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Modeling the Impact of Population Intervention Strategies on Reducing Health Disparities: Water, Sanitation, and Hygiene Interventions and Childhood Diarrheal Disease in Peru

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Abstract. Access to safe water and basic sanitation and hygiene facilities (WASH) are important for childhood health globally. However, inequalities in WASH access persist, and local governments need to better understand the potential impact of scaling up WASH services on childhood health. Using 2011 Peru Demographic and Health Survey data as a case study, we applied a modified substitution estimator approach to assess the impact of scaling up access (20–100%) to WASH on diarrhea prevalence among children < 5 years. The modified substitution estimator approach can help identify population subgroups or areas where WASH interventions and sustained implementation could be most beneficial and reduce existing disparities. Using findings from a recent meta-analysis and computing bootstrapped estimates and 95% CIs, we examined inequalities in the effect of WASH on self-reported diarrhea by urbanicity, maternal education level, household wealth, and district of residence. Increasing access (100% change) to improved water sources, sanitation, and hygiene facilities reduced population-level prevalence of childhood diarrhea by 8.2% (95% CI: 4.1, 12.3), 5.5% (95% CI: 0.7, 9.8), and 5.2% (95% CI: 2.2, 8.1), respectively. In stratified analyses, increased access to improved water sources and hygiene facilities was associated with decreased prevalence of diarrhea, with the largest reduction in rural areas and households with lower maternal education and lower wealth. Our findings suggest targeted WASH implementation in Peru is needed in rural areas and among lower socioeconomic-status households. In addition, even low levels of change in overall WASH access may decrease diarrhea prevalence.

INTRODUCTION

Reliable sources of safe water, access to basic sanitation facilities, and good hygiene practices, which include handwashing with soap and water (water and basic sanitation and hygiene facilities [WASH]), are important for childhood survival and development.[1,2] Children younger than 5 years in low- and middle-income countries are the most at risk for waterborne diseases, with diarrhea estimated to account for 446,000 deaths in 2016.[2] In addition, inadequate access to safe water, lack of basic sanitation facilities, and poor hygiene practices are important risk factors for childhood diarrhea.[3–5] Elevated diarrhea morbidity also negatively impacts normal childhood growth, physical fitness, and cognitive function.[6–8]

Generally, interventions which improve water quality (e.g., installation of piped water sources into the dwelling or point-of-use water treatment with safe storage), sanitation conditions (e.g., installation of improved toilets), and hygiene practices (e.g., promoting handwashing with soap and water) have been found to effectively reduce diarrhea risk among children across international settings[4] and have been shown to be cost-effective.[9] Two systematic reviews found that point-of-use water interventions and handwashing interventions reduce childhood diarrhea by between 25% and 50%.[10,11] In addition, a recent systematic review and meta-analysis by Wolf et al.,[3] based largely on studies of self-reported diarrhea, found diarrhea risk among children < 5 years was reduced by interventions which improved point-of-use water sources (RR = 0.39; 95% CI: 0.32, 0.48), sanitation facilities (RR = 0.75; 95% CI: 0.63, 0.88), and hygiene facilities (RR = 0.70; 95% CI: 0.64, 0.77). However, contrary to findings from WASH studies using subjective measures of childhood diarrhea, two recent WASH trials (WASH Benefits and the Sanitation, Hygiene, Infant Nutrition Efficacy trial)[12–14] found no impact of WASH interventions on objectively measured diarrhea outcomes. These authors suggest that for WASH interventions to be effective, there is a need for consistent public health interventions to support long-term behavior change[14] because implementation of WASH services often struggle to achieve high coverage, compliance, and continuous use over time.[15]

Globally, an estimated 2.1 billion people still lack access to safe water sources and 4.2 billion lack access to basic sanitation facilities.[16] Furthermore, disparities persist in access to WASH services, particularly in rural (versus urban) settings and by household wealth.[16] For example, worldwide, only one of three people with access to safe water sources and two of five people with access to safely managed sanitation services live in rural areas.[17] In addition, basic WASH coverage is twice as high among those in the highest wealth quintile compared with those in the lowest.[16] Given these disparities, the benefits of evidence-based WASH service implementation may differ by population characteristics (e.g., socioeconomic status [SES]) and contextual factors (e.g., urbanicity). Thus, when identifying targets for implementation of WASH services, it is important to consider variability in these estimates to select the most effective targets. To support the scale-up of WASH services, it is essential to better understand how improving access to basic WASH may improve health outcomes across the population, including in lower SES households and those living in rural areas.

Peru is a country with high diarrheal disease burden among children younger than 5 years.[18] In addition, Peru has high national coverage of safe drinking water (e.g., water piped into dwelling or within building) and basic sanitation facilities (e.g., access to toilets inside or outside dwelling), estimated to be 87% and 73%, respectively.[19] However, these national estimates mask variations in coverage among subgroups, particularly lower SES and rural populations, making it an ideal

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context to study this topic. For example, in Peru, the majority of the 3.8 million people who lack access to safe water sources and 9.7 million who lack access to basic sanitation live in rural areas.[20] Previous studies in Peru have found that lower maternal education was also associated with disparities in WASH access and childhood health.[21,22] Although Peru has improved access to basic WASH[5,16,19] and achieved the fourth Millennium Development Goal (MDG) of reducing mortality among children younger than five by two-thirds,[16,23] there continue to be disparities among high-risk populations (i.e., lower SES households and those in rural areas). Furthermore, over the last 50 years, rapid urbanization and environmental change have led to concerns over water scarcity,[24] which may increase disparities in WASH access. Targeted WASH service implementation may decrease these inequalities in WASH access and improve childhood health in Peru.

To support WASH service scale-up and identify high-impact service implementation targets, it is necessary to first understand both their efficacy and their potential impact on childhood health. Although traditional analytic methods, such as the estimation of population-attributable risk[25] or health impact assessments (HIA),[26,27] allow for the quantification of hypothetical change in disease with (full or partial) removal of an exposure (e.g., access to unimproved water sources, sanitation facilities, and hygiene facilities), they do not consider existing dose–response relationships, population composition (age structure, education level, etc.), and confounding structures. Indeed, in HIA or when using population-attributable risks, it is assumed that the population composition where the estimates are drawn is the same as the target population. Yet, given the potential effect modification for the relationship of interest (i.e., effect of WASH on diarrhea) from these population composition characteristics,[28] it is important to use local empirical data that are representative of the target population. In the same vein, the confounding structure may vary between two populations, which motivates the use of empirical adjusted relationships that are relevant for the target population.

A recent method, the substitution estimator method described by Ahern et al.,[29] allows for the assessment of potential plausible shifts (e.g., 20% reduction) in exposure, which can provide a better understanding of the potential impact of different intervention implementation scenarios. Such an approach also allows for the consideration of both contextual and compositional characteristics of clusters to which we aim to model the potential benefits. This method can also be extended to include heterogeneity in the potential benefits of shifting WASH exposures across different population subgroups (e.g., those with lower SES or living in rural areas) or geographic regions.

In addition, previous studies simulating intervention benefits[29–31] have typically assumed that the intervention of interest is 100% effective at decreasing disease incidence. To account for a more realistic effectiveness of WASH interventions at reducing diarrhea among children, we modified the substitution estimator methods to account for differential effectiveness scenarios based on published estimates.[3] In doing so, we aimed to use Peru as a case study to estimate the absolute effect of scaling up access to improved WASH services on self-reported diarrhea among children younger than 5 years. In addition, this study aimed to assess inequalities in the impact of WASH on childhood diarrhea by maternal education, place of residence (rural versus urban), and poverty status and to examine differences by district to identify locations where potential WASH interventions may have the greatest impact.

MATERIALS AND METHODS

To estimate the impact of hypothetical changes in access to improved water sources, sanitation facilities, and hygiene facilities on diarrhea among children younger than 5 years, we used data from the 2011 Demographic and Health Surveys (DHS) in Peru as a case study. The DHS are nationally representative cross-sectional surveys that are conducted annually mainly focusing on maternal and child health. Women aged 15–49 years were interviewed to assess mother and child demographics and health information, as well as household characteristics. For the current study, data from the "children" questionnaire included maternal age, maternal education, child gender, and whether the child had diarrhea in the 2 weeks before the survey. Data from the "household" questionnaire corresponding to each record from the "children" questionnaire included source of drinking water, type of sanitation facility, type of hygiene facility, variables identifying the district and household, and variables for household assets. Data from both the "children" and "household" datasets were merged to allow for measurement of child-level, mother-level, and household-level variables.

Measures. For all children < 5 years, diarrhea prevalence was assessed by asking mothers whether a child had an episode of diarrhea in the 2 weeks before the interview, resulting in a dichotomous measure ("yes" or "no") of self-reported diarrhea. We defined water and sanitation as "improved" or "unimproved" based on the 2011 WHO guidelines.[32,33] "Improved" water sources included sources that were piped into the dwelling or piped outside the dwelling but within building, whereas "unimproved" water sources included public tap or standpipe, a well inside the building, a public well, a natural water source (e.g., spring, river, dam, lake, stream, canal, or irrigation channel), rainwater, a tanker truck, bottled water, and other sources. Sanitation facilities were defined as "improved," based on the 2011 WHO guidelines,[32,33] if they had a toilet inside the dwelling, a toilet outside the dwelling, or a ventilated latrine, whereas "unimproved" sanitation facilities included those with shared facilities, a septic well, latrines, a river or canal, or no service. To evaluate whether shared status modified the impact of sanitation facility, we also coded a version excluding shared status. Because of the lack of a WHO definition in 2011 and considering the current WHO definitions of an "improved" versus "unimproved" hygiene facility,[34] we categorized hygiene facilities based on the presence of handwashing stations; those which included both soap and water were considered "improved," whereas the absence of either was considered "unimproved."

Maternal years of education was categorized as "less than secondary education" (0–8 years) and "secondary education or higher" (≥ 9 years), and maternal age in years was categorized as "15–19," "20–29," "30–39," and "40+". Place of residence was defined as "urban" or "rural" and distract was defined based on the 24 administrative districts in Peru plus the Lima metropolitan area (Lima and Callao). Principal component analysis was used to recalculate the household wealth index, similar to the DHS index,[35] but excluding variables about water and sanitation facility. Variables included to recalculate the household wealth

index were type of floor, wall, and roof materials as well as whether households had the following assets: electricity, a radio, a television, a refrigerator, a bicycle, a motorcycle, and a car. The households were then divided into wealth quintiles based on the recalculated index. The bottom two quintiles of the recalculated household wealth index were used to define household poverty status ("poorer" or "wealthier").

Statistical analysis. We described the distribution of covariates by improved and unimproved access to a water source, sanitation facility, and hygiene facility. We constructed separate models to assess the relationship between water source, sanitation facility, hygiene facility, and self-reported diarrhea prevalence among children < 5 years. For this analysis, modified Poisson regression models[36] with log link and random intercepts, to account for clustering at the administrative district level, were used, and prevalence ratios (PR) were estimated. Models were weighted using DHS sampling weights to account for complex survey design.[37] Confounders were identified a priori using directed acyclic graphs on the relationship among water source, sanitation facility, hygiene facility, and childhood diarrhea.[38] We constructed separate models for the type of water source, sanitation facility, and hygiene facility. All models were adjusted for identified confounders (place of residence, child gender, maternal age, maternal education, and household poverty status). Unadjusted and adjusted PR and 95% CIs are reported.

Substitution estimation procedure. Based on the models described previously, we conducted an imputation-based modeling approach to estimate the population effect of increasing access to improved water source, sanitation facilities, and hygiene facilities. We applied a modified version of the method previously described by Ahern et al.[29] This method estimates the population-level effect of a hypothetical change in exposure to a public health intervention (i.e., improved access to water source, sanitation facility, or hygiene facility) on the outcome of interest (i.e., diarrhea prevalence) while conditioning on the specific set of confounders in the target population.

First, the effect estimates from the multivariable models described earlier are used to predict the outcome (i.e., diarrhea) for each individual had they experienced the exposure (i.e., an improved water source, sanitation, or hygiene facility). We extended the previous method by accounting for the effectiveness of each intervention, namely, point-of-use water treatment with safe storage, basic sanitation facility, and handwashing with soap and water.[3] Effectiveness estimates for potential sanitation and hygiene interventions were calculated using pooled estimates from a random effects meta-analysis reported by Wolf et al.[3] Water-based interventions were found to be the most effective in this systematic review, so we calculated the effectiveness of sanitation- and hygiene-based interventions relative to the water-based intervention. Specifically, using estimates from Wolf et al.,[3] we considered an effectiveness estimate of 100% for improved water source interventions, 48% for improved sanitation facility, and 44% for improved hygiene facility. (Details for calculations provided in the Supplemental Appendix.)

Second, the imputed individual outcome probabilities were averaged to estimate the population-level diarrhea prevalence had all individuals received the exposure. Third, we compared the average predicted probabilities observed empirically with that imputed, to estimate the absolute and relative changes in diarrhea prevalence associated with this hypothetical shift in exposure. We also modified the previous analyses by

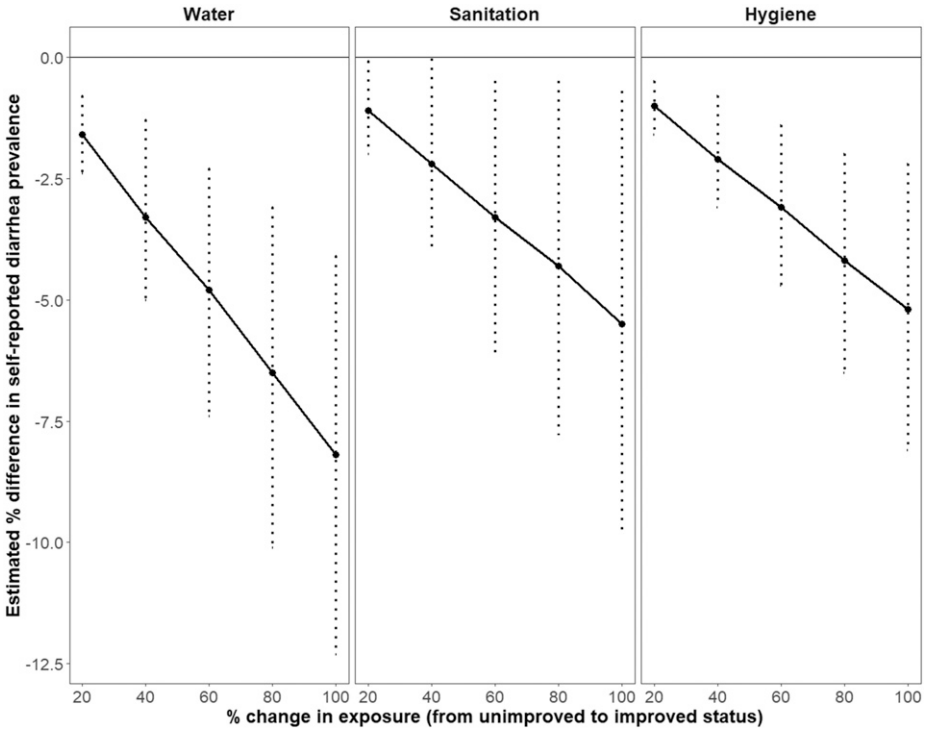

FIGURE 1. Estimated relative (%) difference in self-reported diarrhea prevalence with % change in exposure (from unimproved to improved) in water source, sanitation facility, and hygiene facility among children < 5 years, Peru Demographic and Health Survey 2011.

bootstrapping calculation of the estimate of change and 95% CIs with 500 iterations. (Equations and more detailed modeling procedures described in Supplemental Appendix.)

Given that complete elimination of unimproved sources of water, sanitation facilities, and hygiene facilities may not be a realistic goal, we assessed the impact of WASH on diarrhea, given a change in access from unimproved WASH to improved WASH by 20%, 40%, 60%, 80%, and 100%. These levels of change were chosen to represent different incremental scenarios where a varying proportion of the population would switch from unimproved sources of water, sanitation facilities, and hygiene facilities to improved ones. For example, when considering a scenario with a change of 100% for water source, it means that after the hypothetical intervention, all households would have access to an improved source of water.

Assessing inequalities in potential WASH intervention effectiveness. We also conducted analyses stratified by place of residence (rural or urban), maternal education (less than secondary or secondary and higher), poverty status (poorer or wealthier), the 24 administrative districts plus metropolitan Lima, and for sanitation by whether facility was shared or unshared. For all analyses, we applied the Bonferroni correction for multiple comparisons. Data management was conducted using SAS 9.4 (SAS Institute, Cary, NC), and all analyses were conducted in R (R Foundation for Statistical Computing, Vienna, Austria). The code to reproduce our findings is provided in Supplemental Material.

RESULTS

In our study sample (N = 7,560), diarrhea prevalence among children < 5 years was 16.7%. Of the 7,560 children < 5 years, DHS sampling weighted estimates found that 22.0% had access to an unimproved source of drinking water, 43.2% had access to an unimproved sanitation facility, and 40.6% had access to an unimproved hygiene facility (Supplemental Table 1). Those with access to unimproved sources of drinking water (N = 1,780) mostly lived in rural settings (56.6%) and had lower levels of household wealth (poorer: 57.6%), including mothers with lower maternal age (< 30 years: 56.2%) and lower levels of education (< secondary education: 50.5%). Among children with unimproved access to sanitation (N = 4,355), most lived in rural settings (62.3%) and had mothers with lower maternal age (< 30 years: 54.0%) and levels of education (< secondary education: 52.5%). Among those with unimproved hygiene facility access (N = 3,376), most lived in urban settings (53.4%) and had lower levels of household wealth (poorer: 47.2%), including mothers with lower maternal age (< 30 years: 52.3%) and lower levels of education (< secondary education: 46.0%).

After adjusting for selected confounders, our final multivariable modified Poisson regression models showed having access to an unimproved (versus improved) WASH, including source of water (PR: 1.35; 95% CI: 1.13, 1.62), sanitation facilities (PR: 1.22; 95% CI: 1.04, 1.43), or hygiene facilities (PR: 1.32; 95% CI: 1.09, 1.59), is associated with an increased risk of diarrhea among children < 5 years (Supplemental Table 2).

Using the subject-level estimates of the probability of self-reported diarrhea from these multivariable models, we generated estimates for the population-level effect of decreasing the proportion of the sample exposed to unimproved WASH. We assessed changes of 20%, 40%, 60%, 80%, and 100% in unimproved (to improved) access to water sources, sanitation facility, and hygiene facility on childhood diarrhea (Supplemental

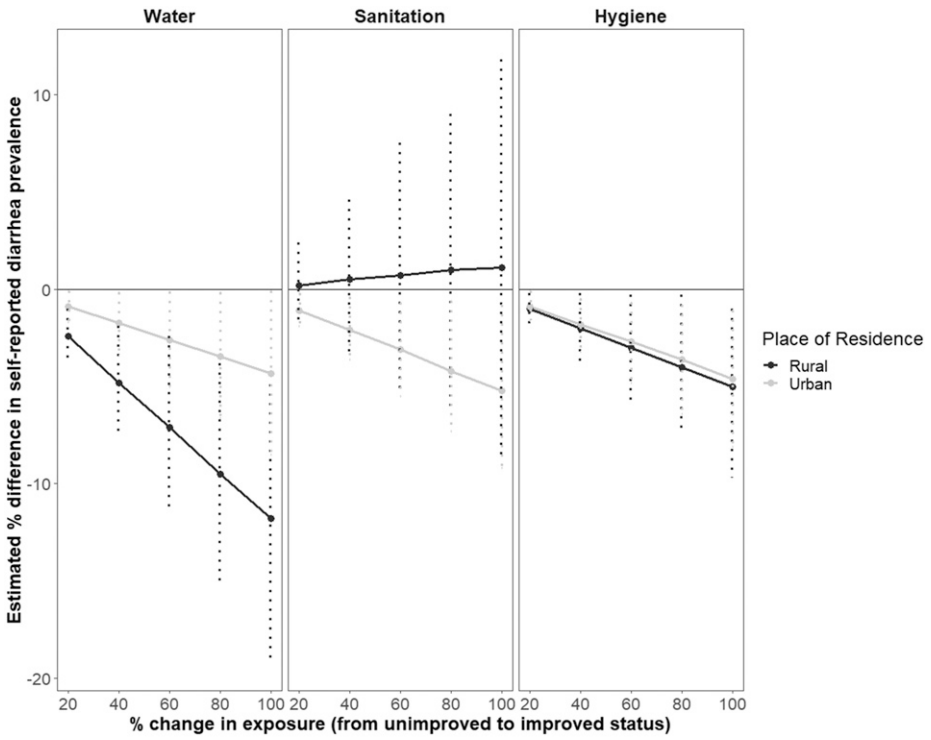

FIGURE 2. Estimated relative (%) difference in self-reported diarrhea prevalence with % change in exposure (from unimproved to improved) in water source, sanitation facility, and hygiene facility among children < 5 years stratified by place of residence, Peru Demographic and Health Survey 2011.

Table 3). We showed that with 100% change from unimproved to improved water source, sanitation facility, and hygiene facility access, prevalence of childhood diarrhea would decrease by 137.0 cases (per 10,000; 95% CI: 67.7, 209.1), 92.0 cases (per 10,000; 95% CI: 11.7, 167.0), and 87.2 cases (per 10,000; 95% CI: 39.3, 134.3), respectively. In addition, with 100% change from unimproved to improved WASH access, we estimated relative decreases (Supplemental Table 4, Figure 1) in diarrhea prevalence of 8.2% (95% CI: 4.1, 12.3), 5.5% (95% CI: 0.7, 9.8), and 5.2% (95% CI: 2.2, 8.1). Even without a 100% change in unimproved WASH, we found that 20–80% changes in access to improved WASH resulted in decreases in diarrhea prevalence.

In analyses stratified by place of residence (rural versus urban; Supplemental Table 5; Figure 2), a 100% shift in access to improved water source and hygiene facility among those in rural settings resulted in a decrease in the prevalence of childhood diarrhea by 11.8% (95% CI: 4.9, 19.1) and 5.0% (95% CI: 1, 9.7). However, we saw no change in diarrhea prevalence associated with improved sanitation facility access in rural areas. In analyses stratified by maternal education level (Supplemental Table 10, Figure 3), those with mothers who had less than secondary education showed the largest decrease in prevalence of childhood diarrhea with complete elimination of access to unimproved water sources (17.4% [95% CI: 9.7, 25.4]) and hygiene facility (9.0% [95% CI: 3.3, 14.1]). When stratified by poverty status (Supplemental Table 12, Figure 4), we again saw the largest decreases in diarrhea prevalence among those in poorer households, associated with complete removal of access to unimproved water sources (17.6% [95% CI: 10.5, 25.4]) and hygiene facility (9.3% [95% CI: 5.3, 13.9]).

DISCUSSION

In this study, we applied a substitution estimator method to simulate the potential impact of interventions to increase access to improved water sources, sanitation facilities, and hygiene facilities on childhood diarrheal disease and reduction of existing disparities. Consistent with previous research, we found access to unimproved water sources, sanitation facilities, and hygiene facilities were associated with increased risk of diarrhea among children <5 years in Peru.[1,3,4,18] Interestingly, we found that water source interventions were systematically associated with higher benefits, especially among mothers with lower levels of education, lower wealth households, and living in rural areas. This result can be explained by both the larger effect estimates for unimproved (versus improved) water sources on childhood diarrhea (see Supplemental Table 2) and estimates of effectiveness for point-of-use water source interventions based on real-world water source interventions from Wolf et al.[3] In addition, in stratified analyses, we did not find improved sanitation facilities to be associated with decreased diarrhea prevalence. These findings are consistent with previous studies which have indicated improvement of sanitation facility alone may not effectively reduce diarrhea risk.[39–41]

Using substitution estimator methods, we found that increasing access to improved water sources, sanitation facilities, and hygiene facilities may effectively reduce diarrhea morbidity among children < 5 years in Peru. Although the complete elimination of unimproved access is unlikely in the short term, a low to moderate change in access to WASH could significantly decrease diarrhea prevalence among children with important variability between population subgroups

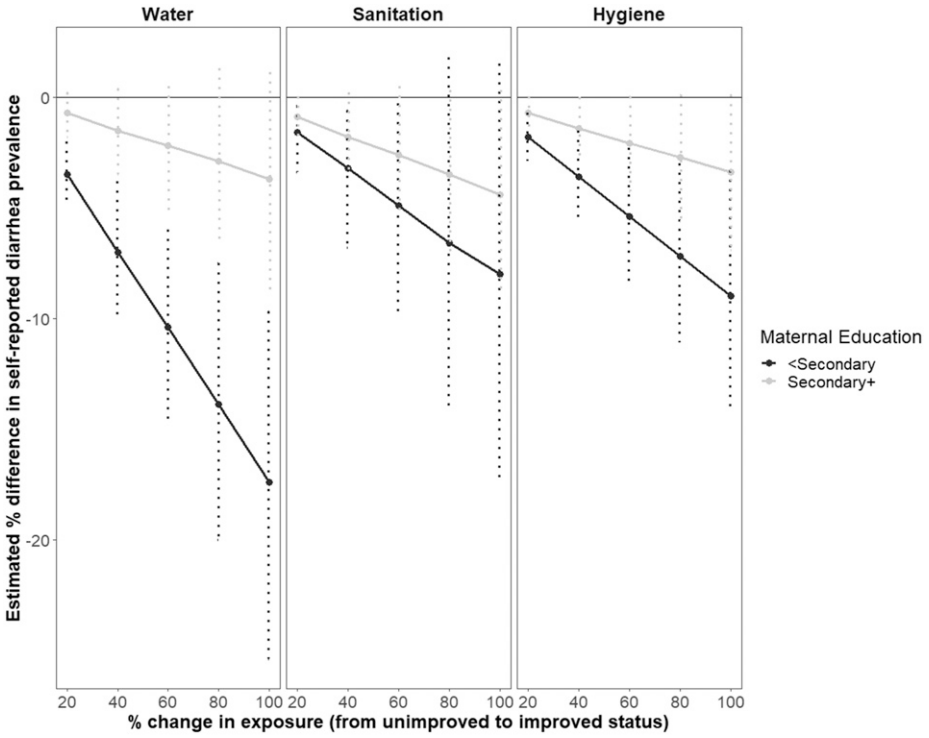

FIGURE 3. Estimated relative (%) difference in self-reported diarrhea prevalence with % change in exposure (from unimproved to improved) in water source, sanitation facility, and hygiene facility among children < 5 years stratified by maternal education, Peru Demographic and Health Survey 2011.

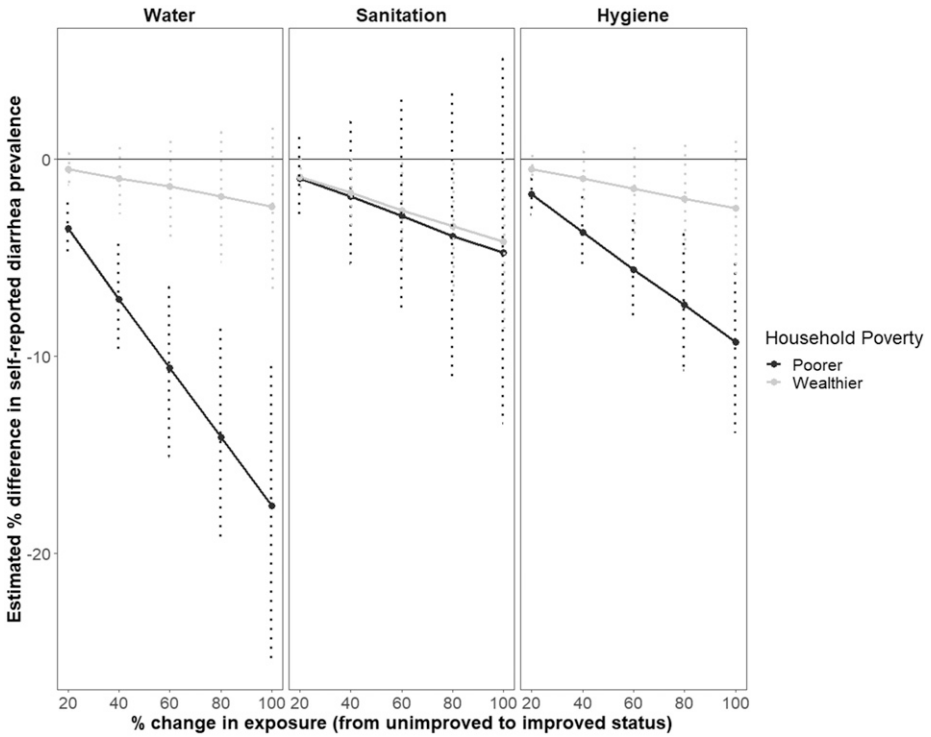

FIGURE 4. Estimated relative (%) difference in self-reported diarrhea prevalence with % change in exposure (from unimproved to improved) in water source, sanitation facility, and hygiene facility among children < 5 years stratified by poverty status, Peru Demographic and Health Survey 2011.

and areas. Similar to other studies, we found the largest potential benefit associated with scaling up improved water source and hygiene facility access.[4,10] However, our estimates of the overall impact of WASH scale-up on childhood diarrhea were more modest than those reported by Darvesh et al.[4] for point-of-use water filtration (40% decrease) and hygiene education with provision of soap (27% decrease).

Given Peru has relatively high coverage of improved WASH access,[19] the greatest benefit may come from addressing existing inequalities in access with targeted water service implementation and improved hygiene facilities in rural areas, those with lower wealth, and among mothers with lower levels of education. However, trials of the effectiveness of WASH interventions have had low levels of coverage and compliance, particularly for sanitation upgrades, point-of-use water treatment, and basic handwashing interventions, when implemented in rural areas.[3,12,13,42] In Peru, access to WASH is significantly lower in rural areas than urban areas, and the limited delivery of WASH interventions has negatively impacted childhood health.[16,17] We found that in rural areas, increased access to improved water sources and hygiene facilities reduced diarrhea prevalence among children younger than 5 years. Specifically, we found moderate reductions in diarrhea prevalence associated with even just a 20% change from unimproved to improved status for water source and hygiene facility, even without complete elimination of unimproved access. Taken together, these findings indicate that scaling up WASH services among subpopulations at high risk may effectively increase equity in access and improve childhood health in Peru.

Although Peru has achieved the fourth MDG of reducing mortality among children younger than five by two-thirds,[23] there are remaining inequalities in childhood health and mortality. Bohra et al.[22] found large maternal education–based inequalities in childhood mortality and access to water and sanitation in Peru. Our results are in accord with this and suggest that interventions which improve access to WASH among lower SES households could be effective at decreasing diarrhea incidence among children in Peru. There is also a need to address the economic and educational inequalities in Peru which influence WASH access and negatively impact childhood health.

These findings should be considered in light of their limitations. First, this study used self-reported data from the cross-sectional DHS study; thus, our findings may be subject to recall and reporting bias.[43] Second, our exposure definitions were based on household access to water sources, sanitation facilities, and hygiene facilities, and there is potential for exposure to other sources of unimproved WASH that we were unable to account for, which may have resulted in the misclassification of the exposure. We also had to consider the relationship between WASH variables and diarrhea to be linear, so the estimates we obtained can correspond to documented estimates from hypothetical interventions. Yet, it is possible that nonlinear relationships between sanitation access and self-reported diarrhea exist. In future intervention studies, it would be interesting to report potential nonlinear dose–response relationships in the effectiveness of WASH interventions. Furthermore, we considered interventions on water, sanitation, and hygiene as independent interventions, given that data on their potential joint benefits were not documented. Whereas it is reasonable to assume that the benefits of joint interventions may be more effective than isolated interventions, recent studies have not consistently found this to be true.[12–14] Therefore, our estimates can be considered as conservative because they do not allow

for any extrapolation regarding the impacts of potential joint interventions. In addition, the estimates of WASH effectiveness from Wolf et al.[3] were chosen as the best available pooled estimates to examine the impact of WASH interventions in a new setting; thus, our findings are dependent on these assumed levels of intervention effectiveness. We were also unable to distinguish the differential effectiveness of various water interventions (e.g., household water treatment and safe storage), and our estimates should be interpreted as point-of-use filter interventions with safe storage as documented by Wolf et al.[3] Finally, given that estimates of intervention effectiveness from Wolf et al.[3] were largely based on self-reported diarrhea and there is some evidence they overestimate the effect of WASH on objective measures of diarrhea, the potential impact of WASH may be overestimated in some settings. We encourage future research to validate these findings in settings where pre- and post-data are available for WASH and childhood diarrhea. Nevertheless, this study was the first to apply a modified version of the substitution estimator approach while accounting for previous estimates of WASH intervention effectiveness. This study can also serve as a guide for future research evaluating the impact of potential public health intervention implementation on other health outcomes.

CONCLUSION

Using a modified version of the substitution estimator methods described by Ahern et al.,[29] which accounted for the effectiveness of water, sanitation, and hygiene interventions,[3] we found potential benefits in scaling up access to WASH in reducing health disparities. Our findings suggest there is a need for targeted WASH service implementation in Peru, and rural areas and lower SES households will benefit the most from these interventions, and even low levels of change in overall access may decrease the prevalence of childhood diarrhea. As such, polices which support the targeted implementation of sustained WASH services among high-risk populations should be prioritized and may significantly improve childhood health in Peru.

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REFERENCES

1. Pruss-Ustun A et al., 2014. Burden of disease from inadequate water, sanitation and hygiene in low- and middle-income settings: a retrospective analysis of data from 145 countries. *Trop Med Int Health 19:* 894–905.
2. GBD 2016 Diarrhoeal Disease Collaborators, 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. *Lancet Infect Dis 18:* 1211–1228.
3. Wolf J et al., 2018. Impact of drinking water, sanitation and handwashing with soap on childhood diarrhoeal disease: updated meta-analysis and meta-regression. *Trop Med Int Health 23:* 508–525.
4. Darvesh N, Das JK, Vaivada T, Gaffey MF, Rasanathan K, Bhutta ZA, Social Determinants of Health Study Team, 2017. Water, sanitation and hygiene interventions for acute childhood diarrhea: a systematic review to provide estimates for the Lives Saved Tool. *BMC Public Health 17:* 776.
5. UNICEF, 2015. *Progress on Sanitation and Drinking Water: 2015 Update and MDG Assessment*. New York, NY: UNICEF.
6. Checkley W et al., 2008. Multi-country analysis of the effects of diarrhoea on childhood stunting. *Int J Epidemiol 37:* 816–830.
7. Guerrant DI, Moore SR, Lima AA, Patrick PD, Schorling JB, Guerrant RL, 1999. Association of early childhood diarrhea and cryptosporidiosis with impaired physical fitness and cognitive function four-seven years later in a poor urban community in northeast Brazil. *Am J Trop Med Hyg 61:* 707–713.
8. Niehaus MD, Moore SR, Patrick PD, Derr LL, Lorntz B, Lima AA, Guerrant RL, 2002. Early childhood diarrhea is associated with diminished cognitive function 4 to 7 years later in children in a northeast Brazilian shantytown. *Am J Trop Med Hyg 66:* 590–593.
9. Hutton G, Haller L, Bartram J, 2007. Global cost-benefit analysis of water supply and sanitation interventions. *J Water Health 5:* 481–502.
10. Clasen TF, Alexander KT, Sinclair D, Boisson S, Peletz R, Chang HH, Majorin F, Cairncross S, 2015. Interventions to improve water quality for preventing diarrhoea. *Cochrane Database Syst Rev 2015:* CD004794.
11. Ejemot-Nwadiaro RI, Ehiri JE, Arikpo D, Meremikwu MM, Critchley JA, 2015. Hand washing promotion for preventing diarrhoea. *Cochrane Database Syst Rev 2015:* CD004265.
12. Luby SP et al., 2018. Effects of water quality, sanitation, handwashing, and nutritional interventions on diarrhoea and child growth in rural Bangladesh: a cluster randomised controlled trial. *Lancet Glob Health 6:* e302–e315.
13. Null C et al., 2018. Effects of water quality, sanitation, handwashing, and nutritional interventions on diarrhoea and child growth in rural Kenya: a cluster-randomised controlled trial. *Lancet Glob Health 6:* e316–e329.
14. Pickering AJ et al., 2019. The WASH Benefits and SHINE trials: interpretation of WASH intervention effects on linear growth and diarrhoea. *Lancet Glob Health 7:* e1139–e1146.
15. Martin NA, Hulland KRS, Dreibelbis R, Sultana F, Winch PJ, 2018. Sustained adoption of water, sanitation and hygiene interventions: systematic review. *Trop Med Int Health 23:* 122–135.
16. WHO, UNICEF, 2019. *Progress on Household Drinking Water, Sanitation and Hygiene 2000–2017: Special Focus on Inequalities*. Geneva, Switzerland: World Health Organization.
17. WHO, UNICEF, 2017. *Progress on Drinking Water, Sanitation and Hygiene: 2017 Update and SDG Baselines*. Geneva, Switzerland: World Health Organization.
18. GBD 2016 Diarrhoeal Disease Collaborators, 2017. Estimates of global, regional, and national morbidity, mortality, and aetiologies of diarrhoeal diseases: a systematic analysis for the Global Burden of Disease Study 2015. *Lancet Infect Dis 17:* 909–948.
19. WHO, 2015. *UN-water Global Analyssi and Assessmention of Sanittion and Drinking-Water: Peru*. Geneva, Switzerland: World Health Organization.
20. World Bank, 2018. *Project Appraisal Document on a Proposed Loan in the Amount of $70 Million to the Republic of Peru for a Modernization of Water Supply and Sanitation Services Project*. Washington, DC: World Bank.
21. Heitzinger K, Rocha CA, Quick RE, Montano SM, Tilley DH, Jr., Mock CN, Carrasco AJ, Cabrera RM, Hawes SE, 2015. "Improved" but not necessarily safe: an assessment of fecal contamination of household drinking water in rural Peru. *Am J Trop Med Hyg 93:* 501–508.
22. Bohra T, Benmarhnia T, McKinnon B, Kaufman JS, 2017. Decomposing educational inequalities in child mortality: a temporal trend analysis of access to water and sanitation in Peru. *Am J Trop Med Hyg 96:* 57–64.

23. United Nations Organization, 2014. *The Millennium Development Goals Report 2014*. New York, NY: United Nations.
24. Ioris AAR, 2012. The geography of multiple scarcities: urban development and water problems in Lima, Peru. *Geoforum 43:* 612–622.
25. Fewtrell L; World Health Organization, 2007. *Water, Sanitation and Hygiene: Quantifying the Health Impact at National and Local Levels in Countries with Incomplete Water Supply and Sanitation Coverage*. Geneva, Switzerland: WHO.
26. Mueller N, Rojas-Rueda D, Cole-Hunter T, de Nazelle A, Dons E, Gerike R, Gotschi T, Int Panis L, Kahlmeier S, Nieuwenhuijsen M, 2015. Health impact assessment of active transportation: a systematic review. *Prev Med 76:* 103–114.
27. Lock K, 2000. Health impact assessment. *BMJ 320:* 1395–1398.
28. Rudolph KE, Schmidt NM, Glymour MM, Crowder R, Galin J, Ahern J, Osypuk TL, 2018. Composition or context: using transportability to understand drivers of site differences in a large-scale housing experiment. *Epidemiology 29:* 199–206.
29. Ahern J, Colson KE, Margerson-Zilko C, Hubbard A, Galea S, 2016. Predicting the population health impacts of community interventions: the case of alcohol outlets and binge drinking. *Am J Public Health 106:* 1938–1943.
30. Ahern J, Hubbard A, Galea S, 2009. Estimating the effects of potential public health interventions on population disease burden: a step-by-step illustration of causal inference methods. *Am J Epidemiol 169:* 1140–1147.
31. Marshall BD, Elston B, Dobrer S, Parashar S, Hogg RS, Montaner JS, Kerr T, Wood E, Milloy MJ, 2016. The population impact of eliminating homelessness on HIV viral suppression among people who use drugs. *AIDS 30:* 933–942.
32. WHO, 2011. *Guidelines for Drinking-Water Quality*, 4th edition. Geneva, Switzerland: World Health Organization. WHO Chronicle 38: 104–108.
33. WHO, 2011. *Guidelines on Sanitation and Health*. Geneva, Switzerland: World Health Organization.
34. UNICEF, WHO, 2020. *WHO UNICEF JMP Hygiene*. Available at: https://washdata.org/monitoring/hygiene. Accessed April 18, 2020.
35. USAID, 2018. *Wealth Index Construction*. Available at: https://www.dhsprogram.com/topics/wealth-index/Wealth-Index-Construction.cfm. Accessed June 1, 2019.
36. Zou G, 2004. A modified Poisson regression approach to prospective studies with binary data. *Am J Epidemiol 159:* 702–706.
37. Rutstein SO, Rojas G, 2006. *Guide to DHS Statistics*. Calverton, MD: ORC Macro.
38. Greenland S, Pearl J, Robins JM, 1999. Causal diagrams for epidemiologic research. *Epidemiology 10:* 37–48.
39. Feachem RG, Bradley DJ, Garelick H, Mara DD, 1983. *Sanitation and Disease: Health Aspects of Excreta and Wastewater Management*. Chichester, United Kingdom: John Wiley & Sons.
40. Greene LE, Freeman MC, Akoko D, Saboori S, Moe C, Rheingans R, 2012. Impact of a school-based hygiene promotion and sanitation intervention on pupil hand contamination in Western Kenya: a cluster randomized trial. *Am J Trop Med Hyg 87:* 385–393.
41. Chard AN, Levy K, Baker KK, Tsai K, Chang HH, Thongpaseuth V, Sistrunk JR, Freeman MC, 2020. Environmental and spatial determinants of enteric pathogen infection in rural Lao People's Democratic Republic: a cross-sectional study. *PLoS Negl Trop Dis 14:* e0008180.
42. Garn JV, Sclar GD, Freeman MC, Penakalapati G, Alexander KT, Brooks P, Rehfuess EA, Boisson S, Medlicott KO, Clasen TF, 2017. The impact of sanitation interventions on latrine coverage and latrine use: a systematic review and meta-analysis. *Int J Hyg Environ Health 220:* 329–340.
43. Arnold BF, Galiani S, Ram PK, Hubbard AE, Briceno B, Gertler PJ, Colford JM, Jr., 2013. Optimal recall period for caregiver-reported illness in risk factor and intervention studies: a multicountry study. *Am J Epidemiol 177:* 361–370.