Article

Estimates of Nitrogen, Phosphorus, Biochemical Oxygen Demand, and Fecal Coliforms Entering the Environment Due to Inadequate Sanitation Treatment Technologies in 108 Low and Middle Income Countries

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1 **Estimates of Nitrogen, Phosphorus, Biochemical Oxygen Demand, and Fecal**
2 **Coliforms Entering the Environment Due to Inadequate Sanitation Treatment**
3 **Technologies in 108 Low and Middle Income Countries**

4 *For Publication as an Original Research Article in Environmental Science and*
5 *Technology*

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22

23 **Abstract**

Understanding the excretion and treatment of human waste (feces and urine) in low and middle income countries (LMICs) is necessary to design appropriate waste management strategies. However, excretion and treatment are often difficult to quantify due to decentralization of excreta management. We address this gap by developing a mechanistic, stochastic model to characterize phosphorus, nitrogen, biochemical oxygen demand (BOD), and fecal coliform pollution from human excreta for 108 LMICs. The model estimates excretion and treatment given three scenarios: 1) use of existing sanitation systems, 2) use of World Health Organization-defined “improved sanitation”, and 3) use of best available technologies. Our model estimates that more than 10^9 kg/yr each of phosphorus, nitrogen and BOD are produced. Of this, 22(19-27)%, 11(7-15)%, 17(10-23)%, and 35(22-47)% (mean and 95% range) BOD, nitrogen, phosphorus, and fecal coliforms, respectively, are removed by existing sanitation systems. Our model estimates that upgrading to “improved sanitation” increases mean removal slightly to between 17-53%. Under the best available technology scenario, only approximately 60-80% of pollutants are treated. To reduce impact of nutrient and microbial pollution on human and environmental health, improvements in both access to adequate sanitation and sanitation treatment efficiency are needed.

43 **Introduction**

44 Global development efforts in sanitation are largely focused on promoting
45 improved technologies in regions where there is little-to-no sanitation
46 infrastructure. Specifically, the United Nations Millennium Development Goals set
47 the target to reduce, by half, the proportion of people without access to improved
48 sanitation from 51% to 25% by 2015.¹ Improved sanitation is defined as access to
49 facilities that hygienically separate human feces from human contact.¹ Improved
50 sanitation facilities include: flush or pour flush to piped sewer system, septic tank or
51 pit latrine; ventilated improved pit latrines; pit latrines with slab; and composting
52 toilets.¹ Unimproved sanitation (such as open pit latrines, bucket latrines, hanging
53 toilets, and open defecation, i.e. the act of defecating in areas with no infrastructure)
54 is defined in contrast to improved sanitation facilities; they do not separate human
55 feces from contact.¹ Coverage of sanitation facilities (improved and unimproved) is
56 quantified using country level surveys, such as Demographic and Health Surveys.²

57 Although progress in global sanitation provisions is evident, current trends
58 suggest the target will not be reached.¹ In 1990, 2.7 billion people (51% of the 1990
59 global population) did not have access to improved sanitation.¹ An estimated 2.4
60 billion people (32% of the 2015 global population) will still lack access to improved
61 sanitation by the end of 2015, short of the target by over 500 million people.¹
62 Almost half without improved sanitation (approximately 1 billion people) still
63 practice open defecation.¹ Even the population classified as having access to
64 improved sanitation may not be adequately protected from contact with human
65 feces. Having access to improved sanitation does not guarantee the technology is

being used nor that it is hygienically safe and sustainable.^{3,4}

The main motivation to promote access to improved sanitation technology is to reduce impact on human and environmental health of pollutants, such as phosphorus (P), nitrogen (N), biochemical oxygen demand (BOD), and fecal coliforms. Reduction of nutrients, by decreasing concentrations released in the environment, capturing waste streams, and/or treating waste streams, ameliorates ecosystem impacts including the risk of eutrophication and oxygen deprivation in aquatic systems.⁵ Similarly, reductions of fecal pathogens reduces disease transmission risks.⁶ Diarrheal disease burden is an important factor driving investment in sanitation technologies in LMICs: an estimated 700,000 children under five years of age die due to gastroenteritis every year.⁷ Fecal coliforms (FC) are of particular interest as an indicator of disease transmission risk because they often co-occur with pathogens (e.g., bacteria such as diarrheagenic *E. coli*, gastrointestinal viruses, and protozoa) transmitted via the fecal-oral route.^{5,8}

Effective quantification and tracking of human waste (feces and urine) in LMICs is needed in order to appropriately plan human waste collection and treatment systems. Modern sanitation services in high income countries (e.g., activated sludge systems) provide relatively high levels of treatment consistently and their performance is typically monitored.⁵ Conversely, the decentralized human waste treatment characteristic of LMICs provides inconsistent treatment and is not typically monitored for performance. Due to the lack of monitoring in LMICs, there are few methods of quantifying and tracking the movement of human waste and human waste components (P, N, BOD, and FC).⁹⁻¹¹ Efforts to track fecal sludge

through quantification and characterization have been made in Hanoi, Vietnam and Kampala, Uganda.¹² Sludge accumulation was quantified based on data specific to demography, onsite sanitation technologies used, fecal sludge collection and transport service providers, and new data collection.¹² Fecal sludge quantification and characterization in these locations required sufficient availability of demographic data and access to sampling sites.¹² Based on their work, Schoebitz et al. noted that human waste quantification and tracking is needed to adequately design fecal sludge management systems, specifically in LMICs where few human waste collection and treatment services exist.¹²

Looking beyond current Millennium Development Goals, the United Nations has proposed post-2015 Sustainable Development Goals to eliminate poverty and promote sustainable growth.¹³ One proposed goal is to ensure availability and sustainable management of water and sanitation for all.¹³ Specifically in Sustainable Development Goal 6.2 to “achieve access to adequate and equitable sanitation and hygiene for all, and end open defecation” by 2030 and in Sustainable Development Goal 6.3 to “improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater.”¹³ To measure the progress toward this or similar targets, both definitions and indicators for the safe management of excreta are needed. Indicators for safe human waste management require knowledge of both the sanitation technologies in use as well as the level and efficiency of sanitation management.

In the present study, we developed a framework for estimating the efficiency of sanitation technologies globally by modeling nutrient and microbial pollution entering the environment from human waste due to inadequate sanitation. This model aims to bridge a knowledge gap between the information needed to plan and provide global sanitation access and the lack of experimental human waste data. Towards this goal, we account for human waste pollutant removal by including both access to, and efficiency of, sanitation technologies in our model. Model input parameters are based on literature reviews, country-level sanitation surveys, and published estimates for sanitation technology treatment efficiency. The outcomes from the model include both global and country-level estimates of P, N, BOD, and FC entering the environment due to human waste under current conditions and two improvement scenarios.

Methods

Model Framework

We developed a mechanistic-stochastic model (Figure 1) of fecal and urinary production, treatment, and removal for 108 countries (Table S1 of Supporting Information) in 6 World Health Organization (WHO) regions (Africa, Americas, South-East Asia, Europe, Eastern Mediterranean, Western Pacific). The 108 countries were chosen based on availability of Demographic and Health Surveys (DHS) from 2006-2013 or, if no DHS data were available, the availability of WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation (JMP) country files.^{2,14} The model uses country-level data on type and use of sanitation technologies to estimate the mass of fecal and urinary components (P, N, BOD, FC)

that enter the environment (hereafter referred to as “human waste pollution”) per year, the mass of human waste pollution entering the environment annually per square kilometer of each country, and the total percent removal of human waste pollutants due to sanitation infrastructure. As part of our estimations, we included the impact of various sanitation technology upgrade scenarios and identified factors influencing country-level and global human waste pollution. Stochasticity is introduced via a Monte Carlo simulation constructed in MATLAB R 2012b (The Mathworks, Inc., Natick, Massachusetts, USA), using parameters and associated distributions as described in Tables 1 and 2.

Model Parameters

Probability distribution functions describing central tendency and variability for each model parameter were obtained from literature reviews. Additional data on derivation of probability distributions for parameters is provided in the Supporting Information. Specifically, reviews were conducted to determine distributions for fecal weight, diarrheal fecal weight, diarrhea duration and diarrhea incidence for both adults and children. Literature was also reviewed to determine the distributions of human waste pollutants in urine and feces. Survey data were collected from DHS and the JMP on sanitation technology types.^{2,14} Population data were based on the United Nations Population Division.¹⁵ The percentage of the population living in urban and rural areas was based on The Progress on Drinking Water and Sanitation-2012 Update and World Bank data.^{16,17} The removal efficiencies of human waste pollutants for the majority of sanitation technologies were based on reported ranges from Nelson and Murray.¹⁸ Finally, as country-level

data on the percent of sewage treated in piped sewer systems are limited,¹⁹ we estimated percent treatment based on an analysis of the relationship between treatment and Gross Domestic Product (GDP). Detailed methods for each model parameter are available in Supporting Information.

Analysis

We used the model to estimate the mass of human waste pollutants entering the environment per square kilometer of each country per year based on existing sanitation technology treatment, Scenario I. We also investigated impacts of two potential sanitation technology upgrade investment scenarios. Scenario II models the upgrade of open defecation and all unimproved technologies to the minimum technology needed to meet the JMP's improved sanitation definition. Specifically open defecation, unimproved technologies ("pit latrine without slab", "bucket toilet", "hanging toilet" and "no facility"), and uncertain technologies ("flush to somewhere else" or "don't know where" and "other") were modeled as upgraded to a "pit latrine with slab", the minimum technology meeting JMP's definition. Scenario III models the best-case scenario by upgrading everyone to the best available technology. Here, we differentially define best available technology for urban and rural areas, consistent with Fry et al.²⁰ In urban areas, the best-case scenario is defined as universal access to a piped sewer system with 100% activated sludge treatment. In rural areas, the best-case scenario is defined as universal access to septic tanks or, if a piped network is already available, access to an improved piped sewer with 100% activated sludge treatment. We assumed rural areas were upgraded to septic tanks (as opposed to piped sewers) to avoid the costly investments required for supplying

180 piped sewers in regions with presumably low population density. Analyses for
181 urban and rural regions are combined to estimate pollutant excretion and removal
182 at the country-level, though separate analyses are also provided in the Supporting
183 Information.

184 Pollutant rates, in units of kg/yr, and rates per unit surface area, in units of
185 kg/km²-yr, for both total excretion and excreta entering the environment were
186 estimated at the country-level for each of the three scenarios. Pollutant removal
187 efficiency was calculated as one minus the fractional value of the mass of pollutant
188 that enters the environment (kg/yr) divided by the mass of pollutant excreted by
189 the national population (kg/yr). We used Monte Carlo simulation with 1000
190 simulations, and we performed separate Monte Carlo simulations for global and
191 regional estimates of human waste pollutant removal. Similarly, separate
192 simulations were performed for human waste pollutant removal in rural, urban, and
193 combined regions.

194 *Sensitivity Analysis*

195 We combined both parameter sensitivity and uncertainty in one estimate of
196 variability in the Monte Carlo simulation, heretofore referred to as sensitivity
197 analysis. Sensitivity analysis was conducted to quantify the model parameter
198 impacts on total pollutant mass entering the environment and percent of human
199 waste pollutant removed under current sanitation technology access for the global
200 simulation and for WHO regions individually. Two methods were used to investigate
201 sensitivity analysis: bivariate correlation coefficients between parameter inputs and
202 model outputs; and parameter input contributions to total variance explained by

linear regression of model outputs.²¹ For bivariate correlation coefficients, we determined Spearman's ρ and corresponding level of statistical significance (p-value) of the relationship between each input parameter and model output (human waste pollutant entering the environment and percent of human waste pollutant removed). The Bonferroni correction method was used to adjust the level of p-values required for identifying statistically significant relationships to account for multiple comparisons.²²

The total variance explained by a linear regression model was also used to determine sensitivity of model outputs to input parameters using the method of Loucks et al.²¹ We estimated total variance explained by a linear model of the total human waste pollutants entering the environment and percent of human waste pollutants removed globally as a function of all input parameters. Total explainable variance was estimated using the model's R^2 value. Bivariate regression models were used to estimate individual input parameter's contributions to model variance again using the model's R^2 value. The model is more sensitive to parameters that contribute a greater portion of the total variance.

Results

Model Parameters

Literature values were used to identify probability distribution functions for model parameters (Table 1, Table 2, Supporting Information). Estimates of normal fecal production for adults, normal fecal production for children, diarrhea fecal production for adults, and diarrhea duration for adults and children were described by truncated normal distributions (Table 1). Diarrhea feces production for children

was described by a log normal distribution (Table 1). Distributions were truncated to remove unrealistic values (i.e. less than zero). Diarrhea incidence estimates were described as point values because they were reported as incidence rates with 2.5th and 97.5th percentiles from a standard non-parametric bootstrap estimator in Fischer Walker et al.²³ (Table 1). Removal efficiency of human waste pollutants for each technology type was determined from reported ranges and converted to either a uniform distribution, triangular distribution or point value (Table 2). Human waste pollutant characteristic distributions were modeled as uniform or triangular distributions due to insufficient data availability for estimates of variances (Table 1). Urine component distributions were based on Udert²⁴ and modeled as normal distributions (Table 1). Adult population, child population and the percentage of the population living in urban areas were modeled as point values. The analysis of the correlation between GDP per capita and the percent of treated piped sewage yielded a bivariate distribution for countries with GDP per capita less than or equal to 6000 described by a uniform distribution of (0,5) and countries with GDP per capita greater than 6000 described a triangular distribution with range 0 to 100 and a peak at 25 (Table 1 and Figure S1 of Supporting Information).

Analysis

The results of the Monte Carlo simulations for Scenarios I, II, and III demonstrate the impact of sanitation upgrades on pollutant removal efficiency (Table 3). Global mean (and 95% range) of phosphorus, nitrogen, BOD, and fecal coliform removal, under current access (Scenario I), are estimated as 16.5 (10.2-23.1)%, 11.3 (7.4-14.9)%, 22.5 (19.1-27.2)%, and 35.2 (22.9-46.7)%, respectively.

Percentage removed varied across the six WHO regions. For example, mean phosphorus removal varied from 28.7 (12.5-50.6)% in Europe to 17.0 (10.1-22.9)% in Africa. Greater removals were demonstrated for Scenarios II (upgrade everyone including those practicing open defecation to pit latrines with a slab) and III (global access to piped sewer or septic tank), as expected (Table 3). For example, global phosphorus removal increased from 16.5 (10.2-23.1)% in Scenario I to 23.0 (12.6-32.3)% in Scenario II, and 58.0 (49.4-64.8)% in Scenario III. When pollutant mass entering the environment is calculated based on land area, regional differences are apparent. In general, Bangladesh, India, Rwanda, and Haiti have the highest pollutant mass per square kilometer and Mongolia, Suriname, Zambia, and Chile have the lowest pollutant mass per square kilometer (Figure 2). Urban and rural simulations resulted in similar trends as the global model (Tables S2 and S3 of Supporting Information). Notably, though, pollutant removal percentage is substantially higher in urban settings than rural settings in Scenario III. This is a result of the greater waste treatment assumed for piped waste streams (urban) as compared to septic tanks (rural).

Sensitivity Analysis

The sensitivity analysis identified that the parameters with the greatest influence (as indicated by Spearman's ρ , where a value of 1 signifies perfect correlation) on fecal mass entering the environment are adult normal fecal weight (0.96), adult diarrhea fecal weight (0.15), and adult duration of diarrhea (0.14). Percent piped sewer in areas with GDP per capita greater than 6000 (international dollar) is a significant parameter in total mass of phosphorus and BOD entering the

environment (Table S4 of Supporting Information). Adult normal fecal weight is a significant parameter in all pollutants entering the environment except for fecal coliforms. Fecal pollutant composition of urine and/or feces is significant in overall pollutant entering the environment for all four human waste pollutants (Table S4 of Supporting Information). Percent piped sewer in areas with GDP per capita greater than 6000 (international dollar) is also a significant parameter in the removal of all four pollutants (Table S5 of Supporting Information). Regional results follow similar trends to the global simulation (Tables S4 and S5 of Supporting Information).

Using linear regression, the model parameters that most explained the variance of both the pollutant entering the environment and the percent treatment varied by the pollutant. Linear models for mass of phosphorus, nitrogen, BOD, and fecal coliforms entering the environment explained 84-99% of the variance (Table S6 of Supporting Information). The parameters that most explained variance were amount of the pollutant in adult feces (for BOD and fecal coliforms) and/or urine (for nitrogen and phosphorus). More importantly for the phosphorus model, though, was weight of adult normal feces which explained 50% of the variance. This is in contrast to the other pollutants, for which weight of adult normal feces explained less than 5% of the variance. Linear models for percent pollutant removal explained 87-99% of the variance (Table S7 of Supporting Information). The parameters that most explained the variance were septic tank pollutant removal (for phosphorous, nitrogen, and fecal coliforms), and percent of piped sewer where per capita GDP > USD 6000 (for all pollutants). Pollutant removal by pit latrines with a slab (nitrogen,

fecal coliforms) and without a slab (phosphorus, nitrogen, and fecal coliforms) also explained a large portion (8-19%) of the variance.

Discussion

Even with global access to the best available sanitation technologies (as we modeled in Scenario III), an estimated minimum of 32 (29-34)% of all nutrient and 20 (7-38)% of fecal coliforms from human waste pollutants would still enter the environment untreated. Nutrient and microbial pollution affect both human health and the environment. Human excreta transmits harmful pathogens that can result in gastrointestinal illness. In addition, the nutrients in human feces can damage natural systems when present in excess amounts. Our model predicts that annually an average (95% range) of 2.6×10^{11} (9.1×10^{10} - 4.9×10^{11}) kg of human feces is produced. More than 10^9 kg/yr each of phosphorus, nitrogen and BOD are produced. Of this, less than 22 (19-27)% of the nutrients and 35 (23-47)% of fecal coliforms are removed due to existing sanitation infrastructure. Even the best available sanitation technologies (piped sewers with 100% treatment in urban areas and septic tanks in rural areas) are inadequate to protect the environment from human waste pollution.

The total mass of nutrient and microbial pollution (P, N, BOD, and FC) entering the environment is regionally disparate and driven, largely, by population. Not surprisingly, LMICs with the largest total populations (i.e., India, Indonesia, Brazil, Pakistan, and Nigeria) produce the most human waste (more than 10^8 - 10^9 kg of N, P, and BOD per year for each country). Similarly, countries with high population densities (i.e. Bangladesh, India, Comoros, Rwanda, Haiti) produce the

greatest mass of human waste pollutants per square kilometer under current conditions (Scenario I). Yet, as our model reveals, population density is not the only indicator of human waste pollution per unit area. For example, Chile has a higher population density than Zambia but releases less pollution (per square kilometer) because Chile has higher improved sanitation system coverage. Chile's sanitation systems are predominately septic tanks and piped sewer systems whereas Zambia is characterized by open defecation and predominance of pit latrines without slabs. Even in countries with high population densities, effective sanitation is capable of reducing nutrient and microbial pollution in the environment.

The model predictions of the percentage of human waste contaminants removed by sanitation infrastructure are heavily influenced by the quality of country level sanitation data. According to the model, Cape Verde, Fiji, Tonga, Republic of Moldova and the Solomon Islands have the lowest percentage removal of human waste pollutants (Table S1 of Supporting Information). However, all but the Solomon Islands have limited data and are dominated by sanitation survey categories of "flush don't know where" and "other". To be conservative, we assumed that both of these categories implied no treatment. Of the countries with more detailed data available, Solomon Islands, Chad, Sao Tome and Principe, India, and Cambodia have the lowest percent removal of pollutants. In all five of the countries listed above, almost 50% or more of the population practice open defecation. Interestingly, Syrian Arab Republic also has a low percent removal of pollutants due to a high percentage of piped to flush sewer but a low percent treatment value which we estimated based on GDP. More detailed data are needed on sanitation

system usage and treatment efficiency to improve estimates of sanitation efficacy. In particular, more data are needed on the percent of waste that is treated in areas with existing piped sewer systems.¹⁹

Increasing access to improved sanitation technology provides only marginal reductions in human waste pollutants entering the environment. Findings from our model suggest that upgrading current sanitation systems to the minimum technology type (pit latrine with slab) that meets the “improved” standards does not provide a large reduction in human waste pollution. Even with the best possible available technology (Scenario III), reduction of the pollutants modeled does not exceed 90% removal efficiency. Although piped sewage systems with adequate treatment (e.g. activated sludge systems) have the potential for effective pollutant removal, rural areas rely on decentralized treatment (e.g. septic tanks) with lower pollutant removal efficiency. The impact of lower pollutant removal efficiency of decentralized systems is observed in the lower percentage estimates for WHO regions with higher proportions of rural residents (Scenario III in Table 3). Our findings suggest that current models for improved forms of sanitation, particularly pit latrines with slabs and septic tanks are not providing adequate reductions of human waste pollutants. Even piped sewer systems are limited by the efficacy of wastewater treatment facility processes.

It is important to note that the low percentage of pollutant removal we estimate does not necessarily indicate risks to environmental and human health. Risks from microbial and nutrient pollution are population density dependent.^{25,26} In some regions, natural remediation of nutrient and microbial pollutants is often

sufficient. In the United States, for example, pollutant loading into water bodies is regulated in part by Total Maximum Daily Loads (TMDLs) which specify maximum pollutant loads based on perceptions of minimal impact to environmental and/or human health.²⁷ Similarly, human fecal pollution is only one anthropogenic source of nutrient and microbial pollution into the environment. Other sources (i.e., agricultural and industrial practices) may be as much, or more, of a concern.^{28,29} Nonetheless, an increase in nutrient pollution from sewage emissions due to population growth and increased global development is expected.³⁰

The primary limitation in our model is the lack of data available on variability of pollutant removal efficiency for the various sanitation technology types. Specifically, we assumed that pollutant removal efficiency was only influenced by technology type, and not by other factors including siting, age, or management of infrastructure. For example, there may be disparities between different “pit latrines with slabs” depending on location and maintenance. Similarly, our model is limited by the assumption that both septic tanks and pit latrines have the same pollutant removal efficiency, which is unlikely in practice. Finally, our estimates of fecal pollution removed assume sanitation technology access implies use. Reliance on measures of access to imply use in our model likely overestimates pollution removal as access does not guarantee usage.^{3,31} Usage is difficult to measure or corroborate.^{31,32} These assumptions highlight the need for better data on site-specific sanitation. Additionally, the model relies on the assumption that unimproved sanitation technology types, including open defecation, bucket latrines, and hanging toilets do not remove any human waste pollutants from the

environment. Finally, the model relies on the assumption that national-level GDP per capita is an indicator of the fraction of waste from piped sewer that is treated. Again, better data are needed on the fraction of waste that is treated from piped sewer systems in LMICs. All of our study limitations are related to the need for better data on waste treatment in LMICs, which was part of the motivation for developing this model.

Shifting the focus of sanitation development from access to technology types to level of waste treatment has the potential to have large impacts on reducing environmental pollution due to human waste. The driver of current nutrient and microbial pollution entering the environment is the removal efficiency of a few select sanitation technology types. As our sensitivity analysis showed septic tank removal efficiency and pit latrines with/without slab have the greatest influence on removal of contaminants. Improving the removal efficiency of these technology types has the potential to greatly reduce overall nutrient contamination. This is also evident in the limited improvement seen in Scenario I. Currently, Millennium Development Goal 7C focuses on providing sanitation at the household level as defined by the type of sanitation technology, distinguished as “improved” vs. “unimproved.”¹ To better improve sanitation removal efficiency of pollutants, post-2015 goals should focus less on the presence/absence of technology and more toward quantifying safe storage, movement, and treatment of waste to reduce impacts on human and environmental health.

Collection and treatment of fecal waste to remove microbial and nutrient pollution provides opportunities for reductions in environmental fecal pollution.

The best-case scenario of upgrading sanitation access to 100% coverage with piped sewers with 100% treatment and septic tanks is unlikely to be achieved due to the large required capital costs, which are not considered in this model. Even if the best-case scenario could be achieved, our model estimates that between approximately 20-40% of pollutants remain untreated. Greater emphasis is needed on building sustainable, effective sanitation treatment that capture and/or treat microbial and nutrient pollutants. Addressing the gap between sanitation technology and collection services allows for resource recovery in addition to protecting humans from unsafe human waste.³³ For example, urine diversion toilets capture nutrients, notably nitrogen and phosphorous, for reuse. These approaches, in addition to reducing the release of nutrients into the environment, also have the potential to reduce the reliance on artificial fertilizers.³⁴

Looking forward, the resolution of the model can be improved from national level to a local scale. Increased resolution can help prioritize limited resources through a better understanding of community level human waste contamination. The model can also leverage support for human waste management systems over sewer based systems. Human waste management systems not only provide an opportunity for resource recovery but also are economically viable compared to sewer based systems.³⁵

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432 **Supporting Information**

433 Supporting Information includes methods and results for model parameters,
434 sensitivity analysis results, model results for urban and rural areas, statistical
435 analysis of model parameter distributions, percent piped sewer treated distribution,
436 the Matlab code for the Monte Carlo simulations, and the percent removal of all
437 pollutants for each of the 108 countries.

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Figures and Tables

Figure 1: Conceptual diagram of mechanistic-stochastic model of fecal production, treatment and removal globally in low and middle income countries.

Parameter, units	Distribution	Source
Fecal Weights		
Adult (Normal), grams per day	Truncated Normal (125, 59)	This Study
Adult (Diarrhea), grams per day	Truncated Normal (7000, 6000)	This Study
Child (Normal), grams per day	Truncated Normal (53, 32)	This Study
Child (Diarrhea), grams per day	Lognormal (6.2, 0.9)	This Study
Fecal Composition		
Nitrogen, %	Uniform (5,7)	36
Phosphorus, %	Uniform (3,5.4)	36
BOD, grams per stool	Uniform (15,20)	37
Fecal Coliforms, CFU per grams	Uniform 10 ⁶ (6,9)	38
Moisture Content (Normal), %	Uniform (66,80)	36
Moisture Content (Diarrhea), %	Triangular (85,85,100)	39
Urine Composition		
Nitrogen, mmol per person per day	Normal (795, 220)	24
Phosphorus, mmol per person per day	Normal (31, 9.9)	24
BOD, grams per person per day	Normal (6.1, 2.2)	24
Diarrhea Duration		
Adult, days	Truncated Normal (3, 3)	40,41
Child, days	Truncated Normal (3, 3)	This Study, ⁴¹
Diarrhea Incidence		
Adult (Africa), cases per year	Point value (0.9)	23,42
Adult (Americas), cases per year	Point value (0.7)	23,42
Adult (Eastern Mediterranean), cases per year	Point value (0.6)	23,42
Adult (Europe), cases per year	Point value (0.2)	23,42
Adult (South East Asia), cases per year	Point value (0.6)	23,42
Adult (Western Pacific), cases per year	Point value (0.7)	23,42
Child (Africa), cases per year	Point value (3.3)	23
Child (Americas), cases per year	Point value (4.0)	23
Child (Eastern Mediterranean), cases per year	Point value (3.0)	23
Child (Europe), cases per year	Point value (4.0)	23
Child (South East Asia), cases per year	Point value (2.4)	23
Child (Western Pacific), cases per year	Point value (2.3)	23
Piped Sewer Treatment		
GDP per capita ≤ 6000 (International dollar) %	Uniform (0,5)	This Study
GDP per capita > 6000 (International dollar) %	Triangular (0,25,100)	This Study
Demographics		
Population (Adult), people*	Point value	15
Population (Child), people*	Point value	15
Urban, %*	Point value	16,17

Table 1: Values, distribution parameters, and sources parameters used to estimate total human waste production, percent nutrient and microbial pollutant removal, and total pollutant levels entering the environment. Distributions defined as normal (mean, standard deviation), lognormal (mu, sigma), uniform (lower bound, upper bound) and triangular (lower bound, peak, upper bound). Point values signify a single estimate with no distribution. *Demographic data varied for each of the 108 countries modeled, and was assumed as a point value of the data from the United Nations Populations Division, The Progress on Drinking Water and Sanitation-2012 Update, and the World Bank.¹⁵⁻¹⁷

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Parameter, units	BOD Removal	Nitrogen Removal	Phosphorous Removal	Fecal Coliform Removal
Flush to Piped Sewer, %	Uniform (45,80)	Triangular (0, 30, 30)	Uniform (75,90)	Point value (90)
Flush to Septic Tank, %	Uniform (35,40)	Triangular (0, 30, 30)	Triangular (0, 35, 35)	Triangular (0, 90, 90)
Flush to Pit Latrine, %	Uniform (35,40)	Triangular (0, 30, 30)	Triangular (0, 35, 35)	Triangular (0, 90, 90)
Flush to Do Not Know, %	Point value (0)	Point value (0)	Point value (0)	Point value (0)
Pit Latrine (VIP / With Slab / Without Slab), %	Uniform (35,40)	Triangular (0, 30, 30)	Triangular (0, 35, 35)	Triangular (0, 90, 90)
Compositing Toilet, %	Triangular (40, 40, 70)	Triangular (30, 30, 94)	Triangular (0, 0, 50)	Point value (90)
No Facility / Hanging Toilet / Bucket Latrine, %	Point value (0)	Point value (0)	Point value (0)	Point value (0)

Table 2: Estimates and distributions parameters of nutrient (nitrogen, phosphorous, biochemical oxygen demand) and microbial (fecal coliform) pollutant removal efficiency for each sanitation technology type. Values for “Flush to Piped Sewer”, “Flush to Septic Tank”, “Flush to Pit Latrine”, and “Pit Latrine (VIP / With Slab / Without Slab)” were based on Nelson and Murray; “Composting Toilets” on Anand and Apul, Bai and Wang, and Hotta and Funamizu;and “Flush to Do Not Know” and “No Facility / Hanging Toilet / Bucket Latrine” conservatively assumed as providing no treatment. ^{18, 43-45}

	Global	Africa	Americas	South East Asia	Europe	Eastern Mediterranean	Western Pacific
n	108	41	23	10	13	10	11
Phosphorus							
<i>Scenario I</i>	16.5 (10.2-23.1)	17.0(10.1-22.9)	26.7 (11.6-46.7)	11.0 (5.8-14.9)	28.7 (12.5-50.6)	17.2 (10.6-24.6)	17.9 (8.1-24.7)
<i>Scenario II</i>	23.0(12.6-32.2)	23.1 (9.0-33.1)	28.6 (13.2-49.2)	21.8 (10.2-30.0)	28.9 (12.6-50.2)	21.3 (12.1-29.3)	22.4 (11.4-30.8)
<i>Scenario III</i>	58.0 (49.4-64.8)	51.2 (41.9-58.8)	77.2 (71.2-83.1)	50.8 (40.5-58.2)	76.5 (70.6-82.3)	69.4 (63.0-75.9)	47.8 (36.8-55.4)
Nitrogen							
<i>Scenario I</i>	11.3 (7.4-14.9)	12.9 (7.4-17.1)	11.5 (5.9-18.4)	9.2 (4.5-12.7)	13.1 (7.2-20.7)	11.4 (7.2-15.3)	17.2 (8.9-23.2)
<i>Scenario II</i>	17.0 (8.8-23.2)	18.6 (7.1-26.0)	13.3 (6.8-20.8)	18.4 (8.6-25.9)	13.4 (7.4-21.4)	14.6 (8.5-19.7)	20.9 (11.4-28.4)
<i>Scenario III</i>	57.9 (49.3-67.4)	50.4 (40.9-58.8)	78.6 (71.0-89.9)	49.6 (39.8-58.1)	77.8 (70.5-89.2)	69.9 (62.5-79.9)	46.6 (36.6-54.7)
BOD							
<i>Scenario I</i>	22.5 (19.1-27.2)	25.0 (22.8-27.9)	27.1 (16.0-43.6)	17.6 (16.8-18.4)	29.8 (17.5-48.7)	23.2 (19.9-28.5)	30.0 (28-31.7)
<i>Scenario II</i>	33.4 (29.9-38.1)	35.4 (32.4-38.8)	30.5 (19.2-47.0)	34.7 (33.0-36.4)	30.5 (18.3-48.9)	29.2 (25.5-34.7)	37.1 (35.2-38.9)
<i>Scenario III</i>	68.4 (65.7-71.3)	62.3 (59.8-64.9)	85.1 (81.6-88.6)	61.7 (59.4-64.3)	84.6 (81.0-88.0)	78.2 (75.2-81.4)	58.9 (56.6-61.4)
Fecal Coliforms							
<i>Scenario I</i>	35.2 (22.9-46.7)	39.4 (22.3-53.1)	41.3 (21.9-64.5)	28.4 (14.0-37.9)	45.7 (25.4-68.8)	36.5 (23.7-48.0)	48.4 (22.6-65.5)
<i>Scenario II</i>	53.2 (27.8-72.5)	55.9 (20.6-79.8)	47.1 (26.9-70.8)	55.3 (26.8-76.7)	46.9 (25.8-71.2)	45.4 (28.4-60.7)	60.2 (30.6-81.5)
<i>Scenario III</i>	80.1 (62.4-93.1)	76.5 (52.8-92.3)	92.0 (86.4-96.9)	76.1 (53.3-92.3)	91.4 (85.5-96.7)	87.5 (77.1-95.6)	74.3 (47.2-91.6)

Table 3: Estimated mean percentage (95% range) of removal of nutrient (phosphorus, nitrogen, and biochemical oxygen demand) and microbial (fecal coliform) pollutants by global population and WHO region under current sanitation access conditions (Scenario I) and two improvement scenarios (Scenarios II and III).

Scenario I: Existing sanitation technologies.

Scenario II: 100% WHO standards for improved sanitation access.

Scenario III: 100% piped sewerage (urban) or septic tank (rural) access.

Figure 2: Estimated nutrient (phosphorus, nitrogen, and biochemical oxygen demand) and microbe (fecal coliform) pollutants emitted per square kilometer globally under current sanitation access conditions (Scenario I) and two improvement scenarios (Scenarios II and III).

Scenario I: Existing sanitation technologies.

Scenario II: 100% WHO standards for improved sanitation access.

Scenario III: 100% piped sewerage (urban) or septic tank (rural) access.

TOC/Abstract Art