

## Review Paper

# Rapid evidence assessment of the impacts of sewerage, drainage, and piped water chlorination in urban settings of low- and middle-income countries

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### ABSTRACT

The aim of this review was to rapidly synthesize the available evidence regarding the expected impacts of piped water chlorination, drainage, and sewerage on individuals living in low- and middle-income urban settings. A systematic search was conducted in bibliographic databases and library catalogs. Impact evaluations that included a comparator and one of the three interventions of interest, attempted to control for confounding and selection bias, and took place in urban settings in a low- or middle-income country were considered. Outcomes related to health, well-being, economic growth, and the bacterial content of water were considered. A total of 1,483 articles were identified, with 18 included after final screening. Most studies were case-control and took place in Brazil, the Pacific Islands, or south-western Asia. Fifteen studies considered sewerage, five considered chlorination, and two studies considered drainage with some studies considering multiple interventions. All primary outcomes were related to health. When implemented alone, the sewerage and chlorination interventions were largely successful. The evidence regarding the effects of chlorination, drainage, and sewerage interventions is limited and generally has a high risk of bias. When properly implemented, sewerage and chlorination are likely to have positive health impacts. However, when implemented poorly, all three interventions can have negative health impacts.

**Key words** | chlorination, drainage, impact, LMIC, sewerage, WaSH

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### HIGHLIGHTS

- Most studies focused on sewerage interventions.
- Chlorination and sewerage interventions were successful in reducing disease burden.
- Contamination sources included lack of improved WaSH, sources in the nearby environment, and household hygiene practices.
- Infrastructure maintenance issues affected the interventions' impacts.
- Proper household hygiene practices should be included for effective interventions.

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doi: 10.2166/washdev.2020.256

## INTRODUCTION

Access to clean water and sanitation is a human right (United Nations 2019a). However, three billion people lack access to basic sanitation (United Nations 2019a). Only 36% of the world's population has access to sewerage (WHO/UNICEF JMP 2017). Although 90% of the world's population has access to basic drinking water sources (defined as sources that are protected from outside contamination such as fecal matter where water collection takes less than 30 min round trip), water quality remains low around the world (United Nations 2019b; WHO/UNICEF JMP 2019). In addition, about two million people die from diarrheal diseases each year because of poor hygiene and sanitation (United Nations 2019a). These numbers are slightly better in urban settings, where 96% of the population have access to an improved water supply and 79% have access to improved sanitation (United Nations 2018). However, the health impacts of poor water and sanitation can be accentuated in urban settings where people are in close contact with one another (Mackinnon *et al.* 2019). Despite this, the evidence regarding the health effects of water, sanitation, and hygiene (WaSH) interventions in urban settings remains poor (Mackinnon *et al.* 2019). Of the seven studies identified by Mackinnon *et al.* (2019) that assessed the impact of urban WaSH interventions on health, only one study found a statistically significant reduction in diarrhea and dysentery; the remaining studies either did not find an effect or were focused on behavioral or microbial contamination outcomes. There is even less evidence regarding what works in decreasing the health impacts of poor-quality water and sanitation in urban settings (Mackinnon *et al.* 2019).

The challenges to providing clean and sustainable water and sanitation to a population are compounded within cities (United Nations 2018; Sosa-Rodriguez *et al.* 2019). Because of this and other factors, improvements in access to WaSH resources have been slower in urban settings than rural settings (United Nations 2018). Demographic and health trends continue to make urban settings more crowded, worsening the health impacts of poor water and sanitation in these settings (Mackinnon *et al.* 2019). In 54 of the 120 countries for which data are

available, growth in access to sewerage has not kept pace with urban growth (United Nations 2018). Due to how cities are structured, cities need a separate drainage system and sewerage system that is resilient to floods (Sosa-Rodriguez *et al.* 2019). In many urban contexts, less than 8% of the wastewater is treated (Sosa-Rodriguez *et al.* 2019). Consequently, more investment in urban WaSH is needed to support human health and well-being (United Nations 2018).

Here, we present the results from a rapid evidence assessment (REA) in which we systematically reviewed and summarized the available, impact evaluations of three major urban WaSH infrastructure interventions (piped water chlorination, drainage, and sewerage) in low- and middle-income countries (LMICs). The primary objective of this review was to identify the expected health, social, and economic effects of these three interventions in urban LMICs. An REA uses a systematic process to search and screen studies but limits the scope and search strategy of the review to ensure that it is 'rapid' (Barends *et al.* 2017). This review is an REA as we have limited the scope of the review to focus only on three interventions (piped water chlorination, drainage, and sewerage) in urban settings. We have also narrowed the search strategy to five databases and exclude sector-specific databases. We also comment on the factors affecting the impact of the intervention and additional considerations that should be incorporated into the design of these interventions. We hope this work is used by policymakers and practitioners in informing the design and implementation of their initiatives to improve access to water and sanitation.

In the subsequent sections, we review the theory of change for the three interventions included in this study. We then provide the methods used to produce this REA and summarize the results from the included studies. We leverage the literature search that was conducted for this REA in order to comment upon common challenges in the implementation, sustainability, and evaluation of WaSH infrastructure interventions. We conclude by discussing the synthesized results, limitations, and implications.

## Interventions and theoretical model

We considered three interventions which are likely to be impactful in urban settings: chlorination of the centralized water distribution system, expansion of the drainage system, and installation of the sewerage system. These interventions were chosen because the Millennium Challenge Corporation, an implementing organization, indicated a lack of sufficient, synthesized information in the available literature. The interventions are theorized to decrease population-level exposure to pathogens by improving drinking water, decreasing the amount of standing water, and decreasing exposure to fecal contamination (Figure 1). By decreasing pathogen exposure, the interventions may decrease morbidity. Such decreases in morbidity can be measured by the incidence of diarrheal disease, typhoid, and other communicable diseases caused by inadequate WaSH infrastructure. Decreased disease incidence can ultimately result in better educational outcomes, accelerated economic growth, and a variety of other societal benefits. WaSH infrastructure can also have direct effects on these downstream outcomes by improving human dignity, increasing tourism, and supporting self-efficacy. There is significant evidence supporting the links from improved drinking water, decreased standing water, and decreased fecal contamination to decreased morbidity and improvement in

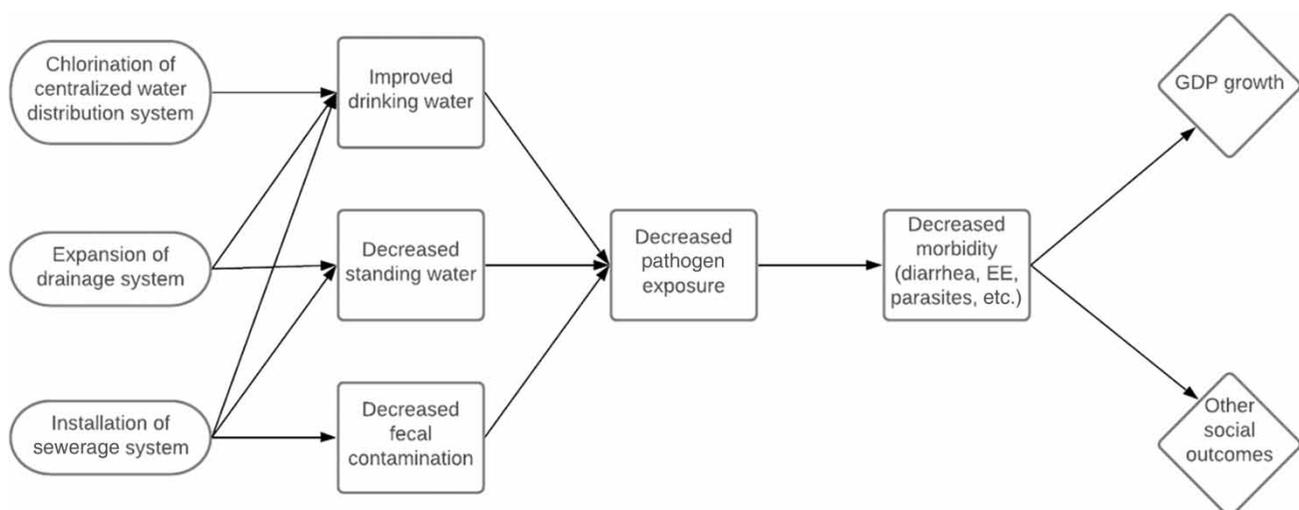
GDP growth and other social measures (Water Supply and Sanitation Collaborative Council & World Health Organization 2005). However, evidence linking the three interventions of interest to the downstream effects is lacking in the literature. Many of the steps along this causal chain are difficult to quantify. As such, only paths that have been examined through rigorous impact evaluations are considered here.

## METHODS

The protocol for the REA was finalized *a priori* to decrease risk of selection bias (Supplementary material, Appendix A). The following section outlines the search process and inclusion criteria for this review.

### Search strategy

A systematic search of academic bibliographic databases and library catalogs was completed to identify qualifying studies (Supplementary material, Appendix B). Due to the narrow scope of this REA, sector-specific databases were not included in the search. An example of search strings employed by the strategy is presented in Supplementary material, Appendix C.



**Figure 1** | Theory of change diagram co-created with Millennium Challenge Corporation for this review. The model was informed by Water Supply and Sanitation Collaborative Council & World Health Organization (2005).

## Screening

The selection of studies for data extraction as part of the review was managed using EPPI-Reviewer 4 software (EPPI) and completed by implementing the standard steps of de-duplication, title and abstract screening, and then full-text screening (Supplementary material, Appendix D). Screening was done independently by two reviewers. Disagreements were reconciled through conversation between the two reviewers.

## Inclusion/exclusion criteria

This section presents the criteria used to identify studies included in the review, drawing on the ‘Population, Intervention, Comparisons, Outcomes’ (PICO) format (Higgins *et al.* 2019).

### Population (types of study participants)

The review includes any study with participants residing in urban settings in LMICs. Countries were defined to be LMIC using the WHO definition (WHO 2016). We collected data on differential effects and experiences for sub-populations as far as it is possible and useful to do so using Cochrane PROGRESS-Plus criteria (O’Neill *et al.* 2014) (where Progress stands for place of residence, race/ethnicity, occupation, gender, religion, education, socioeconomic status, and social capital, and ‘Plus’ refers to personal characteristics associated with discrimination, features of relationships, and time-dependent relationships).

### Interventions

The interventions considered here are limited to the chlorination of drinking water in the centralized water distribution system, expansion of storm drainage systems, and installation of a sewerage system. Other WaSH infrastructure, including on-site treatment and disposal, behavior change, or household-level interventions, were not considered for inclusion. Although we recognize their importance, they fall outside the scope of this REA, which was meant to respond to the expressed needs of an implementing organization. Inclusion was based on the

intervention implemented and not whether or not it achieved safely managed water or sanitation, in accordance with JMP guidelines because this would require significantly more information regarding the relative success of implementation. We were not able to assess from the studies if these interventions actually achieved ‘safely managed’.

### Comparison group and study design

We include impact evaluations that employ an experimental or quasi-experimental design and/or analysis method, which seek to robustly measure the net change in outcomes that are attributed to an intervention or policy as compared with some appropriate counterfactual. We include randomized studies and non-randomized studies that attempted to address issues of confounding and selection bias. Feasibility studies, acceptability studies, and nonsystematic literature reviews are not accepted. Process evaluations and qualitative studies are also excluded. Systematic reviews are included so long as some of the included studies would individually qualify for this REA. However, effect sizes are presented only if the meta-effect sizes are reported in such a way that allows for the isolation of the effect of the interventions of interest.

### Outcomes

The review considers outcome(s) that assess a change in some indicator of health, well-being, economic growth, and/or the bacterial content of water (Supplementary material, Appendix E).

### Date, language, and form of publication

Only studies published in English are included. Studies are included if their publication date is between 1900 and December 2019, when the search was concluded. Only peer-reviewed publications are included.

### Data extraction

All articles included after full-text screening underwent the same data extraction process. Two reviewers read the manuscripts and recorded the information in a template similar to

Supplementary material, Table S1. The extracted information from the two reviewers was then combined by a single reviewer with verification by the second reviewer. The results tables were generated by the second reviewer from the combined, extracted data. Narrative summaries of results were written by a single reviewer and reviewed by the other. Due to the heterogeneity in the interventions, outcomes, and comparison groups, a meta-analysis was not conducted.

### Reporting bias

Although there was no formal assessment of bias, we expect that there is considerable risk of reporting bias. Organizations which conducted interventions that did not have positive impacts may choose not to publish their results. Furthermore, journals may not wish to publish articles on projects that had null impacts. In addition, because there is a strong prior hypothesis that these interventions will improve health, results that do not support this hypothesis may be dismissed as erroneous even if they are accurate. As such, results should be interpreted cautiously. Even interventions with several studies indicating positive effects could be subject to this bias as there could be many more unpublished interventions showing a null or even negative effect.

### Inputs regarding implementation, sustainability, and evaluation

In an effort to support the adoption of evidence-informed policy, we have provided additional inputs regarding the implementation, sustainability, and evaluation of chlorination, drainage, and sewerage interventions. These comments were developed alongside the REA. During the screening process for this REA, studies were flagged if they provided relevant information regarding the implementation, maintenance, or evaluation of the relevant interventions but otherwise did not meet the inclusion criteria for this assessment. For the most part, these studies had inappropriate comparators and/or insufficient evaluation design to meet our inclusion criteria. Actionable information for the use of practitioners in implementing, maintaining, and evaluating these interventions was

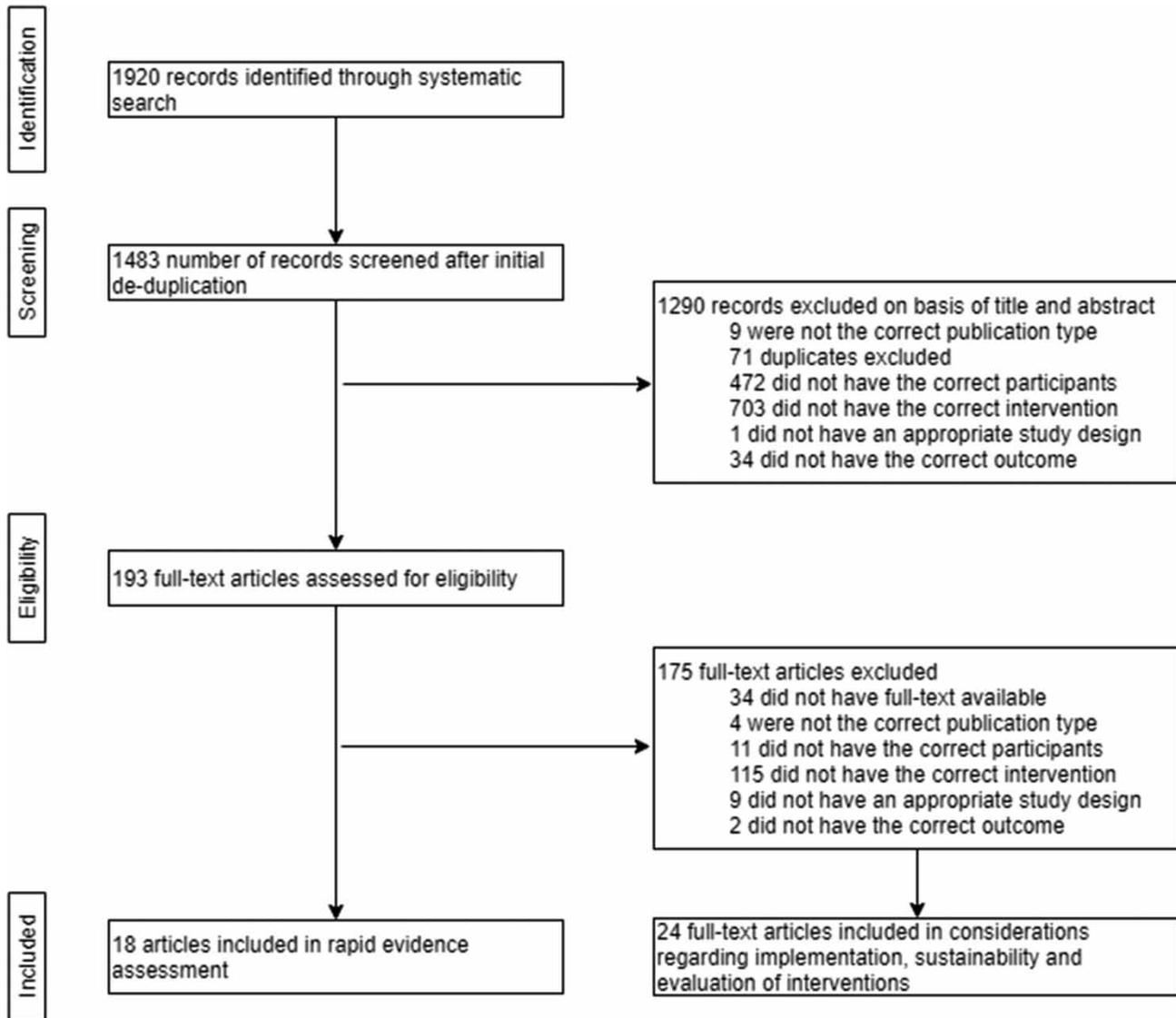
extracted from these studies and is presented after the main results.

## RESULTS

### Search results

Through the search for WaSH infrastructure interventions, we identified 1,920 papers, of which 1,483 remained after de-duplication (Figure 2). After title and abstract screening, 193 papers were included for full-text screening. Finally, 18 studies were identified for inclusion in this REA. Common reasons for exclusion were that the studies did not consider the correct participants or intervention. For example, studies were excluded because they took place in high-income countries or in rural areas. Many studies were excluded because they did not have a clear comparator or the intervention was not clearly defined. They may not have stated if the municipal water supply was chlorinated or if the sewage system connected to a wastewater treatment plant.

The oldest study was published in 1988, and the remainder were published after 2000. Five studies occurred in Brazil and one each in the Philippines, India, Indonesia, Yemen, Iran, Fiji, Peru, Turkey, Montenegro, and Ecuador (Supplementary material, Table S1). Three studies reviewed evidence from multiple countries. Most studies were either case-control (8) or open-cohort (4). Three systematic reviews were included, and the remaining studies were closed cohort (1), cross-sectional (1), or a combined cross-sectional design with a closed cohort (1). Eight studies focused on the installation of a sewerage system alone. Five studies considered sewerage and drainage. Two studies were on chlorination and sewerage. Three studies reported on the effects of chlorinating a central water distribution system. No studies reported on the effects of a drainage system alone. Most studies considered nonspecific indicators of disease, including diarrhea (8), gastroenteritis (2), waterborne illness (1), disease burden (1), and parasites (1) (Supplementary material, Table S2). However, typhoid (2), malaria (1), dengue (1), and visceral leishmaniasis (1) were also considered. Most studies used multivariable regression analyses to assess impact, including logistic regression (9), mixed-effects Poisson regression (1), non-linear probit (1),



**Figure 2** | PRISMA flow diagram of the systematic review process.

propensity score matching (1), and inverse variance method (1) (Supplementary material, Table S3). Two studies used univariate logistic regression and two other studies used chi-square analyses.

## Effects of WASH infrastructure interventions on health

### Results from impact evaluations

*Chlorination has mixed effects on communicable disease outcomes.* One of the three studies that looked at the

impact of chlorinating the municipal water on health found that chlorination reduces the likelihood of contracting a communicable disease (Supplementary material, Table S3). *Sezen et al. (2015)* found that people who drank contaminated water from antique fountains, sometimes hundreds of years old, with unknown underground sources, in Turkey had 20 times (95% CI: 4.6–84) the odds of developing gastroenteritis relative to those who drank from the chlorinated municipal water or from bottled water. However, *Werber et al. (2009)* found that people who drank only chlorinated municipal water had increased odds of

developing acute gastroenteritis relative to those who drank from other sources (OR: 11.2, 95% CI: 1.6,  $\infty$ ). Baltazar *et al.* (1988) found that odds of having clinical diarrhea was not significantly different between children who received both municipal water chlorination and latrine interventions and children who received no intervention or only one of the interventions (OR: 0.79; 95% CI: 0.56–1.13).

*Sewerage reduces disease.* Generally, sewerage reduced disease in the identified studies. In Brazil, Barreto *et al.* (2007) found that the prevalence of diarrhea decreased by 19% after the installation of a sewerage system (Prevalence Ratio: 0.81; 95% CI: 0.78–0.86). In Iran, after the sewerage system was installed, 9% of the reduction in diarrhea in the intervention group was due to the intervention (Kolahi *et al.* 2009). Costa *et al.* (2005) found that people living in households with an inadequate sewage system had increased odds of developing visceral leishmaniasis relative to those that had an adequate system (OR: 4.18; 95% CI: 1.47–11.80). Prasad *et al.* (2018) found that access to a sewerage system decreased odds of developing typhoid fever (OR: 4.30, 95% CI: 1.14–16.21). However, in Ecuador, the inclusion of an indicator for access to a sewerage system did not improve model fit (Stewart-Ibarra *et al.* 2014). This indicates that the sewerage system likely had no impact. In Brazil, the prevalence of sewerage increased from 1.9% in 1996 to 62.2% in 2010 (De Oliveira Serra *et al.* 2015). In both years, the unadjusted odds of having a parasitic infection for households without access to the public sewer system was not statistically different from those in households that were connected (1996 OR: 0.86, 95% CI: 0.10–7.58; 2010 OR: 1.42, 95% CI: 0.87–2.31).

*Combining sewerage with chlorination or drainage interventions does not increase effectiveness.* Combined sewerage and chlorination interventions did not consistently reduce disease burden. In Yemen, Klases *et al.* (2012) found that having chlorinated piped water increased disease burden in both the mountain and coastal regions (mountain  $\beta = 0.0399$ ,  $t$ -value = 1.98,  $p < 0.05$ ; coastal  $\beta = 0.0455$ ,  $t$ -value = 2.76,  $p < 0.01$ ). However, the improved sanitation system increased disease burden in the mountain regions but there was a non-statistically significant decrease in coastal

areas (mountain  $\beta = 0.0187$ ,  $t$ -value = 1.79,  $p < 0.1$ ; coastal  $\beta = -0.0373$ ,  $t$ -value = 0.99,  $p > 0.1$ ). Gasem *et al.* (2001) found that households that did receive the chlorination and sewerage interventions had increased odds of typhoid fever compared with the control households (chlorination OR: 7.19, 95% CI: 1.33–38.82; sewerage OR: 29.18, 95% CI: 2.12–400.8).

Similarly, sewerage and drainage interventions did not have consistent effects on disease burden. Butala *et al.* (2010) found that health insurance claims for waterborne illnesses decreased in slums that received the slum upgrading intervention relative to those that did not ( $\beta = -0.62$ , SE = 0.303). In Brazil, children who lived in households that only received the drainage intervention had 2.97 times (95% CI: 2.0–4.41) the odds of developing diarrhea relative to children in households that received both the sewerage and drainage intervention (Moraes *et al.* 2003). However, Ferrer *et al.* (2008) did not find a statistically significant difference in odds of developing diarrhea between households who used other sewage disposal methods and households that had a sewerage system, drainage system, or a septic tank plus soakaway (OR: 0.74, 95% CI: 0.57–1.02). In Peru, Rosas-Aguirre *et al.* (2015) found that households who lived less than or equal to 200 m away from the water drain had increased odds of having malaria than those who lived further from the drain (OR: 2.3, 95% CI: 1.3–4.0).

## Results from systematic reviews

All three systematic reviews identified considered the impact of sewerage on health outcomes. However, Clasen *et al.* (2010) and Turley *et al.* (2013) did not disentangle the effects of interventions that fell within the scope of this review from other interventions. Turley *et al.* (2013) considered the effects of drainage as well. All three studies found that sewerage interventions could be successful.

Norman *et al.* (2010) report that the relative risk of diarrhea and related illnesses decreases (RR = 0.7, 95% CI: 0.62–0.79) after sewerage interventions, with a larger effect among areas with poor sanitation at baseline. Clasen *et al.* (2010) only identified one study related to the installation of toilets connected to a sewerage system and piped water.

This study found that the risk of diarrhea among intervention households was 0.30 relative to controls. [Turley \*et al.\* \(2013\)](#) considered a suite of interventions referred to as 'slum upgrading'. These included interventions related to sewerage and drainage. They conclude that water-related interventions are successful in reducing diarrheal disease incidence.

### Heterogeneity in effects

Reports of effects by subgroup were generally limited. [Klasen \*et al.\* \(2012\)](#) found some differences in the effects of chlorination and sewerage in mountainous versus coastal regions and adults versus children. However, these differences were inconsistent, with various effects on missed school/work days, disease incidence, diarrheal incidence, and disease severity. [Ferrer \*et al.\* \(2008\)](#) report that access to sewerage decreased the incidence of diarrhea most in children 3–8 years of age, but effect sizes are not presented. [Barreto \*et al.\* \(2007\)](#) found that the installation of sewerage had the largest effect in decreasing incidence of diarrhea in neighborhoods with high baseline risk. The two systematic reviews which included multiple studies that are eligible for this REA found significant heterogeneity in effects as well ([Norman \*et al.\* 2010](#); [Turley \*et al.\* 2013](#)). [Norman \*et al.\* \(2010\)](#) assessed heterogeneity using a parametric bootstrap version of the DerSimonian and Laird *Q* test and found that the proportion of total variance due to between-study variance across all of their included studies was 0.87. [Turley \*et al.\* \(2013\)](#) did not quantify the heterogeneity across included effect sizes.

### Hypothesized sources of contamination

Since these studies considered the spread of disease, many identified various sources of contamination. The failure to address these other sources of contamination could be the reason why many of these studies found null results. Hypothesized sources of contamination fell into four broad categories: general lack of improved water and sanitation, sources in the nearby environment, household hygiene practices, and issues with maintaining infrastructure systems.

### Improved water and sanitation

Five studies highlighted lack of improved water and sanitation as sources of contamination. Having an inadequate sewage system may attract flies and therefore increase the risk for communicable disease ([Costa \*et al.\* 2005](#)). After there were improvements in human excreta disposal systems, contamination from parasites or other pathogens may be reduced ([Baltazar \*et al.\* 1988](#); [Butala \*et al.\* 2010](#); [Clasen \*et al.\* 2010](#); [De Oliveira Serra \*et al.\* 2015](#)).

### Nearby environment and household hygiene

Contaminants in the nearby environment also affected disease burden. Living near open sewers or garbage pits as well as the household's proximity to open drains increased risk for contracting typhoid, diarrhea, or malaria ([Gasem \*et al.\* 2001](#); [Ferrer \*et al.\* 2008](#); [Rosas-Aguirre \*et al.\* 2015](#)). This could be due to proximity to standing water or that low-income households tend to live closer to these exposures. Household hygiene practices such as unsafe storage of water, eating unwashed produce, or lack of handwashing behaviors also increased risk for bacterial contamination ([Klasen \*et al.\* 2012](#); [Stewart-Ibarra \*et al.\* 2014](#); [Prasad \*et al.\* 2018](#)).

### Maintenance and sustainability

Issues with the maintenance and sustainability of the infrastructure systems may have led to contamination. Multiple studies found that leaky pipes increased exposure to pathogens and contaminated water supply ([Klasen \*et al.\* 2012](#); [Sezen \*et al.\* 2015](#); [Prasad \*et al.\* 2018](#)). In sewerage systems, corrosion of the sewer pipes can cause leakage into nearby crops which then contaminated food ([Prasad \*et al.\* 2018](#)). Structural issues with infrastructure systems such as electrical pump failures and an intermittent water supply create a drop in the water pressure that then allows for contaminated water to be pulled into the water distribution system ([Moraes \*et al.\* 2003](#); [Werber \*et al.\* 2009](#); [Klasen \*et al.\* 2012](#)). [Werber \*et al.\* \(2009\)](#) found that the lack of a holding tank to store water prevented the chlorination from working as the chlorine did not have enough contact time with the water for it to actually disinfect.

## Study quality and risk of bias

Although a formal risk of bias assessment was not conducted, many of these studies have a high risk of bias and should be interpreted with caution. Half are case-control studies with significant scope for recall bias. There was a failure in the implementation of the chlorination, drainage, or sewerage system in seven of the studies, which could have significantly affected study findings. Four of the studies pool the effects of the interventions of interest with effects from other interventions. Variation in the comparators of many of the remaining studies makes the comparison of effects across studies challenging and largely inappropriate. Seven of the studies fail to adequately control for confounding, while five studies report unclear or inappropriate statistical approaches. These findings are consistent with what Turley *et al.* (2013) found as they also found a high risk of bias in the literature.

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## IMPLEMENTATION, SUSTAINABILITY, AND EVALUATION OF WASH INFRASTRUCTURE INTERVENTIONS IN URBAN SETTINGS

### Considerations for implementation and sustainability

WaSH infrastructure projects, including piped water and chlorination, have a tendency to degrade with age, causing increased risk of communicable disease (Mermin *et al.* 1999). Large, WaSH infrastructure projects tend to encounter the same set of challenges: an intermittent water supply, leaking pipes, improper spacing between sewer lines and water pipes, and low water pressure. These issues affect the effectiveness of WaSH projects in achieving their desired health and well-being impacts. An intermittent water supply may be caused by leaking pipes and associated with increased *E. coli* in the water (Grimmeisen *et al.* 2016). Furthermore, an intermittent or irregular water supply is associated with acute diarrhea among under-five children (Ferrer *et al.* 2008; Adane *et al.* 2017). The incidence of cholera increased by 155% in the 12 days after a day when the neighborhood tap water was cut in Uvira in the Democratic Republic of Congo (Jeandron *et al.* 2015). In Zimbabwe, there was a typhoid outbreak when access to the chlorinated

municipal water was removed because of non-payments or clogged pipes (Muti *et al.* 2014). If the water supply is unreliable, households are more likely to store water, people may revert to less safe water sources, or hygiene behaviors may be reduced to conserve water (Muti *et al.* 2014; Jeandron *et al.* 2015; Adane *et al.* 2017; Lee *et al.* 2020). All of these behaviors may increase people's exposures to pathogens. Moving from an intermittent to a continuous water supply can have beneficial effects on costs and timesaving, but these effects may disproportionately favor the wealthy (Burt *et al.* 2018).

Leaky pipes in either the water distribution system or sewer lines increase exposure to pathogens. Leaking pipes may diminish the relative benefits of chlorination (Ries *et al.* 1992; Bhunia *et al.* 2009b; Saha *et al.* 2009; Klasen *et al.* 2012; Sezen *et al.* 2015). Leaks in water pipes that are in close proximity to sewage pipes allow suction of sewage water into the pipe during negative pressure moments (Bhunja *et al.* 2009b). When water must travel long distances through pipes in need of repair with low water pressure, it may be more likely to become contaminated (Mermin *et al.* 1999). Low water pressure and inadequate chlorination may contribute to contamination of water with fecal coliforms, especially as the water main system ages (Brainard *et al.* 2018). Fixing leaking pipes may improve water pressure, decrease backflow and contamination, and improve chlorine concentrations (Mermin *et al.* 1999). Improperly repaired pipes also allow for bacterial contamination and affect chlorine concentrations (Topal *et al.* 2019). Due to cracks in the sewage pipelines, lack of pressure in the distribution system, and improper distances between the sewage system and the water system pipelines, sewage may enter the municipal water supply (Cárdenas *et al.* 1993; Saha *et al.* 2009). Corroded sewer pipes can also leak into nearby crops which can contaminate food sources (Prasad *et al.* 2018).

Besides pipe maintenance, the entire infrastructure system needs to be properly constructed and maintained. In Hyderabad, Pakistan, the sewage sludge treatment plants were not properly maintained and sewage was allowed to discharge directly into the river, contaminating household water sources (Yousafzai *et al.* 2019). Electrical pump failures in water distribution can lead to water contamination as water pressure drops (Moraes *et al.* 2003;

Werber *et al.* 2009; Klasen *et al.* 2012). In addition, chlorination is only effective if the chlorine has enough time in the water system for it to disinfect. If the water distribution system does not have a holding tank, the water will not be adequately chlorinated for it to actually reduce pathogen exposure (Ries *et al.* 1992; Werber *et al.* 2009). For chlorination to be effective, the residual chlorine level needs to be greater than 0.3 mg/L. Lu & Zhang (2005) found that when residual chlorine in water samples increased from <0.1 to 0.3 mg/L, bacteria cell counts decreased from 10,000 to 1,000 CFU/mL. Lu *et al.* (2014) found that residual chlorine levels between 0.5 and 1.5 mg/L were able to suppress bacterial growth even when there was sufficient organic substrate.

To ensure the success and sustainability of projects that implement these interventions, these challenges should be addressed during the design phase of the project.

### Considerations for the design of an impact evaluation

The design of a rigorous evaluation of the causal impacts of large-scale infrastructure projects is challenging due to logistical, political, and ethical concerns. It is rarely possible to randomize such projects. Therefore, the analytical approach taken in order to accurately estimate the impact of large-scale infrastructure projects on the health and well-being of their beneficiaries should be established during the study design phase. It is recommended that a pre-analysis plan is written before the beginning of data collection. Such a plan can be registered at Registry for International Development Impact Evaluations (RIDIE) or one of the journals supported by the *Center for Open Science*. The benefit of such an approach is that it ensures that the necessary data are collected to allow for a successful evaluation after the study is completed.

Given the complexities of the evaluation of large-scale infrastructure projects, four analytical approaches are recommended for impact evaluation: propensity score matching, difference-in-difference analysis, synthetic control analysis, and interrupted time series. The choice of methods should be informed by the expected trends in outcomes over time and the availability of adequate controls. Secular trends have been shown in the prevalence of diarrhea (Lee *et al.* 2020). Therefore, if possible, it is beneficial to collect baseline data at several time points before project implementation in

order to establish secular trends. Furthermore, due to the spatial clustering of risk factors for many WaSH-related communicable diseases, it is important to carefully consider suitable control groups (Bi *et al.* 2016). Such groups can be identified through spatial mapping, comparisons of trends over time, and/or matching on known risk factors.

The primary outcome of interest must be designated before the beginning of data collection. Expected effect sizes can then be used to inform power calculations. Based on disease prevalence and expected impacts of sanitation interventions, intestinal diseases (such as cholera, gastroenteritis, and typhoid) are likely to have the largest decreases in response to the proposed interventions. However, which diseases will be impacted is affected by local context. There is an association between the installation of a sewer system and the rate of diarrhea in children under five (Barreto *et al.* 2007). Having a nearby open sewage ditch is associated with increased odds of diarrhea and ascariasis as well (Moubarrad & Assobhei 2005; Ferrer *et al.* 2008). Living in a house with open sewers is also associated with increased odds of typhoid fever compared with living in a house with a closed drainage/sewage system (Gasem *et al.* 2001). Individuals in households who use a chlorinated, municipal water source may have lower odds of developing typhoid than those who use alternate water sources (Gasem *et al.* 2001). Typhoid is also related to the use of public water sources, drinking piped water, and low elevation which may reflect poor drainage (Bhunja *et al.* 2009a; Baker *et al.* 2011; Jenkins *et al.* 2019). Muti *et al.* (2014) found that the number of typhoid fever cases dropped after the municipal water supply was chlorinated. Cholera has also been found to be associated with poor drainage systems and sewage overflow (Rebaudet *et al.* 2013a). Although broader impacts including increased economic output and improved measures of well-being are expected, it may take several years for these to develop. As such, these are likely to be inappropriate primary outcomes for any study under 5 years.

There is likely to be an additive effect in which access to sewage and chlorinated water may improve health outcomes more than access to each one individually (Baltazar *et al.* 1988). If there is a desire to quantify the impacts of each intervention separately and additively, a multi-arm trial design is necessary. Failure to implement such a design results in an inability to separate the effects of

many different interventions which were implemented simultaneously, and may result in future projects replicating ineffective portions of the larger project (Butala *et al.* 2010).

Given the seasonality of rainfall in most regions of the world, there is often also a seasonal variation in the incidence of cholera and likely other waterborne diseases (Rebaudet *et al.* 2013b). As such, it is recommended that studies include matched data collection periods during different seasons over at least a 2-year span. Other climate variations such as unusually heavy flooding may also affect results, but will be harder to account for (Rebaudet *et al.* 2013b).

The microbial content of the same piped water system varies by location: residential, industrial, sewage hub, and more (Bohra *et al.* 2012). Therefore, if water quality is of interest, it may be appropriate to collect water samples at several different types of locations.

There is also a need to collect information on the reliability of water and household coping strategies for intermittent water as these may affect the interventions' impact (Lee *et al.* 2020). If the piped water source is not reliable, households are more likely to rely on stored water and rely on multiple water sources. Household hygienic

practices should also be collected. Household hygiene practices such as unsafe storage of water, eating unwashed produce, or lack of handwashing behaviors also increased risk for bacterial contamination (Ries *et al.* 1992; Moubarrad & Assobhei 2005; Klasen *et al.* 2012; Muti *et al.* 2014; Stewart-Ibarra *et al.* 2014; Prasad *et al.* 2018).

Other transmission sources should also be collected so that the effects of the intervention on disease burden can be isolated. These include food from street vendors, other water sources (including bottled water and ice), and proximity to wastewater effluents (Black *et al.* 1985; Koo *et al.* 1996; Gasem *et al.* 2001; Moubarrad & Assobhei 2005; Bhunia *et al.* 2009a; Lee *et al.* 2020).

Potential confounders identified in the literature that may be on the pathway between WaSH interventions and health/well-being outcomes can be found in Table 1.

## DISCUSSION

Although there was considerable heterogeneity in results, sewerage and chlorination interventions tended to be successful in

**Table 1** | Potential confounders in the pathway between WaSH and health outcomes

Individual-level characteristics	Household-level variables	Village-level characteristics	Intervention-specific variables
Sociodemographic (age, gender, ethnicity, education, marital status, socioeconomic status, employment, and migration history)	Infrastructure (water source, house type, floor type, toilet type, independent kitchen, drainage access, refuse collection, house construction materials, and occurrence of flooding)	Prevalence of access to WaSH infrastructure	Baseline sewage access
Child-specific (low birth weight, nutritional status – LAZ and WLZ, and history of being breastfed)	Household characteristics (number of children less than 5 years, level of health services utilization, and crowding in house)	Neighborhood female education	Background incidence of disease/outcome
Hygiene behaviors (handwashing – observed and/or reported, open defecation, sharing food, ice in beverages or eating ice outside home, and health knowledge/awareness)	Hygiene behavior (food handling practices, boiling water, presence of soap, water storage practices, presence of feces, presence of animals, toilet cleanliness, presence of wash stand, food sources, and hand washing behaviors)	Geographic and climate related (clustering, elevation level, daily precipitation rates, and season)	Spatial risk factors (distance from flowing water body/road and distance from drain)
	Surrounding environment (nearby open sewage ditch/garbage dump, paved roads, streets, or sidewalks)		Residual chlorine levels

improving health, largely measured through reduced incidence of diarrhea and other intestinal diseases, when they were implemented alone. When these interventions were implemented together, we found mixed effects of the combined interventions on disease burden, most likely due to issues with intervention implementation and maintenance. Improper implementation and maintenance can result in humans still coming into contact with human waste, reducing or eliminating the potential benefits of sanitation interventions. The effects of drainage are also ambiguous, raising the possibility that living near a drain could increase disease, possibly due to exposure to standing water. The most commonly cited sources of illness among included studies were a lack of improved water and sanitation, the nearby environment, household hygiene practices, and issues with maintaining infrastructure systems. Chlorination, drainage, and sewerage will address three of these sources, but households must be supported to engage in proper hygiene practices if these interventions are to have their full effect.

### Limitations in available studies

Although 18 studies represent an adequate research base, these studies are not evenly distributed across the three interventions of interest. While there are many interventions which consider sewerage, far fewer consider the effects of chlorination and none identify the effects of drainage alone. The determination of the unique effects of the individual interventions is challenging because interventions were often implemented alongside one another. In addition, authors often pool the effects of our interventions of interest with those of other WaSH interventions (Baltazar *et al.* 1988; Ferrer *et al.* 2008; Butala *et al.* 2010). For example, Ferrer *et al.* (2008) calculate the odds of diarrhea among those with a sewerage network, drainage system, and septic tank plus soakaway relative to those with any other human waste disposal system. Therefore, it is not possible to identify which of the three listed disposal systems is driving the effect estimate or what the effect of sewerage alone is. In other studies, subgroup analyses are mentioned, but not reported in full, making it unclear what effect the intervention actually had (Ferrer *et al.* 2008).

Additionally, many studies use data-driven model selection approaches which tend to result in the reporting of

statistically significant results and null results not being reported. Some considered the intervention in their multi-variable models but did not report the adjusted estimates, most likely because the effects of the interventions were not statistically significant in the final model (Ferrer *et al.* 2008; Stewart-Ibarra *et al.* 2014; De Oliveira Serra *et al.* 2015). Stewart-Ibarra *et al.* (2014) used Akaike Information Criteria (AIC) values to determine which covariates would remain in the final model. Access to sewerage did not make it into the final model which indicates that it may have had a null effect; however, results are not presented, so this conclusion cannot be made. This pattern of using the data to determine model specification and only reporting statistically significant effects induces a form of reporting and publication bias. This may make interventions appear more effective than they are.

Finally, most studies considered the incidence of intestinal disease and did not look at the other outcomes that could be impacted by these interventions. This is likely because these interventions are expected to have the largest effect on intestinal disease outcomes. However, many other outcomes would be of interest and could be affected. In particular, these interventions may have significant effects on perceived welfare and human dignity. They could have long-term economic outcomes by affecting how people relate to each other and improve opportunities for economic growth.

### Implications

Generally, sewerage and chlorination interventions were found to have positive impacts by reducing disease burden when adequately implemented. The impacts of drainage interventions and combined interventions were mixed. Many of the interventions included in this REA were not implemented successfully, which may have contributed to the mixed results. Household hygiene practices, the surrounding neighborhood/environment, and lack of improved water and sanitation modified the impact of these interventions.

### Strengths, limitations, and future directions

The primary strength of this work is that it is a result of a rigorous and systematic search of the available peer-reviewed literature. However, due to the rapid nature of this assessment, the search was limited to only six databases. We did

not perform any searches in the grey literature or in specialist websites. There is a possibility that there may be additional evidence related to the three WaSH infrastructure interventions that was not captured in our search. However, we were still able to identify 18 unique studies through our systematic search. We found that the studies included in our REA considered the impacts on intestinal diseases. We did not find any studies looking at other health outcomes, social well-being, or economic growth nor any studies looking at the impact of drainage interventions alone on health or societal benefits. None of these studies took place in the African continent which is a limitation of the generalizability of this work to that region. Additionally, only a few of the included studies looked at heterogeneity and reported effects by subgroups. The subgroup analyses did not take into account wealth disparities or other equity measures that could impact WaSH programming. This suggests that these are areas where further research is needed. The majority of the studies included were case-control studies where the primary objective was not to evaluate an intervention but to identify potential causes of a disease outbreak. Rigorous studies that are designed *a priori* with the intent to evaluate impact are needed to understand if WaSH infrastructure interventions can improve health and social well-being.

We make no discussion of safely managed water or sanitation, as defined by the Joint Monitoring Programme, in this study. This is because we are unable to speak to whether or not the included studies achieved safely managed standards. Although many of these interventions, if implemented properly, would have qualified, we have evidence that they did not, in fact, meet these standards. As such, we limit the discussion to the interventions and not these standards. Future impact evaluations on these interventions should report on intervention fidelity as well as these intermediate outcomes so that effectiveness results can be interpreted using these indicators.

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## CONCLUSION

Generally, chlorination and sewerage were successful in reducing disease burden when they were implemented alone. Many of the authors of these papers indicated that implementation issues, such as intermittent water supply, leaky pipes,

and ineffective chlorination, affected the impact of the interventions. These challenges likely had the dual effect of decreasing the impact of interventions and making it impossible to determine what the impact of interventions would have been had they been implemented properly. For these interventions to be successful, the infrastructure must be maintained and should be sustainable. We hope that this work will highlight the importance of planning for sustainability in the implementation of infrastructure works. But sustainable infrastructure is not sufficient. Behavior change interventions are needed to ensure that the household engages in proper hygiene practices in order to gain the maximum benefit from infrastructure works. We hope that practitioners use this work when designing their own WaSH infrastructure interventions.

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## ACKNOWLEDGEMENTS

We acknowledge Nicholas Moore, Birte Snilstveit, David de Ferranti, and John Evers from the International Initiative for Impact Evaluation (3ie) for their support and guidance in the development of this REA. We thank Ritwik Sarkar, Bidisha Barooah, and Mark Engelbert from 3ie for reviewing the REA. We also acknowledge Bradley Cunningham from the Millennium Challenge Corporation for supporting this work and providing valuable insight.

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## FUNDING

This study is made possible by the generous support of the U.S. Government through the Millennium Challenge Corporation (MCC). The funder was involved in identifying the three interventions included in this study. They were not involved in any other aspect of the study or in the writing process. The contents are the responsibility of 3ie and do not necessarily reflect the views of MCC or the U.S. Government.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 10 July 2020; accepted in revised form 5 December 2020. Available online 30 December 2020