systems.

4.6.2 Distance to Freshwater

Kummu et al. (2011) provide a global analysis of urban, peri-urban, and rural distances to freshwater, down to 2 km, including information to distinguish between lotic systems (e.g., rivers) and lentic systems (e.g., lakes). The 2-km distance is used to determine the fraction of the population for which either direct deposit or runoff could reach freshwater systems.

4.6.3 Groundwater Depth

Fan et al. (2013) model global groundwater depth at a 30-second resolution. At the country level, we model the distribution of groundwater depth as exponential (many of the input parameters are exponential). From country variance, we can calculate parameters for the distribution (variance = $1/\text{lambda}^2$). Then, the cumulative distribution at a depth < x is given by CDF = 1 - exp(-lambda*x). We use a depth of 2 m to determine the fraction of the population that lives with higher groundwater versus low groundwater. Note that calculations are performed at country level, but we do not differentiate between urban and rural populations in this calculation; i.e., both demographic groups are assigned the same fraction of high and low groundwater in a given country. The global average for high:low groundwater is 8%:92%. All regions have <10% high groundwater, with East and SE Asia middle income being the exception (17% high groundwater).

4.6.4 Trophic Status

We use a global database that estimates potential, rather than actual, eutrophication (McDowell, Noble, Pletnyakov, Haggard, et al. 2020; McDowell, Noble, Pletnyakov, and Mosley 2020). These data are at watershed level; we overlay them with country boundaries to calculate area-weighted country values. These data are used to determine the fraction of population that could discharge material to unified versus not unified water bodies, both freshwater and marine.

4.7 Generation of Waste

The framework for this project tracks the movement of multiple substances through the sewage management chain, where each emission is connected to basis-specific emission factors, such as kg CH_4/kg BOD. Table 4.5 briefly summarizes these emission factor sources.

Table 4.5: Sources for estimating generation of quantities and components of excreta.

Substance	Source
Nitrogen	Following Vol 5, Ch 6 (combining protein supply, consumption, and fraction of nitrogen in protein) (Bartram et al. 2019; FAOSTAT 2018)
BOD	Vol 5, Chapter 6, Table 6.4 (Bartram et al. 2019)
Mass excreta	Rose et al. (2015)
Phosphorus in excreta	Rose et al. (2015)
Pathogens	See pathogen method description (Section Appendix C)

4.8 Process Emissions

In the framework for this work, we model emissions from biochemical processes by using emission factors that relate the quantity of a tracked substance (e.g., nitrogen or BOD) to generated emissions. These process emission factors cover both natural processes (e.g., the release of N_2O from a water body) and engineered processes (e.g., N_2O emissions during secondary treatment in a WWTP).

4.8.1 GHGs

In estimating GHG emissions, this work has aimed to follow guidelines presented by IPCC (Table 4.6).

Table 4.6: IPCC process emission sources.

Volume	Volume Title	Chapter	Chapter Title	Reference
4	Agriculture, Forestry, and Other Land Use	11	N_2O emissions from managed soils and CO_2 from lime and urea	(Hergoualc'h et al. 2019)
5	Waste	2	Waste generation, composition, and management	(Towprayoon, Shmarin, et al. 2019)
5	Waste	3	Solid waste disposal	(Towprayoon, Ishigaki, et al. 2019)
5	Waste	4	Biological treatment of solid waste	(Pipatti et al. 2015)
5	Waste	5	Incineration and open burning	(Towprayoon, Kim, et al. 2019)
5	Waste	6	Wastewater	(Bartram et al. 2019)

Table 4.7 summarizes the emission factors used in the model. Note that in the case of open defecation and CBS, there are no modeled process emissions of GHGs. For open defecation, IPCC does not provide emission factors; the lack of enclosed storage (or treatment) results in very limited anaerobic conditions to produce CH_4 or N_2O, the most problematic GHGs associated with sewage management. In the case of CBS, we assume that the frequent (weekly) emptying of containers are relatively rapid processing of collected material also prevents emission of significant GHGs.

There were cases in which applying these process emission factors was nuanced, or cases in which additional sources were used, as described below.

- A review of latrines (Graham and Polizzotto 2013) cites other work that suggests the fraction of nitrogen leached to groundwater may be 1–50%. IPCC (Hergoualc'h et al. 2019) estimates the fraction of nitrogen applied to managed soils that is lost to leaching and runoff at 25% for wet climates and 0% for dry climates. Therefore, in this work, we use low, expected, and high values of 1, 24, and 50% for wet climates and 0% for dry climates. These values are applied to both lined and unlined latrines.
- Septic systems have emissions related to leach field emissions, which are accounted for in IPCC Volume 5, Table 6.8A (Bartram et al. 2019); the emission factor for nitrogen leached (i.e., runoff) is from IPCC Volume 4, Table 11.3 (Hergoualc'h et al. 2019).

Table 4.7: Summary of emission factors. Units for values are in kg substance / kg basis.

						Source				
Archetype	**Stage**	**Substance**	**Compartment**	**Value**	**Basis**	**IPCC Table**	**IPCC Volume**	**IPCC Chapter**	**Source Other**	**Note**
Dry latrine, communal use, low groundwater	Storage	CH_4	Air	0.3	BOD	6.3	5	6		
Dry latrine, household use, low groundwater	Storage	CH_4	Air	0.06	BOD	6.3	5	6		
Dry latrine (high groundwater) or wet latrine	Storage	CH_4	Air	0.42	BOD	6.3	5	6		
Septic	Storage	CH_4	Air	0.3	BOD	6.3	5	6		
Latrine (dry or wet climate)	Leaching	N_2O	Air	0.011	N	11.3	4	11		A
Septic	Leaching	N_2O	Air	0.0045	N	6.8A	5	6		
Sewer, no treatment, Stagnant	In sewer	CH_4	Air	0.3	BOD	6.3	5	6		
WWTP secondary or tertiary	Treatment	N_2O	Air	0.016	N	6.8A	5	6		
WWTP secondary or tertiary	Treatment	CH_4	Air	0.018	BOD	6.3	5	6		
Multiple	AD	CH_4	Air	0.004	BOD				See LCA data	
Multiple	Compost	CH_4	Air	0.02	BOD				See LCA data	
Multiple	Compost	N_2O	Air	0.03	N				See LCA data	
Multiple	Land application	N_2O	Air	0.024					See LCA data	
Multiple	Landfilling	N_2O	Air	0.025					See LCA data	
Multiple	Landfilling of sludge	CH_4	Air	0.004						
Multiple	Landfilling of digestate	CH_4	Air	0.005						
Multiple, dry climate	Discharge to soil	N_2O	Air	0.005	N	6.8A	5	6		
Multiple, wet climate	Discharge to soil	N_2O	Air	0.006	N	11.1	4	11		
Multiple, eutrophied water body, marine or fresh	Discharge to water	N_2O	Air	0.019	N	6.8A	5	6		

						Source				
Archetype	Stage	Substance	Compartment	Value	Basis	IPCC Table	IPCC Volume	IPCC Chapter	Source Other	Note
Multiple, non-eutrophied water body, marine or fresh	Discharge to water	N_2O	Air	0.005	N	6.8A	5	6		
Multiple, marine or lentic water	Discharge to water	CH_4	Air	0.11	BOD	6.3	5	6		
Multiple, lotic water	Discharge to water	CH_4	Air	0.021	BOD	6.3	5	6		
Latrine or stagnant sewer	Storage or in sewer	NH_3	Air	0.067	Mass				Huang et al., 2012; Rose et al., 2015	B
Multiple	Land application	P_{eq}	Water	0.13	P_{eq}				See LCA data	C
Multiple	Land application of sludge	CO_2 avoided	Air	0.17	Mass				See LCA data	
Multiple	Land application of digestate	CO_2 avoided	Air	0.29	Mass				See LCA data	
Multiple	Land application of compost	CO_2 avoided	Air	0.12	Mass				See LCA data	

Notes:

A No differentiation for leaching based on lined/unlined, wet/dry latrine, or high/low groundwater.

B Emission factor (Huang et al., 2012) multiplied by mass generation (Rose et al., 2015).

C We did not include N emissions from land application sludge, digestate, or compost.

General notes:

- For LCA data, see Section 4.9
- Subscript "eq" indicates equivalents (Peq = P equivalents)
- Emission factors for nitrogen or phosphorus discharged directly to soil or water (e.g., in open defecation) are set to one.
- Emission factors for cryptosporidium and rotavirus are described in the Pathogen methods section (Appendix C).
- Emission factors are consistent across demographics, expect for Pathogens (see the Pathogen calculation section).

4.8.2 NH_3

NH_3 released from human waste is of concern for eutrophication and particulate matter. NH_3 emissions from latrines, septic systems, and stagnant sewers are estimated using an emission factor of 0.787 kg NH_3/year/person, calculated by Huang et al. (2012), which itself is an average of three sources (Buijsman, Maas, and Asman 1987; Möller and Schieferdecker 1989; Yin et al. 2010). As this project focused on GHGs, no uncertainty estimates were created from these sources.

4.8.3 Uncertainties and Limitations for GHG Emission Factors

While a full discussion of uncertainties associated with emission factors is beyond the scope of this report, we highlight one limitation in current emission estimation models: mass balances are not necessarily respected. For example, the generation of CH_4 from BOD will reduce BOD (e.g., in a sewer), resulting in less BOD reaching a subsequent stage of the sewage management chain (e.g., a WWTP). However, connecting BOD *reduction* to CH_4 production is not straightforward. Therefore, we do not model reduction of BOD due to CH_4 emissions. To our knowledge, there is not an empirical or conceptual approach that can be generalized to this setting. Note that the new IPCC emission factor for centralized WWTPs (Bartram et al. 2019) does include a mass flux of incoming, dissolved CH_4 generated in sewers.

A recent assessment of N_2O emissions from Swiss wastewater plants (Gruber et al. 2021) shows the potential for higher performing plants to reduce N_2O emissions. It also shows that the Switzerland average matches the new IPCC average emission factor of 1.6 kg N_2O / kg N (Bartram et al. 2019), which is used in this work. While there is potential for additional reductions in emissions from secondary and/or tertiary treatment, the possibility for certain plants to operate poorly suggests that, for the purposes of this study, using the IPCC average is adequate.

Section 5.6 presents an analysis of the potential range in GHG emissions per archetype.

4.9 LCA: Emissions and Avoided Products

Complementing the process emissions described above, the modeling framework also accounts for indirect emissions, which are emissions related to the processes, but not coming directly from them. For example, if a WWTP uses electricity from a power plant, the power plant will release emissions while generating that electricity, so these emissions would count as indirect emissions for the WWTP. These emissions can also be counted as avoided products. For example, in the case where compost is produced, the application of that compost to soil can avoid the production of synthetic fertilizer. The emissions that are not released in the process of creating an equivalent amount of synthetic fertilizer can be credited to the process.

4.9.1 Transport (Truck Types; Transport Distances)

To account for the energy used in transporting excreta and sludge, we use emission factors from the ecoinvent database (Weidema et al. 2013) for five truck types, representative of a global scenario (i.e., not regionalized). ecoinvent truck types included in this work are light, 3.5–7.5 tons, 7.5–16 tons, 16–32 tons, and >32 tons.

Using population densities, we calculate truck hauling distance using the following observations:

- Round trip default distance is 30 km/trip; it is 24 km in Delhi and 50 km in Kuala Lumpur (Chowdhry and Koné 2012).
- Dewatered sludge is typically hauled up to 160 km one-way (Seiple, Coleman, and Skaggs 2017).

4.9.2 Fuels and Fertilizers

Emission factors for fuels and fertilizers—representative of a global scenario (i.e., not regionalized)—were drawn from ecoinvent version 3 (Weidema et al. 2013). The fuel and fertilizer types modeled are diesel, natural gas, single superphosphate, and urea ammonium nitrate.

4.9.3 WWTP

The United States Environmental Protection Agency (U.S. EPA) Nutrient Removal study (U.S. EPA and ERG 2021) provides a comprehensive dataset that describes WWTP emissions. This dataset also include emissions associated with the construction of WWTPs (e.g., CO_2 release from concrete is distributed across the life of the WWTP).

Table 4.8 shows the treatment systems modeled in the nutrient removal database, the corresponding treatment level (i.e., secondary and tertiary), and whether the systems were included in this study. Multiple tertiary treatment systems were included to provide the opportunity for a sensitivity analysis.

Table 4.8: Treatment systems in the Nutrient Removal Study (U.S. EPA and ERG 2021), corresponding treatment level, and inclusion in this model.

Name	Treatment Level	Included
Conventional plug flow activated sludge	Secondary	
Anaerobic/anoxic/oxic	Secondary	Yes
Activated sludge, three-sludge system	Tertiary	
Activated sludge, three-sludge system	Tertiary	Yes
Modified University of Cape Town process	Tertiary	
Five-stage Bardenpho with denitrification filter	Tertiary	
Four-stage Bardenpho membrane bioreactor	Tertiary	Yes
Five-stage Bardenpho with sidestream reverse osmosis treatment	Tertiary	
Five-stage Bardenpho membrane bioreactor with sidestream reverse osmosis treatment	Tertiary	Yes

The Nutrient Removal study did not include primary treatment, which does not target nutrient removal. Therefore, additional assumptions for primary treatment electricity and effluent discharge were required, as described in sections 4.9.4 and 4.9.5.

Based on a meta-analysis of electricity demands for WWTPs (Longo et al. 2016), we calculate the fraction of electricity required for primary treatment relative to secondary treatment. Based on Table 4.9, we assume that the electricity required for preliminary and primary treatment is ~5% of the required electricity for secondary treatment.

Table 4.9: Summary of options presented in Table 5 of (Longo et al. 2016), showing the sum of options described and the fraction that each stage contributes to the total options, by population (Pop.) served by the WWTP.

Parameter	Pop. < 2 k	2k < Pop. < 10 k	10 k < Pop. < 50 k	50 k < Pop. < 100 k	Pop. > 100 k
Sum (options), kWh/m^3					
Preliminary treatment	0.013	0.0258	0.0739	0.0475	0.0480
Primary treatment	0	0	0.0071	0.0048	0.0043
Secondary treatment	1.03	0.364	1.284	1.574	1.084
Tertiary treatment	0.539	0.109	0.423	0.395	0.302
Percent of total (options)					
Preliminary treatment	0.8%	5.2%	4.1%	2.4%	3.3%
Primary treatment	0.0%	0.0%	0.4%	0.2%	0.3%
Secondary treatment	65.1%	73.0%	71.8%	77.9%	75.4%
Tertiary treatment	34.1%	21.8%	23.7%	19.5%	21.0%

Parameter	Pop. < 2 k	2k < Pop. < 10 k	10 k < Pop. < 50 k	50 k < Pop. < 100 k	Pop. > 100 k
Analysis					
(Preliminary + Primary) / Secondary	1%	7%	6%	3%	5%

It is necessary to estimate emissions both as a function of volume treated and solids treated. Metcalf and Eddy (Metcalf & Eddy and AECOM 2013) provide solids concentration as a function of flow rate, and flow rate is calculated as a function of economic development (E. R. Jones et al. 2021). Taken together, then, these data provided estimates for the solid concentration of wastewater, which is used as an intermediate calculation in the LCA estimates of energy demands for treating wastewater.

4.9.3.1 Uncertainty

We performed a non-exhaustive literature review to validate the estimates of electricity demand associated with WWTP configurations across the five levels of nutrient removal used in the WWTP study discussed above (U.S. EPA and ERG 2021). The identified electricity ranges also provide context for understanding specific configurations referenced in this report and how their energy demand compares to other treatment configurations for the same or different levels of treatment. Table 4.10 summarizes electricity demand estimates from the literature, including minimum, maximum, and average values for each level of nutrient removal.

Table 4.10: Range of reported electricity demand for nutrient removal systems across five performance levels.

Plant Category	Electricity Demand (kWh/m^3) Average	Lower Bound	Upper Bound	Count of Values	Sources
Secondary	0.33	0.16	0.48	5	1, 3, 4, 5
Secondary	0.62	0.30	1.30	5	1, 2, 5
Tertiary	0.55	0.49	0.62	3	1, 5
Tertiary	0.86	0.30	2.10	5	1, 2, 5
Tertiary	1.51	0.31	3.02	5	1, 2, 5

Sources: 1: (Falk et al. 2013); 2: (Rahman et al. 2018); 3: (Chen et al. 2018); 4: (Csicsaiová, Stanko, and Dubcová 2019); 5: (U.S. EPA and ERG 2021)

4.9.4 Electricity

In this analysis, we took emission factors for most regionalized electricity grids from the ecoinvent database (Weidema et al. 2013). For regions lacking an electricity data set in ecoinvent—Asia (excluding China and India), non–European Union (EU) Eastern Europe, North Africa, and Sub-Saharan Africa—we manually developed emission factors: the top country-level producers in each region were identified (IEA 2021a), and country-level weighted averages were developed based on each country's energy output (IEA 2021b) compared to total regional production. These country-level contributions were then applied as scaling factors to the corresponding ecoinvent country-level emission factors and then summed to produce regionalized emission factors.

The emission factors from the approach above served as a starting point in modeling a future 2050 scenario. We calculated emission factors for a projected EU 2050 grid (IEA 2021c) and compared these to emission factors from the ecoinvent existing EU grid; the resulting percent change for each substance was applied to emission factors for all regions in the analysis at either 100%, 50%, 0% depending on the region's HDI categorization of High, Mid, and Low, respectively. Application of the scalar at 100% indicates decarbonization of the electricity grid at a rate equivalent to that of the EU, while 0% indicates little-to-no decarbonization between now and 2050.

Appendix Table E.1 presents emission factors for electricity used in this assessment.

4.9.5 Effluent Discharge

For primary treatment, we assume the following removal percentages, based on the primary clarifier model used by U.S. EPA and ERG (2021).

Table 4.11: Removal percentages for primary treatment (U.S. EPA and ERG 2021).

Constituent	Removal (to Sludge)
Suspended solids	58%
BOD	32%
COD	40%
TKN	5%
Phosphorus	5%

Based on Tables 1-3 and 1-4 in the Nutrient Removal analysis (U.S. EPA and ERG 2021), we calculate the fractions of contaminants that are discharged as effluent, as shown in Table 4.12. These selected systems have a range of performance efficiencies, and the values used in this study are based on these specific values.

Table 4.12: Fraction discharge of influent constituents, for selected systems, based on Tables 1-3 and 1-4 of (U.S. EPA and ERG 2021).

Constituent	A2O	B5	MBR	B5/RO
Suspended solids	9%	4%	4%	1%
BOD	2%	1%	1%	1%
Soluble BOD	3%	3%	3%	2%
COD	5%	1%	3%	0%
Soluble COD	1%	1%	1%	1%
Total phosphorus	6%	4%	2%	0%
Total nitrogen	20%	15%	8%	2%

4.9.6 Sludge Handling

In order to estimate life cycle impacts of AD, we compiled characteristics of composting, land application, incineration and landfilling for each process from multiple sources, including IPCC (2015, 2006) for general material compositions and government reports, as well as the peer-reviewed literature for characterization process inputs and emissions. As applicable and necessary, data were compiled describing mass, BOD and nitrogen loss or transformation, life cycle inventory (LCI) inputs, typical avoided products, and direct GHG emissions. For each process, a range of potential configurations exist, which can have a large influence on the range of inputs included in the LCI. To simplify process models, we identified a short list of LCI inputs for each process based on those that tend to drive life cycle impacts.

Anaerobic digestion involves the partial biological degradation of sludge organic matter. This degradation results in the production of CH_4 that can either be captured and beneficially used in the form of biogas, electricity, or heat; be flared and converted to less impactful CO_2; or escape as fugitive emissions. Accounting for the multiple possible AD configurations is impractical for this project, so we developed a typical configuration where CH_4 is captured and used to produce electricity. For direct emissions, we used emission rates from IPCC (2006), which are dominated by CH_4 (N_2O emissions are assumed negligible) and are a function of the mass of sludge treated. Process, as opposed to upstream, impacts are often dominated by electricity and natural gas inputs (U.S. EPA and ERG 2021). We therefore used average usage rates obtained from a report describing life cycle impacts of typical WWTP configurations across the United States (U.S. EPA and ERG 2021). To translate CH_4 production rates to an equivalent electricity production rate, which we account for as an avoided product (i.e., negative impact), we use the approach used by Morelli (2019), which is based on operational data of similar systems obtained from our literature review.

Composting also involves the partial degradation of organic and nitrogenous compounds in dewatered sludge or digestate, but in an open and mostly aerobic environment that leads to a different suite of emissions. Direct GHG emissions are dominated by CH_4 and N_2O, which we account for by using emission factors from IPCC (2006). LCI inputs include diesel and electricity, which are generally used for aerating and moving material at a composting facility. Input rates were obtained from Morelli et al. (2020), who calculated average values from studies of aerated static pile and windrow composting facilities, which are the most commonly represented configurations in the literature. Although composting does produce a beneficial soil amendment and fertilizer replacement, we do not account for those avoided products directly. Rather, they are accounted for if the produced compost (and its carbon and nutrients) is applied to land.

Land application refers to spreading of sludge, digestate, or compost onto land. Emissions from land application may be due to direct emissions to air or water, emissions associated with process inputs, or avoided products (e.g., avoided fertilizer). For this project, we assume impacts from process inputs (e.g., diesel for tractors to apply the material) are negligible relative to other impacts; therefore, we only calculate direct emissions and avoided products. Air emissions may include N_2O or avoided CO_2 due to sequestering sludge, digestate, or compost organic material within the soil. Emission factors for these pathways are averages from several studies (Boldrin et al. 2011; 2009; Nemecek and Kägi 2007; Yoshida, Gable, and Park 2012). Emissions of phosphorus to water were calculated using average loss rates from (Nemecek and Kägi 2007). Avoided impacts are calculated by assuming the nutrient content of the sludge, digestate, or compost serves as a partial (i.e., less effective) replacement for the nutrient content of a typical mix of conventional fertilizers, including urea and single superphosphate.

Incineration refers to the burning of sludge, digestate, or compost, which results in direct emissions of CH_4 and N_2O. Emission factors for direct emissions are from IPCC (2006). Impacts associated with process inputs are assumed negligible relative to impacts from air emissions.

Landfills can serve as a final endpoint for any sludge material. Impacts from the landfilling process may include a range of direct air emissions (either fugitive or via flaring of landfill gas), avoided emissions due to long-term carbon sequestration, groundwater impacts from leachate contamination, and impacts associated with process inputs and avoided inputs from converting captured CH_4 to natural gas or electricity. For this study, we only account for air emissions of CH_4 and N_2O, avoided CO_2 emissions due to long-term carbon sequestration, diesel use as a process input, and avoided electricity production through conversion of captured CH_4 to electricity. We developed the final emission factors using IPCC methods (IPCC 2019) based on a typical set of values for sewage sludge and digestate (carbon content = 37.5% of dry mass, nitrogen content = 2% of dry mass). The composition and resulting emissions for these materials can vary substantially in practice. Emission factors represent cumulative emissions or carbon storage from a managed landfill over a 100-year period assuming a lifetime gas collection efficiency of 65%, CH_4 oxidation factor of 0.1, fraction degradable organic carbon (DOCf) of 0.64 (U. Lee, Han, and Wang 2017), and a decay constant of 0.18, which is the average across all climate types (U.S. EPA 2020). The DOCf value uses food waste as a proxy because the IPCC classifies both sewage sludge and food waste as rapidly degradable (IPCC 2019). The emission factor for N_2O emissions is based on the conservative assumption that sludge/digestate is used as daily cover, leading to high emissions, and is sourced from Borjesson and Svensson, (1997). Avoided electricity production is calculated based on estimated CH_4 production assuming that 80% of collected landfill gas is utilized in a generating engine with an electrical efficiency of 39%, where electrical efficiency is the average of values from Chiu and Lo (2018) and Yoshida et al. (2012).

5 Results

The modeling framework considers the impact of biochemical processes, choices about sewage management (i.e., adoption of different management options), and population. In this discussion, we focus on the process emissions, presenting results from the perspective of assigning a single user to each archetype in the region of interest. The discussion focuses on the “archetype user” perspective, but results also include per capita perspectives, showing the per person value for a given region (i.e., the sewage of a single person is distributed amongst the archetypes according to their adoption in that region), and total results, in which per capita values are multiplied by population to arrive at total impact for a given region.

While there are important regional differences, the discussion generally focuses on the global, population-weighted averages.

Although the analysis includes a variety of impact categories, the discussion focuses on the following:

- GHG/GWP, the primary focus of the study, and which is driven by CO_2, CH_4, and N_2O.
- Ocean acidification, which is largely driven by only CO_2, and therefore has behavior different than overall GHG.
- Marine eutrophication, which is driven by nitrogen emissions to water.
- Particulate matter impacts on human health, which are driven by emissions of particulate matter and its precursors, NO_x and NH_3.
- Pathogens.

GHG impacts on human health, freshwater eutrophication impacts, and acidification impacts are discussed in Appendix G.1. GHG impacts to human health scale linearly with GHG emissions; freshwater eutrophication tends to have trends similar to marine eutrophication; and acidification has trends similar to particulate matter.

In this section, we first discuss the emissions of climate-relevant gases by archetype. Next, we present individual impacts by archetype. Having discussed the processes and emissions driving global impacts, we then discuss variations throughout the geographic and economic regions of the world. This discussion is followed by an analysis of possible future trends based on archetype adoption scenarios, energy projections, and population projections.

5.1 Climate-Relevant Emissions

Figure 5.1 shows the fraction of biochemical process emissions versus LCA emissions (split into emissions and avoided emissions) for each sewage management archetype. CO_2 is avoided in the case of septic and latrine systems through land application of sludge, digestate, and compost. Wastewater treatment systems can also recover energy (and thus avoid CO_2 emissions) through the use of anaerobic digestion. The fraction of these emissions is larger in the case of latrines and septic systems, which have limited or no use of mechanical/electrical components and treatment chemicals. There is a small amount of avoided N_2O emissions in the case of the container-based system, as producing compost leads to avoided emissions. Overall, these distributions show the relative importance of combining both process emissions and LCA emissions.

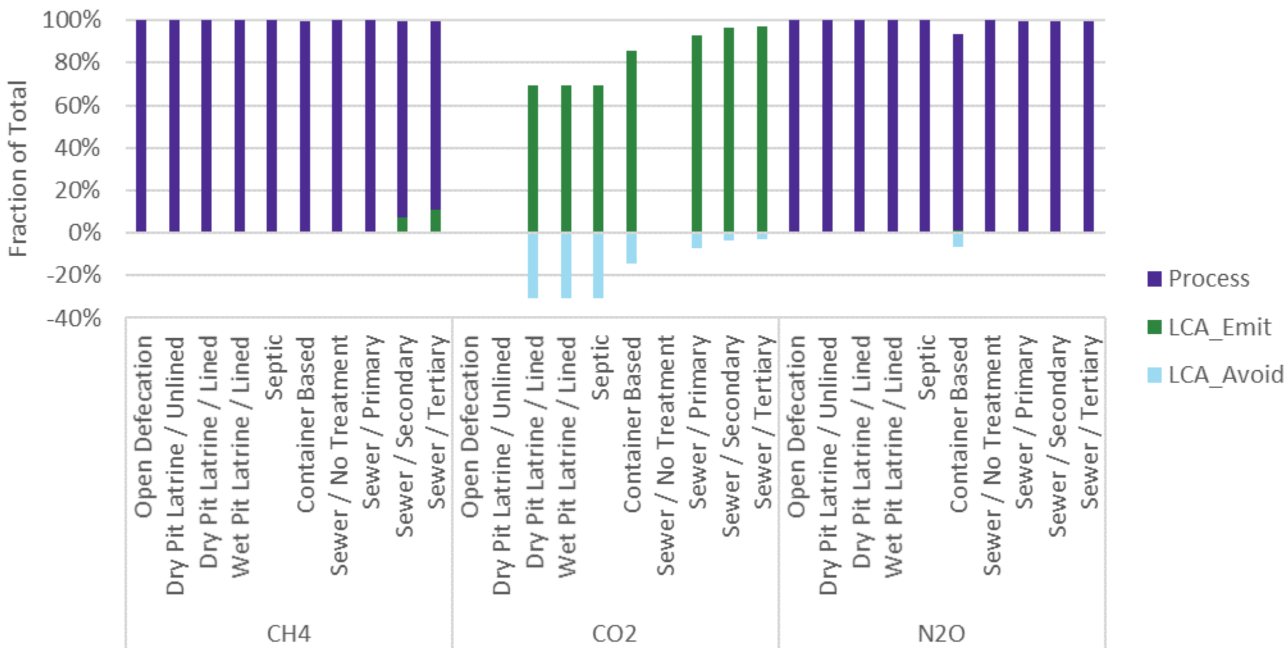


Figure 5.1: Contribution to impacts for the sewage management archetypes, split by type of emission. Data are for rural users, with other demographics showing similar trends.

Figure 5.2 shows the combined process and LCA emissions of CO_2, CH_4, and N_2O for each sewage management archetype. Fossil-based CO_2 is generally emitted because of energy consumption, either for transport or for wastewater treatment. Because a fraction of the emptied excreta from latrines is sent to wastewater treatment, latrines also have an energy demand and CO_2 emissions. CH_4 and N_2O are process emissions (with emission factors summarized in Table 4.7). CH_4 is largely emitted from fecal matter in latrines, septic systems, or in stagnant sewers. The emission factor for latrines where the fecal matter is mixed with water (i.e., a “wet” latrine or a high groundwater latrine) is higher than that for latrines where minimal water is used (i.e., “dry” latrines). N_2O emissions from latrines and septic systems are a result of nitrogen leaching to soil and emptied material being discharged to water bodies. However, the highest N_2O emissions are process-based emissions from biological treatment used in secondary and tertiary WWTPs.

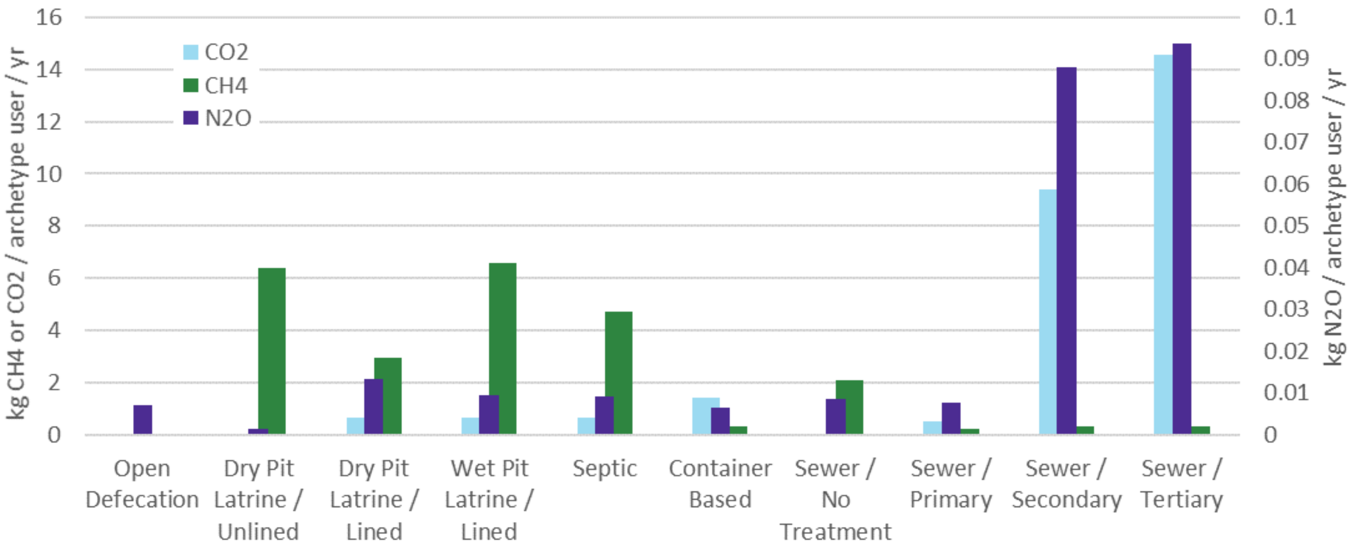


Figure 5.2: Emissions of CO_2, CH_4, and N_2O for the sewage management archetypes (with aggregation from sub-archetype to archetype based on current adoption practices). Data are for rural users, with other demographics showing similar trends.

5.2 Comparison of Archetype Impacts: Current Status

The relative importance of both process and LCA emissions is shown in Figure 5.3, which groups the sewage management archetypes by impact category. Each impact category shows a slightly different mix of these emissions. For GHGs, process emissions are dominant, with some LCA emissions associated with wastewater treatment, which is insignificant in the case of the latrines and septic (i.e., it is not visible on an arithmetic scale). However, these LCA emissions are significant in the case of the container-based system, which has some discharge to wastewater treatment. For the actual wastewater treatment archetypes, the advanced treatment of secondary and tertiary processes that require energy show significant LCA emissions. For ocean acidification, with CO_2 as the primary contributor, energy demand leads to LCA emissions of CO_2. For marine eutrophication, the higher energy wastewater treatment options lead to emissions of NO_x from energy, which subsequently deposits in marine ecosystems and causes eutrophication. Finally, the particulate matter impacts are largely dominated by LCA emissions, where higher energy demand leads to emissions of particulate matter itself, as well as its precursor, NO_x.

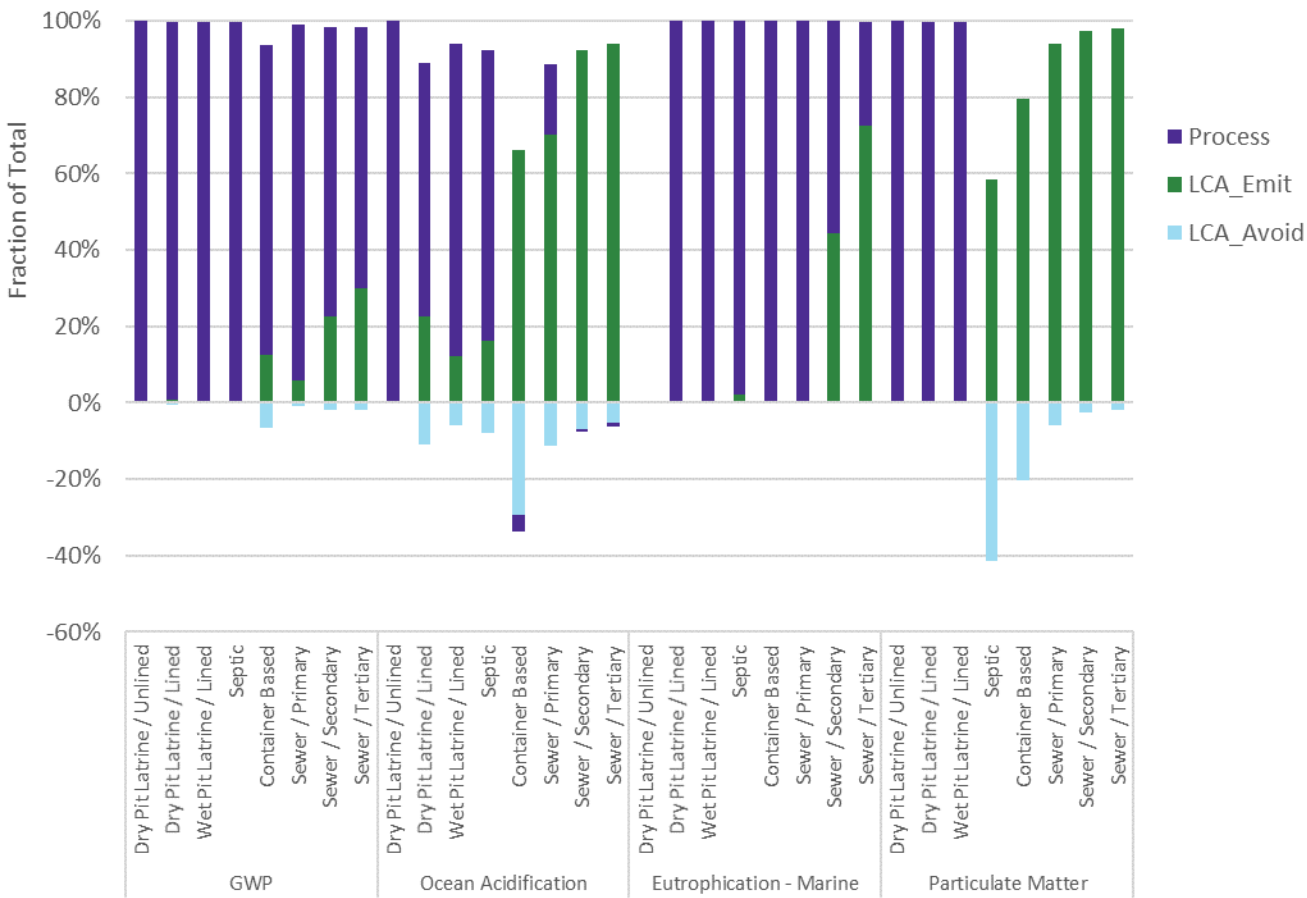


Figure 5.3: Breakdown of emission types for the sewage management archetypes (single user per archetype), split by emission type.

Figure 5.4 shows global GHG emissions, broken down by sewage management stage, by archetype, and from three different perspectives: top, assigning a single user to each archetype; bottom (left axis), per capita; and bottom (right axis), total. From this perspective, process and LCA emissions are not separated, but the insights from Figure 5.3 still apply: the relative importance of process and LCA emissions depend on the management archetype and the impact category.

One of the key drivers for GHG emissions is the anaerobic decomposition of organic matter, which happens more readily in systems with long-term storage (latrines), treatment (septic), or collection (stagnant sewers). The discharge of organic matter to eutrophic water bodies generates both N_2O and CH_4, although with lower absolute emissions. The secondary and tertiary wastewater treatment systems have LCA emissions associated with the energy required for treatment. The bottom of Figure 5.4 shows these emissions scaled to reflect actual use. The high prevalence of lined, dry pit latrines makes this the most impactful archetype in practice. The three latrine archetypes contribute 60% of total GHG emissions, and septic systems account for another 25%. Because container systems are not reported in JMP data, there is no per capita or total impact associated with that archetype.

Human health impacts related to GHGs, shown in Appendix G, are distributed among the archetypes identically.

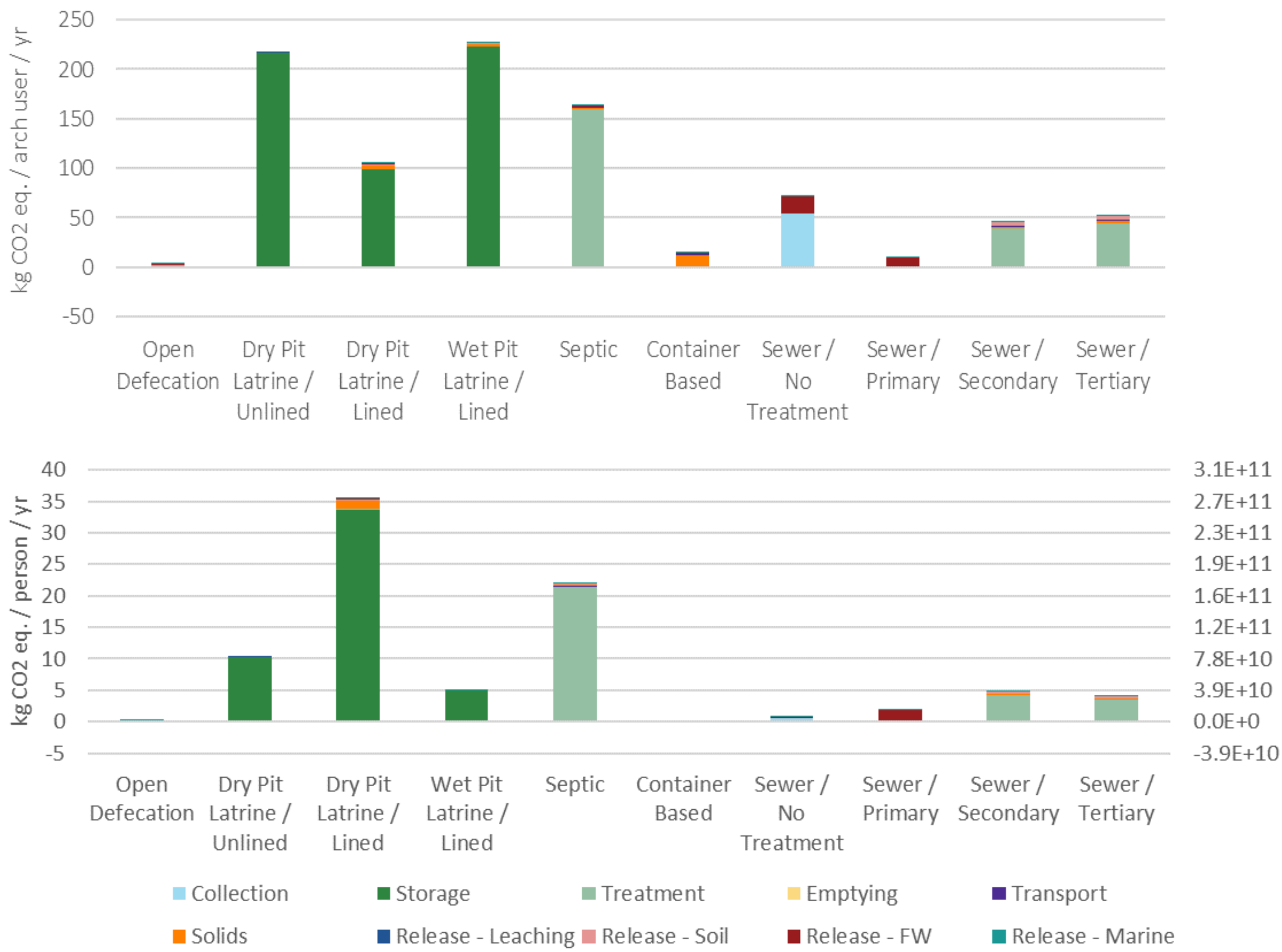


Figure 5.4: Current global GWP emissions. Top: Single user per archetype. Bottom: Per capita (left axis; reflects archetype adoption) and total (right axis; reflects population).

Ocean acidification impacts are shown in Figure 5.5. Emission of CO_2 and CH_4 both contribute to ocean acidification and GWP impacts; however, CO_2 and CH_4 have similar ocean acidification characterization factors (in contrast, CH_4 has a GWP 20 to 30 times higher than that of CO_2). Therefore, CO_2 emissions dominate ocean acidification. In general, ocean acidification impacts are driven by electricity and fuel use. Open defecation and primary treatment have negligible impacts, as these archetypes have little to no energy inputs and there is limited time for excreta to remain stagnant in these systems. Latrines, septic systems, and container-based systems all have modest impacts. Latrine and sewer impacts are driven by CH_4, which can drive pH decrease in the ocean. The container system has emissions related to transport, caused by the frequent emptying and collection of containers. The advanced treatment systems have high energy demands and thus high CO_2 emissions, causing secondary and tertiary WWTP archetypes to have the largest impact on ocean acidification. As shown in the bottom panel of the figure, the high adoption of dry, lined pit latrines creates a significant contribution from that archetype. The relatively high adoption of secondary and tertiary treatment plants, coupled with their high impact, leads to significant contribution from advanced treatment to ocean acidification.

Figure 5.5: Current global ocean acidification impacts. Top: Single user per archetype. Bottom: Per capita (left axis; reflects archetype adoption) and total (right axis; reflects population).

Figure 5.6 shows eutrophication impacts associated with discharges to marine environments from the sewer management archetypes. Eutrophication impacts, both marine and freshwater, are caused by the uncontrolled release of nutrients to water bodies, and to a lesser degree, soil. The model accounts for the possibility of nitrogen transfer from freshwater systems to marine systems. Therefore, even if there is a limited population living close enough to the coast for direct discharge of nutrients to a marine environment, there can be a significant impact to marine systems from inland, freshwater releases. Open defecation has a relatively high impact in this category. The modeling framework includes the option for pit latrines to have their collected material directly released to soil or water, causing these archetypes to have limited impacts. In the case of the container-based system, we model the fate of diverted urine in a similar fashion to collected material from latrines: it can be directly released to the environment or put into a sewer, which may or may not be connected to a treatment plant. Therefore, both the container system and the sewer system without treatment allow for nitrogen to be released directly to the environment. The primary sewer system has the highest impacts per user, also due to the collection and discharge of nutrients. In this case, very little nitrogen is removed in treatment, and the discharge of the treatment plant is generally to a water body rather than soil (which is the case with the container system). Therefore, the primary treatment system serves as an efficient collector of nutrients, as well as an efficient funnel of nutrients directly to water bodies. In practice, as shown in the bottom panel of Figure 5.6, the prevalence of primary treatment plants makes that archetype the largest contributor to marine eutrophication.

Freshwater eutrophication impacts, shown in Appendix G, are distributed among the archetypes in a similar fashion.

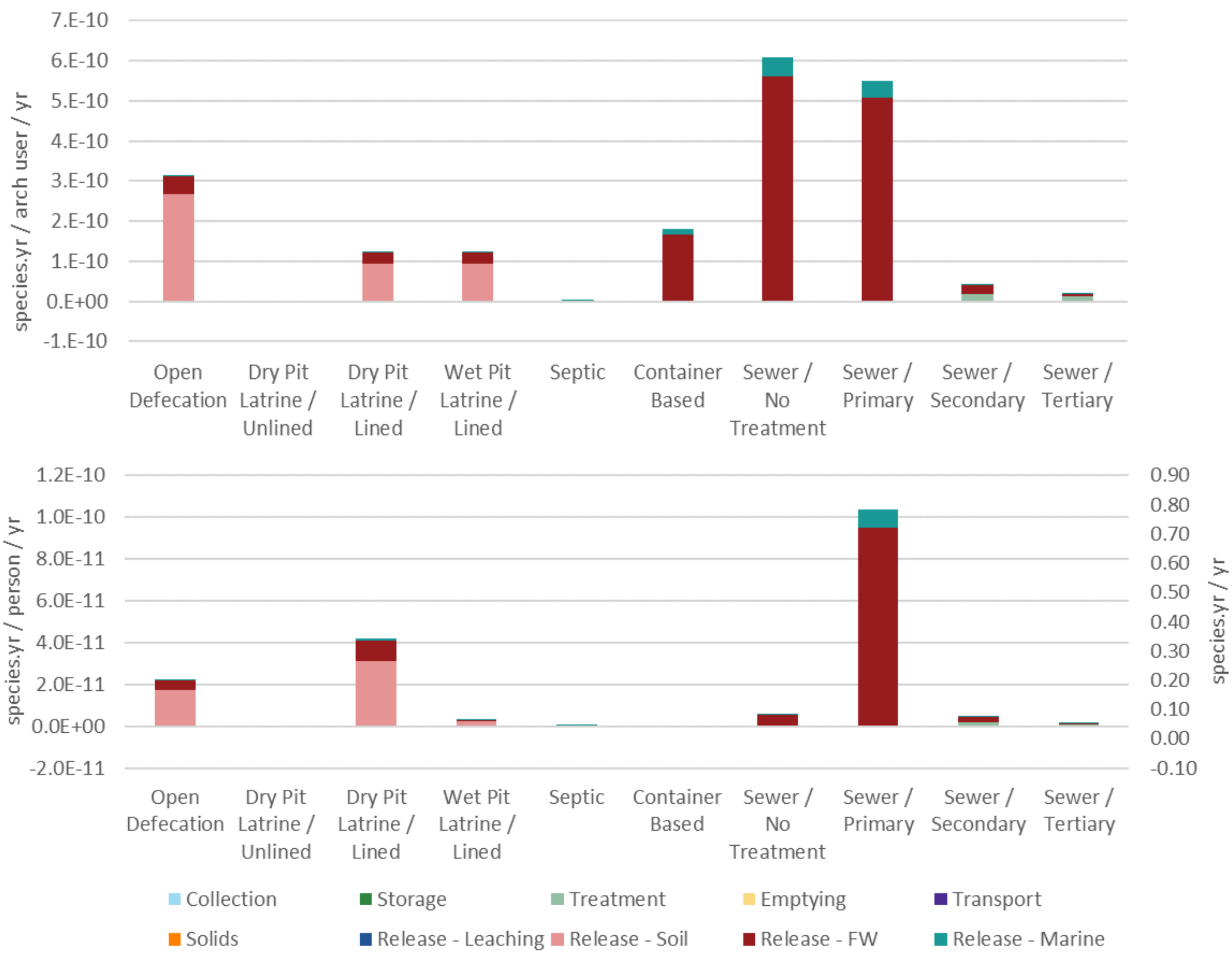


Figure 5.6: Current global eutrophication (marine) impacts. Top: Single user per archetype. Bottom: Per capita (left axis; reflects archetype adoption) and total (right axis; reflects population).

Figure 5.7 shows impacts on human health related to particulate matter emissions. In this case, the emission of both particulate matter itself, released during the combustion of fuel or production of energy, or the emission of particulate matter precursors, such as NH_3, drives the impact. The model includes NH_3 emissions to air from stored excreta (as shown in Table 4.7), which drives the high emissions from the latrine systems and the stagnant sewer systems. To a lesser extent, the particulate matter emitted during energy production for WWTPs also contributes to this impact. Considering the adoption of sewage management archetypes, shown in the bottom panel of Figure 5.7, dry, lined pit latrines are the primary contributor to this impact at the global scale.

Acidification impacts, shown in Appendix G, are similarly distributed. Acidification is largely driven by releases of three substances: NH_3, SO_x, and NO_x. As shown for particulate matter, latrines and stagnant sewer systems have appreciable NH_3 emissions, which account for most of their impacts. The secondary and tertiary sewer systems show some SO_x and NO_x emissions associated with electricity use.

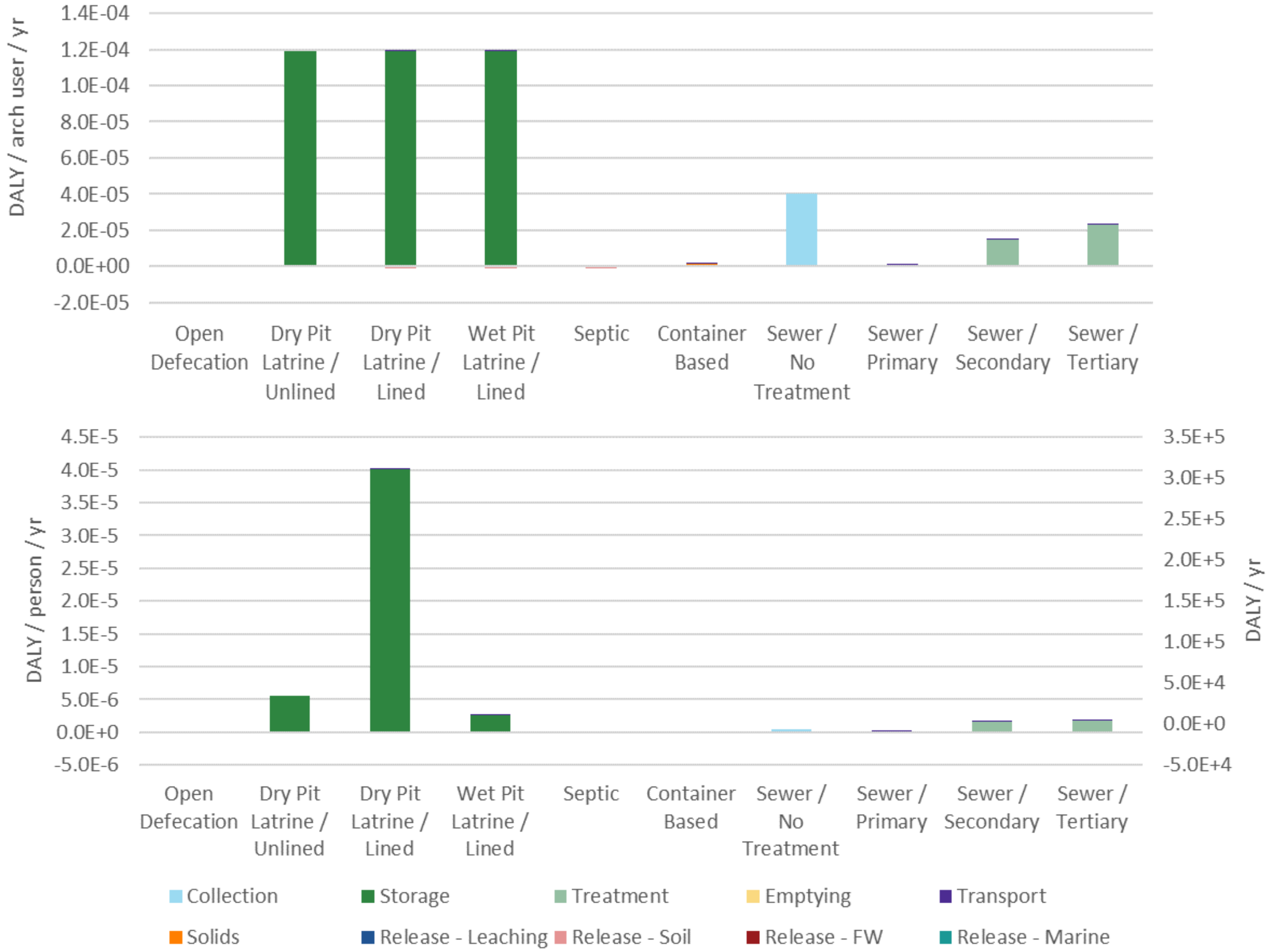


Figure 5.7: Current global particulate matter impacts. Top: Single user per archetype. Bottom: Per capita (left axis; reflects archetype adoption) and total (right axis; reflects population).

Figure 5.8 shows estimated human health impacts for the pathogens cryptosporidium and rotavirus. We note that impacts from open defecation are underestimated, as the model focuses on transfer of pathogens in aquatic systems. Therefore, Figure 5.8 should be interpreted as a relative indication of system safety, where secondary and tertiary treatment have the lowest pathogen impacts. In general, communal latrines provide efficient transfer of pathogens among a population, and the emptying of collected material from latrines, septic systems, or container-based systems can lead to additional exposure. In the model, it is assumed that the emptying of latrines is more informal, and thus increases exposure to pathogens, than the emptying of septic systems or container systems. Open defecation and sewer systems without treatment provide a relatively efficient means of exposure and transfer, as excreted matter is not treated prior to reaching the environment. The primary sewer system also serves as a collector and funnel of pathogens. The removal of pathogens in a primary treatment system is relatively low, resulting in potential transfer of pathogenic load to water bodies. Depending on the demographic context, those water bodies may be sources of exposure for the population. Advanced treatment systems have relatively high removal of pathogens, and those systems tend to be operated in demographic settings where exposure to released pathogens in a water body is relatively low. At the level of adoption, pit latrines appear to have the potential for high pathogen transfer and impact, with the remainder of the archetypes being relatively low. SDG 6.2 (WHO and UNICEF 2017) aims to move people away from open defecation; Figure 5.8 does not contradict that goal, which also includes user safety and dignity concerns, but rather points out that other systems higher on the sanitation ladder also carry pathogen risks.

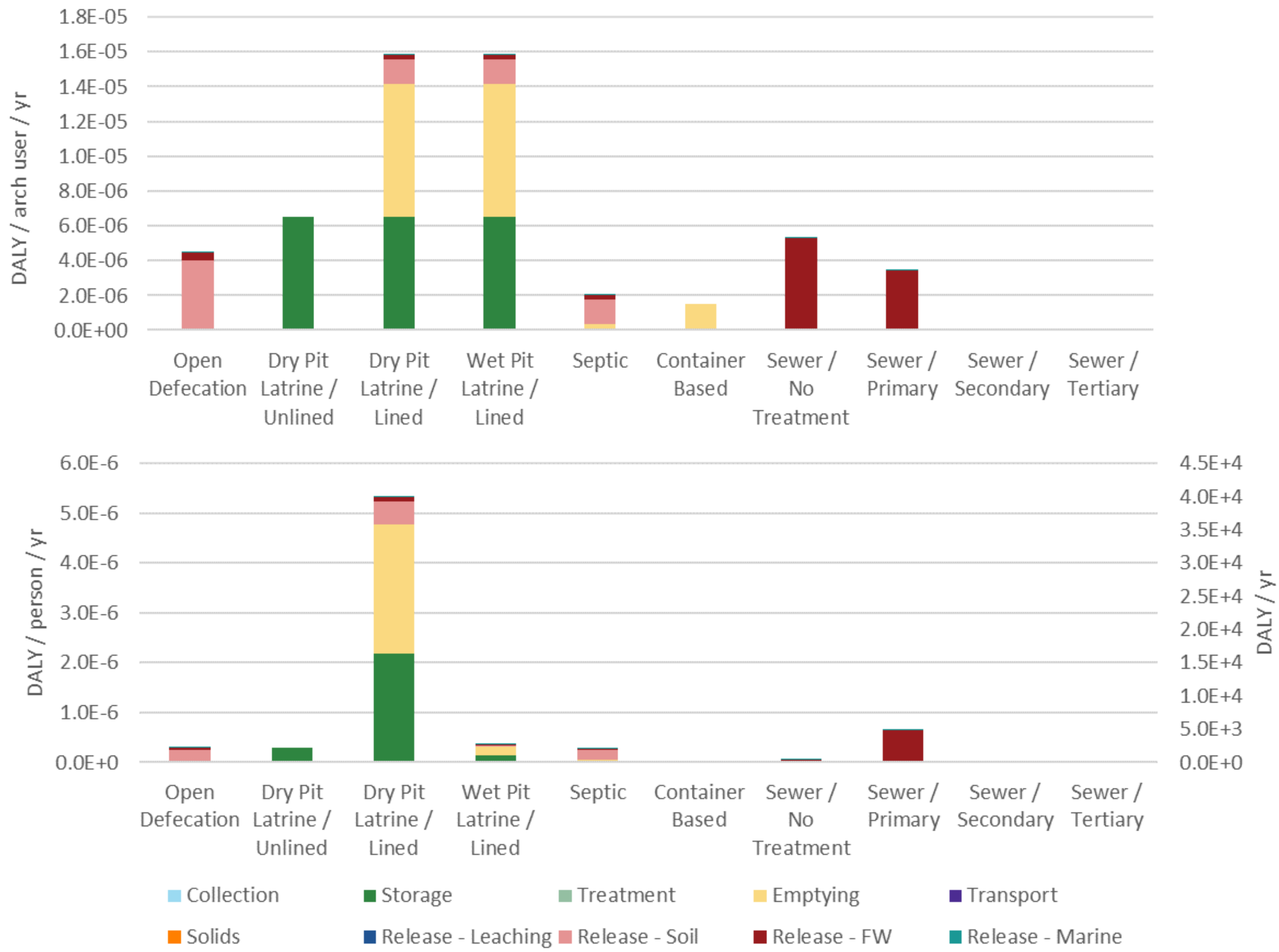


Figure 5.8: Current global pathogen impacts. Top: Single user per archetype. Bottom: Per capita (left axis; reflects archetype adoption) and total (right axis; reflects population).

5.2.1 Comparison Across Archetypes and Impacts

Having considered each of the impacts separately, it is important to consider them together to identify potential tradeoffs among archetypes and impacts. For example, although advanced treatment systems have generally lower GHG emissions than latrines or primary treatment, their higher energy demands means that they also have a higher ocean acidification impact.

Table 5.1 compares all archetypes and impacts at the global level, for a single user per archetype (i.e., adoption of management systems is not considered). This table, therefore, compares the inherent qualities of each management archetype. For each impact category, the maximum impact is assigned a value of 1, and other impacts are scaled in relation to the maximum impact. The values in the table, which range from 0 to 1, are shaded accordingly, with darker shades corresponding to higher values. Therefore, areas of dark shading indicate areas of higher impact. For example, for pathogens, particulate matter, and acidification, the lined latrine systems have the highest impacts, unlined pit latrines and open defecation have slightly lower impacts, as do sewer systems without treatment and (for pathogens) the primary sewer system.

Table 5.1: Relative impact of each management archetype and environmental metric scaled to maximum impact by archetype (i.e., a value of 1 indicates an archetype has or shares the maximum for that impact). Values less than 0.01 set to 0.01.

	Open Defecation	Dry Pit Latrine / Unlined	Dry Pit Latrine / Lined	Wet Pit Latrine / Lined	Septic	Container Based	Sewer / No Treatment	Sewer / Primary	Sewer / Secondary	Sewer / Tertiary
GWP AR5	0.016	0.95	0.46	1	0.72	0.06	0.32	0.048	0.22	0.25
Ocean Acidification	0.01	0.38	0.21	0.43	0.31	0.064	0.12	0.044	0.64	1
Eutrophication - Marine	0.52	0.01	0.21	0.21	0.01	0.3	1	0.9	0.071	0.03
Eutrophication - FW	0.18	0.01	0.092	0.092	0.02	0.14	1	0.9	0.1	0.1
Acidification	0.01	1	1	1	0.01	0.01	0.34	0.01	0.021	0.032
Particulate Matter	0.01	1	1	1	0.01	0.012	0.34	0.01	0.13	0.19
Pathogens	0.28	0.41	1	1	0.13	0.097	0.34	0.22	0.01	0.01

Movement up the JMP Sanitation Ladder towards Safe Sanitation

Table 5.1 can be read horizontally, vertically, or holistically. Horizontally, each impact row highlights which archetypes are associated with high impacts. Vertically, the table shows which impacts are associated with each archetype. Holistically, regions of lower shading are regions of lower impact, and one can look to identify areas of low shading based on projections about archetype adoption or on the relative importance of the impact categories. For example, if GHGs and ocean acidification are of primary concern, then container-based systems and primary wastewater treatment are some of the least impactful archetypes. If eutrophication concerns are added to the mix, then primary treatment is less appealing, and perhaps recommending a mixture of container-based systems and advanced treatment is appropriate, if the advanced treatment could be operated at high efficiency levels or with lower carbon energy sources. These future energy sources are discussed in later sections.

5.3 Regional Comparison: Current

Having considered the global situation in the sections above, we briefly consider regional differences. The figures in this section present results by region, at the per capita level. This perspective allows comparison among regions and reflects the adoption of sewage management practices, without having population emphasize (or deemphasize) certain regions.

Overall, these regional comparisons show that regional differences are driven more by income levels than by geography. There are certain regions, such as the Latin America and Caribbean/High (which includes Chile and Uruguay, where the fraction of the population near the coast is higher than average), that may have geographic differences. However, the analysis shows that geographic differences do not drive significant differences in impacts.

Figure 5.9 shows GHG impacts. For GWP, Figure 5.4 shows generally higher releases with latrine and septic systems, as well as sewer with no treatment. Therefore, as lower income is associated with latrine use and higher income is associated with a larger share of WWTPs, Figure 5.9 shows that the highest emitting regions on a per capita basis are those with lower incomes.

Ocean acidification results (Figure 5.10) emphasize the importance of electricity use, and thus CO_2 emissions. It is those regions with higher fractions of wastewater treatment that contribute more to ocean acidification. East and Southeast Asia/Low, which has a GWP impact per capita similar to Central and Southeast Asia/Low, has an ocean acidification impact that is roughly four times greater than that of Central and Southeast Asia. This change in ranking is due to the much higher proportion of WWTPs in East and Southeast Asia.

Figure 5.11 shows marine eutrophication impacts; these are strongly associated with open defecation, emptying of latrines, and primary treatment. Therefore, higher income regions tend to have lower marine eutrophication impacts. Sub-Saharan Africa is an exception, due to the relatively high fraction of primary treatment in that region.

For particulate matter and pathogens, Figure 5.12 and Figure 5.13 show that the low-income regions, which tend to have higher latrine adoption, have higher impacts.

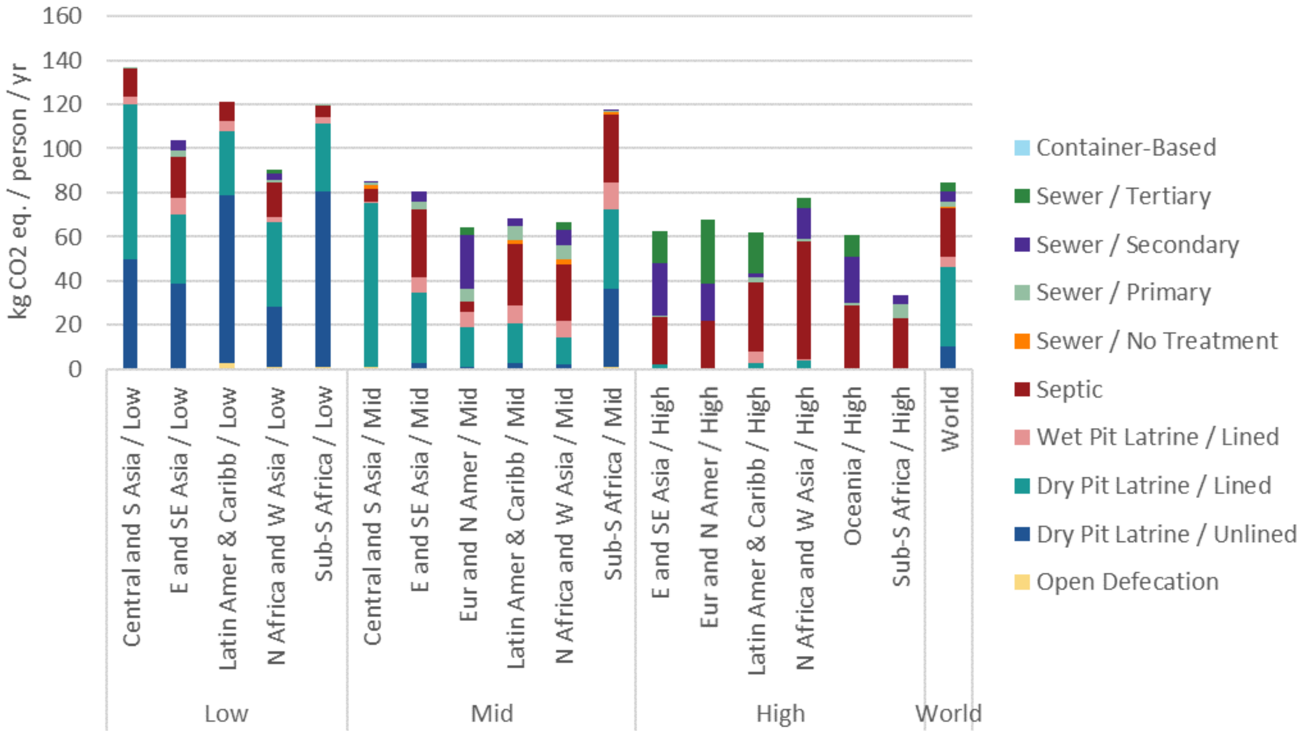


Figure 5.9: Current regional GHG/GWP impacts per capita. (Low, medium, and high income indicated by suffix on region name.)

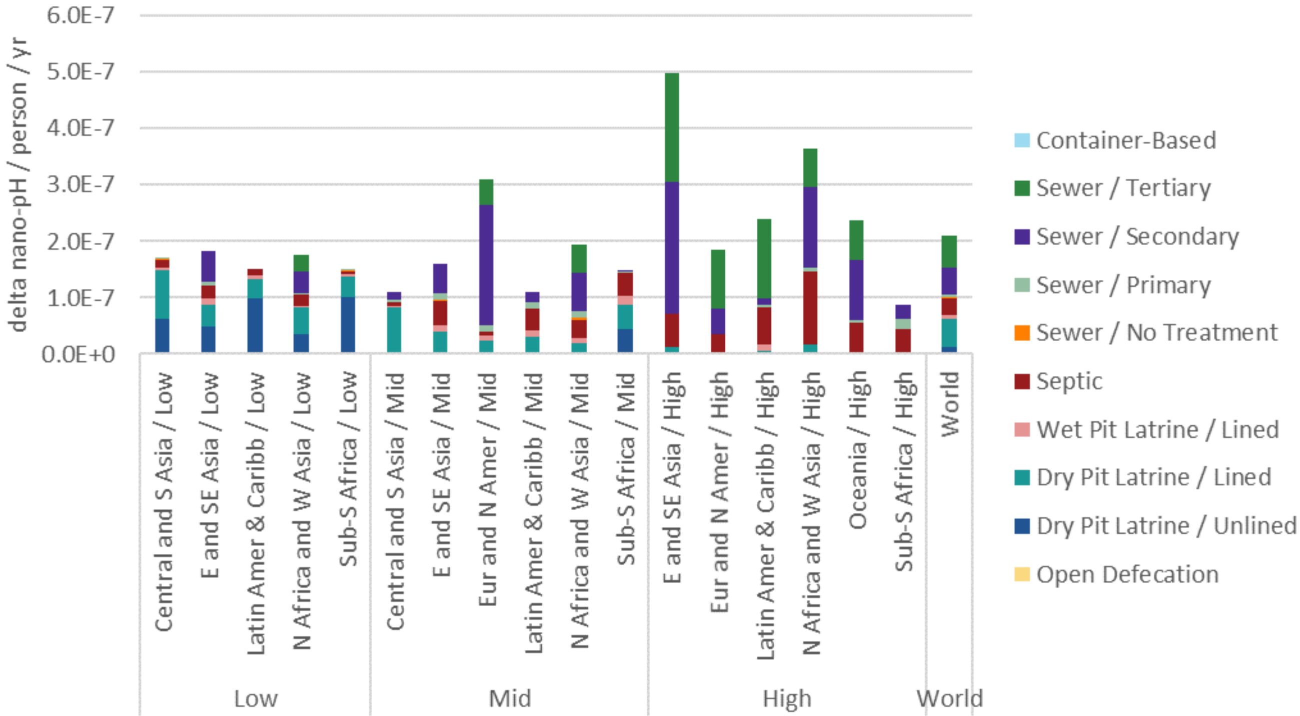


Figure 5.10: Current regional ocean acidification impacts per capita. (Low, medium, and high income indicated by suffix on region name.)

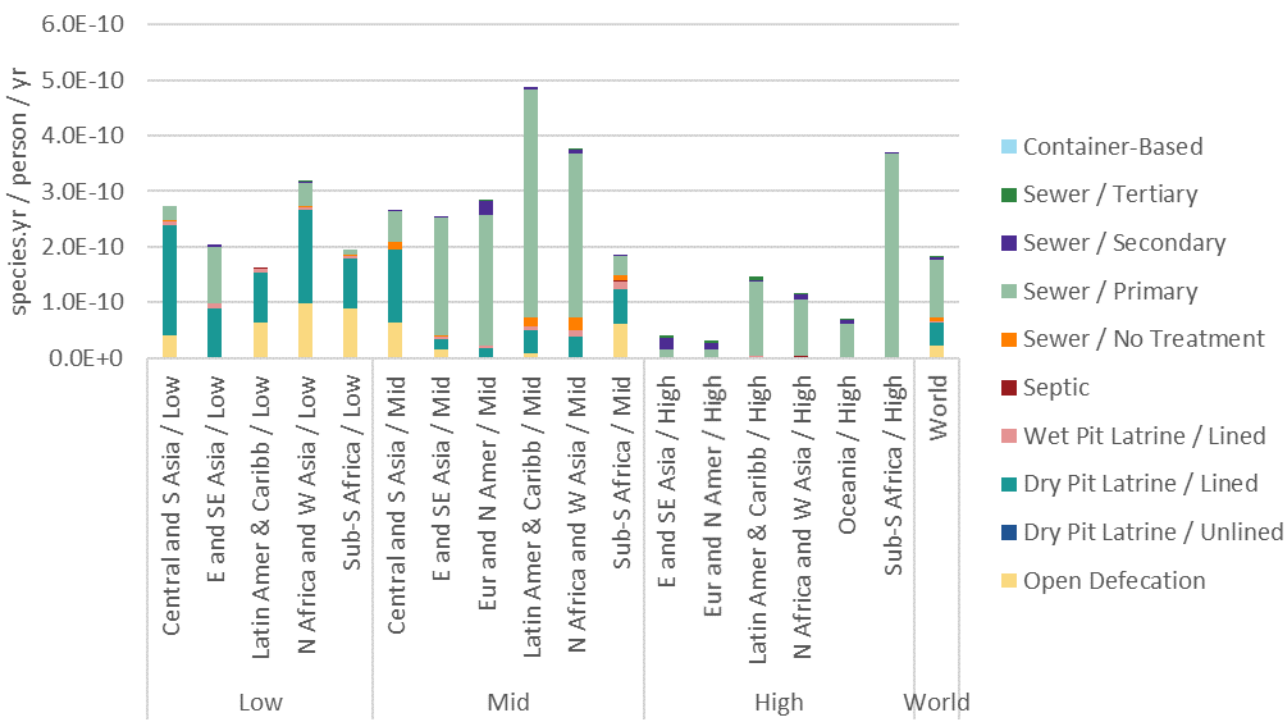


Figure 5.11: Current regional eutrophication (marine) impacts per capita. (Low, medium, and high income indicated by suffix on region name.)

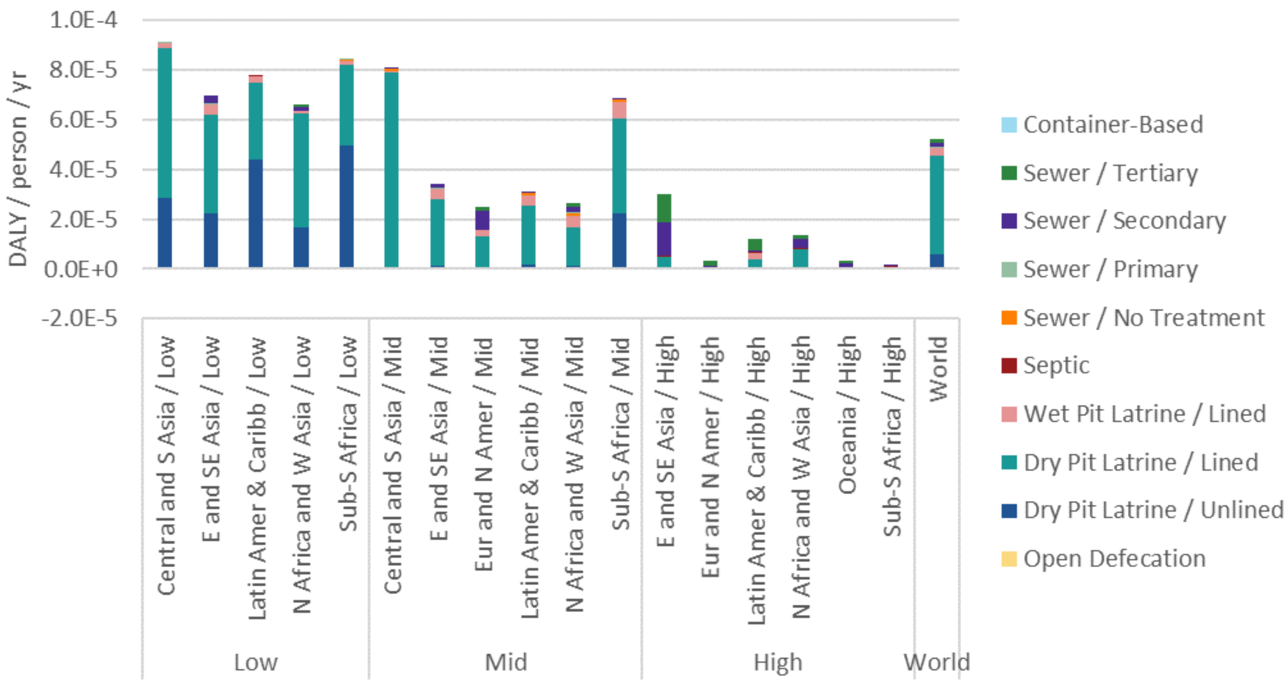


Figure 5.12: Current regional particulate matter impacts per capita. (Low, medium, and high income indicated by suffix on region name.)

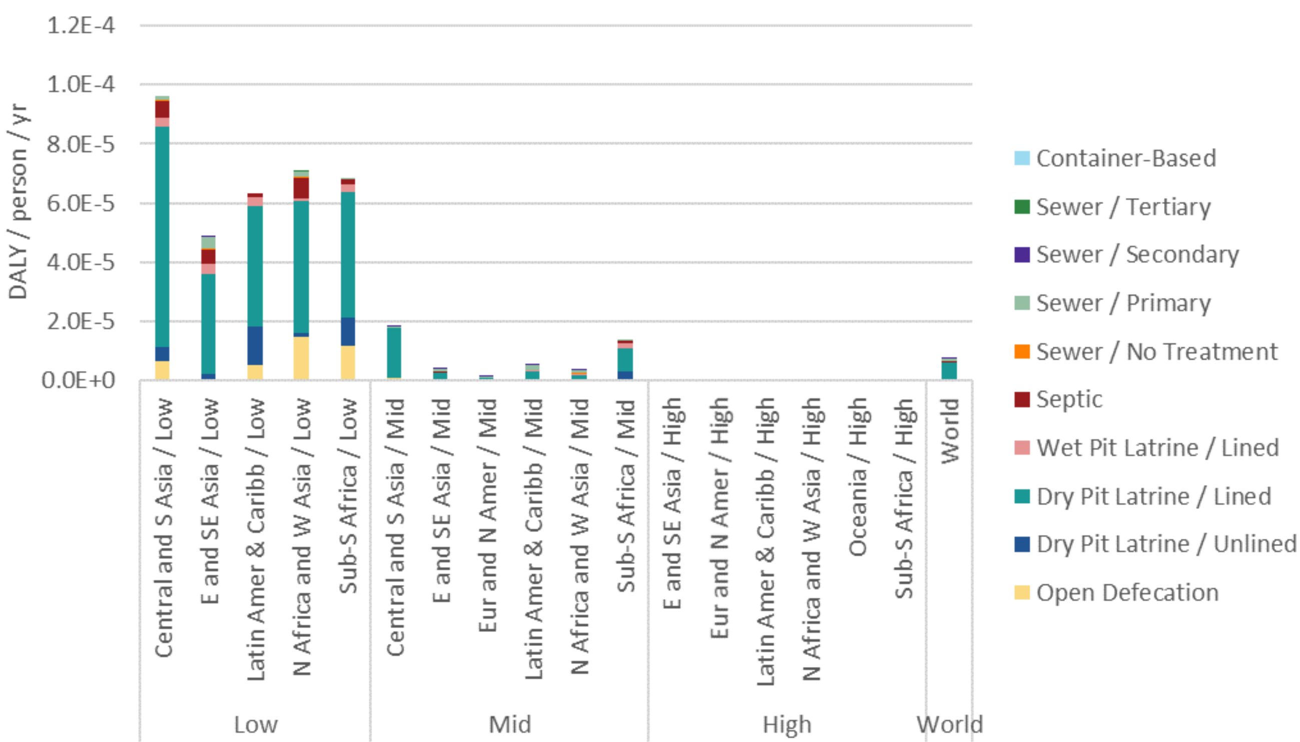


Figure 5.13: Current regional pathogen impacts per capita. (Low, medium, and high income indicated by suffix on region name.)

5.4 Archetype Adoption: Future

Having discussed the current impacts of current adoption practices, we now turn to potential future adoption scenarios (Table 4.4) and future energy scenarios (Section 4.9.4). The following figures show the adoption scenarios (including the current) across the x-axis, with contribution from each of the archetypes shown as stacked bars. The figures reflect the per capita user level, so they allow comparison among scenarios without considering population, but with considering the adoption of archetype management.

For GHGs (Figure 5.14), there are very limited changes among the different scenarios, with the exception of the "no open defecation" option, which transfers a significant number of users to latrines, and the high CBS option, which reduces emissions by almost one third. This reduction is related to CBS' relatively low GHG footprint. The 2050 trend scenario is calculated for both the "default—current" energy scenario and the "IEA 2050" energy scenario, the latter having significantly lower carbon intensity than the present energy mix. In the case of GHGs, where CO_2 is not a critical driver, the effect of the future energy scenario is negligible.

For ocean acidification (Figure 5.15), however, the low carbon energy scenario has a significant impact, reducing per capita impacts approximately 25%. The CBS system, as it has lower energy requirements, has a corresponding lower CO_2 emission profile, as it transfers users away from energy-intensive advanced treatment to lower energy options. The future scenario "2050 Trend, all WWTP to Tertiary", in which all increases in wastewater treatment are directed to energy-intensive tertiary treatment, does result in a significant CO_2 increase (under the current energy scenario). With a lower carbon energy mix, this high tertiary treatment scenario would not have the appreciable increase that it does.

For marine eutrophication (Figure 5.16), the relatively constant presence of primary wastewater treatment drives a relatively constant impact across scenarios. Although CBS moves users away from primary treatment, the current practice of urine diversion associated with CBS does not result in overall reduction of nitrogen discharges to water. The "safe sanitation" scenario, in which users are moved *en masse* away from latrines, results in a higher fraction of the population using primary treatment, which results in a higher marine eutrophication impact.

For particulate matter (Figure 5.17), the use of latrines is the primary contributor to impacts. The high container-based scenario leads to a reduction in the use of latrines, resulting in a corresponding decrease in this impact. Most striking is the "safe sanitation" scenario, in which users are moved away from latrines. In that case, particulate matter impacts reduce by approximately a factor of 10.

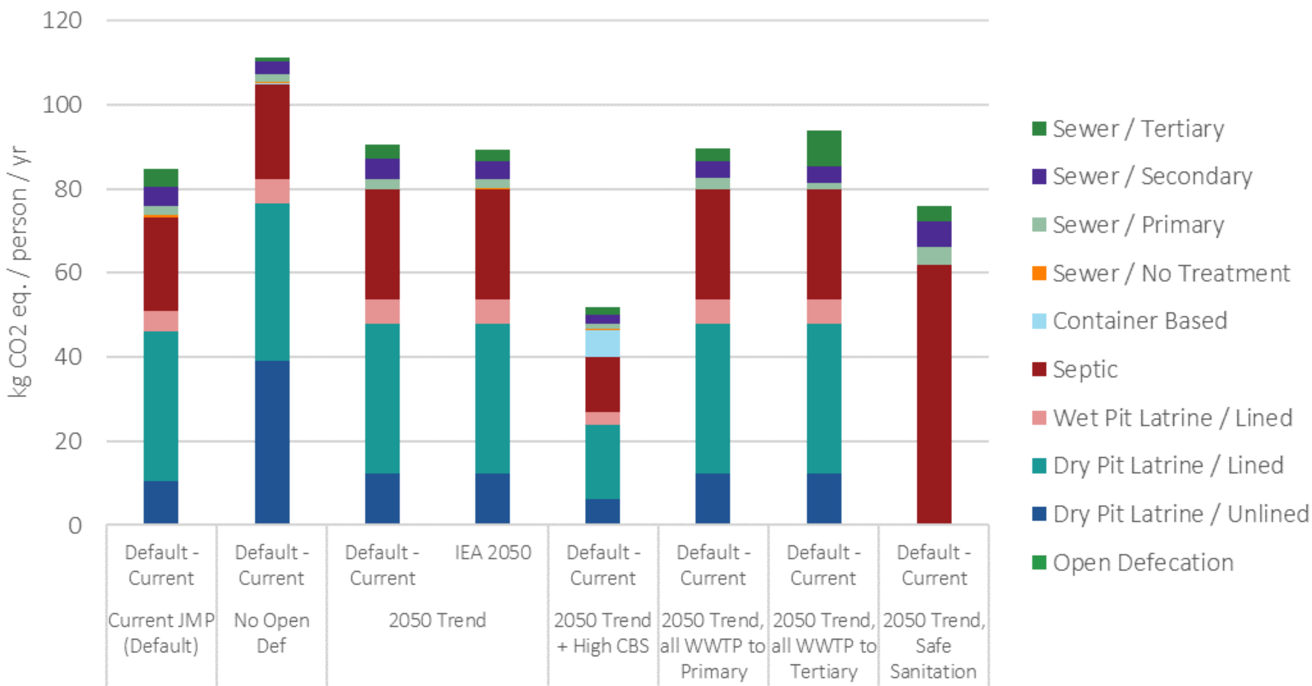


Figure 5.14: Future archetype adoption scenario GHG/GWP impacts, per capita ("Default ‑ Current" and "IEA 2050" refer to energy production scenarios).

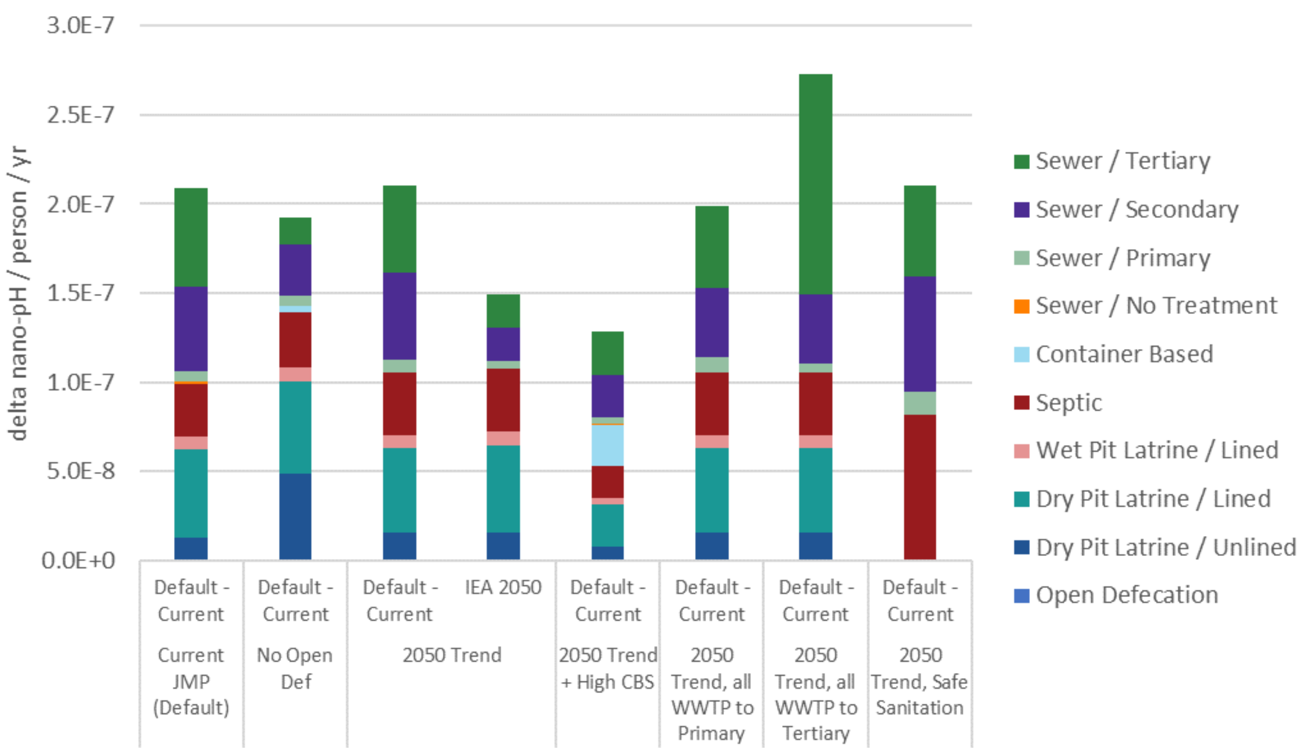


Figure 5.15: Future archetype adoption scenario ocean acidification impacts, per capita ("Default ‑ Current" and "IEA 2050" refer to energy production scenarios).

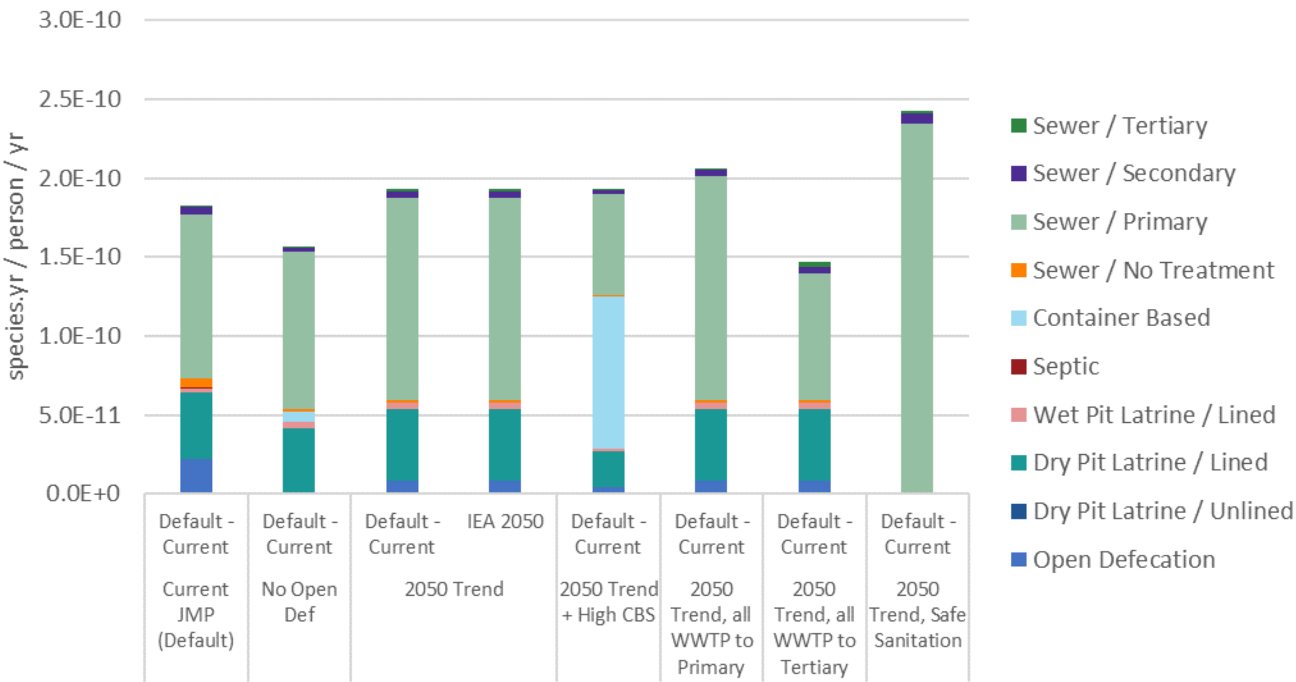


Figure 5.16: Future archetype adoption scenario eutrophication (marine) impacts, per capita.

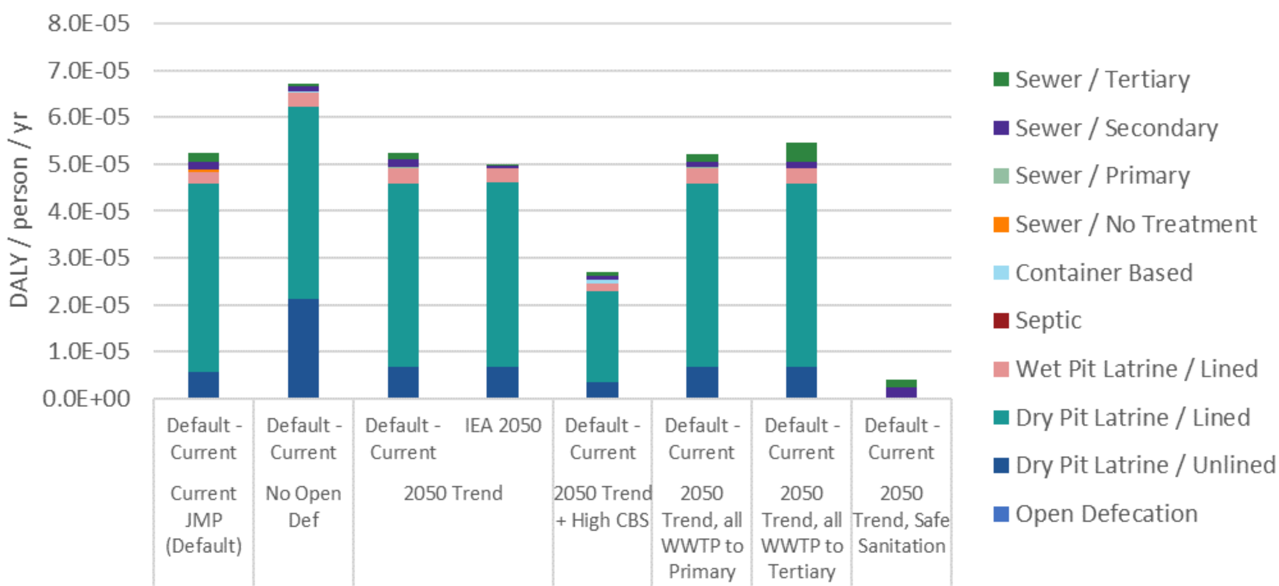


Figure 5.17: Future archetype adoption scenario particulate matter impacts, per capita.

5.4.1 Population

Finally, we combine the future per capita discussion above with population; here we present just the high and low population variants. Clearly, increases in population result in proportional increases in impact. Therefore, the discussion here is restricted to GHG impacts. Figure 5.18 shows projections for total global GHG emissions based on archetype adoption scenarios and population. As discussed above, archetype and population are key drivers for total emissions of not just GHGs, but all impacts considered. For certain archetypes, there are significant differences with respect to emissions, and population scales these differences in emissions directly. Figure 5.18 shows that even high population growth could be offset by changes towards low GHG sewage management, as demonstrated by the notional archetype of high CBS adoption. Overall, there is a factor of 4 range between the lowest and highest future projections at 2100, which demonstrates the potential for mitigation—even with high population growth, shifting significant population fractions away from high impact management archetypes could keep overall emissions close to present levels.

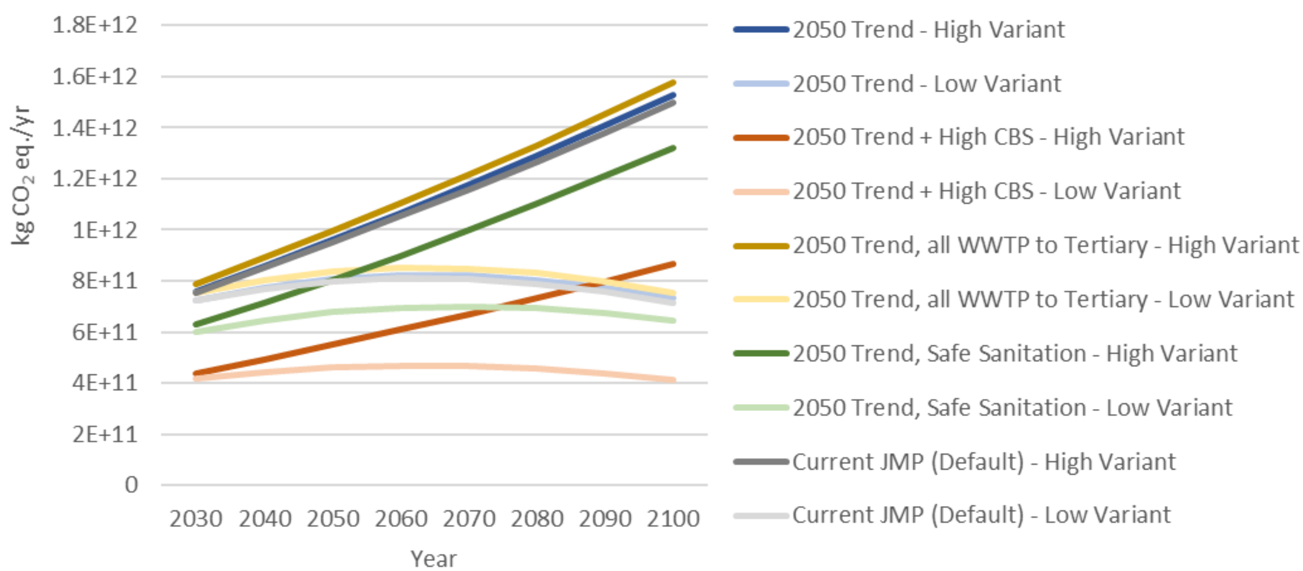


Figure 5.18: Future total GHG emission scenarios for the world (across archetype adoption scenarios, comparing high and low population projection variants).

5.4.2 Comparison Across Impacts

While the previous discussion showed scenario changes for individual impacts, Table 5.2 shows these changes across a variety of adoption scenarios. In this table, the current scenario (current archetype adoption and energy production) is set to a value of 1 across all impacts. Other scenario combinations are then scaled relative to this value.

Increase of specific technologies in the archetype adoption scenarios can also drive impact-specific increases. For example, in the “2050 Trend,” the pathogen impacts increase slightly more than the other impacts, as this impact category is particularly sensitive to increases in primary treatment. Moving the entire population to safe sanitation (“2050 Trend, Safe Sanitation”) creates increases across all impact categories except acidification, which drops significantly as untreated sewer and latrine use is curtailed. The high adoption of CBS results in decreases in nearly all impact categories, despite the population increase. Finally, the comparison of the two scenarios with increases in primary or tertiary WWTPs shows that tertiary treatment would differ from primary treatment in terms of ocean acidification (more energy related emissions), but it would be beneficial in terms of eutrophication, as nutrient discharge is lowered with tertiary treatment.

Table 5.2: Comparison of future scenarios to current, per capita, by impact (values are scaled relative to current, so a value of 1.5 indicates that scenario is 50% more impactful than the current; 0.5 indicates a 50% reduction in impacts).

	2050 JMP Trend; Current Energy	2050 JMP Trend; 2050 Energy	2050 Safe Sanitation; Current Energy	2050 High CBS; Current Energy	2050 WWTP Primary; Current Energy	2050 WWTP Tertiary; Current Energy
GWP AR5+ccf	1.1	1.1	0.9	0.61	1.1	1.1
Ocean Acidification	1	0.72	1	0.62	0.95	1.3
Eutrophication - Marine	1.1	1.1	1.3	1.1	1.1	0.8
Eutrophication - FW	1.1	1.1	1.7	0.86	1.2	0.84
Particulate Matter	1	0.95	0.08	0.52	1	1
Acidification	1	1	0.014	0.51	1	1
Pathogens	1.3	1.3	0.43	0.82	1.4	1.3

5.5 Global Results in Global Context

While the focus of this study is assessing relative changes in environmental impacts across a variety of scenarios, it is also useful to compare some of the values calculated in this work to other data sources. This comparison is not critical for understanding potential relative changes, but it grounds the model in current understanding of overall impacts.

Some differences between the total global GHG value from sewage calculated in this assessment and other estimates include the following:

- We use Fifth Assessment Report (AR5) GWP values with climate-carbon feedback.
- We use the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Bartram et al. 2019) for estimating sewage management emissions.
- We only account for domestic sewage, and do not estimate emissions associated with food waste and household chemicals that may be present in some countries' wastewater streams, nor do we account for treatment of industrial and commercial wastewater. This approach results in lower emissions compared to other estimates for the entire wastewater sector.
- We include the full global population, regardless of whether they are parties to the United Nations Framework on Climate Change (UNFCCC).
- We use global data sets and assumptions to estimate sewage management systems in use and their operational conditions.
- We include GHG emissions associated with energy use, transportation, chemical production, and other LCA emission sources.

Considering these differences, our assessment is consistent with other global GHG estimates, as shown in Table 5.3. Background on the other global sources assessed is provided in Appendix H.

Table 5.3: Comparison of ERG global sewage GHG results to other studies.

Source	Wastewater GHG Emissions (kt CO_2e)	Wastewater Emissions as % of Total GHG Emissions[1]	GWP Values (100-yr)
ERG Analysis (this study; sewage only)	660,000	Not Available	AR5[2]
	505,000	Not Available	AR4
PIK PRIMAP-2018 [3]	649,055	1.34%	AR4
CAIT 2018	635,700	1.34%	SAR
UNFCCC 2019	448,562	1.07%	AR4
Annex I Countries	122,573	0.75%	
Non-Annex I Countries	325,989	1.27%	

[1] Excludes emissions from land use, land use change, and forestry (LULUCF).

[2] AR5 GWP values with climate-carbon feedback.

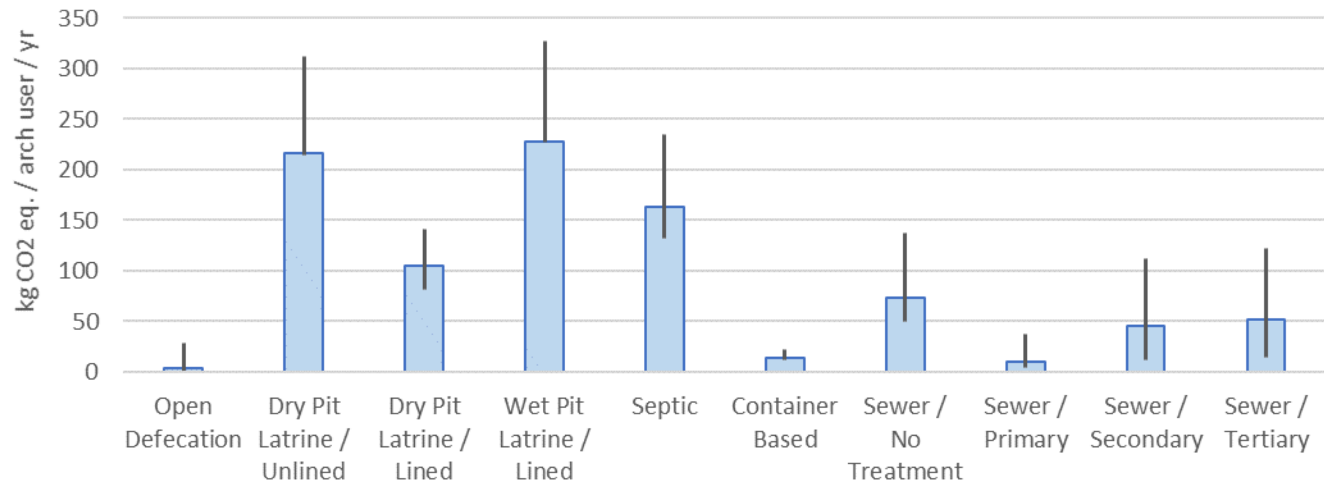
[3] PIK PRIMAP-2018 provided an estimate of GHG emissions from waste, but not specifically wastewater; ERG calculated wastewater emissions using the % of wastewater emissions to total GHG emissions from CAIT 2018.

5.6 Uncertainty and Limitations

A comprehensive uncertainty analysis is beyond the scope of this study. Bearing that in mind, the analysis is most appropriate for making assertions about relative differences between archetypes and adoption scenarios, rather than trying to estimate absolute impacts or compare results to other studies. For climate change impacts, the main focus of the study, we collected ranges (expected, low, and high) of emission factors from IPCC sources where available (Table 4.6). The ranges are reported as low, expected, and high values. As noted in Section 4.9.3.1, we did the same for electricity demands of WWTP systems. By uniformly setting emission factors to low values or high values, we can scale GHG impacts to get a qualitative estimate of how the emission factor uncertainty might impact overall results.

Figure 5.19 shows the low-, expected, and high-uncertainty estimates of GHG emissions for global archetype users (top) and per capita (bottom). Note that some of the CH_4 emission factors have low bounds that match the expected value—therefore, the uncertainty bars for some of the latrine systems have only higher values. Qualitatively, the top figure shows two groups of systems with no likely overlap: the latrines and septic are relatively high; the wastewater systems are relatively low (and sewers without treatment span the two). Thus, within the range of uncertainty, latrine and septic systems have higher emissions per user than wastewater systems. Considering adoption (bottom), the high emissions and high adoption of lined, dry pit latrines make this system the highest contributor to GHG emissions.

The analysis also indicates that there is significant potential for improvement in the wastewater treatment sector. The electricity emission factors (Table 4.10) are based on ranges of reported electricity use. The ranges for WWTP in the figure extend from approximately 10% of expected values to 200%, which indicates that a well-operated system, with low process emissions and low electricity demands, could significantly reduce GHG emissions (and the converse is true, as well).



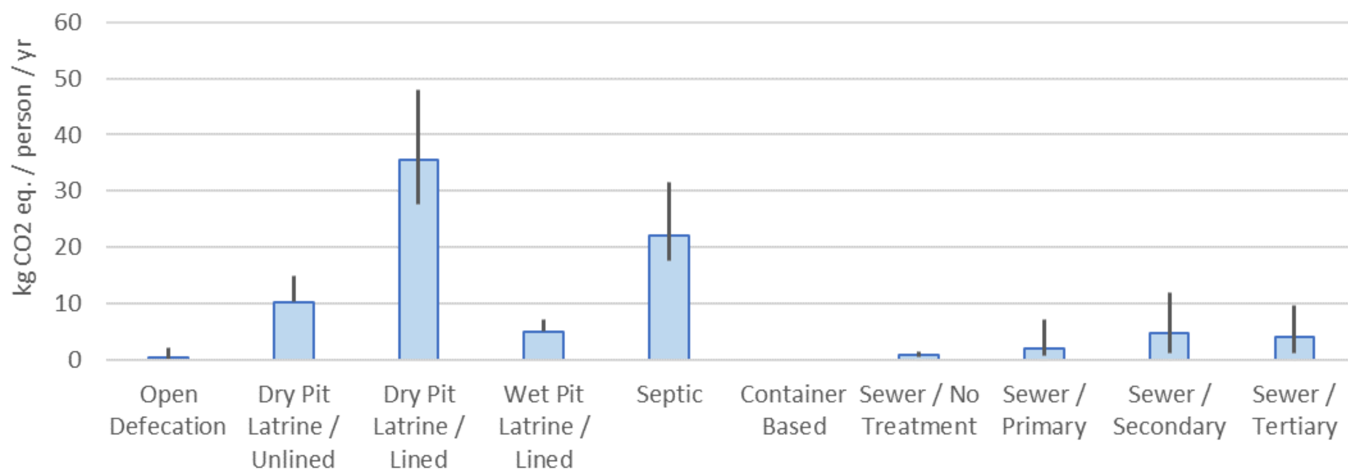


Figure 5.19: Upper and lower bounds for GHG emissions, based on IPCC ranges and WWTP ranges (i.e., cumulative uncertainty for calculation of current global per capita emissions). Top: Emissions based on a single, global user per archetype. Bottom: Per capita global emissions (includes current archetype adoption).

Although they are not a focus of the assessment, the generation of NH_3 and subsequent formation of particulate matter is clearly an issue for latrines and septic systems. The actual impact of that particulate matter, though, is highly spatially dependent. For example, septic systems are generally installed in areas with lower population density, resulting in a relatively limited exposure potential for the particulate matter that is formed. In the case of latrines, the exposure potential could be higher. We have not examined uncertainty ranges based on spatial variation for particulate matter formation due to NH_3 emission.

The other impact categories also have varying degrees of spatial variability. With the exception of demographic-based pathogen transmission and exposure variability, these variations are not addressed in this analysis. Our expert judgment is that including the spatial variability would add nuance; for example, there could be regions of the world with aquatic systems that are relatively susceptible to or resilient against nutrient inputs. In these cases, eutrophication impacts could be under- or overestimated in the current analysis. However, at the global level—and even at the regional—additional spatial information may change calculations but is unlikely to change the overall conclusions.

Given the nature of the model, it is more instructive to consider limitations in the modeling framework itself, rather than the input data. As with any model, the quality of input data is of great importance, especially for parameters that influence the model in a first-order fashion, such as emission factors or fractions of archetype adoption. To our knowledge, we have used the best available global data sources, and thus we make the broad observation that input data quality is important and could be verified against local data where available.

At the spatial scale of the modeling framework, much country and local variability is smoothed away. Country populations are binned into categories such as rural/urban low income/urban high income, near/far from the coast, near/far from freshwater, in wet/dry climates, etc. This approach means that for any given country, local practices and conditions may not be reflected in the model. For those few regions with limited numbers of countries, this is also true to some extent.

Each of the archetypes represents a range of sewage management practices, capturing none precisely but with the intent of capturing the average with relative fidelity. We have used sub-archetypes (see Section 2) to capture some of the variation in management practices and conditions. For example, latrines may be dry or wet, communal or household, and in high or low groundwater. Sewers may be flowing or stagnant. As discussed in sections 4.4.1 and 4.4.2, some of these practices and conditions may have a significant impact on the environmental performance of a given archetype. We have not systematically evaluated the sensitivity of the model to input data regarding practices and conditions. However, the comparison of our estimates to other global GHG emissions estimates provides some indication that the modeling assumptions—in aggregate—are reasonable. Future work could investigate sensitivity of the model to input parameters.

In general, each archetype (with the exception of open defecation) may be operated in a variety of ways. As noted in Section 1.2, there are also variants of these systems (e.g., latrine biogas capture, production of briquettes from CBS) that are not modeled in this work. For both the latrine systems and for systems that require active management (e.g., septic, container, wastewater treatment) there are a range of operating approaches that can lead to more or less efficient system operation, with greater or fewer associated emissions. We have not attempted to capture these ranges. For WWTPs, a poorly operated advanced plant may essentially behave as a primary plant with extra electricity demands. We have not modeled this directly, but the comparison of the future scenarios with higher or lower primary or tertiary treatment provides some insight into the possible implications.

We have also used a limited number of modeling assumptions to capture the range of options available to deal with solids. Among these, we have not modeled fecal sludge ponds, but rather restrict the range of options to landfilling, land application, anaerobic digestion, compost, and incineration (as described in Section 2). To the extent that fecal sludge ponds could result in additional emissions, particularly of CH_4 from stagnant organic matter, the model could underestimate GHG emissions associated with solids.

6 Conclusions and Future Research Needs

This section summarizes the findings and limitations of this assessment, as well as its implications for policy.

This work has demonstrated a flexible framework to evaluate a range of sewage management archetypes across a suite of environmental impacts. Although we report data at a global or regional scale, the spatially flexible data inputs and the structure of the model are amenable to higher-resolution outputs. The model could be augmented to provide high-level, ancillary estimates of country-level GHG emissions for wastewater treatment, which could be of use to organizations such as the JMP.

Any analysis that attempts to be holistic is also inherently limited. The degree to which environmental and human health metrics could be added to this framework is limited by available models. The results of this study should be interpreted in the context of the underlying assumptions and parameters used to generate results.

6.1 Technical Findings

When investigating all impact metrics and sewage management archetypes, this assessment shows the following trends:

- For climate change, latrines and septic systems perform poorly; untreated sewers or advanced (secondary and tertiary) WWTPs have about a quarter or a third of the impacts of latrines. Latrine, septic, and untreated sewer emissions are driven by CH_4 emissions from stagnant human excreta. The secondary and tertiary wastewater treatment emissions are driven by N_2O emissions during processing, as well as electricity demands.

- For ocean acidification, secondary and tertiary wastewater treatment are the poorest performers, with high emissions of CO_2 related to using the electrical grid.
- For eutrophication, both marine and freshwater, primary wastewater treatment is the poorest performer. Primary WWTPs collect waste (and its nutrients), provide relatively little nutrient removal, and then discharge those nutrients to receiving water bodies. Open defecation and untreated sewers also tend to deliver nutrients directly to water bodies (though less "efficiently" than the primary WWTPs), and thus tend to have impacts that are about 40% of the primary treatment system.
- For both acidification and particulate matter, ammonia emitted from excreta is a contributor to acidification and a precursor for particulate matter. For particulate matter, the energy demands of the advanced treatment systems (secondary and tertiary) also lead to particulate matter emissions during energy production.
- For pathogens, as expected, the systems that keep excreta on site, or do not provide much treatment, have higher potential for pathogen transmission.

The container-based system is one of the options with the lowest overall impact (i.e., better performance) across all metrics. It has the advantage of processing excreta (as opposed to letting it decompose on site, as with the latrines); the advantage of processing solids into beneficial products such as compost with relatively little energy input (as opposed to wastewater treatment); and the disadvantage of not handling urine well, resulting in relatively high marine eutrophication impacts. CBS systems are still in development, and these results should be considered in the context of ongoing research on CBS systems. The advanced wastewater treatment (secondary and tertiary) systems also tend to have lower impacts. These systems can have tight controls on process emissions and tend to have low nutrient emissions. However, these low emissions can come at the cost of higher energy demands; to the extent that wastewater systems use a carbon-intensive energy source, they tend to have higher GWP emissions and high ocean acidification impacts.

The push toward "safe sanitation," defined as septic systems and centralized WWTPs, has an uncertain impact on global GHG emissions; more certain is that a "safe sanitation" scenario has a relatively restricted effect on future GHG emissions; 2050 emissions are within +/- 12% of current emissions.

Considering both GHG emissions and eutrophication suggests that a combination of container-based systems and secondary and tertiary WWTPs may be the best solution, provided each system can be improved in key areas. CBS systems do not yet manage urine effectively, resulting in nutrient discharges to water bodies. Secondary and tertiary WWTPs cause negative impacts to ocean acidification associated with energy use. Further research of WWTP or CBS systems—or any system—should take into account life cycle (also called total ownership) cost, technological feasibility, the probability that the system will be operated at the desired efficiency, and the ramifications if the system is not operated correctly.

Improvements to wastewater treatment operation, including operational changes to increase nutrient removal while lowering electricity requirements and recovering biogas from sludge digestion to offset electricity needs, could mitigate ocean acidification impacts. Additional resource recovery options, which have been in development in recent years, include reuse of treated effluent rather than discharge and recovery of nutrients. Such resource recovery could mitigate eutrophication impacts. Implementation of renewable energy sources for electricity could also mitigate the increase in ocean acidification from secondary and tertiary treatment.

6.2 Policy Recommendations

This analysis has focused on forward-looking planning decisions: that is, which sewage management options should policy or funding organizations promote? While the model is used to generate global environmental impacts in the context of this analysis, it could be utilized in the future for more regionally specific analyses.

From the policy perspective, we unequivocally support the SDG aims of increasing access to safe sanitation in order to reduce acute illness and improve human dignity (the latter being beyond the scope of this study, but being an explicitly stated part of the SDGs). This research shows that each sewage management option, including those that meet the SDG definition of safe sanitation, has areas of poor or better environmental performance. Therefore, we also highlight the need for including environmental and other concerns in policy objectives that aim to improve sanitation.

Some of the poorer-performing management archetypes are latrines, open sewers, and (for certain impact categories) primary wastewater treatment. Some of the better-performing management archetypes are CBS and advanced (secondary and tertiary) wastewater treatment. This suggests that moving users away from latrines to other systems is generally desirable. Moving to primary treatment can be beneficial from a climate change perspective, but it may have negative impacts for eutrophication. Such decisions should be considered at the scale and context of individual localities or regions. Moving directly to advanced treatment (i.e., bypassing primary treatment) would be beneficial from a eutrophication perspective, but has a slight negative climate consequence, and does have negative ocean acidification impacts. Improvements to wastewater treatment operation, including operational changes to increase nutrient removal while lowering electricity requirements and recovering biogas from sludge digestion to offset electricity needs, could mitigate impacts to ocean acidification.

CBS may be the most viable choice in certain geographic or economic contexts that are not conducive to implementing sewer collection systems or operating WWTPs. Given the low implementation of CBS, more research is needed for understanding the operational impacts of CBS; however, these systems may be a promising option if urine can be managed appropriately.

6.3 Sewage Management Research and Technology Transfer Needs

In addition to policy recommendations, this analysis has highlighted issues with the sewer management archetypes, both in understanding and in operation.

As CBS is not commonly implemented, it is the most poorly understood of the archetypes considered here. More research on container-based systems, and the variety of their implementation practices, is needed. CBS has not yet fully addressed the problem of urine, and thus nitrogen, management. Advancements in urine diversion could improve the performance of this CBS. Options for using the solids from CBS should also be further explored. This study modeled CBS solids as being composted, but other resource recovery opportunities, such as briquetting the solids for heating and reducing demand for other solid fuel heating, should be considered.

The advanced treatment systems (secondary and tertiary) appear to perform relatively well across impact categories that are not sensitive to the energy grid. Therefore, when renewable sources can be used for these systems, they will be high performers across all impact categories. Although this work did not focus on these systems' range of performance, the operational efficiency of these systems can vary greatly, with corresponding influence on energy use. To the extent that the causes for these efficiencies can be identified and disseminated to operators of the advanced wastewater systems, these systems could be improved in place, without radical changes to the energy grid.

For those situations where a suite of management archetypes is already locked in, disseminating knowledge and continuing research about how to mitigate the environmental impacts identified in this work will be valuable in reducing impacts. For example, where it is still impractical to move beyond latrine use, future research might identify culturally appropriate solutions to reduce CH_4 release from latrines.

7 References

Apte, Joshua S., Julian D. Marshall, Aaron J. Cohen, and Michael Brauer. 2015. "Addressing Global Mortality from Ambient PM2.5." *Environmental Science & Technology* 49 (13): 8057–66. https://doi.org/10.1021/acs.est.5b01236.

Bach, Vanessa, Franziska Möller, Natalia Finogenova, Yasmine Emara, and Matthias Finkbeiner. 2016. "Characterization Model to Assess Ocean Acidification within Life Cycle Assessment." *The International Journal of Life Cycle Assessment* 21 (10): 1463–72. https://doi.org/10.1007/s11367-016-1121-x.

Bartram, Deborah, Michael D. Short, Yoshitaka Ebie, Juraj Farkaš, Céline Gueguen, Gregory M. Peters, Nuria Mariana Zanzottera, and M. Karthik. 2019. "Wastewater Treatment and Discharge." In *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 5: Waste*, edited by Eduardo Calvo Buendia, Kiyoto Tanabe, Andrej Kranjc, Jamsranjav Baasansuren, Maya Fukuda, Sekai Ngarize, Akira Osako, Yurii Pyrozhenko, Pavel Shermanau, and Sandro Federici. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Geneva, Switzerland: Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html.

Bivins, Aaron W., Trent Sumner, Emily Kumpel, Guy Howard, Oliver Cumming, Ian Ross, Kara Nelson, and Joe Brown. 2017. "Estimating Infection Risks and the Global Burden of Diarrheal Disease Attributable to Intermittent Water Supply Using QMRA." *Environmental Science & Technology* 51 (13): 7542–51. https://doi.org/10.1021/acs.est.7b01014.

Boldrin, Alessio, Jacob K. Andersen, Jacob Møller, Thomas H. Christensen, and Enzo Favoino. 2009. "Composting and Compost Utilization: Accounting of Greenhouse Gases and Global Warming Contributions." *Waste Management & Research* 27 (8): 800–812. https://doi.org/10.1177/0734242X09345275.

Boldrin, Alessio, Thomas Højlund Christensen, I. Körner, and U. Krogmann. 2011. "Composting: Mass Balances and Product Quality." In *Solid Waste Technology and Management*, Volume 2. Chapter 9.3:569–82. Chichester, West Sussex, UK: Wiley.

Borjesson, G., and B.H. Svensson. 1997. "Nitrous Oxide Emissions from Landfill Cover Soils in Sweden." *Tellus B: Chemical and Physical Meteorology* 49: 357–63. https://doi.org/10.3402/tellusb.v49i4.15974.

Buijsman, Ed, Hans F. M. Maas, and Willem A. H. Asman. 1987. "Anthropogenic NH_3 Emissions in Europe." *Atmospheric Environment* 21 (5): 1009–22. https://doi.org/10.1016/0004-6981(87)90230-7.

Cao, Long, Ken Caldeira, and Atul K. Jain. 2007. "Effects of Carbon Dioxide and Climate Change on Ocean Acidification and Carbonate Mineral Saturation." *Geophysical Research Letters* 34 (5). https://doi.org/10.1029/2006GL028605.

Center for Advancing Microbial Risk Assessment. 2021. "QMRA Wiki." Quantitative Microbial Risk Assessment Wiki. 2021. http://qmrawiki.org/.

Chen, Zhuo, Dan Wang, Mingxing Sun, Huu Hao Ngo, Wenshan Guo, Guangxue Wu, Wenjie Jia, et al. 2018. "Sustainability Evaluation and Implication of a Large Scale Membrane Bioreactor Plant." *Bioresource Technology* 269 (December): 246–54. https://doi.org/10.1016/j.biortech.2018.08.107.

Chiu, S.L.H., and I.M.C. Lo. 2018. "Identifying Key Process Parameters for Uncertainty Propagation in Environmental Life Cycle Assessment for Sewage Sludge and Food Waste Treatment." *Journal of Cleaner Production* 174: 966–76. https://doi.org/10.1016/j.jclepro.2017.10.164.

Chowdhry, Sangeeta, and Doulaye Koné. 2012. "Business Analysis of Fecal Sludge Management: Emptying and Transportation Services in Africa and Asia." Seattle, WA, USA: The Bill & Melinda Gates Foundation. https://www.susana.org/en/knowledge-hub/resources-and-publications/library/details/1662.

CIESIN. 2012. "National Aggregates of Geospatial Data Collection: Population, Landscape, and Climate Estimates, Version 3 (PLACE III)." Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC); Center for International Earth Science Information Network (CIESIN) Columbia University. https://doi.org/10.7927/H4F769GP.

Csicsaiová, Réka, Štefan Stanko, and Mária Dubcová. 2019. "Usage of the Life Cycle Assessment Method for Environmental Impact Assessment of Wastewater Treatment Plant." *Pollack Periodica* 14 (1): 151–60. https://doi.org/10.1556/606.2019.14.1.15.

Diaz-Valbuena, Libia R., Harold L. Leverenz, Christopher D. Cappa, George Tchobanoglous, William R. Horwath, and Jeannie L. Darby. 2011. "Methane, Carbon Dioxide, and Nitrous Oxide Emissions from Septic Tank Systems." *Environmental Science & Technology* 45 (7): 2741–47. https://doi.org/10.1021/es1036095.

Doney, Scott C., Victoria J. Fabry, Richard A. Feely, and Joan A. Kleypas. 2009. "Ocean Acidification: The Other CO2 Problem." *Annual Review of Marine Science* 1 (1): 169–92. https://doi.org/10.1146/annurev.marine.010908.163834.

Euzen, Agathe, Françoise Gaill, Denis Lacroix, and Ohilippe Cury. 2017. *The Ocean Revealed*. CNRS Editions. https://hal-enpc.archives-ouvertes.fr/hal-01690480.

Falk, Michael W., David J. Reardon, J. B. Neethling, David L. Clark, and Amit Pramanik. 2013. "Striking the Balance Between Nutrient Removal, Greenhouse Gas Emissions, Receiving Water Quality, and Costs." *Water Environment Research: A Research Publication of the Water Environment Federation* 85 (12): 2307–16. https://doi.org/10.2175/106143013x13807328848379.

Fan, Y., H. Li, and G. Miguez-Macho. 2013. "Global Patterns of Groundwater Table Depth." *Science* 339 (6122): 940–43. https://doi.org/10.1126/science.1229881.

Fantke, Peter, Weihsueh A. Chiu, Lesa Aylward, Richard Judson, Lei Huang, Suji Jang, Todd Gouin, et al. 2021. "Exposure and Toxicity Characterization of Chemical Emissions and Chemicals in Products: Global Recommendations and Implementation in USEtox." *The International Journal of Life Cycle Assessment* 26 (899–915). https://doi.org/10.1007/s11367-021-01889-y.

FAOSTAT. 2018. "Food Balance Statistics." Food and Agriculture Organization of the United Nations, Statistics Division. http://www.fao.org/faostat/en/#data/FBS.

Frischknecht, Rolf, and Olivier Jolliet. 2016. "Global Guidance for Life Cycle Impact Assessment Indicators: Volume 1." UNEP / SETAC Life Cycle Initiative. Paris, France: United Nations Environment Program / Society for Environmental Toxicology and Chemistry Life Cycle Initiative. http://www.lifecycleinitiative.org/training-resources/global-guidance-lcia-indicators-v-1/.

Gattuso, J.-P., A. Magnan, R. Billé, W. W. L. Cheung, E. L. Howes, F. Joos, D. Allemand, et al. 2015. "Contrasting Futures for Ocean and Society from Different Anthropogenic CO2 Emissions Scenarios." *Science* 349 (6243): aac4722. https://doi.org/10.1126/science.aac4722.

Graham, Jay P., and Matthew L. Polizzotto. 2013. "Pit Latrines and Their Impacts on Groundwater Quality: A Systematic Review." *Environmental Health Perspectives* 121 (5): 521–30. https://doi.org/10.1289/ehp.1206028.

Gruber, Wenzel, Luzia von Känel, Liliane Vogt, Manuel Luck, Lucien Biolley, Kilian Feller, Andrin Moosmann, et al. 2021. "Estimation of Countrywide N_2O Emissions from Wastewater Treatment in Switzerland Using Long-Term Monitoring Data." *Water Research X* 13 (December): 100122. https://doi.org/10.1016/j.wroa.2021.100122.

Gyawali, P. 2017. "Infectious Helminth Ova in Wastewater and Sludge: A Review on Public Health Issues and Current Quantification Practices." *Water Science and Technology* 77 (4): 1048–61. https://doi.org/10.2166/wst.2017.619.

Hergoualc'h, Kristell, Hiroko Akiyama, Martial Bernoux, Ngonidzashe Chirinda, Agustin del Prado, Asa Kasimir, James Douglas MacDonald, Stephen Michael Ogle, Kristiina Regina, and Tony John van der Weerden. 2019. "N2O Emissions from Managed Soils, and CO2 Emissions from Lime and Urea Application (Chapter 11)." In *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 4 Agriculture, Forestry and Other Land Use*, edited by Hongmin Dong, James Douglas MacDonald, Stephen Michael Ogle, Maria Jose Sanchez, Marcelo Theoto Rocha, Dominique Blain, Fahmuddin Agus, Marta Andrea Alfaro, and Harry Vruels. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Geneva, Switzerland: Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html.

Hofstra, N., A. F. Bouwman, A. H. W. Beusen, and G. J. Medema. 2013. "Exploring Global Cryptosporidium Emissions to Surface Water." *Science of The Total Environment* 442 (January): 10–19. https://doi.org/10.1016/j.scitotenv.2012.10.013.

Huang, Xin, Yu Song, Mengmeng Li, Jianfeng Li, Qing Huo, Xuhui Cai, Tong Zhu, Min Hu, and Hongsheng Zhang. 2012. "A High-Resolution Ammonia Emission Inventory in China." *Global Biogeochemical Cycles* 26 (1). https://doi.org/10.1029/2011GB004161.

Huijbregts, Mark A. J., Zoran J. N. Steinmann, Pieter M. F. Elshout, Gea Stam, Francesca Verones, Marisa Vieira, Michiel Zijp, Anne Hollander, and Rosalie van Zelm. 2017. "Recipe 2016: A Harmonised Life Cycle Impact Assessment Method at Midpoint and Endpoint Level." *The International Journal of Life Cycle Assessment* 22 (2): 138–47. https://doi.org/10.1007/s11367-016-1246-y.

IEA. 2021a. "Countries and Regions - Total Energy Supply." 2021. https://www.iea.org/regions/asia-pacific.

———. 2021b. "Data Tables – Data & Statistics." 2021. https://www.iea.org/data-and-statistics/data-tables.

———. 2021c. "World Energy Outlook 2021." Paris, France: International Energy Agency.

IPCC. 2006. *IPCC Guidelines for National Greenhouse Gas Inventories*. IGES, Japan: Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme. http://www.ipcc-nggip.iges.or.jp/public/2006gl/.

———. 2013. *Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://www.ipcc.ch/report/ar5/wg1/.

———. 2015. "9th Corrigenda for the 2006 IPCC Guidelines." 2015. https://www.ipcc-nggip.iges.or.jp/public/2006gl/corrigenda9.html.

———. 2019. "2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories." Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Switzerland: IPCC.

Irvine, Irina C., Tara Greaver, Jennifer Phelan, Robert D. Sabo, and George Van Houtven. 2017. "Terrestrial Acidification and Ecosystem Services: Effects of Acid Rain on Bunnies, Baseball, and Christmas Trees." *Ecosphere* 8 (6): e01857. https://doi.org/10.1002/ecs2.1857.

Ishimatsu, Atsushi, Masahiro Hayashi, Kyoung-Seon Lee, Takashi Kikkawa, and Jun Kita. 2005. "Physiological Effects on Fishes in a High-CO2 World." *Journal of Geophysical Research: Oceans* 110 (C9). https://doi.org/10.1029/2004JC002564.

ISO. 2006. "ISO 14040: Environmental Management — Life Cycle Assessment — Principles and Framework." ISO 14040:2006(E). The International Organization for Standardization.

James, Spencer L, Chris D Castle, Zachary V Dingels, Jack T Fox, Gregory J Bertolacci, Matthew Cunningham, Nathaniel J Henry, et al. 2020. "Estimating Global Injuries Morbidity and Mortality: Methods and Data Used in the Global Burden of Disease 2017 Study." *Injury Prevention* 26 (Supp 1): i125–53. https://doi.org/10.1136/injuryprev-2019-043531.

Jenkins, Marion W., Oliver Cumming, and Sandy Cairncross. 2015. "Pit Latrine Emptying Behavior and Demand for Sanitation Services in Dar Es Salaam, Tanzania." *International Journal of Environmental Research and Public Health* 12 (3): 2588–2611. https://doi.org/10.3390/ijerph120302588.

Jolliet, Olivier, Assumpció Antón, Anne-Marie Boulay, Francesco Cherubini, Peter Fantke, Annie Levasseur, Thomas E. McKone, et al. 2018. "Global Guidance on Environmental Life Cycle Impact Assessment Indicators: Impacts of Climate Change, Fine Particulate Matter Formation, Water Consumption and Land Use." *The International Journal of Life Cycle Assessment* 23 (11): 2189–2207. https://doi.org/10.1007/s11367-018-1443-y.

Jones, B., and B. C. O'Neill. 2016. "Spatially Explicit Global Population Scenarios Consistent with the Shared Socioeconomic Pathways." *Environmental Research Letters* 11 (8): 084003. https://doi.org/10.1088/1748-9326/11/8/084003.

———. 2020. "Global One-Eighth Degree Population Base Year and Projection Grids Based on the Shared Socioeconomic Pathways, Revision 01." Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/m30p-j498.

Jones, Edward R., Michelle T. H. van Vliet, Manzoor Qadir, and Marc F. P. Bierkens. 2021. "Country-Level and Gridded Estimates of Wastewater Production, Collection, Treatment and Reuse." *Earth System Science Data* 13 (2): 237–54. https://doi.org/10.5194/essd-13-237-2021.

Julian, Timothy R. 2016. "Environmental Transmission of Diarrheal Pathogens in Low and Middle Income Countries." *Environmental Science: Processes & Impacts* 18 (8): 944–55. https://doi.org/10.1039/C6EM00222F.

Khalil, Ibrahim A., Christopher Troeger, Puja C. Rao, Brigette F. Blacker, Alexandria Brown, Thomas G. Brewer, Danny V. Colombara, et al. 2018. "Morbidity, Mortality, and Long-Term Consequences Associated with Diarrhoea from Cryptosporidium Infection in Children Younger Than 5 Years: A Meta-Analyses Study." *The Lancet Global Health* 6 (7): e758–68. https://doi.org/10.1016/S2214-109X(18)30283-3.

Kiulia, Nicholas M., Nynke Hofstra, Lucie C. Vermeulen, Maureen A. Obara, Gertjan Medema, and Joan B. Rose. 2015. "Global Occurrence and Emission of Rotaviruses to Surface Waters." *Pathogens* 4 (2): 229–55. https://doi.org/10.3390/pathogens4020229.

Kraay, Alicia N. M., Andrew F. Brouwer, Nan Lin, Philip A. Collender, Justin V. Remais, and Joseph N. S. Eisenberg. 2018. "Modeling Environmentally Mediated Rotavirus Transmission: The Role of Temperature and Hydrologic Factors." *Proceedings of the National Academy of Sciences* 115 (12): E2782–90. https://doi.org/10.1073/pnas.1719579115.

Kulak, Michal, Nimish Shah, Niteen Sawant, Nicole Unger, and Henry King. 2017. "Technology Choices in Scaling up Sanitation Can Significantly Affect Greenhouse Gas Emissions and the Fertiliser Gap in India." *Journal of Water, Sanitation and Hygiene for Development* 7 (3): 466–76. https://doi.org/10.2166/washdev.2017.005.

Kummu, Matti, Hans de Moel, Philip J. Ward, and Olli Varis. 2011. "How Close Do We Live to Water? A Global Analysis of Population Distance to Freshwater Bodies." *PLOS ONE* 6 (6): e20578. https://doi.org/10.1371/journal.pone.0020578.

Kummu, Matti, Maija Taka, and Joseph H. A. Guillaume. 2018. "Gridded Global Datasets for Gross Domestic Product and Human Development Index over 1990–2015." *Scientific Data* 5 (February): 180004. https://doi.org/10.1038/sdata.2018.4.

Lee, Hannah, and Thai Pin Tan. 2016. "Singapore's Experience with Reclaimed Water: NEWater." *International Journal of Water Resources Development* 32 (4): 611–21. https://doi.org/10.1080/07900627.2015.1120188.

Lee, Uisung, Jeongwoo Han, and Michael Wang. 2017. "Evaluation of Landfill Gas Emissions from Municipal Solid Waste Landfills for the Life-Cycle Analysis of Waste-to-Energy Pathways." *Journal of Cleaner Production* 166: 335–42. https://doi.org/10.1016/j.jclepro.2017.08.016.

Longo, Stefano, Benedetto Mirko d'Antoni, Michael Bongards, Antonio Chaparro, Andreas Cronrath, Francesco Fatone, Juan M. Lema, Miguel Mauricio-Iglesias, Ana Soares, and Almudena Hospido. 2016. "Monitoring and Diagnosis of Energy Consumption in Wastewater Treatment Plants. A State of the Art and Proposals for Improvement." *Applied Energy* 179 (October): 1251–68. https://doi.org/10.1016/j.apenergy.2016.07.043.

McDowell, Rich W., A. Noble, P. Pletnyakov, B. E. Haggard, and L. M. Mosley. 2020. "Global Mapping of Freshwater Nutrient Enrichment and Periphyton Growth Potential." *Scientific Reports* 10 (1): 3568. https://doi.org/10.1038/s41598-020-60279-w.

McDowell, Rich W., Alasdair Noble, Peter Pletnyakov, and Luke M. Mosley. 2020. "Global Database of Diffuse Riverine Nitrogen and Phosphorus Loads and Yields." *Geoscience Data Journal*, no. n/a: 1–12. https://doi.org/10.1002/gdj3.111.

Mehta, Meera. 2018. "Public Finance at Scale for Rural Sanitation—a Case of Swachh Bharat Mission, India." *Journal of Water, Sanitation and Hygiene for Development* 8 (3): 359–73. https://doi.org/10.2166/washdev.2018.002.

Metcalf & Eddy, and AECOM. 2013. *Wastewater Engineering: Treatment and Resource Recovery*. 5 edition. New York, NY: McGraw-Hill Education.

Mijthab, Mona, Raluca Anisie, and Omar Crespo. 2021. "MOSAN: Combining Circularity and Participatory Design to Address Sanitation in Low-Income Communities." *Circular Economy and Sustainability* 1 (3): 1165–91. https://doi.org/10.1007/s43615-021-00118-w.

Mogollón, J. M., A. H. W. Beusen, H. J. M van Grinsven, H. Westhoek, and A. F. Bouwman. 2018. "Future Agricultural Phosphorus Demand According to the Shared Socioeconomic Pathways." *Global Environmental Change* 50 (May): 149–63. https://doi.org/10.1016/j.gloenvcha.2018.03.007.

Mogollón, J. M., L. Lassaletta, A. H. W. Beusen, H. J. M. van Grinsven, H. Westhoek, and A. F. Bouwman. 2018. "Assessing Future Reactive Nitrogen Inputs into Global Croplands Based on the Shared Socioeconomic Pathways." *Environmental Research Letters* 13 (4): 044008. https://doi.org/10.1088/1748-9326/aab212.

Möller, D., and H. Schieferdecker. 1989. "Ammonia Emission and Deposition of NHx in the G.D.R." *Atmospheric Environment (1967)* 23 (6): 1187–93. https://doi.org/10.1016/0004-6981(89)90145-5.

Morelli, Ben, Sarah Cashman, Sam Arden, Ma Xin (Cissy), Jason Turgeon, Jay Garland, and Diana Bless. 2019. "Life Cycle Assessment and Cost Analysis of Municipal Wastewater Treatment Expansion Options for Food Waste Anaerobic Co-Digestion." EPA/600/R-19/094. Washington, D.C.: U.S. Environmental Protection Agency.

Morelli, Ben, Sarah Cashman, Xin (Cissy) Ma, Jason Turgeon, Sam Arden, and Jay Garland. 2020. "Environmental and Cost Benefits of Co-Digesting Food Waste at Wastewater Treatment Facilities." *Water Science and Technology* 82 (2): 227–41. https://doi.org/10.2166/wst.2020.104.

Mraz, Alexis L., Innocent K. Tumwebaze, Shane R. McLoughlin, Megan E. McCarthy, Matthew E. Verbyla, Nynke Hofstra, Joan B. Rose, and Heather M. Murphy. 2021. "Why Pathogens Matter for Meeting the United Nations' Sustainable Development Goal 6 on Safely Managed Water and Sanitation." *Water Research* 189 (February): 116591. https://doi.org/10.1016/j.watres.2020.116591.

Mutai, P., C. Niwagaba, J. B. Tumuhairwe, R. Kulabako, A. Katukiza, P. Nyenje, and F. Kansiime. 2016. "Key Factors Affecting Performance of Biogas Latrines in Urban Informal Areas: Case of Kampala and Nairobi, East Africa." *African Journal of Environmental Science and Technology* 10 (7): 207–20. https://doi.org/10.4314/ajest.v10i7.

Nemecek, Thomas, and Thomas Kägi. 2007. "Life Cycle Inventories of Agricultural Production Systems." 15. Dübendorf and Zürich, Switzerland: Ecoinvent Centre. https://db.ecoinvent.org/reports/15_Agriculture.pdf.

Okaali, Daniel, Nynke Hofstra, Lisanne Nauta, and Matthew Verbyla. 2019. "The Pathogen Flow & Mapping Tool: Preliminary Model Explanation." Water Systems and Global Change Group, Wageningen University, San Diego State University. https://www.waterpathogens.org/sites/default/files/The%20pathogen%20flow%20&%20mapping%20tool_DRAFT_clean.pdf.

Orner, Kevin, Colleen Naughton, and Thor-Axel Stenstrom. 2018. "Pit Toilets (Latrines)." In *Water and Sanitation for the 21st Century: Health and Microbiological Aspects of Excreta and Wastewater Management (Global Water Pathogen Project)*, by Joan B. Rose and Blanca Jiménez Cisneros. East Lansing, MI, USA: Michigan State University, UNESCO. https://doi.org/10.14321/waterpathogens.56.

Pipatti, Riita, Joae Wagner Silva Alves, Qingxian Gao, Carlos Lopez Cabrera, Katerina Mareckova, Hans Oonk, Elizabeth Scheele, et al. 2015. "Biological Treatment of Solid Waste." In *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 5: Waste*, edited by Simon Eggleston, Leandro Buendia, Kyoko Miwa, Todd Ngara, and Kiyoto Tanabe. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Geneva, Switzerland: Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html.

Puijenbroek, P. J. T. M. van, A. F. Bouwman, A. H. W. Beusen, and P. L. Lucas. 2014. "Global Implementation of Two Shared Socioeconomic Pathways for Future Sanitation and Wastewater Flows." *Water Science and Technology* 71 (2): 227–33. https://doi.org/10.2166/wst.2014.498.

Rahman, Sheikh M., Matthew J. Eckelman, Annalisa Onnis-Hayden, and April Z. Gu. 2018. "Comparative Life Cycle Assessment of Advanced Wastewater Treatment Processes for Removal of Chemicals of Emerging Concern." *Environmental Science & Technology* 52: 11346–58. https://doi.org/10.1021/acs.est.8b00036.

Ravallion, Martin, Shaohua Chen, and Prem Sangraula. 2007. "New Evidence on the Urbanization of Global Poverty." WPS4199. World Bank.

Rorat, Agnieszka, Pauline Courtois, Franck Vandenbulcke, and Sébastien Lemiere. 2019. "Sanitary and Environmental Aspects of Sewage Sludge Management." *Industrial and Municipal Sludge*, 155–80. https://doi.org/10.1016/B978-0-12-815907-1.00008-8.

Rose, C., A. Parker, B. Jefferson, and E. Cartmell. 2015. "The Characterization of Feces and Urine: A Review of the Literature to Inform Advanced Treatment Technology." *Critical Reviews in Environmental Science and Technology* 45 (17): 1827–79. https://doi.org/10.1080/10643389.2014.1000761.

Rosenbaum, Ralph K., T.M. Bachmann, L.S. Gold, Mark A.J. Huijbregts, Olivier Jolliet, R. Juraske, A. Koehler, et al. 2008. "USEtox - The UNEP-SETAC Toxicity Model: Recommended Characterisation Factors for Human

Toxicity and Freshwater Ecotoxicity in Life Cycle Impact Assessment." *International Journal of Life Cycle Assessment* 13 (7): 532–46. https://doi.org/10.1007/s11367-008-0038-4.

Russel, Kory C., Kelvin Hughes, Mary Roach, David Auerbach, Andrew Foote, Sasha Kramer, and Raúl Briceño. 2019. "Taking Container-Based Sanitation to Scale: Opportunities and Challenges." *Frontiers in Environmental Science* 7: 190. https://doi.org/10.3389/fenvs.2019.00190.

Seibel, Brad A., and Patrick J. Walsh. 2001. "Potential Impacts of CO2 Injection on Deep-Sea Biota." *Science* 294 (5541): 319–20. https://doi.org/10.1126/science.1065301.

Seiple, Timothy E., André M. Coleman, and Richard L. Skaggs. 2017. "Municipal Wastewater Sludge as a Sustainable Bioresource in the United States." *Journal of Environmental Management* 197 (July): 673–80. https://doi.org/10.1016/j.jenvman.2017.04.032.

Singh, P. K., P. B. Deshbhratar, and D. S. Ramteke. 2012. "Effects of Sewage Wastewater Irrigation on Soil Properties, Crop Yield and Environment." *Agricultural Water Management* 103 (January): 100–104. https://doi.org/10.1016/j.agwat.2011.10.022.

Sørup, Hjalte J. D., Sarah Brudler, Berit Godskesen, Yan Dong, Sara M. Lerer, Martin Rygaard, and Karsten Arnbjerg-Nielsen. 2020. "Urban Water Management: Can UN SDG 6 Be Met within the Planetary Boundaries?" *Environmental Science & Policy* 106 (April): 36–39. https://doi.org/10.1016/j.envsci.2020.01.015.

Steffen, W., K. Richardson, J. Rockström, S. E. Cornell, I. Fetzer, E. M. Bennett, R. Biggs, et al. 2015. "Planetary Boundaries: Guiding Human Development on a Changing Planet." *Science* 347 (6223): 1259855–1259855. https://doi.org/10.1126/science.1259855.

Thye, Yoke Pean, Michael R. Templeton, and Mansoor Ali. 2011. "A Critical Review of Technologies for Pit Latrine Emptying in Developing Countries." *Critical Reviews in Environmental Science and Technology* 41 (20): 1793–1819. https://doi.org/10.1080/10643389.2010.481593.

Tilley, Elizabeth, Lukas Ulrich, Christoph Lüthi, Phillippe Reymond, Roland Schertenleib, and Christian Zurbrügg. 2014. *Compendium of Sanitation Systems and Technologies*. 2nd Revised Edition. Dübendorf, Switzerland: Swiss Federal Institute of Aquatic Science and Technology (EAWAG).

Towprayoon, Sirintornthep, Tomonori Ishigaki, Chart Chiemchasiri, Amr Osama Abdel-Aziz, Mark Edward Hunstone, Chalor Jarusutthirak, Marco Ritzkowski, and Marianne Thomsen. 2019. "Solid Waste Disposal (Chapter 3)." In *Volume 5: Waste*, edited by Deborah M. Bartram, Sirintornthep Towprayoon, Fatma Betul Demirok, and Anke Herold. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Geneva, Switzerland: Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html.

Towprayoon, Sirintornthep, Seungdo Kim, Eui-Chan Jeon, Tomoroni Ishigaki, and Seini Amadou. 2019. "Incineration and Open Burning of Waste (Chapter 5)." In *Volume 5: Waste*, edited by Deborah M. Bartram, Sirintornthep Towprayoon, Fatma Betul Demirok, and Anke Herold. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Geneva, Switzerland: Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html.

Towprayoon, Sirintornthep, Sergii Shmarin, Qingxian Gao, Amr Osama Abdel-Aziz, Juraj Farkas, Nuria Mariana Zanzottera, Muhammad Ijaz, and Chhemendra Sharma. 2019. "Waste Generation, Composition, and Management Data (Chapter 2)." In *Volume 5: Waste*, edited by Deborah M. Bartram, Sirintornthep Towprayoon, Fatma Betul Demirok, and Anke Herold. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Geneva, Switzerland: Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html.

Troeger, Christopher, Brigette F. Blacker, Ibrahim A. Khalil, Puja C. Rao, Shujin Cao, Stephanie RM Zimsen, Samuel B. Albertson, et al. 2018. "Estimates of the Global, Regional, and National Morbidity, Mortality, and Aetiologies of Diarrhoea in 195 Countries: A Systematic Analysis for the Global Burden of Disease Study 2016." *The Lancet Infectious Diseases* 18 (11): 1211–28. https://doi.org/10.1016/S1473-3099(18)30362-1.

Tzanakakis, V.E., N.V. Paranychianaki, and A.N. Angelakis. 2007. "Soil as a Wastewater Treatment System: Historical Development." *Water Supply* 7 (1): 67–75. https://doi.org/10.2166/ws.2007.008.

UN DESA. 2019a. "World Population Prospects 2019: Methodology of the United Nations Population Estimates and Projections." New York, USA: United Nations Department of Economic and Social Affairs, Population Division. https://population.un.org/wpp/Publications/Files/WPP2019_Methodology.pdf.

———. 2019b. "World Urbanization Prospects: The 2018 Revision." ST/ESA/SER.A/420. New York, NY, USA: United Nations Department of Economic and Social Affairs, Population Division. https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf.

UN General Assembly. 2015. *Transforming Our World: The 2030 Agenda for Sustainable Development*. Vol. A/Res/70/1.

U.S. EPA. 2020. "Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM): Management Practice Chapters." U.S. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2020-12/documents/warm_management_practices_v15_10-29-2020.pdf.

U.S. EPA, and ERG. 2021. "Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants." EPA 832-R-21-006. Washington, DC, USA: United States Environmental Protection Agency; Standards and Health Protection Division. https://www.epa.gov/system/files/documents/2021-08/life-cycle-nutrient-removal.pdf.

Vermeulen, Lucie C, Nynke Hofstra, Carolien Kroeze, and Gertjan Medema. 2015. "Advancing Waterborne Pathogen Modelling: Lessons from Global Nutrient Export Models." *Current Opinion in Environmental Sustainability*, Open Issue, 14 (June): 109–20. https://doi.org/10.1016/j.cosust.2015.05.003.

Weidema, Bo P., Christian Bauer, Roland Hischier, C.L. Mutel, Thomas Nemecek, C.O. Vadenbo, and Gregor Wernet. 2013. "Overview and Methodology." In *Data Quality Guideline for the Ecoinvent Database Version 3 (Final)*. St. Gallen, Switzerland: Ecoinvent. http://www.ecoinvent.org/files/dataqualityguideline_ecoinvent_3_20130506.pdf.

WHO and UNICEF. 2017. "Progress on Drinking Water, Sanitation and Hygiene: 2017 Update and SDG Baselines." Geneva, Switzerland: World Health Organization (WHO) and United Nations International Children's Emergency Fund (UNICEF).

WHO, and UNICEF. 2019. "Progress on Household Drinking Water, Sanitation and Hygiene 2000-2017: Special Focus on Inequalities." Geneva, Switzerland: World Health Organization and United Nations Children's Fund (WHO/UNICEF) Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP). https://www.who.int/water_sanitation_health/publications/jmp-report-2019/en/.

———. 2020a. "Sanitation and Sanitation Data." World Health Organization (WHO) and United Nations International Children's Emergency Fund (UNICEF) Joint Monitoring Programme (JMP). http://washdata.org/monitoring/sanitation. http://washdata.org/monitoring/sanitation.

———. 2020b. "SDG (Sustainable Development Goal) Monitoring | JMP." Joint Monitoring Programme—JMP. 2020. https://washdata.org/how-we-work/sdg-monitoring.

———. 2021. "JMP Downloads Index." Joint Monitoring Programme—JMP. 2021. https://washdata.org/data/downloads.

Woods, John S., Karin Veltman, Mark A. J. Huijbregts, Francesca Verones, and Edgar G. Hertwich. 2016. "Towards a Meaningful Assessment of Marine Ecological Impacts in Life Cycle Assessment (LCA)." *Environment International* 89–90 (April): 48–61. https://doi.org/10.1016/j.envint.2015.12.033.

World Bank. 2019. "World Development Indicators | DataBank." January 2019. https://databank.worldbank.org/source/world-development-indicators.

Yin, Sha-sha, Jun-yu Zheng, Li-jun Zhang, and Liu-ju Zhong. 2010. "[Anthropogenic ammonia emission inventory and characteristics in the Pearl River Delta Region]." *Chinese Journal of Environmental Science* 31 (5): 1146–51.

Yoder, Jonathan S., and Michael J. Beach. 2010. "Cryptosporidium Surveillance and Risk Factors in the United States." *Experimental Parasitology* 124 (1): 31–39. https://doi.org/10.1016/j.exppara.2009.09.020.

Yoshida, Hiroko, Joshua J. Gable, and Jae K. Park. 2012. "Evaluation of Organic Waste Diversion Alternatives for Greenhouse Gas Reduction." *Resources, Conservation and Recycling* 60 (March): 1–9. https://doi.org/10.1016/j.resconrec.2011.11.011.

Zeebe, Richard E. 2012. "History of Seawater Carbonate Chemistry, Atmospheric CO2, and Ocean Acidification." *Annual Review of Earth and Planetary Sciences* 40 (1): 141–65. https://doi.org/10.1146/annurev-earth-042711-105521.

Zeebe, Richard E., James C. Zachos, Ken Caldeira, and Toby Tyrrell. 2008. "Carbon Emissions and Acidification." *Science* 321 (5885): 51–52.

Appendix A Example JMP Data

The figures below provide an overview of data available from the JMP. While captions of the figures describe the data fields, we note that for all of these data, there is variability in reporting. Because data for one country is not necessarily available for another, we use regional data to supplement missing country data as needed.

Appendix Table A.1 and Appendix Table A.2 show the global data file, in which aggregated data by country are reported.

Appendix Table A.3 shows a country level file, in which detailed data can be reported for individual countries.

Appendix Table A.1: Example of national level data from JMP, showing ladder distinctions (open, unimproved, improved) by country.

	A	B	C	D	E	F	G	H	I	J	K
1	SANITATION										
2						NATIONAL					
3	COUNTRY, AREA OR TERRITORY	ISO3	Year	Population (thousands)	% urban	At least basic	Limited (shared)	Unimproved	Open defecation	Annual rate of change in basic	Annual rate of change in open fecation
24	Afghanistan	AFG	2020	38 928	26	50	11	28	11	1.43	-0.75
45	Albania	ALB	2020	2 878	62	>99	<1	<1	<1	0.49	-0.04
66	Algeria	DZA	2020	43 851	74	86	11	4	<1	0.07	-0.31
87	American Samoa	ASM	2020	55	87	54	45	<1	<1	-0.52	-
108	Andorra	AND	2020	77	88	>99	<1	<1	<1	0.00	0.00
129	Angola	AGO	2020	32 866	67	52	21	9	18	1.21	-1.24
150	Anguilla	AIA	2020	15	100	-	-	-	-	-	-
171	Antigua and Barbuda	ATG	2020	98	24	-	-	-	-	-	-
192	Argentina	ARG	2020	45 196	92	-	-	-	-	-	-

Appendix Table A.2: Example of national level data from JMP, showing management distinctions (in situ, emptying, wastewater), and archetype (latrine, septic, sewer).

	A	B	C	X	Y	Z	AA	AB	AC	AD	AE
1	SANITATION			NATIONAL							
2				Proportion of population using improved sanitation facilities (excluding shared)					Proportion of population using improved sanitation facilities (including shared)		
3	COUNTRY, AREA OR TERRITORY	ISO3	Year	Safely managed	Disposed in situ	Emptied and treated	Wastewater treated	Annual rate of change in safely managed	Latrines and other	Septic tanks	Sewer connections
24	Afghanistan	AFG	2020	-	-	-	-	-	49	9	3
45	Albania	ALB	2020	48	9	4	35	0.37	16	4	79
66	Algeria	DZA	2020	18	4	<1	14	-0.20	3	6	88
87	American Samoa	ASM	2020	-	-	-	23	-	11	39	49
108	Andorra	AND	2020	>99	<1	<1	>99	4.27	<1	-	>99
129	Angola	AGO	2020	-	-	-	-	-	1	58	13
150	Anguilla	AIA	2020	-	-	-	-	-	-	-	-
171	Antigua and Barbuda	ATG	2020	-	-	-	-	-	-	-	-
192	Argentina	ARG	2020	-	-	-	-	-	-	-	-

Appendix Table A.3 (multi-page): Example of detailed country-specific data (Afghanistan is shown). Note that this country level data can include specific information such as the types of latrines.

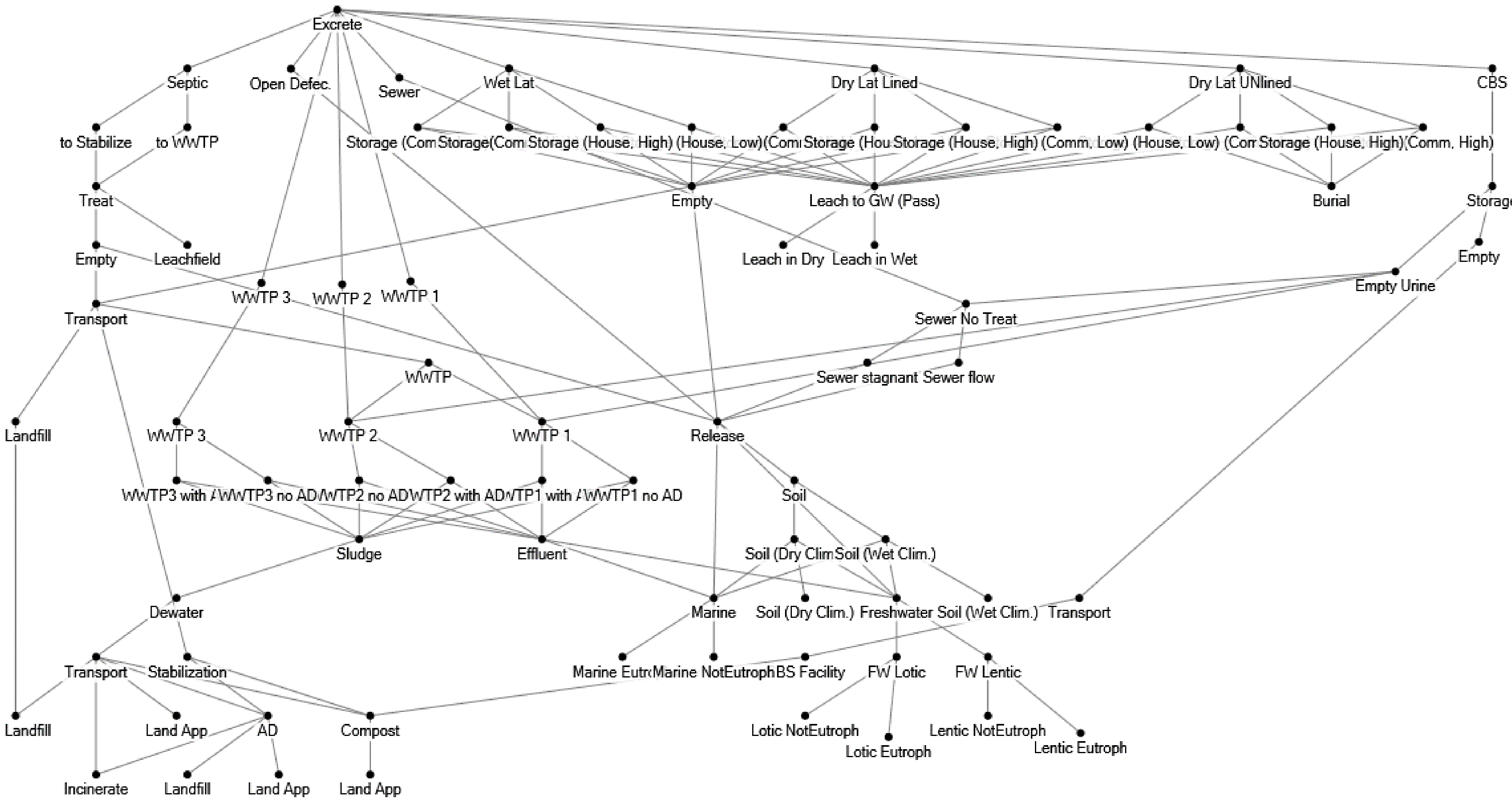
Use of sanitation facilities	Afghanistan			
AFG_2020_IELFS				
Survey with microdata	IELFS			
Definitions	**Facility type estimates**	**Urban**	**Rural**	**National**
	Improved	83.5	61.9	67.2
	Sewer	10.0	1.7	3.7
	Septic	22.6	1.9	6.9
	Other	50.9	58.4	56.6
	Open defecation	0.2	14.9	11.4
	Service level estimates			
	Sewer	10.0	1.7	3.7
Default assumption: 100%	Wastewater enters network			
Default assumption: 100%	Wastewater reaches treatment plant			
	Septic	22.6	1.9	6.9
Default assumption: 50%	Contained/stored and treated			
Default assumption: 100%	Not emptied/treated and disposed in situ			
Default assumption: 0%	Emptied and buried on site			
Default assumption: 0%	Emptied and discharged locally			
Default assumption: 0%	Emptied and removed offsite			
Default assumption: 100%	Delivered to treatment plant			
	Latrines and other improved	50.9	58.4	56.6
Default assumption: 100%	Contained/stored and treated			
Default assumption: 50%	Not emptied/treated and disposed in situ			
Default assumption: 0%	Emptied and buried on site			
Default assumption: 0%	Emptied and discharged locally			
Default assumption: 50%	Emptied and removed offsite			
Default assumption: 100%	Delivered to treatment plant			
	Treated			
Default assumption: 50%	At wastewater treatment plant			
Default assumption: 0% or based on wastewater treatn	At faecal sludge treatment plant			
	Shared			
	Safely managed			

Definitions	Facility type estimates		Urban	Rural	National
Original denomination	Classification		Urban	Rural	National
	Flush and pour flush		*35.9*	*4.6*	*12.2*
		to piped sewer system	*10.0*	*1.7*	*3.7*
		to septic tank	*22.6*	*1.9*	*6.9*
		to pit	*2.3*	*0.7*	*1.1*
		to unknown place/ not sure/DK			
		to elsewhere	*1.0*	*0.3*	*0.5*
	Flush/toilets		*35.9*	*4.6*	*12.2*
Flush to piped sewer system		to piped sewer system	10.0	1.7	3.7
Flush/pour flush toilet to septic tank		to septic tank	22.6	1.9	6.9
Flush/pour flush toilet to pit		to pit	2.3	0.7	1.1
		to unknown place/ not sure/DK			
Flush/pour flush toilet to elsewhere		to elsewhere	1.0	0.3	0.5
		Private flush/toilet			
		to piped sewer system			
		to septic tank			
		to pit			
		to unknown place/ not sure/DK			
		to elsewhere			
		Public/shared flush/toilet			
		to piped sewer system			
		to septic tank			
		to pit			
		to unknown place/ not sure/DK			
		to elsewhere			

Definitions	Facility type estimates		Urban	Rural	National
	Latrines		58.4	63.6	62.3
	Pour flush latrines				
		to piped sewer system			
		to septic tank			
		to pit			
		to unknown place/ not sure/DK			
		to elsewhere			
		Private pour flush latrine			
		to piped sewer system			
		to septic tank			
		to pit			
		to unknown place/ not sure/DK			
		to elsewhere			
		Public/shared pour flush latrine			
		to piped sewer system			
		to septic tank			
		to pit			
		to unknown place/ not sure/DK			
		to elsewhere			
	Dry latrines		58.4	63.6	62.3
		Improved latrines	43.2	41.3	41.8
VIP latrines		Ventilated Improved Pit latrine	16.0	4.7	7.4
Pit latrine - with slab/covered pit		Pit latrine with slab/covered latrine	27.2	36.6	34.3
		Traditional latrine			
Pit latrine - without slab/covered pit		Pit latrine without slab/open pit	15.2	22.2	20.5
		Hanging toilet/hanging latrine			
		Bucket latrine			
		Other			
		Private Latrines			
		Ventilated Improved Pit latrine			
		Pit latrine with slab/covered latrine			
		Traditional latrine			
		Pit latrine without slab/open pit			
		Hanging toilet/hanging latrine			
		Bucket latrine			
		Other			
		Public/shared Latrines			
		Ventilated Improved Pit latrine			
		Pit latrine with slab/covered latrine			
		Traditional latrine			
		Pit latrine without slab/open pit			
		Hanging toilet/hanging latrine			
		Bucket latrine			
		Other			

Definitions	Facility type estimates		Urban	Rural	National
	Composting toilets				
		Composting toilet (private)			
		Composting toilet (shared)			
	Other improved		5.4	16.4	13.7
Single/double vault - with urine diversion		Other	3.0	7.4	6.3
Single/double vault - without urine diversion		Other	2.4	9.0	7.4
	No facility, bush, field		*0.2*	*14.9*	*11.4*
	Other unimproved		*0.1*	0.6	*0.4*
Other		Other	0.1	0.6	0.4
		Other			
	DK/missing information				
	Total		100.0	100.0	100.0

Appendix B Description of Network Nodes



Appendix Figure B.1: Network diagram for all pathways

Appendix Table B.1: Description of all network nodes (see Appendix Figure B.1) and mapping to stages

Node	Display Name	Description	Broad Stage	Detailed Stage
(Pass)_Excretion	Excrete	Top Node	NA	NA
(Define)_Open_Defecation	Open Defec.	Definition node	NA	NA
(Define)_Dry_Latrine_UNlined	Dry Lat UNlined	Definition node	NA	NA
(Define)_Dry_Latrine_Lined	Dry Lat Lined	Definition node	NA	NA
(Define)_Wet_Latrine_Lined	Wet Lat	Definition node	NA	NA
(Define)_CBS	CBS	Definition node	NA	NA
(Define)_Septic	Septic	Definition node	NA	NA
(Define)_Sewer_No_Treat	Sewer	Definition node	NA	NA
Store_Dry_Lat_UNlined_Communal_Low_GW	Storage (Comm, Low)	Storage in latrine type	Storage	Latrine Storage
Store_Dry_Lat_UNlined_Communal_High_GW	Storage(Comm, High)	Storage in latrine type	Storage	Latrine Storage
Store_Dry_Lat_UNlined_House_Low_GW	Storage (House, Low)	Storage in latrine type	Storage	Latrine Storage
Store_Dry_Lat_UNlined_House_High_GW	Storage (House, High)	Storage in latrine type	Storage	Latrine Storage
Store_Dry_Lat_Lined_Communal_Low_GW	Storage (Comm, Low)	Storage in latrine type	Storage	Latrine Storage
Store_Dry_Lat_Lined_Communal_High_GW	Storage(Comm, High)	Storage in latrine type	Storage	Latrine Storage
Store_Dry_Lat_Lined_House_Low_GW	Storage (House, Low)	Storage in latrine type	Storage	Latrine Storage
Store_Dry_Lat_Lined_House_High_GW	Storage (House, High)	Storage in latrine type	Storage	Latrine Storage
Store_Wet_Latrine_Communal_Low_GW	Storage (Comm, Low)	Storage in latrine type	Storage	Latrine Storage
Store_Wet_Latrine_Communal_High_GW	Storage(Comm, High)	Storage in latrine type	Storage	Latrine Storage
Store_Wet_Latrine_House_Low_GW	Storage (House, Low)	Storage in latrine type	Storage	Latrine Storage
Store_Wet_Latrine_House_High_GW	Storage (House, High)	Storage in latrine type	Storage	Latrine Storage
Stored_Leached_to_Groundwater_(Pass)	Leach to GW (Pass)	Pass-through	Release—Leaching	Release—Leaching
Leached_to_Groundwater_DryClimate_(End)	Leach in Dry	Leaching	Release—Leaching	Release—Leaching
Leached_to_Groundwater_WetClimate_(End)	Leach in Wet	Leaching	Release—Leaching	Release—Leaching
Store_CBS	Storage	Storage in CBS	Storage	CBS Storage
Store_Septic	Treat	Storage in Septic	Treatment	Septic Storage
Burial_(End)	Burial	Burial (of latrine)	Release—Leaching	Release—Leaching
Stored_Emptying	Empty	Emptying of stored material	Emptying	Emptying
CBS_Emptying_Urine	Empty Urine	CBS emptying—urine	Emptying	Emptying
CBS_Emptying_Feces	Empty	CBS emptying—feces	Emptying	Emptying
Septic_Emptying	Empty	Emptying of septic	Emptying	Emptying

Node	Display Name	Description	Broad Stage	Detailed Stage
Septic_Leachfield_(End)	Leachfield	Leaching	Release—Leaching	Release—Leaching
EmptiedLatrineSeptic_Transport	Transport	Transport of latrine or septic material	Transport	Transport
EmptiedCBS_Transport	Transport	Transport of CBS material	Transport	Transport
(Pass)_EmptiedLatrineSeptic_Stabilization	Stabilization	Emptied material to Stabilization	Treatment	Treatment
(Pass)_EmptiedLatrineSeptic_WWTP	WWTP	Emptied material to WWTP	Transport	Transport
(Pass)_EmptiedLatrineSeptic_Landfill	Landfill	Emptied direct to landfill	Solids	Solids
(Define)_Septic_to_WWTP	to WWTP	Definition node	NA	NA
(Define)_Septic_to_Stabilize	to Stabilize	Definition node	NA	NA
Sewer_No_Treat_(Pass)	Sewer No Treat	Pass-through	Collection	Collection
Sewer_Flowing_No_Treat	Sewer flow	Flowing sewer	Collection	Collection
Sewer_Stagnant_No_Treat	Sewer stagnant	Stagnant sewer	Collection	Collection
(Pass)_CBS_Facility	CBS Facility	Pass-through	Collection	Collection
(Define)_WWTP1_withAD	WWTP1 with AD	Definition node	Treatment	Treatment
(Define)_WWTP1_noAD	WWTP1 no AD	Definition node	Treatment	Treatment
(Define)_WWTP2_withAD	WWTP2 with AD	Definition node	Treatment	Treatment
(Define)_WWTP2_noAD	WWTP2 no AD	Definition node	Treatment	Treatment
(Define)_WWTP3_withAD	WWTP3 with AD	Definition node	Treatment	Treatment
(Define)_WWTP3_noAD	WWTP3 no AD	Definition node	Treatment	Treatment
WWTP1	WWTP 1	WWTP Primary	Treatment	Treatment
WWTP2	WWTP 2	WWTP Secondary	Treatment	Treatment
WWTP3	WWTP 3	WWTP Tertiary	Treatment	Treatment
(Pass)_WWTP_Effluent	Effluent	Pass-through	Treatment	Treatment
WWTP_Sludge	Sludge	Sludge	Solids	Sludge
WWTP_(End_Lost)	WWTP Lost	Mass-balance node	NA	NA
WWTP_Sludge_Dewater	Dewater	Dewatering of sludge	Solids	Sludge
WWTP_Sludge_Transport	Transport	Transport of sludge	Transport	Transport
AD	AD	Anaerobic digestion	Solids	AD
Compost	Compost	Composting	Solids	Compost
AD_Digestate	AD Digested	Digestate	Solids	AD
Compost_Digestate	Compost Digested	Digestatet	Solids	Compost
AD_(End_Lost)	AD Lost	Mass-balance node	NA	NA

Node	Display Name	Description	Broad Stage	Detailed Stage
Compost_(End_Lost)	Compost Lost	Mass-balance node	NA	NA
Land_Application_Sludge_(End)	Land App	Land application of sludge	Release—Soil	Land Apply
Land_Application_Digestate_(End)	Land App	Land application of digestate	Release—Soil	Land Apply
Land_Application_Compost_(End)	Land App	Land application of compost	Release—Soil	Land Apply
Landfill_Sludge_(End)	Landfill	Landfilling of sludge	Solids	Landfill_Sludge
Landfill_Digestate_(End)	Landfill	Landfilling of digestate	Solids	Landfill_Digestate
Incineration_(End)	Incinerate	Incineration	Solids	Incineration
(Pass)_Release	Release	Pass-through	NA	NA
(Pass)_Soil	Soil	Pass-through	Release—Soil	Release—Soil
(Pass)_Soil_Dry_Climate	Soil (Dry Clim.)	Pass-through	Release—Soil	Release—Soil
(Pass)_Soil_Wet_Climate	Soil (Wet Clim.)	Pass-through	Release—Soil	Release—Soil
Soil_Dry_Climate_(End)	Soil (Dry Clim.)	Release to soil in dry climate	Release—Soil	Release—Soil
Soil_Wet_Climate_(End)	Soil (Wet Clim.)	Release to soil in wet climate	Release—Soil	Release—Soil
(Pass)_Marine	Marine	Pass-through	Release—Marine	Release—Marine
(Pass)_Freshwater	Freshwater	Pass-through	Release—Marine	Release—Marine
(Pass)_FW_Lotic	FW Lotic	Pass-through	Release—FW	Release—FW
(Pass)_FW_Lentic	FW Lentic	Pass-through	Release—FW	Release—FW
Marine_Eutrophic_(End)	Marine Eutroph	Release to eutrophic marine	Release—Marine	Release—Marine
Marine_NotEutrophic_(End)	Marine NotEutroph	Release to non-eutrophic marine	Release—Marine	Release—Marine
Lotic_Eutrophic_(End)	Lotic Eutroph	Release to eutrophic, lotic (freshwater)	Release—FW	Release—FW
Lotic_NotEutrophic_(End)	Lotic NotEutroph	Release to non-eutrophic, lotic (freshwater)	Release—FW	Release—FW
Lentic_Eutrophic_(End)	Lentic Eutroph	Release to eutrophic, lentic (freshwater)	Release—FW	Release—FW
Lentic_NotEutrophic_(End)	Lentic NotEutroph	Release to non-eutrophic, lentic (freshwater)	Release—FW	Release—FW

Appendix C Modeling of Pathogens: Emission and Impact

The pathogen characterization factors (CFs) used this work are meant to illustrate relative differences in the potential impact due to pathogen transmission; they are not meant to be quantitative estimates of actual impacts. Indeed, other works have attempt to address the latter question. For example, the Global Burden of Disease research program (James et al. 2020) presents information about incidence and impacts of a variety of risk factors, with additional focus on specific issues such as diarrheal disease (Troeger et al. 2018) and cryptosporidium specifically (Khalil et al. 2018). In addition, there are ongoing efforts to model the emission and transmission of various pathogens relevant to this study, such as cryptosporidium (Hofstra et al. 2013) and rotavirus (Kiulia et al. 2015). In this study, we combine the estimates of emission and pathogen transfer with the impact related to exposure to those pathogens. As a demonstration of the concept, we focus on crypto and rotavirus, as some of the most infectious of diarrheal agents (Julian 2016).

In the US, ~90% of cryptosporidium outbreaks have been related to recreational water use, with the majority of those outbreaks in treated venues (e.g., swimming pools) as opposed to untreated venues (e.g., lakes); drinking water has accounted for ~10% of outbreaks (Yoder and Beach 2010). (Food, person-person, and animal-person transmission routes are relatively uncommon for outbreaks.) The main risk factors are contact with infected persons, contact with cattle, swimming, and drinking unboiled drinking water (Yoder and Beach 2010).

Globally, direct transmission of pathogens is typically considered to be more important than indirect (e.g., water-mediated), but for rotavirus, slow-moving water in cooler temperatures can be an important transmission route (Kraay et al. 2018). A number of routes for exposure that do not involve environmentally mediated water transfer: soils (including crops) and floors, drinking water, inanimate objects (fomites), and flies (Julian 2016). Most of these are directly related to drinking water or hygiene practices that are beyond the scope of this project.

This work includes direct transmission and environmentally mediated transfer of the pathogen cryptosporidium and rotavirus. The analysis is simplified and only partially accounts for nuances such as the age of the infected persons. For example, recent work has suggested that the disease burden of cryptosporidium in children is significantly underestimated (almost by factor of 2), because lifelong issues associated with undernutrition during diarrheal episodes is not included (Khalil et al. 2018). This study does not include these updated crypto impacts, because similar values for rotavirus are not available.

C.1 Shedding (emissions):

Cryptosporidium: The infected fraction of the population is 10% in developing (HDI ≤ 0.785) countries and 5% otherwise. Infected individuals excrete 1 x 10^9 oocysts / year. (Hofstra et al. 2013)

Rotavirus: The fraction of the population under 5 experiencing a case per year is 24% in developing (HDI ≤ 0.785) countries and 8% otherwise. For adults in developed countries, the infected fraction is 1%. Infected individuals shed 7 x 10^10 genome copies per case days, with this high shedding occurring during the first 7 days (Kiulia et al. 2015). We assume the population under 5 is ~10% of total population, such that the developed country infection fraction is 0.08*0.1 + 0.01*0.9 = 0.017. For developing countries, we assume the adult infection rate is 1/8 the under 5 rate, yielding a country fraction of 0.051.

Appendix Table C.1: Assumed XF (exposure factor) values for country income level. Values indicate the fraction of potential exposure that results in exposure.

Pathogen	HDI level	Overall infected population fraction (one case / year)	Shedding rate (infectious units shed / person-year)
Crypto	HDI ≤0.785	10%	1 x 10^9
Crypto	HDI > 0.785	5%	1 x 10^9
Rotavirus	HDI ≤0.785	5.1%	4.9 x 10^11
Rotavirus	HDI > 0.785	1.7%	4.9 x 10^11

C.2 Impact (characterization):

The conceptual framework of existing LCA methods, such as USEtox, provides a useful starting point establish the impact of pathogen emissions. As described for human toxicity due to chemical emissions in Fantke et al. (2021), the impact of an emission can be subdivided into the following factors (adapted to describe pathogens):

- TF, Transfer Fraction (infectious units to receptor / infectious units emitted)
- XF, Exposure Factor (infectious units exposed / possible exposure)
- DRF, Dose Response Factor (case risk / infectious unit exposure)
- SF, Severity Factor (DALY / case)

Taken together, the characterization factor is calculated as the product of these factors:

CF (DALY / units emitted) = TF (infectious units potentially reaching humans / infectious units emitted) * XF (infectious units exposed / possible exposure) * DRF (case risk / infectious unit exposure) * SF (DALY / case)

For pathogens, the emission is described in terms of infections units: oocysts (Cryptosporidium); viruses (Rotavirus).

The following sections describe each component of the above equation.

C.2.1 TF, Cumulative Transfer Fraction (infectious units potentially reaching humans / infectious units emitted)

Oocysts and viruses are relatively stable in the environment. For cryptosporidium, Hofstra et al. (2013) note the that oocysts can persist in surface waters up to 120 days; while oocysts are inactivated naturally, the rate is low. Hofstra et al. do not account for inactivation in their model. Rotavirus also has high survival in the environment (a meta-analysis found an 18 day median survival (Kraay et al. 2018)).

We use an estimate of global diarrheal DALYs (109,000 per year total) from a study of cryptosporidium, rotavirus, and campylobacter (Bivins et al. 2017) to retrospectively calculate a TF of 4x10^-13.

Note that in the model used in this study, we assume wastewater treatment plants remove some fraction of the pathogens (in the inventory portion of the LCA). We further assume that emissions to freshwater (from WWTP or via defection or dumping) as the only way to get the material back to human exposure. As noted by Hofstra et al. (2013), the management of fecal matter from pit latrines and septic systems should be considered as potential sources for other oocysts when that sludge is used as fertilizer. As these and other authors have noted (Vermeulen et al. 2015), a model that would truly capture potential multimedia transfer routes for protozoan viruses is not yet available. Therefore, we take the conservative assumption that it is open defecation (with potential transfer to freshwater sources) and sewers that provide potential pathways for exposure; for latrines, septic, and CBS, the exposure is zero.

Note that the inactivation of pathogens in wastewater treatment is accounted for in the inventory portion of the LCA. Hofstra et al. (2013) note several challenges in estimating oocyst removal efficiencies of treatment technologies, such as uncertainty of measurement and issues in treatment operation (e.g., overflows may not be captured). Their estimated removal efficiencies are shown in the table below:

Appendix Table C.2: Removal efficiencies by wastewater treatment type

Treatment type	Cryptosporidium (Hofstra et al. 2013)	Rotavirus (Kiulia et al. 2015)
Primary	10%	20%
Secondary	50%	97.5%
Tertiary	95%	99.21%

C.2.2 XF, Exposure Factor (infectious units exposed / possible exposure)

Exposure to a pathogen is a function both lifestyle (frequency of contact with untreated water) and infrastructure (the level of treatment available for drinking water). In this work, we assume that the XF (exposure fraction) is a consistent across pathogens and is function of country income as follows:

Appendix Table C.3: Assumed XF (exposure factor) values for country income level. Values indicate the fraction of potential exposure that results in exposure.

Country Income Level	XF
Low	90%
Middle	50%
High	10%

Defining the XF in this manner is in keeping with the approach for ecological effect in USEtox (Rosenbaum et al. 2008), rather than a intake-based exposure. Stated another way, rather than modeling the volume of water compartments, accounting for dilution and human intake rates, we assume that emitted pathogenic units are transferred directly to humans, after accounting for lifestyle reductions.

C.2.3 DRF, Dose Response Factor (case risk / infectious unit exposure)

The DRF is calculated from the ID50, the infectious dose causing a case in 50% of a population. ID50s are collected from peer-reviewed literature by Michigan State University's Quantitative Microbial Risk Assessment (QMRA) wiki (Center for Advancing Microbial Risk Assessment 2021).

Appendix Table C.4: Dose response (DRF) factors for pathogens.

Pathogen	ID50 (units exposed / case)	DRF (case / units exposed)
Crypto	176.5	0.043
Rotavirus	6.17	0.16

C.2.4 SF, Severity Factor (DALY / case)

To calculate DALYs associated with cases of the disease is of interest, it is necessary to have information on the number of deaths associated with disease, the ages with those deaths occur, and the total number of cases. These data are largely available in a GBD study of diarrhea (Troeger et al. 2018). In that work comment ages are not directly specified, although age ranges are given. The following table shows the data available in that work, as well as assumptions about ages of death and life expectancy (based on an average expectancy of 87 years, used in Khalil et al.) and the median impact per case used in this study.

Appendix Table C.5: Dose response (DRF) factors for pathogens.

Pathogen	Age Range	Assumed age	Life expectancy	Deaths	Cases (million)	Acute DALY / case	Median DALY / case
Crypto-sporidium	all ages	43.5	43.5	57,203	69.52	0.036	0.046
	< 5 years	2.5	84.5	48,301	44.84	0.091	
	> 70 years	70	17	1,996	0.74	0.046	
Rotavirus	all ages	43.5	43.5	228,047	591.73	0.017	0.034
	< 5 years	2.5	84.5	128,515	258.2	0.042	
	> 70 years	70	17	57,594	29.03	0.034	

Combining the constituent factors described above, we calculate the final CFs as follows. Note that the variation between high and low income is approximately a factor of 10, and the difference between rotavirus and crypto is approximately a factor of 3 (rotavirus being higher), driven largely by the higher DRF of rotavirus.

Appendix Table C.6: Calculation of CFs for pathogens.

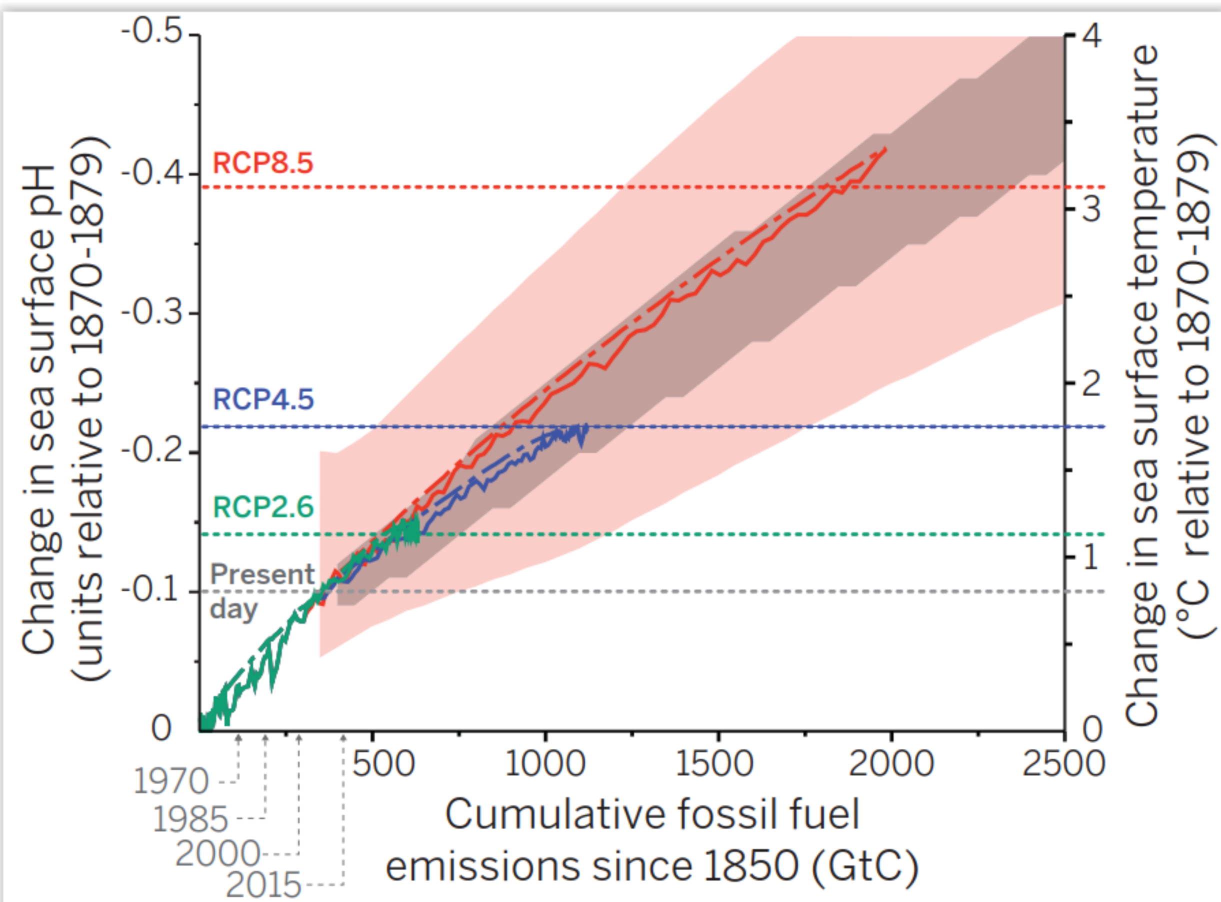
Pathogen	Income Level	TF, Transfer Fraction (units to receptor / units emitted)	XF, Exposure Factor (units exposed / possible exposure)	DRF, Dose Response Factor (case risk / unit exposure)	SF, Severity Factor (DALY / case)	CF (DALY / unit emitted)
Cryptosporidium	Low	1.1 x 10^-12	0.9	0.043	0.047	0.0018
Cryptosporidium	Middle	1.1 x 10^-12	0.5	0.043	0.047	0.0010
Cryptosporidium	High	1.1 x 10^-12	0.1	0.043	0.047	0.00020
Rotavirus	Low	1.1 x 10^-12	0.9	0.162	0.035	0.0051
Rotavirus	Middle	1.1 x 10^-12	0.5	0.162	0.035	0.0028
Rotavirus	High	1.1 x 10^-12	0.1	0.162	0.035	0.00056

Appendix D Modeling of Ocean Acidification: Impact

A brief literature review suggests that there is only set of peer-reviewed characterization factors for ocean acidification. That model (Bach et al. 2016) considers atmospheric behavior of substances relative to CO_2, and accounts for H+ increase is the ocean systems due to dissolution of CO_2(g) into the aqueous phase. The model of Bach et al. (2016), as well as a roadmap article (Woods et al. 2016) highlight the numerous impacts that ocean acidification can cause, and these impacts are also well-addressed in the marine science literature (e.g., Doney et al. 2009; Zeebe et al. 2008). However, modeling uncertainties in the response of ocean ecosystems have limited the development of CFs that describe impacts to species or ecosystem services. One author notes that ocean acidification, "…remains practically unknown, as its magnitude and its consequences have only recently been discovered" (Euzen et al. 2017).

In this work, we have used the model of Bach et al., and added the extra connection to pH change. While the ocean's response to acidification and warming is complex (e.g., stratification), there are data available to show change in (global) surface pH as a function of total CO_2 emissions (see Appendix Figure D.1, from (Gattuso et al. 2015)). From these data, it is possible to estimate a pH response vs. CO_2 atmospheric emissions. Taking the average of the RCP8.5 and RCP2.6, we arrive at a response of -5.06 x 10^-8 nano pH / kg CO_2. (Where nano pH = 1 x 10^-9 pH units.)

Indeed, the absolute change per kg of CO_2 is quite small. This result is not surprising; in the last 250 years, ocean pH has decrease 0.1 pH units (from 8.2 to 8.1); as pH is a log scale, though, this represents a 30% change (Euzen et al. 2017). Thus, although the results for an individual sector, such as wastewater, will be small in terms of pH change, presenting results as pH helps differentiate from the CO_2 equivalents typically used for global warming.



Appendix Figure D.1: Change in pH vs cumulative emissions (Gattuso et al. 2015)

Combining the equivalency of Bach et al. (2016) with the marginal response of Gattuso et al. (2015), final CFs are calculated in the following table:

Appendix Table D.1: Calculation of CFs for ocean acidification

Substance	kg CO_2eq / kg substance	CF (nano-pH / kg substance)
CO_2	1	5.06E-08
CH_4	0.84	4.25E-08
CO	0.87	4.40E-08

Appendix E Electricity Emission Factors

Appendix Table E.1: Emission Factors for electricity use, comparing current and future (IEA 2050) scenarios

Scenario	SDG1+WB	CH_4-Air	CO_2-Air	N_2-Air	N_2O-Air	Neq-Soil	Neq-Water	NH_3-Air	NO_x-Air	Peq-Soil	Peq-Water	PM_{10}-Air	$PM_{2.5}$-Air	SO_x-Air
Current	Central and S Asia / Low	0.0012	0.67	1.4E-6	1.8E-5	5.4E-9	6.5E-6	1.2E-5	0.0015	1.3E-7	5.3E-5	3.2E-4	2.7E-3	1.9E-3
Current	Central and S Asia / Mid	0.0012	1.2	9.5E-6	2.9E-5	5.1E-9	5.6E-6	3.7E-5	0.0027	4.2E-8	8.0E-5	3.0E-4	2.4E-3	3.1E-3
Current	E and SE Asia / High	0.0012	0.67	1.4E-6	1.8E-5	5.4E-9	6.5E-6	1.2E-5	0.0015	1.3E-7	5.3E-5	3.2E-4	2.7E-3	1.9E-3
Current	E and SE Asia / Low	0.0012	0.67	1.4E-6	1.8E-5	5.4E-9	6.5E-6	1.2E-5	0.0015	1.3E-7	5.3E-5	3.2E-4	2.7E-3	1.9E-3
Current	E and SE Asia / Mid	0.0041	0.81	9.3E-7	1.9E-5	8.9E-8	4.7E-6	6.7E-6	0.0025	4.7E-7	3.2E-5	4.4E-4	1.2E-3	2.3E-3
Current	Eur and N Amer / High	0.00077	0.42	1.5E-6	1.8E-5	2.6E-9	5.8E-6	2.7E-5	0.0006	5.5E-7	4.7E-5	7.0E-5	5.7E-4	1.1E-3
Current	Eur and N Amer / Mid	0.0019	0.66	1.4E-6	6.1E-5	7.4E-9	5.0E-6	6.8E-6	0.0013	6.8E-8	4.4E-5	1.2E-4	1.0E-3	2.2E-3
Current	Latin Amer & Caribb / High	0.00093	0.32	8.2E-7	5.1E-5	2.1E-9	4.2E-5	3.3E-5	0.00073	1.2E-6	9.0E-6	8.1E-5	5.0E-4	1.1E-3
Current	Latin Amer & Caribb / Low	0.00093	0.32	8.2E-7	5.1E-5	2.1E-9	4.2E-5	3.3E-5	0.00073	1.2E-6	9.0E-6	8.1E-5	5.0E-4	1.1E-3
Current	Latin Amer & Caribb / Mid	0.00093	0.32	8.2E-7	5.1E-5	2.1E-9	4.2E-5	3.3E-5	0.00073	1.2E-6	9.0E-6	8.1E-5	5.0E-4	1.1E-3
Current	N Africa and W Asia / High	0.0011	0.82	6.7E-7	3.1E-5	4.9E-9	1.8E-5	4.4E-6	0.0017	5.0E-8	1.6E-5	1.2E-4	8.3E-4	2.4E-3
Current	N Africa and W Asia / Low	0.00097	0.68	9.9E-7	2.0E-5	4.0E-9	7.0E-6	7.3E-6	0.0013	7.3E-8	3.1E-5	1.8E-4	1.4E-3	1.7E-3
Current	N Africa and W Asia / Mid	0.00092	0.7	8.3E-7	2.2E-5	3.7E-9	8.8E-6	5.4E-6	0.0013	5.2E-8	2.2E-5	1.2E-4	9.6E-4	1.7E-3
Current	Oceania / High	0.00075	0.89	2.1E-6	5.8E-5	1.9E-9	6.1E-6	1.8E-5	0.0017	8.2E-8	1.6E-4	1.2E-4	6.0E-4	2.2E-3
Current	Oceania / Mid	0.0012	0.67	1.4E-6	1.8E-5	5.4E-9	6.5E-6	1.2E-5	0.0015	1.3E-7	5.3E-5	3.2E-4	2.7E-3	1.9E-3
Current	Sub-S Africa / High	0.00047	0.33	6.8E-8	1.4E-5	7.5E-10	2.6E-6	1.9E-7	0.00038	1.4E-8	1.6E-7	4.2E-6	1.2E-5	2.9E-4
Current	Sub-S Africa / Low	0.00047	0.33	6.8E-8	1.4E-5	7.5E-10	2.6E-6	1.9E-7	0.00038	1.4E-8	1.6E-7	4.2E-6	1.2E-5	2.9E-4
Current	Sub-S Africa / Mid	0.00044	0.4	1.4E-6	2.0E-5	1.4E-9	2.7E-6	5.0E-6	0.00083	1.3E-8	9.9E-6	5.4E-6	2.1E-5	1.2E-3
Current	World	0.0018	0.75	3.2E-6	2.5E-5	2.7E-8	8.3E-6	1.9E-5	0.0018	3.2E-7	4.1E-5	2.3E-4	1.2E-3	2.0E-3
Future	Central and S Asia / Low	0.0006	0.17	1.0E-9	1.7E-6	6.3E-12	1.3E-7	3.3E-8	0.00052	2.7E-8	3.0E-9	9.5E-6	1.1E-4	1.5E-4
Future	Central and S Asia / Mid	0.00087	0.42	1.1E-8	3.6E-6	1.9E-11	1.4E-7	1.5E-7	0.0013	9.9E-9	4.2E-9	9.1E-6	1.0E-4	3.2E-4
Future	E and SE Asia / High	0.0006	0.17	1.0E-9	1.7E-6	6.3E-12	1.3E-7	3.3E-8	0.00052	2.7E-8	3.0E-9	9.5E-6	1.1E-4	1.5E-4
Future	E and SE Asia / Low	0.0006	0.17	1.0E-9	1.7E-6	6.3E-12	1.3E-7	3.3E-8	0.00052	2.7E-8	3.0E-9	9.5E-6	1.1E-4	1.5E-4

Scenario	SDG1+WB	CH_4-Air	CO_2-Air	N_2-Air	N_2O-Air	Neq-Soil	Neq-Water	NH_3-Air	NO_x-Air	Peq-Soil	Peq-Water	PM_{10}-Air	$PM_{2.5}$-Air	SO_x-Air
Future	E and SE Asia / Mid	0.0031	0.26	9.2E-10	2.3E-6	1.1E-10	1.0E-7	2.3E-8	0.0012	1.6E-7	1.4E-9	1.3E-5	5.1E-5	2.4E-4
Future	Eur and N Amer / High	0.00054	0.25	8.9E-7	7.7E-6	1.8E-9	2.5E-6	6.3E-6	0.00032	2.3E-7	2.1E-5	5.7E-5	4.7E-4	4.5E-4
Future	Eur and N Amer / Mid	0.0015	0.23	1.6E-9	7.9E-6	8.9E-12	8.7E-8	2.4E-8	0.00062	1.7E-8	1.7E-9	3.8E-6	4.4E-5	2.4E-4
Future	Latin Amer & Caribb / High	0.00073	0.11	9.6E-10	6.7E-6	3.6E-12	1.0E-7	1.4E-7	0.00035	4.4E-7	8.4E-8	2.5E-6	2.1E-5	1.2E-4
Future	Latin Amer & Caribb / Low	0.00073	0.11	9.6E-10	6.7E-6	3.6E-12	1.0E-7	1.4E-7	0.00035	4.4E-7	8.4E-8	2.5E-6	2.1E-5	1.2E-4
Future	Latin Amer & Caribb / Mid	0.00073	0.11	9.6E-10	6.7E-6	3.6E-12	1.0E-7	1.4E-7	0.00035	4.4E-7	8.4E-8	2.5E-6	2.1E-5	1.2E-4
Future	N Africa and W Asia / High	0.00073	0.27	6.3E-10	3.8E-6	6.9E-12	2.1E-7	1.4E-8	0.00079	1.2E-8	3.0E-8	3.6E-6	3.4E-5	2.5E-4
Future	N Africa and W Asia / Low	0.00059	0.2	8.7E-10	2.3E-6	5.5E-12	8.1E-8	2.1E-8	0.00055	1.6E-8	8.1E-9	5.2E-6	5.8E-5	1.6E-4
Future	N Africa and W Asia / Mid	0.00061	0.22	7.8E-10	2.7E-6	5.5E-12	8.6E-8	1.7E-8	0.00059	1.2E-8	1.3E-8	3.7E-6	3.9E-5	1.7E-4
Future	Oceania / High	0.00032	0.17	1.3E-9	4.0E-6	1.9E-12	6.1E-8	3.8E-8	0.00045	1.5E-8	1.3E-9	2.7E-6	2.2E-5	1.3E-4
Future	Oceania / Mid	0.0006	0.17	1.0E-9	1.7E-6	6.3E-12	1.3E-7	3.3E-8	0.00052	2.7E-8	3.0E-9	9.5E-6	1.1E-4	1.5E-4
Future	Sub-S Africa / High	0.00036	0.12	9.0E-10	3.5E-6	2.2E-12	5.1E-8	1.8E-9	0.00019	5.1E-9	4.9E-9	1.6E-7	5.6E-7	3.4E-5
Future	Sub-S Africa / Low	0.00036	0.12	9.0E-10	3.5E-6	2.2E-12	5.1E-8	1.8E-9	0.00019	5.1E-9	4.9E-9	1.6E-7	5.6E-7	3.4E-5
Future	Sub-S Africa / Mid	0.00034	0.14	2.3E-9	4.2E-6	5.7E-12	5.0E-8	2.1E-8	0.00041	4.7E-9	4.6E-9	1.9E-7	9.2E-7	1.3E-4
Future	World	0.0013	0.26	1.0E-7	4.0E-6	2.4E-10	3.8E-7	7.8E-7	0.00082	1.1E-7	2.4E-6	1.3E-5	1.0E-4	2.5E-4

Appendix F Summary of Global Modeling Inputs

A summary of input data to the model is provided in the following tables.

Generation and WWTP	World
BOD5, kg/pers/yr	15.6
N Excretion, kg N/pers/year	4.2
Dry weight excreta, kg/pers/year	11.9
Total solids Influent to WWTP, kg/m3	0.66
BOD Influent to WWTP, kg/m3	0.4
Total N Influent to WWTP, kg/m3	0.069

Latrines	World
Latrine Rural Communal Fraction	0.92
Latrine Rural Household Fraction	0.078
Latrine Urb Low Communal Fraction	0.24
Latrine Urb Low Household Fraction	0.24
Latrine Urb High Communal Fraction	0
Latrine Urb High Household Fraction	0.51

Emptied Material (Latrines, Septic) Handling	World
Emptied Material, Rural Direct Release Fraction	0.47
Emptied Material, Rural FurtherTreat Fraction	0.53
Emptied Material, Urban Direct Release Fraction	0
Emptied Material, Urban FurtherTreat Fraction	0
EmptiedFurtherTreat Rural Stabilize Fraction	0.25
FurtherTreat, Rural WWTP Fraction	0
FurtherTreat, Rural Landfill Fraction	0.75
FurtherTreat, Urban Stabilize Fraction	0.3
FurtherTreat, Urban WWTP Fraction	0.5
FurtherTreat, Urban Landfill Fraction	0.2
Stabilize, Rural Compost Fraction	1
Stabilize, Rural AD Fraction	0
Stabilize, Urban Compost Fraction	0.47
Stabilize, Urban AD Fraction	0.53

Sewer No Treatment—Stagnant vs. Flowing	World
SewerNoTreat Stagnant Fraction	0.47
SewerNoTreat Flowing Fraction	0.53

Solids Handling	World
Rural AD Fraction	0
Rural Compost Fraction	0.27
Rural Incineration Fraction	0
Rural Landfill Fraction	0.27
Urb Low AD Fraction	0.014
Urb Low Compost Fraction	0.079
Urb Low Incineration Fraction	0.13
Urb Low Landfill Fraction	0.073
Urb Low LandApply Fraction	0.19
Urb High AD Fraction	0.095
Urb High Compost Fraction	0.077
Urb High Incineration Fraction	0.13
Urb High Landfill Fraction	0.029
Urb High LandApply Fraction	0.19
WWTP_Sludge_AD_Disposition Rural Incinerate Fraction	0
WWTP_Sludge_AD_Disposition Rural Landfill Fraction	0.37
WWTP_Sludge_AD_Disposition Rural LandApply Fraction	0.63
WWTP_Sludge_AD_Disposition Urban Incinerate Fraction	0
WWTP_Sludge_AD_Disposition Urb Low Incinerate Fraction	0.16
WWTP_Sludge_AD_Disposition Urb Low Landfill Fraction	0.081
WWTP_Sludge_AD_Disposition Urb Low LandApply Fraction	0.24
WWTP_Sludge_AD_Disposition Urb High Incinerate Fraction	0.19
WWTP_Sludge_AD_Disposition Urb High Landfill Fraction	0.044

Distance to Water	World
ProximityMarine Rural Near Coast Fraction	0.039
ProximityMarine Urb Low Near Coast Fraction	0.042
ProximityMarine Urb High Near Coast Fraction	0.045
Proximity FW Lentic Rural Near Lentic Fraction	0.03
Proximity FW Lentic Urb Low Near Lentic Fraction	0.02
Proximity FW Lentic Urb High Near Lentic Fraction	0.021
Proximity FW Lotic Rural Near Lotic Fraction	0.24
Proximity FW Lotic Urb Low Near Lotic Fraction	0.11
Proximity FW Lotic Urb High Near Lentic Fraction	0.12

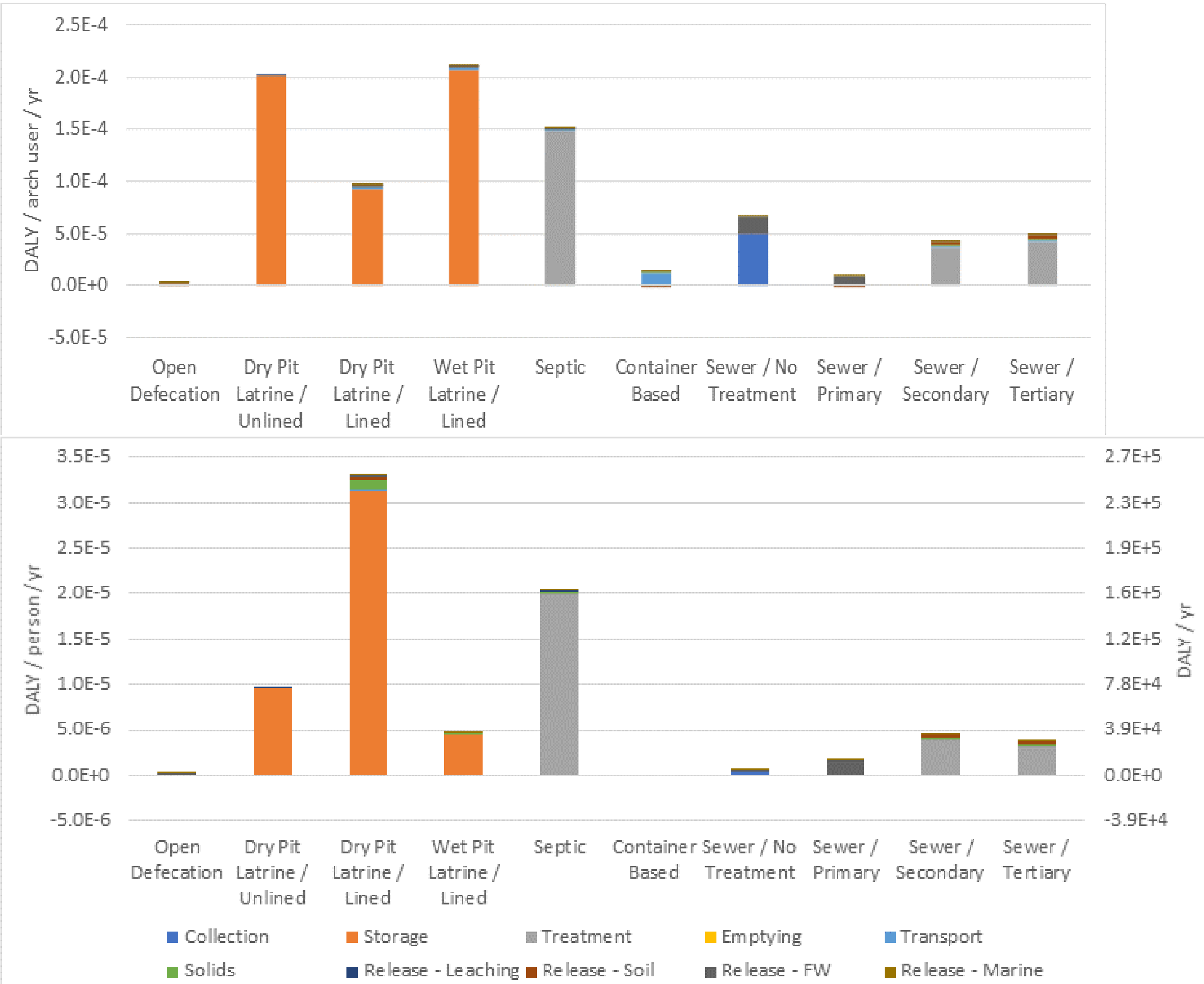
Groundwater Depth	World
Shallow Fraction	0.078
Deep Fraction	0.92

Eutrophication (Freshwater and Marine)	World
Eutro, Fraction	0.29
NOT Eutro, Fraction	0.71

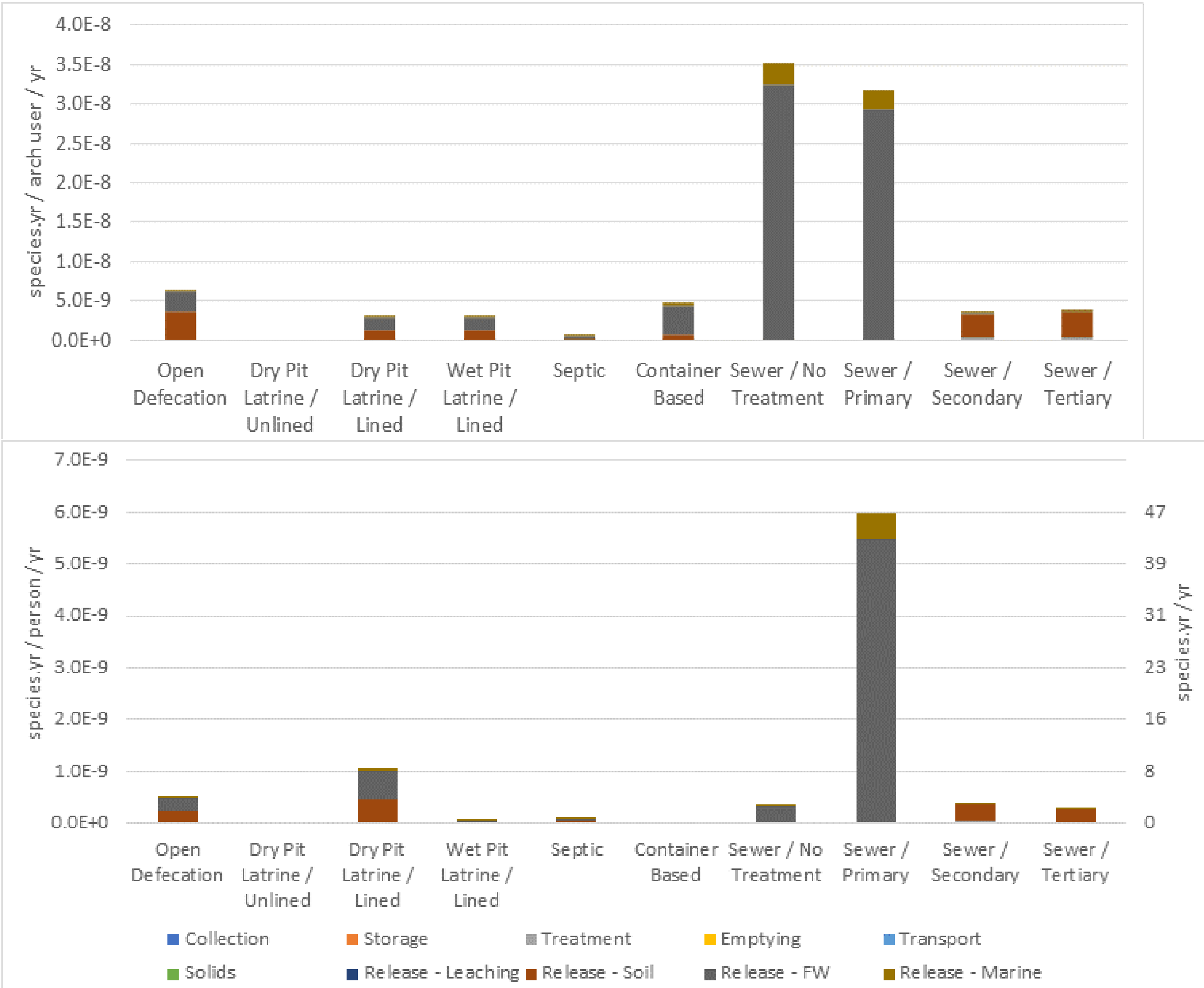
Appendix G Additional Detailed Results

This appendix provides additional results for other impact categories assessed.

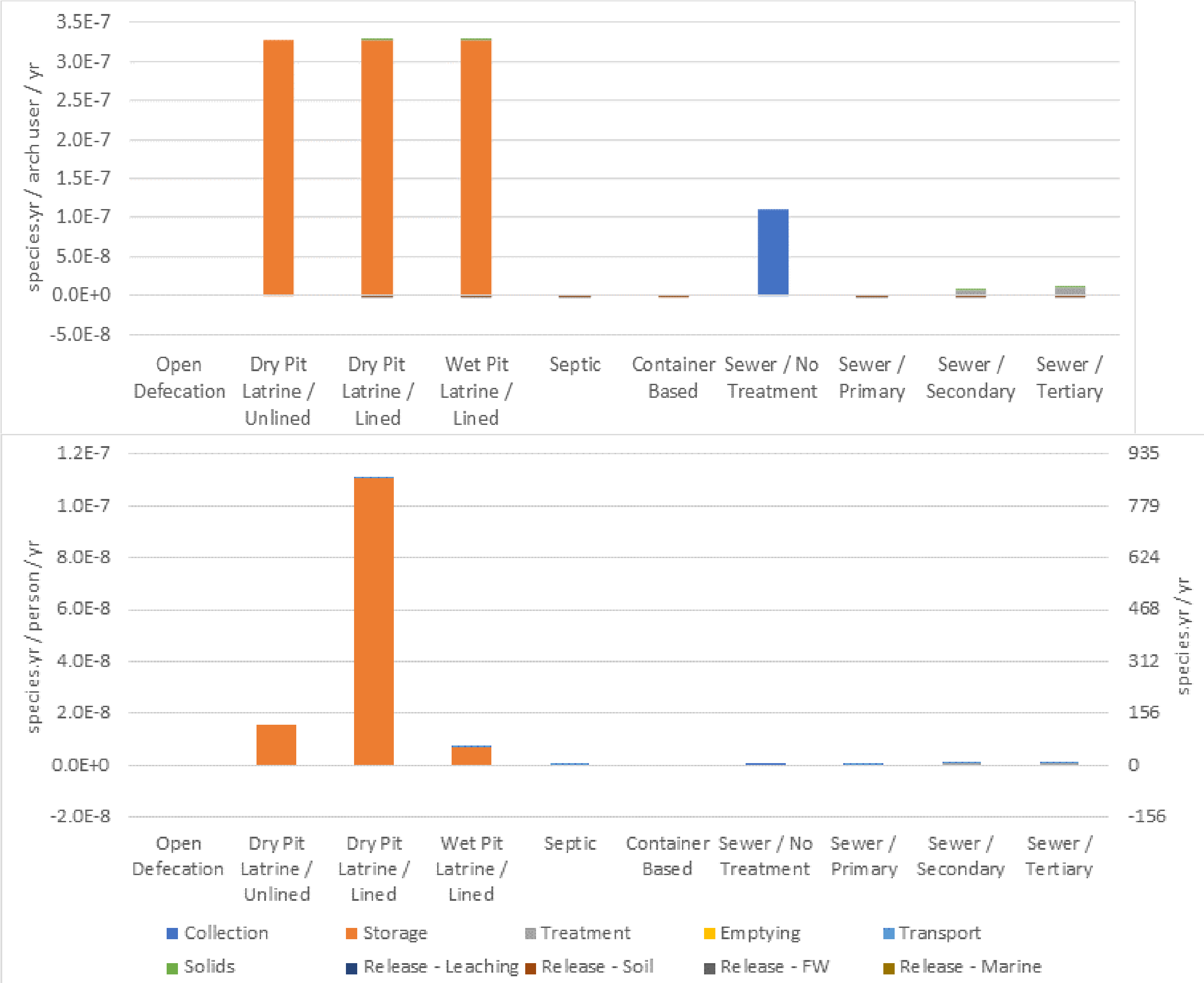
G.1 Overall



Appendix Figure G.1 Current global GHG / human health impacts. Top = single user per archetype. Bottom = per capita (left axis; reflects archetype adoption) and total (right axis; reflects population)

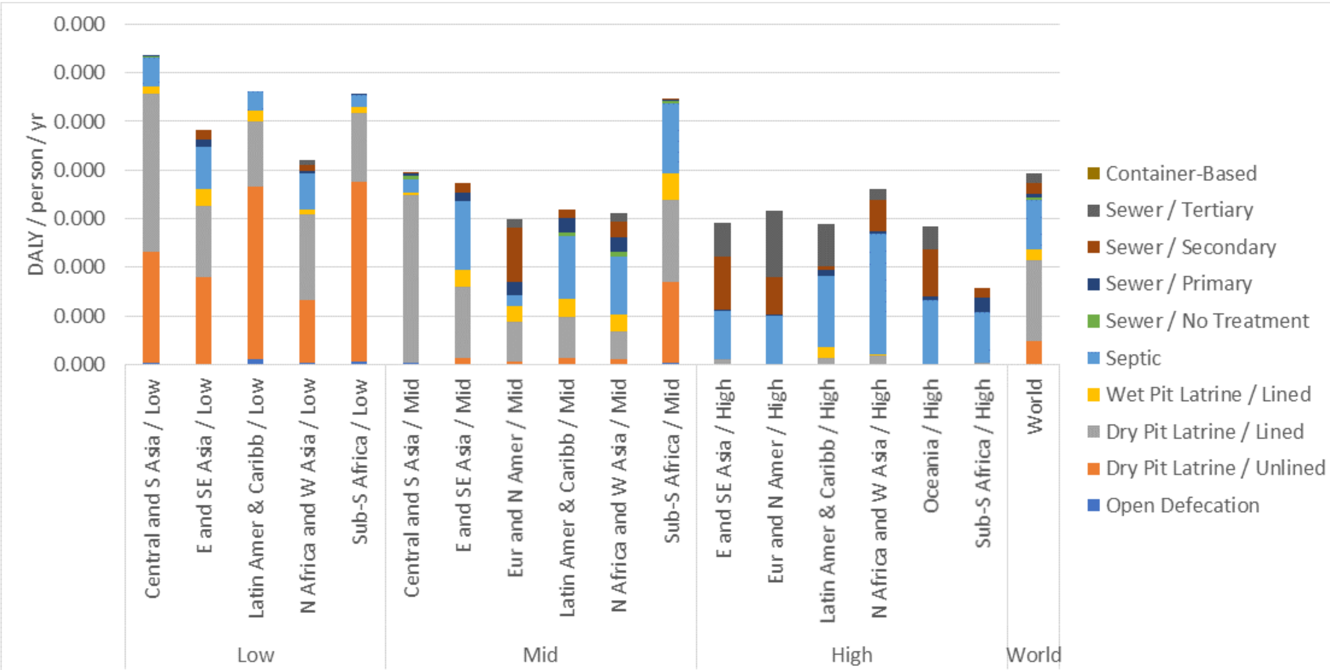


Appendix Figure G.2: Current global eutrophication (freshwater) impacts. Top = single user per archetype. Bottom = per capita (left axis; reflects archetype adoption) and total (right axis; reflects population)

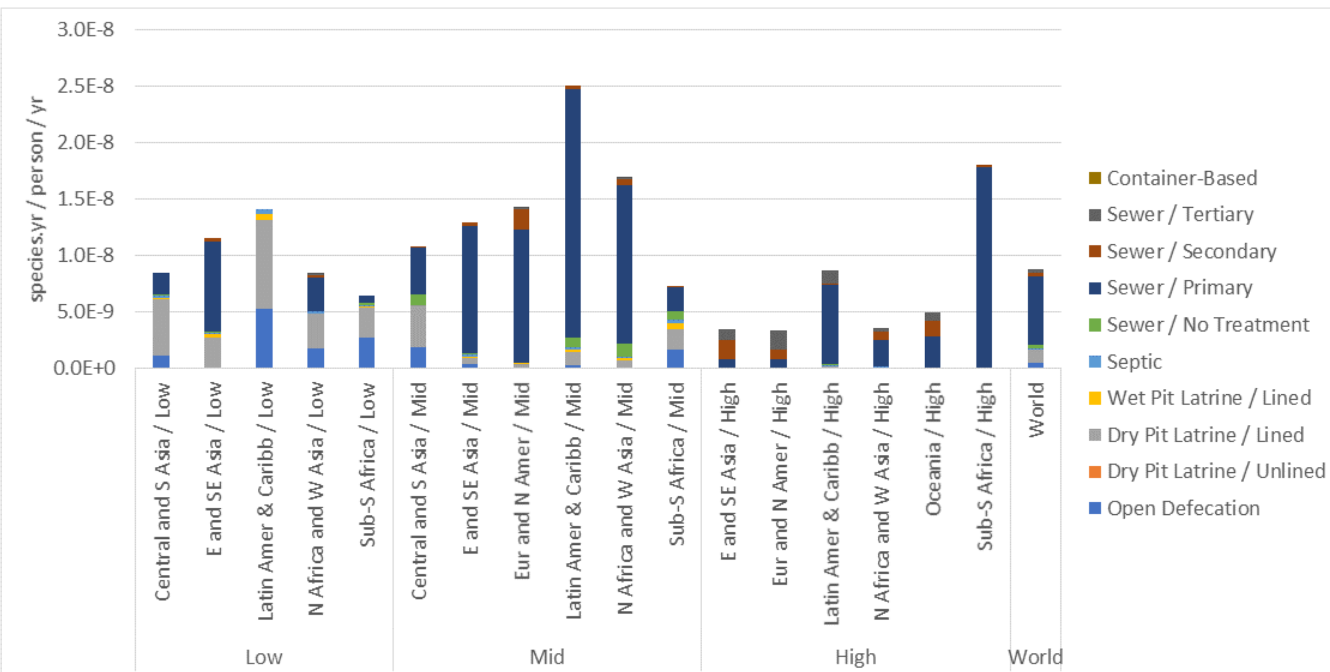


Appendix Figure G.3: Current global terrestrial acidification impacts. Top = single user per archetype. Bottom = per capita (left axis; reflects archetype adoption) and total (right axis; reflects population)

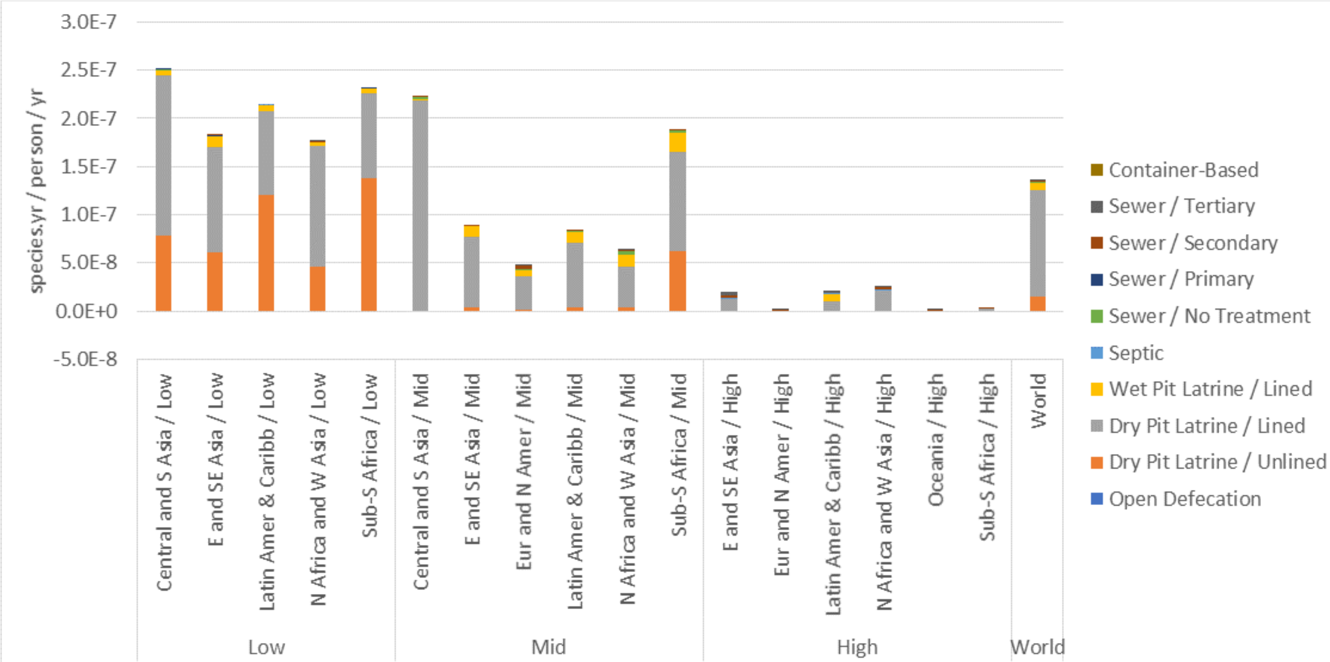
G.2 Regional



Appendix Figure G.4: Current regional GHG / human health impacts per capita

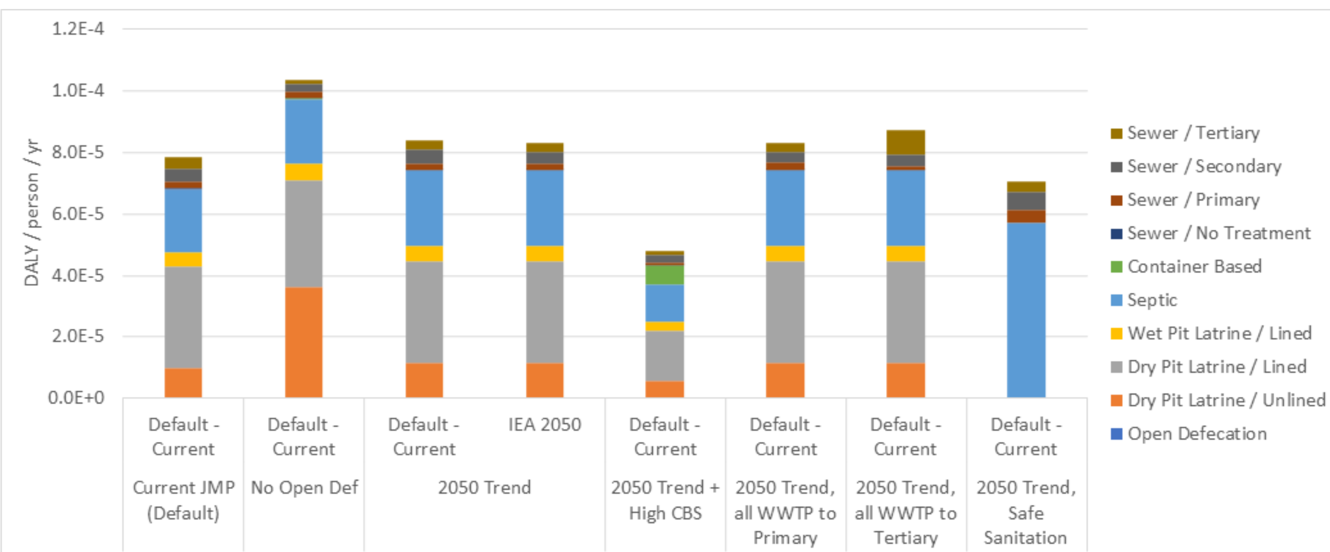


Appendix Figure G.5: Current regional eutrophication (freshwater) impacts per capita

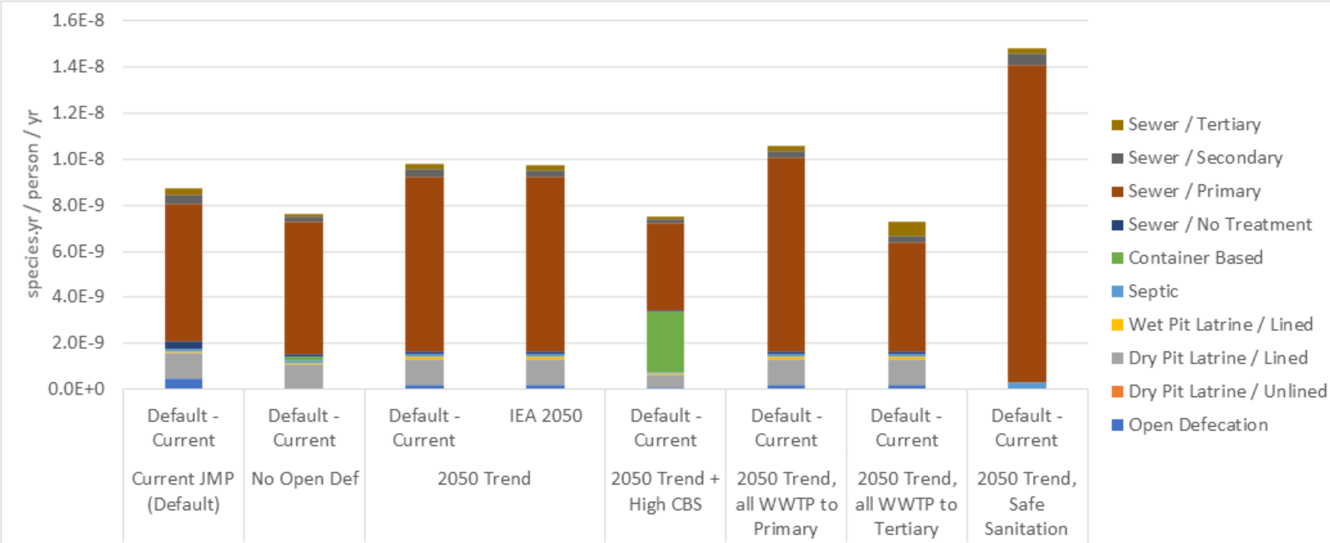


Appendix Figure G.6: Current regional acidification impacts per capita

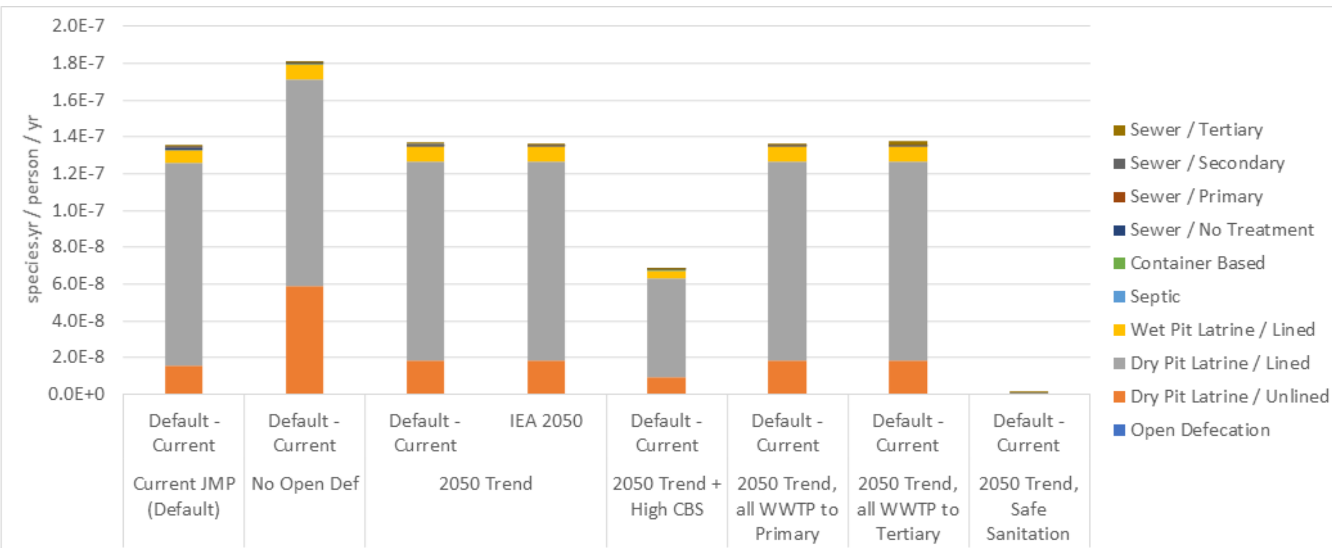
G.3 Scenario Contribution



Appendix Figure G.7: Future archetype adoption scenario GHG / human health impacts, per capita



Appendix Figure G.8: Future archetype adoption scenario eutrophication (freshwater) impacts, per capita



Appendix Figure G.9: Future archetype adoption scenario acidification impacts, per capita

Appendix H Global Wastewater GHG Estimates

We compared our estimate to the following three sources of country-level GHG emissions:

H.1 United Nations Framework Convention on Climate Change (UNFCCC):

https://unfccc.int/process-and-meetings/transparency-and-reporting/greenhouse-gas-data/ghg-data-unfccc/ghg-data-from-unfccc

Includes data reported by countries in their national inventories.

Annex I countries are required to follow the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines), through some countries may start to use the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories in the future (2019 IPCC Refinement).

Non-Annex I countries should use the Revised 1996 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (1996 IPCC Guidelines) and are encouraged to apply the IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC Good Practice Guidelines).

Wastewater emissions include both domestic and industrial wastewater treatment

H.2 Climate Analysis Indicators Tool (CAIT) Dataset:

https://www.wri.org/data/climate-watch-cait-country-greenhouse-gas-emissions-data

Estimates GHG emissions using a consistent methodology for all countries based on the 2006 IPCC Guidelines and does not use national inventory reported data.

Wastewater emissions did not account for sludge removed during treatment or CH_4 recovery and therefore may over or underestimate treatment emissions.

Wastewater emissions include both domestic and industrial wastewater treatment

H.3 PIK PRIMAP-hist Dataset:

https://www.pik-potsdam.de/paris-reality-check/primap-hist/

Combines available datasets, including UNFCCC reported data and does not include LULUCF emissions.

Wastewater emissions include both domestic and industrial wastewater treatment