Environmental Science & Technology

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Sanitation: A Global Estimate of Sewerage Connections without Treatment and the Resulting Impact on MDG Progress

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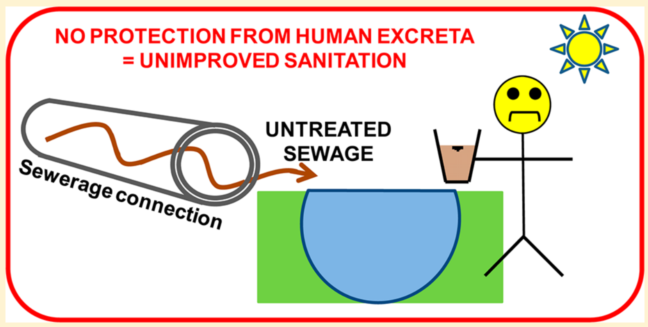
S Supporting Information

ABSTRACT: Progress toward the sanitation component of Millennium Development Goal (MDG) Target 7c was reassessed to account for the need to protect communities and the wider population from exposure to human excreta. We classified connections to sewerage as "improved sanitation" only if the sewage was treated before discharge to the environment. Sewerage connection data was available for 167 countries in 2010; of these, 77 had published data on sewage treatment prevalence. We developed an empirical model to estimate sewage treatment prevalence for 47 additional countries. We estimate that in 2010, 40% of the global population (2.8 billion people) used improved sanitation, as opposed to the estimate of 62% (4.3 billion people) from the WHO/UNICEF Joint Monitoring Programme (JMP), and that 4.1 billion people lacked access to an improved sanitation facility. Redefining sewerage-without-treatment as "unimproved sanitation" in MDG monitoring would raise the 1990 baseline population using unimproved sanitation from 53% to 64% and the corresponding 2015 target from 27% to 32%. At the current rate of progress, we estimate a shortfall of 28 percentage points (1.9 billion people) in 2010 and a projected 27 percentage point shortfall in 2015.



INTRODUCTION

The United Nations Millennium Development Goal (MDG) Target 7c seeks to reduce by half, "the proportion of the population without sustainable access to ... basic sanitation" between 1990 and 2015.[1] The World Health Organization (WHO) and United Nations Children's Fund (UNICEF) Joint Monitoring Programme (JMP) for Water Supply and Sanitation monitors progress toward this target.[2] Access to basic sanitation is measured using the indicator "proportion of population using an improved sanitation facility", where the following sanitation facilities are considered to be improved: ventilated improved pit (VIP) latrine, pit latrine with slab, composting toilet, and flush or pour-flush to (i) piped sewer system; (ii) septic tank or; (iii) pit latrine. Unimproved sanitation facilities include: flush or pour-flush to elsewhere (not to piped system, septic tank, or pit latrine), pit latrine without slab/open pit, bucket, hanging toilet or hanging latrine, any type of shared facility, and use of bush or field.[2] Using this categorization and national survey data, JMP estimated that 4.3 billion people were using an improved sanitation facility in 2010, whereas 2.6 billion people were using an unimproved sanitation facility.[3]

JMP definitions of improved sanitation require that a facility "hygienically separates human excreta from human contact";[1] however for sewerage systems, there is no mention of sewage treatment. Globally, a common practice is to discharge sewage without treatment and as a result, more than 50% of the world's rivers, oceans, and lakes are polluted with untreated wastewater.[4] Untreated sewage contains excreted pathogens and can lead to adverse health effects in individuals exposed to these pathogens through contamination of drinking-water, pollution of fish and shellfish-growing waters, contamination of irrigated crops or direct contact.[5] The associated infections include some caused by viruses (e.g., rotavirus, norovirus), bacteria (e.g., *Vibrio cholerae, Shigella* spp., *Campylobacter* spp.), and protozoa (e.g., *Entamoeba histolytica*, *Cryptosporidium* spp., *Giardia lamblia*).[4] Other excreta-related diseases include schistosomiasis (associated with human contact with infested waters) and bancroftian filariasis (spread to humans by insects or rodents who are exposed to untreated sewage).[4] Thus, sanitation facilities that are categorized as improved by JMP include some which do not "hygienically separate human excreta from human contact", and therefore do not protect the population from exposure to human excreta and associated adverse health effects.

In the 2004 Millennium Project Interim Report of Task Force 7 on Water and Sanitation, which provided recommendations on achieving MDG Target 7, the need for an alternative definition of improved sanitation was recognized.

Received: April 5, 2012
Revised: January 13, 2013
Accepted: January 16, 2013
Published: January 16, 2013

The report proposed a working definition of access to basic sanitation as "access to, and use of, excreta and [wastewater] disposal facilities and services that provide privacy and dignity while at the same time ensuring a clean and healthful living environment *both at home and in the immediate neighborhood of users*"[6] (our emphasis). Nelson and Murray,[7] in a review of sanitation technologies, also stressed the need to define sanitation more broadly to include treatment of all waste materials, as "the entire community, *as well as downstream populations*, must be protected from discharge of untreated wastes"[7] (our emphasis). Finally, Langford et al.,[8] in the context of human rights, recently proposed the following definition: "sanitation constitutes the ability to effectively access space and facilities (whenever and wherever needed), that afford privacy, dignity and safety, in which to urinate, defecate and practice related hygiene, including menstrual hygiene, in a culturally acceptable manner; which by virtue of their design, management and accompanying services *protect the user, the locality (e.g., households, school, workplace, hospital or community) and wider population from the adverse consequences of contamination* from the process"[8] (our emphasis). Thus there is recognition that surrounding communities and distal populations as well as facility users should not be adversely impacted by the handling and disposal of human excreta.

In this study we explore the feasibility of accounting for the need to protect communities and the wider population, as well as facility users, from exposure to human excreta. We treat connection to sewerage systems as "improved" only if the sewage is treated and by doing so, we reassess the global population with access to improved sanitation and revise the baseline, target and estimate of progress toward MDG Target 7c. The objectives of this work were therefore to collate and synthesize data on national levels of sewage treatment; and assess the impact on global sanitation status and trends of categorizing untreated sewage discharged into the environment as "unimproved sanitation". To the knowledge of the authors, no global estimate has been published on the prevalence of sewerage systems lacking sewage treatment.

■ MATERIALS AND METHODS

Data for Sewerage Connections. Data for the proportions of rural and urban populations with access to sewerage connection were taken from the JMP Country Files which use nationally representative surveys for each country.[9] The rural and urban sewerage connection data were separately extrapolated using linear regression and following JMP rules[10] to estimate sewerage connection coverage for 1990 (baseline year of the MDGs) and 2010. To determine the total population with sewerage connection at each year, the urban and rural percentages of sewerage connection were multiplied by their respective populations (United Nations Department of Economic and Social Affairs Population Division[11]) and summed. The percentage of the population with sewerage connection at the national level (combined urban and rural) was then calculated by dividing the population with sewerage connection by the total population.

For countries that did not have sewerage connection data available in the JMP Country Files, the United Nations Statistics Division (UNSD[12]) makes available information from national statistical offices and/or ministries of the environment regarding the proportion of the population connected to a wastewater collection system − this value is representative of the entire country and does not differentiate between rural and urban areas. Using JMP rules, the sewerage connection percentage at national level was estimated for 1990 and 2010. In cases where a country had sewerage connection data from both the JMP Country Files and the UNSD, the former values were used as they provide rural and urban disaggregation. All sewerage connection values used in this study are from the above-mentioned sources (no predictions were made) and are presented in Table S1 of the Supporting Information (SI).

Data for Sewage Treatment. Data on the percentage of sewage collected that undergoes treatment (sewage treatment prevalence) is not available for all countries. The main sources of data for sewage treatment were the following databases: UNSD database,[12] Eurostat from the European Commission,[13] AQUASTAT from the Food and Agriculture Organization (FAO) of the United Nations,[14] and the Organisation for Economic Co-operation and Development (OECD) database.[15] These databases consolidate and make available statistical information obtained from each country's national statistical office and/or ministry of environment. In addition to these databases, we searched the databases of UNICEF, the World Bank, and the Demographic and Health Surveys (DHS) and found no relevant information.

For countries that did not have sewage treatment prevalence in any of the above-mentioned databases, we searched for country or regional reports via search engines such as Google Scholar. Our search terms were "wastewater treatment" and "sewage treatment". Selection criteria required that sewage treatment was estimated on a national level, for either the urban population or combined urban and rural populations. Data from subnational regions and individual cities were disregarded unless the specified city operated the only sewerage system in the country.

We included data relating to any type of treatment. Sources from which estimates of sewage treatment were obtained described the degree of wastewater treatment as anything from "some degree of treatment" through "secondary: activated sludge; ponds; moving to tertiary" to no comment at all on degree of treatment. For databases that offered sewage treatment prevalence data for more than one year, we used linear extrapolation following JMP rules to estimate sewage treatment prevalence at 1990 and 2010. If estimates were available from multiple databases for the same year, we used the average value. Sewage treatment prevalence values used in this study are shown in Table S1 of the SI.

Prediction of Sewerage Treatment Prevalence. Country-level estimates of sewage treatment prevalence in 2010 and 1990 were available for 84 and 93 countries, respectively. For the remaining countries, an empirical model was developed for each year independently, where the prevalence of sewage treated was predicted as a function of the following eight social, health, and political indicators: urban access to improved sanitation as defined by JMP,[3] government effectiveness as evaluated by the World Bank,[16] gross national income (GNI) per capita calculated using the Atlas method,[17] percentage of population attaining tertiary education,[18] percentage of the female population attaining secondary education,[18] percentage of the population living below $1 a day,[12] trade (percentage of GDP),[17] and under-5 DALYs per 100 000 children attributed to water, sanitation, and hygiene.[19]

Of the countries with sewage treatment prevalence values, only 30 countries in 2010 and 28 countries in 1990 had data for all eight indicators listed above. We identified 36 and 48 countries for 2010 and 1990, respectively, with data missing for

only one or two indicators. For countries missing data on the percentage of the population living below $1 a day, we assumed that this value was zero for countries with a 2010 GNI per capita value greater than 30 000. Using SAS 9.2 (SAS Institute Inc., Cary, NC), we performed single value imputation and obtained a complete data set of 66 and 76 countries for 2010 and 1990, respectively. Imputation is a method used to handle missing data and has been used in studies to estimate child mortality[20] and in the construction of a global water quality index.[21] We used the expectation-maximization algorithm to impute missing values using data available from the other indicators. The expectation-maximization algorithm uses an iterative process based on maximum likelihood estimation and thus has strong statistical principles. Based on the estimate of variances, the maximum proportion of missing data was 5% for both 2010 and 1990 data sets.

Using the complete data set of 66 countries for 2010 and 76 countries for 1990, for each year we fitted the sewage treatment prevalence values to all combinations of the eight parameters (a total of 255 combinations) using a fractional logistic model in STATA 12 (StataCorp LP, College Station, TX). The fractional logistic model was used in place of the ordinary least-squares (OLS) regression because the predicted values from the fractional logistic model are restricted between 0 and 1, whereas use of OLS regression can lead to negative treatment values or treatment values greater than 100%. The fitted model coefficients in the fractional logistic model are determined based on a quasi-maximum likelihood method, rather than minimization of the sum of squared residuals as in OLS, and thus no R-squared value exists to assess the fit of the model. Using the fractional logistic model and requirement of robust standard errors, we obtain log pseudolikelihood rather than log likelihood values. As log pseudolikelihoods are not "true" likelihoods, the likelihood ratio test, commonly used to compare two models, does not apply. Instead, we evaluate goodness of fit by directly comparing the log pseudolikelihood and deviance values, where higher log-pseudo likelihoods and lower deviances are associated with the model with the best predictive performance.

In addition to developing an empirical model using the full set of countries, we also considered whether empirical models developed for specific country income groups would improve the predictive performance, since the indicators that predict treatment prevalence may be significantly different between high and low income countries. The criteria for classifying a country as low, lower middle, upper middle, and high income are defined by the World Bank and are based on the gross national income (GNI) per capita calculated using the Atlas method.[22] We divided the countries into two groups based on income level and refer to these two groups as "group A" and "group B". There are three ways to divide the four income levels into two groups: (M1) group A as low income only, and group B as lower middle, upper middle, and high income; (M2) group A as low and lower middle income, and group B as upper middle and high income; and (M3) group A as low, lower middle, and upper middle income, and group B as high income only.

For each of the six groups (M1-A, M1-B, M2-A, M2-B, M3-A, M3-B), we fitted sewage treatment prevalence values to a fractional logistic model for all combinations of the eight indicators and selected the best model as that having the highest log pseudolikelihood, lowest deviance, and all coefficients with a statistical significance level (p-value) of at least 0.05. The final "combined M1" model is the combination of the results of the M1-A and M1-B models, with a similar procedure used to obtained the "combined M2" and "combined M3" models. Following this nomenclature, we designate the model previously developed for all countries (no income group separation) as M4. We compared the results of combined models M1, M2, and M3 with the results of M4 using a plot of model estimated versus literature reported values and calculating the sum of squared residuals. For each year of 2010 and 1990, the final empirical model used to predict sewage treatment prevalence is the model (M1, M2, M3, or M4) with the lowest sum of squared residuals.

Progress toward MDG Target 7c for Basic Sanitation. To reassess progress toward MDG Target 7c, JMP estimates of global access to improved sanitation were adjusted by discounting the proportion of households that have sewerage connection without sewage treatment. For each country, we estimated the number of people with access to sewerage connection without treatment by multiplying the total population by both the national-level sewerage connection percentage (see Data for Sewerage Connections section above) and the prevalence of untreated sewage (100% minus the prevalence of treated sewage, calculated as described in the previous section). The global population with access to sewerage connection without treatment was calculated as the sum of the corresponding individual values for all countries. The proportion of the world population with access to improved sanitation is the difference between the JMP estimate of the population with improved sanitation and the population with untreated sewerage connection, all divided by the total population. Estimates were calculated at 2010 and the MDG baseline year of 1990. The revised 2015 MDG target value was calculated by halving the new 1990 baseline value. Projections for global progress on MDG Target 7c in 2015 were estimated following the JMP approach, which uses linear extrapolation of 1990–2010 data.

RESULTS AND DISCUSSION

Comparison of Model Estimates to Literature Values for Sewage Treatment Prevalence. Sewage treatment prevalence data were available in the literature for 68 and 78 countries in 1990 and 2010, respectively, for which sewerage connection data was available and are listed as Group I countries in Table S1 of the SI. To predict sewage treatment prevalence for countries that do not have available data, an empirical model was independently developed for each year following the methodology outlined in the Materials and Methods section. We present in Table S2 of the SI the regression coefficients, robust standard errors, significance levels (shown as p), and other modeling parameters obtained for the best predictive model from each of groups M1, M2, M3, and M4. We compared the sum of squared residuals from these four models and selected the final model based on the lowest sum of squared residuals value. The model used in predicting sewage treatment prevalence for countries without treatment data is model M2 for both 2010 and 1990. As described in the Materials and Methods section, group M2 is divided into M2-A (low and lower middle income countries) and M2-B (upper middle and high income countries). For 2010, the predictors for M2-A were urban access to improved sanitation, GNI per capita, tertiary education, female secondary education, below $1/day, under-5 DALYs, and trade, whereas the predictors for

dx.doi.org/10.1021/es304284f | Environ. Sci. Technol. 2013, 47, 1994–2000

M2-B were urban access to improved sanitation, GNI per capita, and female secondary education.

Figure 1 presents the model estimated values plotted against the literature reported values for sewage treatment prevalence in 2010 for (a) the final model selected, M2 and (b) the M4 model without separation of countries by income level as a comparison (similar figure for 1990 model estimated and reported values are presented in Figure S1 of the SI). Analysis of the sum of squared residuals values allows the model with the best overall predictability to be identified, and use of a scatter plot as shown in Figure 1 helps identify whether a model predicts well for the entire range of values, or only in one range of values. Points on the 1:1 line indicate good model predictability, whereas scatter above or below the 1:1 line indicates overestimation or under-estimation, respectively, of the model. As observed in the figure, both M2 and M4 models show that the data points follow the 1:1 line with relatively uniform scatter at sewage treatment values greater than 50%. At treatment values less than 5%, the predictive performance of the M2 model is better than that of the M4 model, as seen by the decreased scatter.

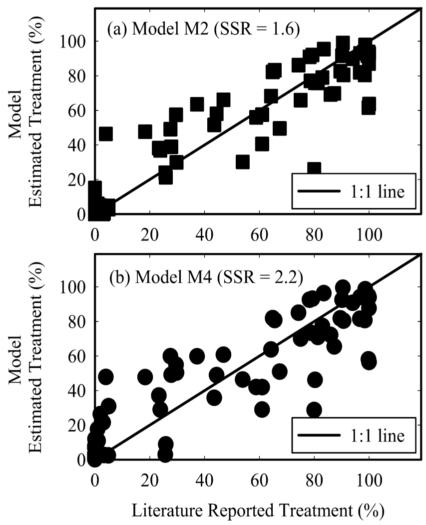


Figure 1. Comparison of model estimated and literature reported sewage treatment prevalence in 2010 for (a) Model M2, the final model selected and (b) Model M4, as a basis for comparison. Sum of squared residuals (SSR) shown in brackets.

Estimation of Global Sewerage Connection and Sewage Treatment Prevalence. The empirical M2 model was used to predict treatment prevalence in 1990 and 2010 for 62 and 56 countries, respectively, for which published sewage treatment prevalence data are not available. While some of the model predicted values may not necessarily be accurate (e.g., sewage treatment prevalence of 100% for Peru in 2010), SI Table S1 provides full details of the values used to calculate global sewage treatment, thus allowing for transparency of our method and also emphasizing a need for increased data collection and reporting of sewage treatment. For the purpose of the discussion below we grouped countries in Groups I, II, and III (See also Table S1 of the SI) defined as follows: Group I − countries have both sewerage connection and treatment prevalence values from literature; Group II − countries have sewerage connection values from literature and treatment prevalence values predicted by our empirical model; and Group III − countries do not have sewerage connection values from literature and/or sewage treatment prevalence were not available and could not be empirically predicted. Group I represents 47% and 22% of the world population for 1990 and 2010, respectively. Collectively, the countries with data on both sewerage connection and sewage treatment prevalence (Groups I and II combined) represent 86% of the world population in 1990 and 83% in 2010.

We estimate that access to sewerage connection was 36% in 2010 using data from Groups I and II combined. The percentage of the population connected to sewerage that had some form of sewage treatment was 39%. The results of sewerage connection and treatment prevalence for 1990 and 2010 are presented in Table 1. We also present in Table 1 the distribution of countries by income group for Groups I and II combined and Group III. For 2010, the percentage of countries in the low, lower middle, upper middle, and high income groups were 29%, 30%, 25%, and 16%, respectively, for Groups I and II combined, and 20%, 29%, 19%, and 32%, respectively, for Group III. The data shows that, for both groups (I and II combined, and III), countries were randomly distributed among all four income groups. We therefore assume that the estimates of sewerage connection and prevalence of sewage treatment from the Group I and II countries can be treated as global estimates.

Table 1. Global Sewerage Connection and Sewage Treatment Prevalence

	group I[a] countries	group II[b] countries	group I and II countries combined	group III[c] countries
1990				
n	68	39	107	108
% of world population	47%	39%	86%	14%
% with sewerage connection	33%	18%	26%	
% with treatment, given connection	63%	50%	59%	
% distribution by income group[d]			*L* = 26%	*L* = 27%
			LM = 38%	LM = 38%
			UM = 15%	UM = 19%
			H = 21%	*H* = 17%
2010				
n	77	47	124	91
% of world population	22%	61%	83%	17%
% with sewerage connection	51%	30%	36%	
% with treatment, given connection	66%	22%	39%	
% distribution by country income group[d]			*L* = 29%	*L* = 20%
			LM = 30%	LM = 29%
			UM = 25%	UM = 19%
			H = 16%	*H* = 32%

[a]Countries for which connection and treatment data from literature are available. [b]Countries for which connection data is available and treatment prevalence are estimated using our empirical model. [c]Countries for which either connection data is not available in literature and/or treatment prevalence is not available in literature and cannot be estimated with our model. [d]Country income group abbreviations are *L* = low income, LM = lower middle income, UM = upper middle income, *H* = high income (percentages are given as number of countries in each income group divided by total number of countries).

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Figure 2 presents by country income group the proportion of the 2010 population in Groups I and II combined with access

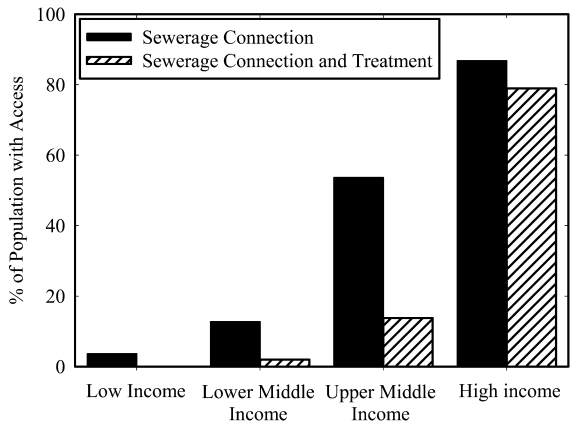

Figure 2. Global access to sewerage connection alone and to sewerage connection with sewage treatment in 2010, by country income group.

to (i) sewerage connection and (ii) sewerage connection with sewage treatment. The sewerage connection data (shown in solid bars) was obtained from JMP Country Files and is considered by JMP to be equivalent to having an improved sanitation technology. Data for sewerage connection with sewage treatment (shown in hatched bars) represents our definition that a sewerage connection is only considered an improved sanitation technology if the collected waste is treated. Of the sewage treatment prevalence values used, 47 out of the 124 values were predicted by our empirical model. The difference between the two bars represents the population using a sewerage connection for sanitation that discharges untreated sewage.

As observed in Figure 2, for low income countries, less than 4% of the population has sewerage connections and thus, even though the sewage treatment prevalence is low, the population using an untreated sewerage connection will be small. In contrast, while more than 50% of the population in upper middle income countries has a sewerage connection, only 14% of the population has both sewerage connection and treatment. This results in a small fraction (25%) of those with sewerage connections also having sewage treatment. The upper middle income group is thus the group of countries which contribute the most to the population using a sewerage connection that discharges untreated sewage.

Global Population with Access to Improved Sanitation. Using the calculated values of the proportion of the global population with sewerage connection and with sewerage connection and sewage treatment (as discussed in the previous section), we estimate that, of the 4.3 billion people that JMP considered to have used "improved sanitation" globally in 2010, 1.5 billion used sewage connections without treatment and therefore did not protect the community and wider population from exposure to human excreta. Figure 3 illustrates that Asia accounts for the largest proportion (69%) of these 1.5 billion people and that Europe and South America correspond to 12% and 11%, respectively. Figure 3 indicates that if improved sanitation were redefined to exclude sewage connections without treatment, the decrease in the proportion of the population with access to improved sanitation would be mainly due to Asia. Discounting this 1.5 billion population that we estimate to have had sewerage connections without treatment

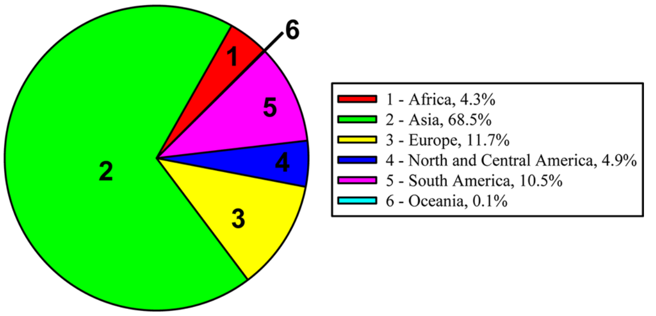

Figure 3. Distribution by continent of the 1.5 billion people using sewerage facilities with no treatment in 2010.

in 2010, from the 4.3 billion population that the JMP estimated to have had improved sanitation, lowers the estimated level of improved sanitation worldwide in 2010 to 2.8 billion and increases the level of unimproved sanitation to 4.1 billion from 2.6 billion. This would increase the 2010 proportion of the population without access to improved sanitation from 38% (JMP estimate) to 60%.

To assess progress toward MDG Target 7c, the 1990 baseline proportion of population without access to improved sanitation was adjusted to discount sewerage without treatment and thereby increased from 53% to 64%. Applying the Target 7c formula of halving the proportion of the unserved would require that the population lacking access to improved sanitation be reduced to 32% in 2015, which is 5 percentage points higher than the current target of 27%. Figure 4 presents

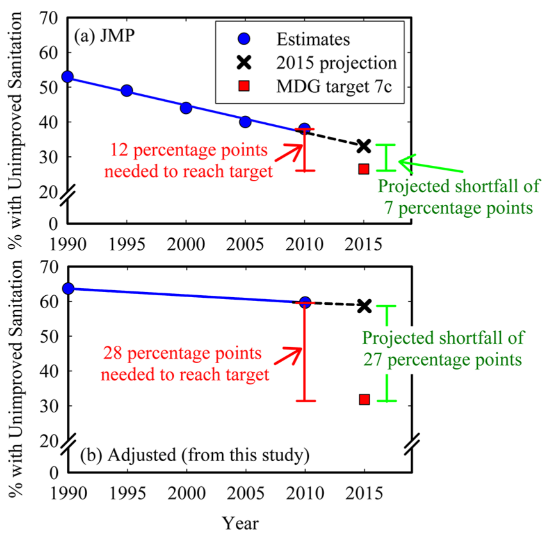

Figure 4. Progress toward MDG Target 7c to halve the proportion of the global population using unimproved sanitation. Progress at 2010 and projections for 2015 are shown for both (a) current JMP estimates and (b) estimates from this study (where sewerage connection facilities that discharge untreated waste are considered to be unimproved sanitation). Dotted lines represent linear projections to 2015.

the 2010 progress and 2015 projection for MDG Target 7c using (a) the current JMP data and (b) the data derived in this study. Using data from the JMP Data Resources Bank,[3] Figure 4a plots the 1990−2010 data (circles) of the proportion of the population using unimproved sanitation. Applying the JMP method of linear extrapolation to this data, the projected proportion of the population in 2015 with unimproved

dx.doi.org/10.1021/es304284f | Environ. Sci. Technol. 2013, 47, 1994−2000

sanitation (cross) is 33%. This represents an estimated shortfall of 12 percentage points (790 million people) in 2010, and a projected 7 percentage point shortfall in 2015. These shortfall values differ slightly from the WHO 2012 update on sanitation progress,[23] which uses 1990 and 2010 estimates different from the JMP Data Resource Bank. In Figure 4b, we plot the 1990 and 2010 data points on the proportion of the population with unimproved sanitation based on our approach, where sewerage connections without treatment are considered unimproved sanitation. Following JMP rules, we linearly extrapolate our data to 2015 and obtain a projection of 59% of the population using unimproved sanitation. By requiring that sewerage connections provide some level of treatment, we estimate a shortfall of 28 percentage points (1.9 billion people) at 2010, with a projected 27 percentage point shortfall in 2015.

For the countries in which sewage treatment prevalence was predicted, a sensitivity analysis was performed to determine how variability in these model predictions would affect the calculated proportion of the population without access to improved sanitation. We varied our model predictions of sewage treatment prevalence by a factor of 5 and reassessed the 2010 and projected 2015 percentage shortfall toward reaching MDG Target 7c. The best-case scenario presented here occurs when the 1990 model overestimated while the 2010 model underestimated sewage treatment prevalence values, and the worst-case scenario occurs when the 1990 model underestimated while the 2010 overestimated sewage treatment prevalence values. In the best-case scenario, we varied the 1990 and 2010 model predictions by factors of 0.2 and 5, respectively. This led to a 2015 MDG target of 33% for the proportion of the population with unimproved sanitation, a shortfall of 16 percentage points between 2010 and 2015, and a projected 2015 shortfall of 12 percentage points. In the worst-case scenario, we varied the 1990 and 2010 model predictions by factors of 5 and 0.2, respectively. This led to a 2015 MDG target of 31% for the proportion of the population with unimproved sanitation and shortfalls of 33 percentage points for both 2010 and 2015. Results from this sensitivity analysis indicate that even with a 5-fold error in our model predictions, progress toward MDG Target 7c is less than current JMP estimates and the projected 2015 shortfall will be greater than the JMP estimate of 7 percentage points.

Assumptions That Affect the Estimates of Global Sewerage Connection, Sewage Treatment Prevalence and Perceived Level of Public Health Protection. Our estimate of the global population with access to improved sanitation required several assumptions which may have led to under- or overestimation. For countries with published data for sewage treatment prevalence, some countries only provided prevalence data for urban populations which were applied to the entire country. While in these countries there is no data available to compare rural and urban sewage treatment prevalence, it is unlikely that the treatment prevalence is the same for both regions. Accordingly, the use of urban sewage treatment prevalence to represent the entire country likely results in an under- or overestimation of the population with treatment.

Of the sewage treatment prevalence values obtained from literature, there is variability among countries and between facilities in the type of sewage treatment performed. Accounting for treatment type (primary, secondary, tertiary) was not possible and we assume in our calculations that all forms of sewage treatment provided the same level of protection. As some forms of treatment provide minimal or insufficient protection against human exposure to human excreta, this assumption leads to an overestimation of the perceived level of public health protection.

Effective protection of public health may be affected by the adequacy of the infrastructure. Sewer lines which are not maintained may allow leakage of sewage into the environment, possibly contaminating drinking water sources. Thus, even if a wastewater treatment plant reports that all of its waste is treated, it is possible that untreated sewage has leaked from pipes, leading to human exposure. In addition, sewerage systems become overloaded at times due to high rainfall or seasonal population surges and excess flow may be discharged untreated through "combined sewer overflows". In this study, we were not able to account for the condition of the sewerage system or for the occurrence of overloading. Since treatment systems may also be improperly operated, inadequately maintained, become obsolete, and/or ineffective, and sewerage overload cannot always be prevented, our findings may suggest a greater level of health protection than is actually achieved.

Using our classification system, sewerage connections without sewage treatment are treated as unimproved sanitation and associated with a low level of public health protection. However, the population exposure to untreated sewage is not necessarily proportional to the population whose sewage is not treated. Not all untreated sewage that is discharged to the environment comes into contact with humans. For example long sea (marine) outfalls, when properly designed and implemented, minimize health risk. Conversely, untreated sewage from a small fraction of the population may be discharged downstream to an area that affects a larger portion of the population (e.g., discharge to slums). Thus interpretation of our estimates of untreated sewage discharge as indicative of health risk may under- or overestimate the actual level of public health protection.

Policy Implications. JMP categorizations of improved sanitation do not require treatment of sewage and therefore some sanitation facilities classified as "improved" may not protect the population from exposure to human excreta. However, various sources[6−8] propose definitions of improved sanitation that require not only protection of the user but also their communities and the wider population from exposure to human excreta. As observed from Figure 2, there is a large difference between JMP estimates of access to improved sanitation where no sewage treatment is required and our estimates where sewage treatment is required for sewerage connections. Our results thus support the need to re-evaluate the definition of improved sanitation.

Redefining improved sanitation to encompass the need to protect both the individual and the collective right to a clean and healthy environment is a topic of interest as we approach the end of the Millennium Development Goals. Post-2015 goals, targets, and indicators are being developed for Sustainable Development Goals (SDGs) and this study is relevant to the discussion on how improved sanitation is assessed. There is a need to include public health and environmental protection when assessing sanitation and thus sewage treatment prevalence should be recognized as an important indicator to be monitored by JMP. Current JMP estimates do not incorporate sewage treatment due to insufficient data, thereby emphasizing the need for increased data collection and reporting.

This paper accounts for the impact of inadequate sewerage systems; however, a similar logic would suggest that the fraction of other sanitation facilities that lead to contamination of the household, community, and/or wider environment should also be discounted from estimates of coverage with improved sanitation. We focused our attention on sewerage connections because (i) sewerage connections account for over half of all improved sanitation (Table 1 and JMP Data Resources Bank [3]); (ii) JMP provides sewerage connection data disaggregated into rural and urban areas; (iii) there is clear evidence for adverse health and environmental effects from sewage contamination; and (iv) the available evidence suggested a substantive proportion of sewage is untreated. Another important improved sanitation technology which was not considered in this study and can lead to contamination of the household and community is the use of pit latrines which are often emptied close to the community and the contents may not be treated. By accounting for inadequacy in other technologies, we would expect an additional increase in the 1990 unimproved sanitation baseline levels, an increase in the progress required to meet MDG Target 7c, and a decrease in the estimated proportionate progress achieved to date.

■ ASSOCIATED CONTENT

Supporting Information

National sewerage connection and sewage treatment prevalence estimates used in this study, modeling parameters for 1990 and 2010 models, figure of predicted versus actual sewage treatment prevalence values for 1990. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank Christopher Wiesen from the Odum Institute at UNC-Chapel Hill for help in data imputation procedures and Kyle Onda from UNC-Chapel Hill for help in the use of STATA.

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