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Effectiveness of a combined sanitation and household-level piped water intervention on infrastructure coverage, availability and use, environmental fecal contamination, and child health in rural Odisha, India: a matched cohort study

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An abstract of
A dissertation submitted to the Faculty of the
James T. Laney School of Graduate Studies of Emory University
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2017

Abstract

Effectiveness of a combined sanitation and household-level piped water intervention on infrastructure coverage, availability and use, environmental fecal contamination, and child health in rural Odisha, India: a matched cohort study

By Heather E. Reese

Over half of the almost 1 billion people who practice open defecation live in India. While access to community water sources has improved in rural India, few households have on-site piped water. Although a primary motivation for water, sanitation and hygiene improvements is associated improvements in health, there is mixed evidence of effective interventions, especially in India.

We conducted a matched cohort study to evaluate a combined intervention, where household piped water connections were contingent on community-wide household toilet and bathing room construction, implemented in rural Odisha, India. Forty-five intervention villages were randomly selected from a list of those where the program was implemented, and matched to 45 control villages. We conducted surveys and observations, and collected stools and environmental samples (source water, drinking water, and rinses of children's hands) between June 2015-October 2016 in households with a child under five (N=2398). Health surveillance included diarrhea, acute respiratory infection, soil-transmitted helminthiasis, and anthropometry to assess undernutrition. Source water, drinking water, and children's hands were assayed for fecal indicator bacteria, and select waterborne pathogens.

Multilevel regression using generalized linear models was used to assess the effect of the intervention on WaSH coverage, availability and use; fecal environmental contamination; and child health. Compared to controls, intervention villages had substantially higher improved toilet coverage and use. Although the intervention was associated with higher access to piped water on the household premises, both study arms experienced intermittencies in water availability. Most source and drinking waters in both study arms were positive for *E. coli*, and there was no intervention effect on *E. coli*. in source water, drinking water, or on children's hands. However, the intervention substantially reduced the prevalence of *S. dysenteria* and *S. flexneri* in source water (aRR: 0.59, 95% CI: 0.35, 0.97). Similarly, there was no intervention effect on child diarrhea or respiratory infection. However, compared to the control, children in intervention villages had lower odds of helminthiasis (aOR: 0.44, 95% CI: 0.18, 1.00) and improved HAZ (+0.17, 95% CI: 0.03-0.31). Future research should focus on the pathways through which these mixed effects on fecal environmental contamination and health outcomes occur.

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List of Abbreviations

AAT – Alpha-1-antitrypsin
ALRI – Acute Lower Respiratory Infection
ARI – Acute Respiratory Infection
BPL – Below the Poverty Line
CE – Collective Efficacy
CFU – Colony-Forming Unit
CI – Confidence Interval
DALY – Disability-Adjusted Life-Year
DHS – Demographic and Health Surveys
EED – Environmental Enteric Dysfunction
EPA – Environmental Protection Agency
EPG – Eggs Per Gram
ETEC-LT – Enterotoxigenic *E. coli* Heat-labile Enterotoxin
FSM – Fecal Sludge Management
GPS – Geographic Positioning System
HAZ – Height-for-age Z Score
IMCI – Integrated Management of Childhood Illness
JMP – Joint Monitoring Programme
MANTRA – Movement and Action Network for Transformation of Rural Areas
MDG – Millennium Development Goals
MPO – Myeloperoxidase
NEO – Neopterin
NGO – Non-governmental Organization
OR – Odds Ratio
RR – Risk Ratio
SDG – Sustainable Development Goals
STH – Soil-transmitted Helminth
TSC – Total Sanitation Campaign
WaSH – Water, Sanitation and Hygiene
WAZ – Weight-for-age Z Score
WEAI – Women’s Empowerment in Agriculture Index
WHO – World Health Organization
WHZ – Weight-for-height Z Score

Chapter 1. Introduction

Poor sanitation and lack of access to a sufficient quantity and quality of water are pervasive problems throughout the developing world, contributing a large burden of morbidity and mortality. Unimproved sanitation and water supply are major risk factors for diarrheal diseases and acute lower respiratory infections (ALRI), the second and first leading cause of under-five child mortality worldwide, as well as soil-transmitted helminth infections (STH), and undernutrition[1–3].

Although there have been substantial gains in access to sanitation globally, these gains have barely matched population growth in India; of the 2.3 billion people worldwide without access to an improved sanitation facility in 2015, 576 million live in India[4]. In India, those who lack access to improved sanitation facilities may not use any facilities at all. Indeed, the majority of people worldwide practicing open defecation live in India, and of these, the majority live in rural areas[5].

Interventions to improve sanitation primarily focus on increasing coverage and occasionally on increasing use of latrines. Much of the motivation for increasing access to sanitation facilities in low-income settings is based on the premise that these facilities will keep human feces separate from human contact, including through contact with contaminated water. However, the association between household access to improved sanitation and a direct health impact is highly heterogeneous in low-income developing country contexts. Two recent randomized controlled trials of sanitation interventions in rural India found no effect on diarrheal diseases[6,7]. A third study, which employed a matched cohort design similar to this study, also showed no health impact from a sanitation intervention[8]. However, in all of these studies, community-level sanitation coverage was low.

Interventions to improve drinking water quality focus primarily on protection at either the water source or at the point-of-use within the household level. While source water protection can provide some reduction in health risk, there is the potential for recontamination of drinking water stored at the household level[9]. Thus, provision of high quality water within the household, through connection to a piped network system, will likely provide the greatest impact on health. Although there is evidence of heterogeneity in the effectiveness of water quality interventions, several meta-analyses have found the effectiveness of individual or combined water, sanitation and hygiene interventions decrease diarrheal disease prevalence by up to 34%[10–13]. However, there is limited evidence of the added benefit of combining water and sanitation interventions, though this may be due to poor uptake and inconsistent use[11–13].

While the government of India has implemented programs to help develop improved community level water sources and improved household sanitation facilities, India still lags behind the rest of the world for open defecation. As of 2015, 85% of the population in rural India had access to improved sources of water[4]. However, only 14% had access to piped water at the household level[5]. Only 25% of the population in rural India has access to improved sanitation, dropping to only 14% in rural Odisha state as of 2011.

And over 53% of the world’s population practicing open defecation live in India[5]. Similar to the trend with access to improved sanitation, 21% of children’s feces are disposed safely in India, compared to only 7% in Odisha. The low coverage and use of sanitation facilities and safe disposal of children’s feces, paired with relatively high access to improved water sources, places India in a unique context. It is possible that low acceptance of improved sanitation is culturally based; recent evidence shows an association between household latrines, cultural views of ritual pollution, and changing perceptions of the lowest castes in India.[14]

Over the past decades there has been global commitment to determine water and sanitation interventions with demonstrated effectiveness, not just efficacy[15]. Low compliance, both with coverage and use of sanitation facilities, was a primary concern in many previous sanitation interventions and likely contributed to low observed health impact. Gram Vikas follows a unique approach requiring compliance of the entire community; each household must construct their own toilet and bathing room prior to the completion of a piped water network for the village, with three connections to each household.

There is evidence to suggest that the Gram Vikas approach may be more effective in reducing disease than other interventions that have been evaluated to date, especially within the unique sanitation context in India. First, the intervention requires every household in the entire village to participate and construct a toilet and bathing room; many other interventions recruit individual households and achieve village sanitation coverage levels of approximately 35% to 65%, resulting in continued high levels of open defecation[6–8,16]. Second, Gram Vikas claims high levels of toilet use. Both sanitation coverage and use are necessary to reduce exposure to fecal pathogens. Finally, Gram Vikas combines the sanitation intervention with piped water supply at the household level, a measure that is both likely to increase use of pour-flush toilets, and improve the quantity and microbial quality of water used at the household level. This study will be the first to rigorously evaluate the effect of this combined household sanitation and piped water supply intervention in rural India.

With the majority of people practicing open defecation worldwide living in India, there is the impetus to focus on determining effective and sustainable interventions for this context. This study seeks to evaluate the impact of the combined improved sanitation and piped water intervention implemented under Gram Vikas.

Dissertation Aims

Aim 1. To determine the effect of the combined intervention on coverage, availability and use of improved sanitation, improved water supplies, and hygiene facilities.

Aim 2. To determine the effect of the combined intervention on environmental fecal contamination of water sources, drinking water, and children's hands.

Aim 3. To determine the effect of the combined intervention on diarrheal diseases, acute respiratory infections, soil-transmitted helminthiasis, and undernutrition.

These aims will be addressed throughout this dissertation. Chapter 2 provides background on diarrheal diseases, acute respiratory infection, soil-transmitted helminths, and undernutrition. Chapter 3 provides background on water and sanitation interventions. Chapter 4 describes the rationale and study design for the overarching study. Chapters 5 and 6 describe the methods, results and conclusions which address the aims. Chapter 7 provides a summary of the dissertation findings and overall implications, reflects on limitations of the research, and proposes future directions.

Chapter 2. Diarrheal diseases, soil-transmitted helminthiasis, acute respiratory infection, and undernutrition: burden of disease, etiology, and preventative measures

Diarrheal diseases

Worldwide, diarrheal diseases accounted for over 1.31 million deaths in 2015, including almost 500,000 deaths in children under five years[17]. In addition to the high mortality attributed to diarrheal diseases, they also contribute a large burden of morbidity, disproportionately affecting the youngest children. The majority of deaths due to diarrheal disease are in neonates and children under two years[18]. Although the child under five mortality rate due to diarrheal diseases has substantially decreased in the past decade by 33%, morbidity has been slower to decline and has improved faster in some geographic regions and populations than others[17]. Over 20% of child under five deaths due to diarrheal disease worldwide were in India. Although diarrheal disease prevalence in India has decreased over the last decade, the still relatively high prevalence and large growing population make diarrheal diseases one of the leading causes of child death. In addition, diarrheal diseases in children under five in India are estimated to contribute almost 9.5 million disability adjusted life years (DALYs)[17].

Diarrheal diseases include any symptomatic diarrheal illness caused by intestinal infection by enteric bacteria, virus, protozoa, or other parasites. Infection alters the normal digestion and absorption processes to result in increased passage of watery feces and pathogen shedding. While the main etiologies of diarrheal diseases are diverse and differ by population and context, transmission of enteric pathogens follows similar transmission pathways from person-to-person and through the environment. Each enteric pathogen differs in the ability to survive and replicate in the environment outside the human host, how easily transmissible it is, and in its infectiveness. Globally, the most common etiologies of moderate and severe diarrheal disease in children under five are infection or co-infection with rotavirus and *Shigella* spp.[17,19]. These pathogens are also the most common causes of diarrheal disease in India, causing an estimated 34-43% of diarrhea cases depending on child age[19]. While diarrhea itself contributes a large burden of morbidity through severe dehydration and damage to the intestinal wall, a single episode of diarrheal disease is generally self-limiting. However, diarrhea also increases susceptibility to other infections and conditions, with repeated bouts of diarrheal diseases resulting in long-term impacts on child health, including undernutrition[18].

Soil-transmitted helminthiasis

Soil-transmitted helminths (STHs) are gastrointestinal nematodes infecting an estimated 1.5 billion people, almost a quarter of the world’s population. However, prevalence alone does not provide an accurate estimate of the effects of helminthiasis since morbidity is correlated with the intensity of the infection, often estimated as the eggs per gram (epg) of feces. According to the 2015 Global Burden of Disease Study, over 3.3 million all age DALYs are attributable to soil-transmitted helminthiasis, with the majority due to infection with hookworms[20]. Although mortality due to helminth infection has decreased over the past decade, over 2.5 thousand deaths were attributed to helminth infection in 2015[21]. STHs are endemic throughout the developing world. In India, an estimated 220 million children under 5 are at risk for helminthiasis and require preventative chemotherapy[22]. Morbidity due to helminthiasis can include diarrhea, abdominal pain, and poor physical and neurocognitive development which can result in both protein-energy and micronutrient malnutrition, including iron and Vitamin A deficiencies[23].

The most common etiologic agents include the round worm *Ascaris lumbricoides*, the whipworm *Tricuris thichiura*, and the hookworms, *Necator americanus* and *Ancylostoma duodenale*[23]. Since STHs cannot replicate within the host, the life cycles are different than those for enteric bacteria and viruses, requiring favorable environmental conditions for infective forms to mature in the soil. Infection with *A. lumbricoides* and *T. trichiura* is very similar, and occurs through ingestion of infective embryonated ova. Ova may be on any contaminated fomite, including unwashed and unpeeled fresh produce, in drinking water, or in soil that may be directly consumed by children through geophagy. Infection with hookworms is through dermal contact with the infective filariform larval stage, usually from walking on contaminated soil. Depending on the species, adult worms can survive in the intestine for over a year[24]. And reinfection is rapid, with the prevalence of infection with *A. lumbricoides* and *T. trichiura* rising to baseline levels within 12 months after chemotherapy[25]. There is evidence that co-infection with more than one helminth species is common, especially in individuals with a high intensity infection[23].

Acute respiratory infection

Worldwide, acute lower respiratory infection (ALRI) accounted for over 2.7 million deaths in 2015, including over 700,000 deaths in children under five years[17]. Although the age-standardized mortality rate for ALRI fell by over 20 percentage points in the past decade, the total number of deaths has remained constant. ALRI is still the leading infectious cause of child under five deaths worldwide. The majority of deaths due to ALRI are in the youngest children, with over 80% of deaths occurring in neonates and children under two years[18]. The burden of morbidity and mortality due to ALRI is highest in sub-Saharan Africa and South Asia, with the largest number of child under five deaths occurring in India[17]. In India, ALRI is responsible for over 140,000 child under five deaths, disproportionately affecting girls. In addition, respiratory infection in children under five in India is estimated to contribute almost 12.1 million DALYs[26].

Lower respiratory infections may be caused by infection with one of several bacteria or viruses. Globally, the most common causes include *Streptococcus pneumoniae* and *Haemophilus influenzae*. In India, almost 60% of respiratory infections in children under five are due to pneumococcal pneumonia and 14% to infection with *Haemophilus influenzae* type b[27]. In community settings, transmission is usually through inhalation of aerosolized droplets, or through contact with contaminated hands or other fomites, or aspiration of bacteria from the upper airways[28]. The most common long-term effect of ALRI in an otherwise healthy individual is reduction in lung capacity. However, other common childhood infectious diseases such as measles increase susceptibility to lower respiratory infection.

Undernutrition

Malnutrition due to deficiencies in diet include protein-energy malnutrition, i.e. stunting, wasting, and underweight, as well as micronutrient malnutrition due to deficiencies in vitamins and minerals. In 2015, almost 200,000 child under five deaths were attributed to nutritional deficiencies[21]. Stunting, defined as low height for age, is usually the result of persistent or recurrent undernutrition in the early stages of child development. Evidence suggests that the first 1000 days, from conception to two years old, is the critical window to ensure adequate growth and development[29,30]. However, there is evidence that children from low- and middle-income countries are born at a disadvantage, with length at birth below the international WHO growth standards[31]. After birth, height-for-age z scores drop rapidly during the first 24 months, with patterns of growth faltering seeming to differ between populations. In India, children are below even the average for low- and middle-income countries by their first month, and on average rapidly drop below -2.0 HAZ by 24 months[31]. Although worldwide prevalence of stunting has decreased in the past two decades, 23% of children under five are still stunted[29]. Stunting predominately affects children in low resource settings, with over 61 million children under five in South Asia stunted. Stunting results in not only severe physical and neurocognitive development, but also has long-term negative effects on human, social and economic capital[32,33].

Wasting, defined as low weight for height, is an acute condition often due to a rapid decrease in diet quantity or quality, or in the child’s ability to adequately absorb dietary nutrients[34]. Worldwide, over 50 million children under five were wasted in 2015, with more than two thirds of wasted children living in Asia[34,35]. Unlike with stunting, the prevalence of wasting has remained relatively stable over the past decade. Although wasting is treatable, moderate and severe wasting substantially increases the risk of death. Underweight, defined as low weight for age, is due to a combination of chronic and acute undernutrition, and provides a less specific indicator of the likely causes of undernutrition than stunting or wasting[36]. Worldwide, over 16% of children under five were underweight in 2015, with over 69 million underweight children living in Asia[29].

Preventative measures

There is a cyclical relationship between undernutrition and infection—especially recurrent diarrheal diseases, ALRI, parasitic infection, and measles. Diarrheal diseases and respiratory infection lower immune response and increase susceptibility to other concurrent infections[37]. In addition, diarrheal disease co-morbidity with undernutrition increases risk of mortality[38]. Both enteric and respiratory infections as well as undernutrition are strongly linked to poverty. Poor sociodemographic conditions and lack of appropriate infrastructural barriers exacerbate these conditions, continuing the cycle.

Preventative measures for diarrheal diseases, STHs, and ALRI, fall into three main categories: nutritional, vaccines, and environmental. Undernutrition is not only a cause of substantial neonatal and child morbidity and mortality, but also a leading risk factor for both diarrheal diseases and lower respiratory infections[17,26]. In addition, specific nutritional measures including breastfeeding and micronutrient supplementation have been shown to reduce to the incidence of diarrheal diseases and pneumonia[3]. The

Global Burden of Disease Study estimates that improvements in undernutrition in the past decade are responsible for a 10% reduction in DALYs due to diarrheal diseases and an almost 9% reduction in DALYs due to ALRI[17,26].

Vaccines are available for *H. influenzae* type b and pneumococcal infection, as well *V. cholerae* O1 and rotavirus. While pneumococcal conjugate and *H.* influenzae type b vaccination resulted in a reduction in severe pneumonia in developing countries, there is evidence that the effectiveness of rotavirus vaccines is substantially lower in developing countries compared to developed[3,39]. In contrast, there are several issues with the cholera vaccine, including relatively low efficacy as well as effectiveness, and limited evidence of long-term effectiveness[40,41]. In the absence of environmental protections and other public health measures, vaccination is not sufficient for protection against endemic diarrheal diseases.

Environmental measures include improved WaSH and reduced household air pollution[3]. Improvements in water and sanitation in the past decade are responsible for an over 13% decrease in DALYs for diarrheal diseases[17]. Similarly, transmission of ALRI could be substantially reduced through consistent hygiene practices[3,42]. The protections provided by improvements in WaSH are the focus of this dissertation and are discussed in more detail in Chapter 3. In addition, there is strong evidence that reductions in air pollution exposure, usually due to improvements in cookstove and household lighting technologies, are associated with decreases in ALRI. Improvements in air pollution exposure in the past decade are responsible for a 4% reduction in DALYs due to lower respiratory infection[26].

Chapter 3. Water, sanitation and hygiene interventions

Enteric pathogens responsible for diarrheal diseases and soil-transmitted helminth infections, and contributing to undernutrition, are transmitted through multiple environmentally mediated pathways. Infrastructure and behavioral interventions can limit or eliminate transmission along specific pathways. Adequate sanitation, where both improved sanitation infrastructure ensures excreta are isolated from further human contact and there is a system to safely manage fecal sludge, provides a primary barrier to enteric pathogen transmission. Use of unimproved sanitation infrastructure or a poorly managed fecal waste system can add additional transmission pathways through environmental contamination. Sanitation should block transmission through all pathways to human fecal contamination aside from transmission via hand contamination. Consistent and adequate hygiene behaviors, including handwashing with soap and water at critical times after defecation and before food handling, provide both a primary barrier to enteric pathogen transmission via hand contamination and a secondary barrier via food or fomite contamination. Hand hygiene also provides protection against other infectious agents transmitted through fomites, such as those bacteria and viruses responsible for lower respiratory infections. Water interventions provide a secondary barrier to transmission though appropriate treatment, transportation, and if necessary, storage, of water used for all purposes. Since no single infrastructure or behavioral intervention will interrupt all enteric pathogen transmission pathways, some combination must be implemented to eliminate exposure to fecal contamination.

The Sustainable Development Goals (SDGs) highlight the need to not only assess access to adequate sanitation and water infrastructure as did the Millennium Development Goals (MDGs), but to more fully assess both coverage and quality of water, sanitation and hygiene services as well as disease attributable to poor water, sanitation and hygiene (WaSH) conditions. SDG 3 specifically calls for monitoring the fractions of diarrheal disease, intestinal nematode infections, and protein-energy undernutrition deaths attributable to poor WaSH conditions.

Piped water on household premises

Interventions that protect water at the point-of-use, including safe storage and treatment measures, are effective at reducing exposure to enteric pathogens and improving health; however, these interventions rely on consistent behaviors[10,43]. Several studies have shown that even a minimal lapse in water treatment or other protection measures which impact water quality results in substantial decreases in health improvements[44,45]. Therefore, interventions that minimize the potential for human error are likely to be the most effective.

Networked water supply systems that distribute piped water from a centralized facility to households provide quality water and associated health benefits at the community level, without the reliance on consistent treatment or storage behaviors at each household. Piped water access at the household has two primary benefits: the water source is in close proximity to the household, and the water should be of high microbiological and chemical quality. Water sources located on the household premises have the potential to reduce exposure to enteric pathogens by limiting the need for water collection and household storage, and thus the risk of post-collection contamination. In addition, there is evidence that water access close to the household increases the quantity of water used, and improves hygiene behaviors[46]. Water access on the household premises is also associated with lower prevalence of helminth infections and diarrheal diseases, and improved height-for-age[47–49]. Piped systems delivering high quality water, in particular, are associated with the greatest reductions in diarrheal diseases[43].

Although networked water systems can provide quality water through centralized treatment before distribution, water can become contaminated in the process of being distributed to households. Within the distribution system itself, breaks in the physical pipelines, hydraulic breaches including water pressure changes and water service intermittencies, and inadequate water quality and chlorine residual within the network are all potential risks allowing contamination to enter the system. A recent systematic review assessed whether deficiencies in water system distribution networks were associated with increased risk of gastrointestinal illness[50]. Ercumen *et al*. determined that distribution systems with any deficiencies increased risk of gastrointestinal illness compared to system with no deficiencies[50]. There was an increased risk associated with any individual system deficiency, including water service intermittency and inadequate chlorine residual. However, the majority of these studies assessed water distribution systems in developed countries; and the few studies in developing countries assessed urban systems. There is a dearth of evidence on piped water systems from both developing and rural contexts, where the need for access to improved water sources is arguably the greatest.

Previous international efforts to ensure all populations have access to clean drinking water focused on infrastructure, categorizing water sources as improved (piped, borehole, and protected well/spring) and unimproved (unprotected well/spring, and surface water). The top rung of the updated Joint Monitoring Programme (JMP) drinking water ladder defines safely managed water as a water source located on the household premises, with no interruptions in service, and free from microbial and chemical contamination. Although the international target has shifted to providing water sources on household premises, there is limited evidence of the health effects of on-premise water, or even coverage of the top rung of the water ladder, piped water connections, in the most at-risk populations.

Worldwide, over 71% of people used safely managed water sources in 2015, but this drops to only 58% in the central and southern Asia region[4]. In many developing countries, including India, there is not sufficient data available currently to estimate access to safely managed water sources. However, India was one of only a few countries that met the MDG of halving the proportion of the population without access to improved drinking water sources in both urban and rural areas. While access to improved drinking water sources in India was high in both urban (94%) and rural (93%) populations in 2015, access to piped water on the household premises is substantially lower in rural than urban populations (16% and 54%, respectively)[51].

Community-level sanitation

There is strong biological plausibility for sanitation to provide health benefits through the elimination of fecal contamination of the environment. However, there is mixed evidence of the effectiveness of sanitation interventions on primary health outcomes. A recent meta-analysis by Freeman *et al.* shows mixed associations between sanitation coverage and diarrhea, soil-transmitted helminth infection, and height-for-age[52]. Two recent randomized controlled trials of rural sanitation interventions implemented under the Total Sanitation Campaign in India showed no effect on prevalence of child diarrheal diseases, soil-transmitted helminthiasis, or select nutritional outcomes[6,7]. In both studies, this may be attributed in part to low use of improved toilets, even with increases in sanitation coverage. In both studies, community level improved sanitation coverage was on average below 63% of households, with at most 37% of households reporting that any household member used an improved toilet. In contrast, a randomized controlled trial of community-led total sanitation (CLTS) in Mali, reported substantial decreases in open defecation (down to <10% for adults)[53]. This study also had no effect on child diarrhea, but reported improvements in child height-for-age.

Several studies have found associations between community level sanitation and reductions in diverse health outcomes including diarrheal diseases, STH, *Giardia duodenalis* infections, and stunting[54–56]. A systematic review found similar evidence that community sanitation offers similar magnitude reductions on diarrheal disease prevalence as household level sanitation[57]. However, the overall quality of evidence was poor. While the importance of improving community coverage is widely accepted, there is limited evidence of effective interventions which focus on the community as a whole instead of individual households. Community-led total sanitation emerged as an early approach focused on community mobilization and commitment to end the practice of open defecation. While it was initially developed in Bangladesh, CLTS has now been implemented throughout the world[58]. However, aside from the previously described Mali study, there is little rigorous evidence of the effectiveness of this intervention approach on sustained use of improved sanitation at the community level[53]. There is a need to determine an approach that will sustainably improve sanitation coverage and use at the community level, especially in settings where open defecation is prevalent.

Previous international efforts to ensure all populations have access to adequate sanitation focused on infrastructure at the household level, categorizing sanitation as improved (connection to a sewer/septic system, pour-flush, ventilated improved pit latrine) and unimproved (shared latrine, open pit, bucket, open defecation). The top rung of the updated JMP sanitation ladder defines safely managed sanitation as a private household latrine with fecal sludge disposed of in situ or treated off site. Although international targets have expanded to include the entire sanitation chain from the containment of human feces within improved facilities to treatment and safe disposal, the focus is still at the household level.

Worldwide, only 39% of people used safely managed sanitation in 2015, with almost 900 million people still practicing open defection[4]. Despite substantial improvements in the past decade, over half of the 892 million people practicing open defection live in India, with the majority living in rural areas[4]. Similar to the new water targets under the Sustainable Development Goals, there is limited data available to estimate the new indicator for safely managed sanitation. Although India has made improvements to sanitation coverage over the past decade, it has continued to be an international focus under both the MDG and SDG monitoring updates. Given the large number of people practicing open defection in India, substantially faster progress than in the past decade is required to meet the SDG target of ending open defecation by 2030. Access to improved sanitation in India was relatively high in urban (65%) compared to rural (34%) populations in 2015[4].

Chapter 4. Design and rationale of a matched cohort study to assess the effectiveness of a combined household-level piped water and sanitation intervention in rural Odisha, India[1]

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ABSTRACT

Introduction. Government efforts to address massive shortfalls in rural water and sanitation in India have centered on construction of community water sources and toilets for selected households. However, deficiencies with water quality and quantity at the household level, and community coverage and actual use of toilets has led Gram Vikas, a local NGO in Odisha, India, to develop an approach that provides household-level piped water connections contingent on full community-level toilet coverage.

Methods. This matched cohort study was designed to assess the effectiveness of a combined piped water and sanitation intervention. Households with children under five years in 45 randomly selected intervention villages and 45 matched control villages will be followed over 17 months. The primary outcome is prevalence of diarrheal diseases; secondary health outcomes include soil-transmitted helminth infection, nutritional status, seroconversion to enteric pathogens, urogenital infections, and environmental enteric dysfunction. In addition, intervention effects on sanitation and water coverage, access and use, environmental fecal contamination, women's empowerment, as well as collective efficacy, and intervention cost and cost-effectiveness will be assessed.

Ethics and dissemination. The study protocol has been reviewed and approved by the ethics boards of the London School of Hygiene and Tropical Medicine, U.K. and KIIT University, Bhubaneswar, India. Findings will be disseminated via peer-reviewed literature and presentation to stakeholders, government officials, implementers and researchers.

Trial registration identifier. NCT02441699

STRENGTHS AND LIMITATIONS OF THIS STUDY

- The study assesses a combined household-level piped water and sanitation intervention that requires complete community-level compliance.
- The intervention was not randomly allocated; but, controls are selected through a restriction process to limit possible partial exposure to the intervention through spillover, and matched to intervention villages using pre-intervention data.
- The study uses a holistic definition of health to assess intervention impacts on physical, mental and social well-being, including more novel outcomes such as seroconversion to enteric pathogens, environmental enteric dysfunction, and sanitation insecurity. It also assesses intervention coverage, cost-effectiveness, and collective efficacy.
- The time lapse between intervention completion and the beginning of the evaluation process prevents baseline comparison or assessment of immediate intervention impacts. However, it allows for a biologically plausible length of time for die-off of even the most persistent pathogens in the environment, and provides time for children to have be born into this environment.

INTRODUCTION

Of the one billion people practicing open defecation worldwide, over half live in India[51]. While international and national pressure on improving sanitation conditions in India has led to over 350 thousand people gaining access to improved toilets since 1990, it has barely kept up with population growth[51,59]. Recent studies show that even in areas with access to household-level improved sanitation, use of these toilets is low[8,14,60]. This may be due in part to a mismatch between the culturally acceptable pour-flush toilets and the level of water access. Coverage of improved water sources, usually community-level pumps or taps, is relatively high even in rural areas in India, but it may not be sufficient for flushing purposes on top of other daily water needs[51,61].

Although the effectiveness of water, sanitation and hygiene (WASH) interventions vary, meta-analyses have found that individual or combined WASH interventions decrease diarrheal disease prevalence by up to 48%[10–13,62]. While combined interventions would be expected to have a greater influence on multiple exposure pathways and thus a greater combined impact on health, there is limited evidence of additive benefits[63]. This may be due to poor uptake, inconsistent use, or an incomplete understanding of relevant pathways[11–13]. In India, combining water and sanitation interventions may be more critical than just interrupting multiple transmission pathways for enteric infection; evidence suggests that household-level water access is integral to the use of improved sanitation in this context[64].

While the intent of improved sanitation facilities is to separate human feces from human contact, most of the focus is on constructing household toilets to increase improved sanitation coverage—the primary metric used in monitoring progress toward international targets. However, studies in India have further shown that toilet construction does not translate into toilet use in this context[6–8,65]. Moreover, with the interdependence between members of households and households within communities, safe water and sanitation is a community-level issue. There is growing emphasis on assessing health risk from poor water and sanitation conditions not simply due to individual or even household-level risk factors, but also from conditions in the community environment[66]. There is evidence that even households without toilets, and households which do not filter drinking water, showed decreased health risk if they live in communities with high levels of coverage and use[56,67,68].

Moreover, the effectiveness of community interventions may be higher in communities with positive perceptions of their collective ability to come together to improve their conditions. Collective efficacy, a latent construct comprised of the structural and cognitive components that facilitate a community's shared belief in its ability to come together and execute actions related to a common goal, may explain some variance in intervention effectiveness across communities receiving WASH interventions[69].

A main risk of poor WASH conditions is enteric infection, caused by a diverse array of bacteria, viruses, protozoa, and parasites, including soil-transmitted helminths. These infections may cause diarrhea, the second leading cause of mortality for children under five years worldwide and in India, a leading cause of mortality regardless of age[70,71]. There is also growing evidence that asymptomatic enteric infections may pose a similar risk, with repeat enteric infections contributing to chronic malnutrition, environmental enteric dysfunction, poor cognitive outcomes, and poor vaccine uptake[1,72–76]. Poor WASH conditions are also linked to increased risk of respiratory infection, the leading cause of mortality for children under five years worldwide[70,77,78]. Poor water and sanitation access can also affect the social, physical and mental well-being of women, acting through pathways ranging from unsafe menstrual hygiene management practices and increased risk of violence[79–81].

Description of the intervention

Over the past decades there has been a global commitment to determine water and sanitation interventions with demonstrated effectiveness, not just efficacy[15]. Gram Vikas, a non-governmental organization based in Odisha, India (http://www.gramvikas.org/), has responded by implementing its MANTRA (Movement and Action Network for Transformation of Rural Areas) water and sanitation program in more than 1000 villages since 2002[82]. This approach includes both household-level piped water connections, and community-level mobilization for culturally appropriate household toilets. A previous interrupted time series analysis of the MANTRA intervention reported it to be protective against diarrheal diseases[83]. However, in addition to limitations of design, this study relied on outcome data collected and reported by Gram Vikas, the intervention implementer, and did not assess intervention coverage or impacts on environmental fecal contamination.

The MANTRA water and sanitation intervention is rolled out in a three-phase process over an average of three years. During the first, or Motivational, phase (approximately 8-12 mo), representatives of Gram Vikas visit the identified village several times to assess village interest and progress towards a set of Gram Vikas requirements, including: 1) the commitment of every household to participate, 2) creation of a village corpus fund from contributions from every household, and 3) development of village guidelines for maintenance and use of facilities.

Once this set of requirements is achieved, the village progresses into the second, or Operational, phase of the intervention (approximately 17-35 mo). Each household constructs a pour-flush toilet with two soak-pits and a separate bathing room. The households hire a local, skilled mason and provide their own unskilled labor and locally available materials to complete the superstructure. Gram Vikas provides external materials such as PVC pipes and porcelain pans. At the same time, a water tank, community meeting space, and piped water distribution system connected to every household, with taps in the toilet and bathing rooms and a separate tap in the kitchen, is constructed through a similar collaborative process.

All households must construct a toilet and bathing room for the village to progress into the final, or Completed, phase of the intervention, in which the water system is turned on. Notably, this three-phase process only allows each household access to piped water once every household in the village has a toilet and bathing room. This model contrasts with most previous water and sanitation interventions, including those implemented under India’s Total Sanitation Campaign and other government programs, which do not require community-level sanitation compliance and do not provide a piped water supply at the household level[84].

Study aims

The primary objective of this study is to evaluate the effectiveness of the combined household-level water supply and sanitation intervention, as implemented by Gram Vikas in Odisha, India. Toward that objective, this study aims to:

1) Assess the effectiveness of the intervention in improving water and sanitation infrastructure coverage, access, and use, and to assess fecal sludge management practices in intervention communities.
2) Assess the effectiveness of the intervention in reducing environmental fecal contamination.
3) Assess the effectiveness of the intervention in improving health. This includes reported diarrheal disease in children under 5 years (primary outcome), acute respiratory infection, infection with soil-transmitted helminthes, nutritional status, environmental enteric dysfunction, seroconversion for selected enteric pathogens, and urogenital diseases associated with menstrual hygiene management practices. Mental and social well-being will be explored through assessment of sanitation insecurity and women's empowerment.
4) Assess the cost and cost-effectiveness of the intervention.
5) Develop and assess a theoretically-grounded, empirically informed collective efficacy scale; and determine the effect of collective efficacy on intervention effectiveness.

METHODS

Setting

The study is located in Ganjam and Gajapati districts in eastern Odisha, India (Figure 1). These two contiguous districts were a single district until 1992. Over 44% of the population in these districts is recognized by the Government of India as being below the poverty line (BPL)[85]. As of 2008, a majority of households in both districts had access to an improved, likely community-level, drinking water source, with over 23% of households in Ganjam having access to any sanitation facility, compared to only 8% of households in Gajapati[85]. The area is primarily rural and agrarian, and the climate is characterized by a monsoon season from June to September, with an average rainfall of ~1400 mms/year.

Study design

This study uses a matched cohort design to assess the effectiveness of a completed intervention with data collected across four study rounds from June 2015 to October 2016 (Figure 2). Data were collected in all study rounds for diarrhea, acute respiratory infection, nutritional status, and stored and source water outcomes to assess seasonality. Data were collected in rounds 2 and 4 for environmental enteric dysfunction, seroconversion, and hand-rinses, and cross-sectionally in one or more rounds for the remaining outcomes. As described below, control villages were matched to randomly selected intervention villages through a multi-step restriction, genetic matching, and exclusion process using the following eligibility criteria.

Eligibility criteria for villages

1. Restriction. Intervention villages were randomly selected from a list of Gram Vikas villages in Ganjam and Gajapati districts provided by the NGO, after restriction to villages with a Motivation phase start date between 2002-2006 and a Construction phase start date no earlier than 2003. Since the intervention process takes on average three years, the criteria for the Motivation start date helped to identify those villages with ongoing interventions at the same time. In addition, this allowed the use of the Government of India Census 2001 and the Below Poverty Line (BPL) Survey 2002 data to characterize baseline characteristics used in the matching process in both intervention and control villages.

Eligible control villages include all villages without a Gram Vikas intervention within the study districts which: 1) are not within the same Gram Panchayat (a political subdivision with some administrative responsibility for water and sanitation comprised of several villages) as a Gram Vikas village, or bordering a Gram Vikas village, and 2) had not received a Motivation visit from the Gram Vikas NGO. These criteria serve to limit the possibility of previous partial exposure to the intervention through spillover from adjacent villages or direct contact with the NGO. These criteria also increase the strength of the comparison provided by the control villages, i.e. it increases the likelihood that if they had received a motivation visit from Gram Vikas, the control villages would have been equally as likely as the intervention villages to demand the intervention.

In addition, to be eligible for inclusion both intervention and control villages must: 1) appear in the Government of India Census 2001 and the BPL Survey 2002, 2) have a population of at least 20 households, and 3) be within approximately three hours travel from the study office in Brahmapur, Ganjam District. This last criterion is due to logistical constraints.

2. Matching. After restriction, genetic matching was used to match potential control villages to the randomly selected intervention villages without replacement[8,86,87]. Villages were exact matched on district to limit any political or large scale geographic variation between district populations, and were also matched on pre-intervention demographic, socioeconomic, sanitation, and water access characteristics listed in Table 4.1[8]. These village-level matching variables were selected due to their theorized association with the primary outcome, diarrheal diseases, as well as data availability.

3. Exclusion. The field team visited matched potential control villages and intervention villages to assess suitability for the study through a rapid assessment interview with village leadership and to ensure accessibility. Villages were excluded if they are not within three hours travel of the field office in Brahmapur, had sustained major infrastructure damage due to a natural disaster, or if there was a current or planned sanitation or water intervention by an organization external to the village in the next 12 months as determined through the rapid assessment interview with village leadership. In addition, villages were excluded if there were fewer than three households with children under five years old. As villages were removed from the pool of prospective control villages, the matching process was repeated for all intervention villages and remaining eligible control villages, and balance measures were assessed. The matching and exclusion processes were repeated as necessary.

After the iterative matching and exclusion process was complete, covariate balance was assessed for all matching variables for the final set of intervention and control villages through examination of balance measures[88–90]. Matching resulted in an improvement in balance as assessed through comparison of several measures including q-q plots, Kolmogorov-Smirnov bootstrap p-values, and standardized differences. After matching, there were no significant differences between intervention and control groups (Table 4.1).

Eligibility criteria for households

Households within selected intervention and control villages were eligible if they had at least one child under 5 years old at time of enrollment, verified with birth or immunization card, and expected to reside in the village for the duration of the study. If there were more than 40 eligible households within a village, 40 were randomly selected to be enrolled. Informed consent was obtained from the male and/or female head of the selected households. All children under five years within each enrolled household were eligible and do not age-out over the course of the study. Households with newborn children were enrolled as they became eligible on an ongoing basis throughout the study, in villages with fewer than 40 enrolled households.

Sample Size

Sample size was determined through a simulation estimating the log odds of diarrheal disease (the primary outcome) through a multilevel random effects model and parameterized with data from a previous study in a neighboring district in Odisha[6]. Sample size estimates were also checked with G*Power[91]. The simulation assumes a longitudinal 7-day period prevalence for diarrhea of 8.8% in children under five years, a heterogeneity variance between villages of 0.07, a heterogeneity variance between households of 0.57, and four study rounds[6]. An effect size of 0.20 was selected for public health importance and based on estimates of effect from systematic reviews of water and sanitation studies[43]. Assuming at least 80% power, 0.05 significance level, 10% for loss to follow up, and at least one child per household, we estimate a sample size of 45 villages per study arm and 26 households per village. This estimate was the most conservative compared to sample size estimates for secondary outcomes, and was therefore used for the broader study population.

Outcome Measurement

Outcomes, and individual, household, and community-level risk factors, will be measured through surveys, interviews, or through the collection and analysis of environmental, stool or dried blood spot samples. All survey questions will be translated into the primary local language, Odia, and back-translated to confirm wording. Household surveys include household and individual factors and will be verbally administered by trained field workers to the mother or primary caregiver of the youngest child under five in each household, unless otherwise specified below. Community surveys will be verbally administered to the *sarpanch* (village head) or other member of village leadership.

Survey data will be collected on mobile phones using Open Data Kit[92]. GPS coordinates for households, water sources and other relevant sites will be collected using Garmin eTrex 10 or 20 devices (Garmin Ltd., Olathe, KS, USA).

Coverage, access and use of sanitation, water and hygiene infrastructure

Coverage, access and use of WASH infrastructure will be assessed in all four rounds. Presence of and access to toilets, water sources and hand-washing stations will be assessed through standard questions from the Demographic and Health Surveys (DHS) and confirmed through spot observations. Spot observations of household toilets and hand-washing stations will be further used to assess indicators of functionality, maintenance, recent use. Reported water and sanitation practices, including child feces disposal practices, will be captured through household survey questions.

Diarrheal diseases

The primary outcome for this study is prevalence of diarrheal diseases, recorded as both daily point prevalence over the previous three days and seven-day period prevalence, for all household members in all four rounds. Although self-reported diarrhea is a subjective outcome with a well-established risk of bias, three-day recall reduces recall bias[93,94]. Diarrheal disease will be measured using the World Health Organization (WHO) definition of three or more loose stools in a 24-hour period, with or without the presence of blood. Field workers will use a simple calendar as a visual aid to help respondents with recall. Each household member will be asked to recall his or her own disease status and the mother or primary caregiver will be asked to report disease for children.

Respiratory infection

Prevalence of respiratory infections will be recorded as both daily point prevalence over the previous three days and seven-day period prevalence for all household members in all four rounds. Respiratory infection is defined as the presence of cough and/or shortness of breath/difficulty breathing according to WHO's Integrated Management of Childhood Illness (IMCI)[95]. The full IMCI case definition for acute lower respiratory infection also includes measurement of respiratory rate and observation of chest indrawing, stridor and other danger signs; these criteria were excluded from our definition as there was concern about the technical support required to produce consistent and accurate data within this context[95]. Our definition provides a broad assessment of respiratory illness burden. Each household member will be asked to recall his or her own disease status and the mother or primary caregiver will be asked to report disease for children.

Nutritional status

Anthropometric data will be collected for children under age five in all four rounds using standard methods as established by WHO[36,96]. Field workers will be trained and standardized in line with WHO protocols to reduce measurement error [96]. Weight will be measured for all children under five years of age using Seca 385 digital scales, with 20g increment for weight below 20kg and a 50g increment for weight between 20 and 50kg. Recumbent length will be measured for children under two years of age using Seca 417 measuring boards with 1mm increment. Standing height will be measured for children two to five years of age using Seca 213 portable stadiometers with 1mm increment. Height and weight will be used to calculate height-for-age z-scores (HAZ) and weight-for-height z-scores (WHZ) based on WHO reference standards. A random subset of 10% of households will receive back check visits each day to repeat height/length measurements to ensure inter-observer reliability.

Soil-transmitted helminth infection

Stool samples will be collected in rounds 2 and 4 from all household members in a randomly selected subset of 500 households, and used to assess the presence and intensity of soil-transmitted helminth (STH) infection. Formalin ether concentration and microscopy will be used to quantify worms and ova for hookworms, *Ascaris lumbricoides*, and *Tricuris trichura*[97]. Quality assurance includes independent duplicate assessment of all positive and 10% of negative samples. After stool collection, each participant will be offered a single dose of Albendazole, a broad-spectrum antihelmenthic drug recommended by the Ministry of Health and Family Welfare, Government of India. Stools collected in round 2 will allow for comparison of STH infection prevalence between intervention and control villages, while the stool samples collected approximately 8 months later in round 4 will provide a measure of re-infection rate.

Environmental enteric dysfunction

Stools from a randomly selected subset of 200 children under two years old, collected in rounds 2 and 4, will be used to assess environmental enteric dysfunction (EED) through quantification of biomarkers of intestinal inflammation and permeability. Fecal myeloperoxidase (MPO), alpha-1-antitrypsin (AAT), and neopterin (NEO), markers for neutrophil activity, intestinal permeability and TH1 immune activation, respectively, were selected for this study based on evidence of association with EED, subsequent linear growth deficits, and household environmental fecal contamination[1,72,98].

Seroconversion for enteric pathogens

Serological assays that assess antibody production against various enteric pathogens can provide an objective measure of exposure to enteric infections[99]. Enrolling children aged 6 to 18 months will reduce the potential for interference from maternally acquired antibodies and permit analysis of seroconversion data in a critical window for young children who experience higher diarrheal disease morbidity and mortality before two years of age[100–105]. Children who are 6 to 12 months during round 2 will have capillary blood drawn by fingerstick or heelstick, as appropriate, and will be visited again during round 4 for a second capillary blood sample. All blood samples will be preserved on TropBio (Sydney, Australia) filter discs and stored within 7 days of collection at -20°C. Seroconversion against markers for norovirus, *Giardia intestinalis*, *Cryptosporidium parvum*, *Entamoeba histolytica*, enterotoxigenic *E. coli* heat-labile enterotoxin (ETEC-LT), *Salmonella* spp., *Campylobacter jejuni*, *Vibrio cholera*, and *Toxoplasma* spp. will be assessed using multiplex immunoassay technology on the Luminex xMAP platform[106].

Environmental fecal contamination

Field workers will collect samples of household stored drinking water and source water from a random subset of 500 households in all four rounds, and child hand rinses in rounds 2 and 4. All water and hand rinse samples will be stored on ice during transport and analyzed within 6 hours of collection using membrane filtration. Three assays will be used: 1) plating on m-Coli Blue 24 (Millipore, Billerica, MA) for *E.coli* according to EPA Method 10029, 2) alkaline peptone water enrichment prior to plating on thiosulfate citrate bile salts sucrose agar and slide agglutination serotyping for *V. cholerae*, and 3) plating on xylose lysine desoxycholate agar, and slide agglutination serotyping for *Shigella* spp.[107–109]. Source and stored water samples will be assayed for *E. coli*, *Vibrio cholerae* and *Shigella* spp., and hand rinse samples will be assayed for *E. coli* and *Shigella* spp. *E. coli* was selected as a standard non-human specific indicator of fecal contamination, though the limitations of this indicator are well-established[110–112]. In order to better characterize human fecal contamination of the household environment, *Vibrio cholerae* and *Shigella* spp. were selected based on prevalence in southern Asia, evidence of public health importance, and field laboratory limitations[113–115].

Cost and cost-effectiveness

Costs and potential cost savings (i.e., averted costs) associated with the intervention will be assessed through an economic costing approach that recognizes and quantifies costs and benefits from a societal perspective[116]. Data on program and point-of-delivery inputs will be collected at household, community, and implementer levels in round 3. Field workers will administer community surveys to a village leader, and household surveys to the household decision-maker for toilet installation, in 20 randomly selected households in twenty matched intervention and control villages. Given cost-effectiveness analyses require the effect of the intervention to be measured against a counterfactual, and the intervention of interest is a community-based intervention, cost and effectiveness measures will be summarized at the village level [117]. Surveys will collect data on household- and community-level inputs related to materials and labor required to construct household toilets and wash rooms, the community water tank and distribution system, and household water connections; longer-term water supply and toilet maintenance costs; and financing required for this infrastructure as well as perceived benefits, including averted social opportunity costs. Implementer inputs from Gram Vikas will be collected through an enumeration exercise, interviews, and examination of the implementer's financial records.

Collective efficacy

Collective efficacy (CE) is a latent construct comprised of the structural and cognitive components that facilitate a community's shared belief in its ability to come together and execute actions related to a common goal[69]. A review of the literature and established conceptual frameworks will be performed to define the CE construct. A sequential exploratory mixed qualitative and quantitative design will be used to develop and refine a scale to measure CE and test hypotheses. Field workers will administer the refined, multi-item, Likert-type CE scale to one randomly selected household member aged 18 years or older in each household in round 3.

Women's empowerment

Four dimensions of women's empowerment will be measured in rounds 3 and 4: group participation, leadership, decision-making and freedom of movement. Group participation and leadership will be measured using modules from the Women's Empowerment in Agriculture Index (WEAI), which has been tested in South Asia[118]. Decision-making will be measured using questions from the women's status module of Demographic and Health Surveys. Freedom of movement will be measured using questions from the project-level Women's Empowerment in Agriculture Index (pro-WEAI). These measures will be collected for the primary female caregiver of the youngest child under 5, and were selected based on the importance of women's empowerment for child nutrition[29,119]. Women's empowerment is conceptualized as both an outcome and a potential mediator along the pathway between the Gram Vikas intervention and child health outcomes.

Menstrual hygiene management

Menstrual hygiene management practices vary worldwide and depend on personal preference, socioeconomic status, local traditions and beliefs, and access to water and sanitation resources[120]. Unhygienic washing practices are common in rural India and among women and girls in lower socioeconomic groups, and may increase risk of urogenital infection[121–123]. However, the link between access to water and sanitation, menstrual hygiene management and urogenital infections has been poorly studied. Household surveys will be administered in round 4 to a randomly selected woman aged 18 or older, in a subset of 800 households, and will capture self-reported urogenital infection, defined as at least one of the following symptoms: 1) abnormal vaginal discharge (unusual texture and color/more abundant than normal), 2) burning or itching in the genitalia, 3) burning or itching when urinating, or 4) genital sores[122].

Sanitation Insecurity

This study will assess the associations between sanitation access and sanitation insecurity with mental health among women. In previous research in Odisha, a contextually specific definition and measure for sanitation insecurity was developed, with associations between facets of sanitation insecurity and mental health independent of sanitation facility access[124]. This previously developed measure will be used to determine if levels of sanitation insecurity differ between intervention and control villages and how it may be associated with mental health outcomes, specifically well-being, anxiety, depression, and distress. Household surveys will be administered in round 4 to a randomly selected woman aged 18 or older, in a random subset of 800 households.

Fecal sludge management

In sanitation systems where sewerage is not feasible, such as the household toilets constructed as part of the MANTRA intervention, safe management of fecal waste is necessary. Although there is growing emphasis on safe fecal sludge management (FSM), research has mainly focused on urban settings[125,126]. Preliminary research in Odisha suggests that fecal sludge management in this rural setting is a substantial challenge, and may impact household use of toilets. In round 3, household surveys and spot checks of toilets in intervention villages will be used to assess toilet use and fecal sludge management practices.

STATISTICAL ANALYSES

The effect of the intervention on infrastructure coverage, access, and use (aim 1), and the effect of the intervention on improving health (aim 3), will be analyzed using logistic, linear, log binomial, or negative binomial multilevel regression depending on the outcome, to compare intervention versus control villages. Prevalence of fecal sludge management practices in intervention communities will be assessed using multilevel regression (aim 1). For all models, the hierarchical structure of the data will be accounted for using random effects. Estimation of relative risks through Poisson regression or binary regression methods for binary outcomes will be considered to ensure robustness of results. Mediation of the potential association between intervention and nutritional status outcomes by women's empowerment will be assessed using multilevel structural equation modeling, and statistical approaches to reduce bias will be explored as needed[127].

The impact of intervention on reducing environmental fecal contamination (aim 2), will be assessed through two methods. First, hierarchical logistic and negative binomial multilevel regression to estimate intervention effects on the relative scale will be used to compare intervention versus control villages. Estimation of relative risks through Poisson regression or binary regression methods for binary outcomes will be considered to ensure robustness of results. Second, a stochastic microbial risk framework will be used to assess differential fecal environmental contamination between intervention and control villages.

The cost and cost-effectiveness of the intervention (aim 4) will be assessed in two steps. Incremental intervention benefits will be ascertained by combining health benefit data, from analysis of health outcome data and established averted cost data, with other averted social opportunity costs. An incremental cost-effectiveness ratio, expressed in cost per disease-specific DALY, will be calculated by dividing the incremental intervention costs by the incremental intervention benefits.

The collective efficacy scale will be analyzed using a psychometric approach in which factor analytics are employed to identify an appropriate factor solution and test the reliability and validity of the CE scores. Once a CE factor solution and an empirically derived multilevel data structure have been identified, the association between CE and intervention effectiveness will be analyzed using multilevel generalized linear mixed models to estimate relative risks[128,129]. (aim 5). For all outcomes, variables used in the matching process may be considered as covariates, as needed, in addition to individual, household, and community-level risk factors. Covariates that are statistically associated with outcomes of interest in bivariate analyses will be considered for inclusion in final multivariable models, following standard stepwise model-building approaches. Secondary analyses may also evaluate models for effect modification as relevant, including exposure-mediator interaction for mediation models and cross-level interaction, by assessing changes in parameter values based on potential effect modifiers. Potential effect modifiers may include breastfeeding for seroconversion outcomes, and climate factors and population density for environmental fecal contamination and health outcomes. However, this study was not designed to assess effect modification and therefore is not specifically powered for these analyses. For all outcomes, unadjusted models will be presented along with models adjusting for covariates.

DISCUSSION

This matched cohort study is one of the first to evaluate the effect of a rural combined household-level piped water and sanitation intervention, implemented at the community level, on a large scale. The matched design provides a rigorous means for estimating causal effects given that randomization to intervention group was not feasible due to the several year implementation process[8]. By focusing on an intervention where the implementation process is complete, it also limits the risk presented by randomized controlled trials, where the intervention has little uptake, an especially important study challenge given interdependence of exposure and outcomes within communities, and a problem that has characterized previous trials of sanitation interventions in India[6,7].

A strength of this study is the assessment of health impacts using the holistic WHO definition of health, including not just disease status, but also mental, social, and physical well-being[130]. Outcomes along the causal chain include standard, but more subjective measures, such as reported diarrheal diseases and respiratory infection, as well as more objective measures such as fecal environmental contamination, soil transmitted helminth infection, and anthropometry. Although there is risk of response bias for reported outcomes, it is unlikely to be differential by intervention status since the study team is not directly linked to Gram Vikas. Even though field workers may be aware of village intervention status, lab staff analyzing water, hand rinse, stool, and blood samples will be blinded. In addition, this study includes the more novel use of seroconversion for enteric pathogens, biomarkers of environmental enteric dysfunction, and measures of collective efficacy in an evaluation assessment. While there are limitations inherent to observational studies, the matched study design and multivariable modeling analysis plan reduce the potential for confounding. However, there is still the potential for residual unmeasured confounding.

Ethics and Dissemination. This study has been reviewed and approved by the Ethics Committee of the London School of Hygiene and Tropical Medicine, U.K (No. 9071) and Institute Ethics Committee of the Kalinga Institute of Medical Sciences of KIIT University, Bhubaneswar, India (KIMS/KIIT/IEC/053/2015). Efforts will be made to communicate the central findings and implications with study communities, the implementing organization and government officials in India. The results of this study will be submitted for publication in peer reviewed journals and presented at conferences. The data collected in the study will be publicly available, with personal identifiable data redacted, following the publication of the primary results within 24 months of the final data collection date.

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Competing Interests: None declared.

Contributions from authors: TC, HR, PR, BT, and HC contributed to study design. HR, LZ and BT developed laboratory protocols. HR, BT, GS, MD, SS, LZ, and BC developed data collection tools. All authors contributed to editing and revising the manuscript.

Figure 4.1. Study sites in Ganjam and Gajapati districts, Odisha, India with intervention villages in black and control villages in white. Inset shows location of districts in India.

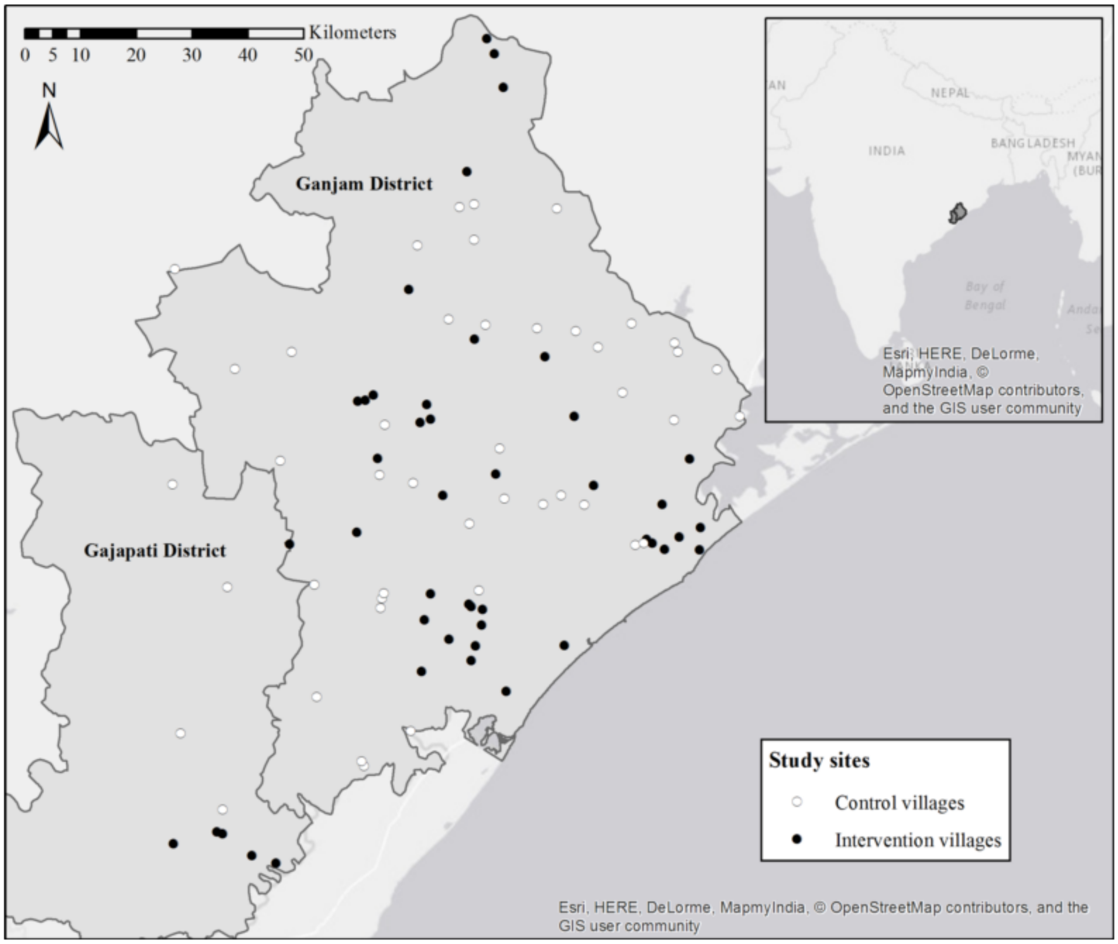

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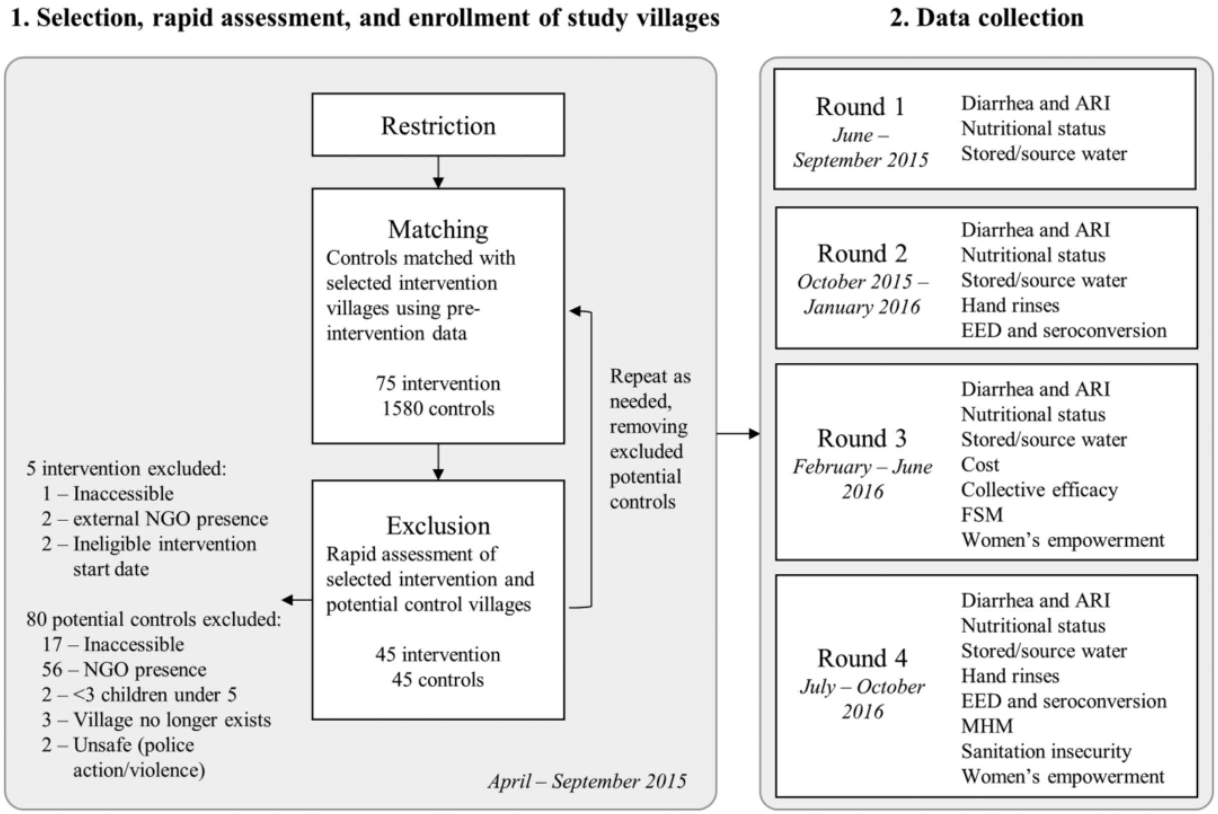
Figure 4.2. Restriction, matching and exclusion process for selection of intervention and control villages (1), and timeline for study rounds and outcome data collection (2).



1. Selection, rapid assessment, and enrollment of study villages

2. Data collection

Table 4.1. Pre-intervention characteristics used in matching, and balance diagnostics before and after matching and exclusion process.

Variable	**Intervention** (n=45)	**Control** (all eligible) (n=1580)	Std Diff (all eligible)	**Control** (study) (n=45)	Std Diff (study)
Number of households	157.9	215.5	0.37	148.1	0.06
Population under 6 years (%)	16.2	16.9	0.19	16.3	0.02
Household income score ($\bar{x}$)	2.9	3.1**	0.26	2.9	0.01
Household goods owned ($\bar{x}$)	1.1	1.2*	0.27	1.1	0.02
Pucca house (%)	59.2	61.6	0.09	60.5	0.05
≥2 meals a day (%)	57.7	63.7	0.19	57.8	0.01
Scheduled caste (%)	11.5	18.7**	0.46	11.8	0.01
Scheduled tribe (%)	33.4	19.1*	0.31	29.8	0.08
Female literacy (%)	30.9	29.8	0.07	30.9	0.00
Open defecation (%)	95.6	95.2*	0.04	95.8	0.01
Improved drinking water source[ǂ] (%)	38.6	42.5	0.10	37.2	0.02
Water source <500m and 50m elevation (%)	81.5	72.2	0.31	81.7	0.01

All eligible: all villages that are eligible for the matching process after restriction

Std Diff (absolute standardized difference): a value greater than 0.1 is considered meaningful imbalance [88]

ǂ Ganjam villages only; no data available for Gajapati villages

Kolmogorov-Smirnov bootstrap p-values: * <0.05 ** <0.01

Chapter 5. Effect of a combined household-level piped water and sanitation intervention on child diarrhea, acute respiratory infection, soil-transmitted helminthiasis, and nutritional status: a matched cohort study in rural Odisha, India[2]

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[2] This chapter is a manuscript currently under review at PLOS Medicine. The structure, length and format are in keeping with journal requirements.

ABSTRACT

Background. Open defecation is widespread in rural India, and few households have piped water connections. While government campaigns increased toilet coverage in India, evaluations found limited impact on health, possibly due to sub-optimal toilet use or household water access.

Methods and Findings. We conducted a matched cohort study to assess a combined household-level piped water and sanitation intervention implemented by Gram Vikas, in 90 villages in rural Odisha, India. Forty-five intervention villages were randomly selected from a list of those where the program was implemented, and matched to 45 control villages. We conducted surveys and observations, and collected stool samples between June 2015-October 2016 in households with a child under five (N=2398). Health surveillance included diarrhea (primary outcome), acute respiratory infection, soil-transmitted helminthiasis, and anthropometry to assess nutritional outcomes. Compared to controls, intervention villages had substantially higher improved toilet coverage (85% v. 18%), as well as increased toilet use by adults (74% v. 13%) and for child feces disposal (35% v. 6%) (all $p<0.001$). There was no intervention effect on diarrhea (OR: 0.94, 95% CI: 0.74-1.20) or respiratory infection. Compared to the control, children in intervention villages had lower prevalence of helminthiasis (OR: 0.44, 95% CI: 0.18, 1.00) and improved HAZ (+0.17, 95% CI: 0.03-0.31).

Conclusions. This combined intervention, where household water connections were contingent on community-wide household toilet construction, was associated with improved household sanitation use and HAZ, and was suggestive of reduced child soil-transmitted helminthiasis, though not reduced diarrheal disease or acute respiratory infection. Further research should explore the mechanism through which these heterogenous effects on health may occur. This study is registered with ClinicalTrials.gov (NCT02441699).

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INTRODUCTION

Globally, over 2.4 billion people lack access to improved sanitation, and almost one billion people practice open defecation—over half of whom reside in India[51]. Efforts to address these massive sanitation shortfalls have primarily focused on construction of pour-flush toilets for selected households within communities. The government of India has implemented a succession of large-scale sanitation campaigns across the country[59]. However, health evaluations of these programs have shown limited impact, possibly due to sub-optimal increases in community-level sanitation coverage and use[6,7,59].

The primary purpose of establishing safe water and improved sanitation is to limit exposure to pathogens associated with a wide range of poor health outcomes. Diarrheal diseases and acute respiratory infection (ARI) are the two leading causes of death for children under five worldwide; in India, diarrhea and pneumonia kill over 290 thousand children under five combined annually, the largest burden of any country worldwide[131]. In addition, soil-transmitted helminth (STH) infection is highly prevalent in poor sanitation settings, with an estimated 223 million children in India requiring preventive chemotherapy for STH infection[2,132,133]. Poor nutritional outcomes are also linked with enteric pathogen exposure, with both underweight and stunting associated with poor household and community level sanitation[53,55,134]. In India, almost half of children under five are stunted or severely stunted[135].

Coverage of community-level improved water sources is relatively high in rural India, but may not be sufficient for flushing or post-defecation cleaning purposes[51]. While combined water and sanitation interventions have shown limited additive benefits, providing piped water at the household, in addition to sanitation, may prove important to increasing use of pour-flush toilets in this context[64,136]. However, research on the effects of household level piped water in combination with sanitation is lacking.

The objective of this study was to assess the effectiveness of a previously completed community-level combined household piped water and sanitation intervention implemented by Gram Vikas, a non-governmental organization (NGO) based in Odisha, India[82]. We assessed intervention impact on water and sanitation coverage, availability, and use, as well as on diarrheal diseases, acute respiratory infection, soil-transmitted helminthiasis, and nutritional outcomes.

METHODS

The intervention

The MANTRA program (Movement and Action Network for the Transformation of Rural Areas) was developed by Gram Vikas, an Indian NGO, as previously described[137]. It consists of: 1) a household pour-flush toilet with dual soak-away pits, 2) an attached bathing room, and 3) household piped water connections[137].

Importantly, for a village to be eligible for participation, every household in the village must agree to construct their own toilet and bathing room. For households below the poverty line, government incentives may cover all or part of toilet construction costs. Gram Vikas then works with the community to develop a piped water system, which is not turned on until every household has completed toilet construction. The village is responsible for ongoing costs of operation and maintenance.

Study design and participants

Full details regarding the study design have been previously reported[137]. Since the intervention takes an average of three years, a randomized controlled trial design was not practical. Instead, we used a matched cohort design [138]. Intervention villages were randomly selected from a list of villages where Gram Vikas had previously completed the intervention in Ganjam and Gajapati districts, Odisha, India, with an intervention start date of 2003-2006. Forty-five control villages were matched to the 45 randomly selected intervention villages through a multi-step restriction, genetic matching, and exclusion process[86,87,137]. Households with a child under five at any time during surveillance were eligible; if more than 40 households were eligible in a village, 40 were randomly selected. The male and/or female head of the household provided written informed consent for the household.

Procedures and outcome measures

Field workers collected data in four study rounds approximately every four months between June 2015-October 2016. Household surveys on socio-demographics, household and individual water, sanitation and hygiene (WaSH) behaviors, and self-reported illness were administered to the primary caregiver in the Odia language. For each of the following outcomes, each household member reported his own disease status over the previous seven days, and the primary caregiver reported disease status for children[139]. Diarrheal disease was defined as at least one occasion of three or more loose stools in the a 24 hour period[19]. ARI was defined as cough and/or shortness of breath/difficulty breathing due to chest congestion[141]. Both diarrheal disease and ARI outcomes were collected every study round. Prevalence of bruising or scrapes (combined) was collected in round 3 (February-June 2016) as a negative control to allow qualitative assessment of differential reporting bias for the self-reported health outcomes[142].

We used direct observation to assess water, sanitation and hygiene infrastructure characteristics. We defined improved sanitation, improved water sources, and presence of a handwashing station, a designated location with water and a cleansing agent present, according to Joint Monitoring Programme standard definitions[51]. We collected reported interruption in the preferred drinking water source using two measures: 1) source unavailable for ≥24 hours in the previous two weeks, and 2) source unavailable at any time in the previous 24 hours. The first measure was collected in all rounds, and the second was collected starting round 2. To limit missing data, interruption in water source was categorized as any interruption, using either measure, across all study rounds. Usual defecation location was self-reported for the following categories within each household: elders ≥60 years, men 18-59 years, women 18-59 years, and children 5-17 years. For children under five, the caregiver reported the disposal location for the last defecation event, and improved child feces disposal was defined as disposal into an improved toilet. We calculated household sanitation use as the proportion of household members who reported improved toilet use for defecation (members >5 years) or for child feces disposal (members <5 years), for each household.

We collected anthropometric measurements for children under five during round 3 (February-June 2016), according to WHO standard methods[36,96]. Field workers measured recumbent length for children <2 years, standing height for children 2-5 years, and weight for children <5 years. Height/length were collected in duplicate, and if measurements differed by more than 0.7 cm, a third was collected; the mean of measurements was used to calculate z-scores according to WHO 2006 growth standards (R igrowup macro)[143]. Back-checks on height/length were conducted on a randomly selected 10% of households. Stunting, wasting and underweight were defined as z-scores less than -2.0, and severe stunting, wasting and underweight as z-scores less than -3.0.

Field workers collected stool samples in round 2 (October 2015-January 2016) from all household members in a randomly selected subset of 500 households to assess prevalence of common soil-transmitted helminths. After stool sample collection, participating household members, excluding pregnant and breast-feeding women, were given one dose of albendazole, a broad spectrum anti-helminthic, in accordance with WHO recommendations. We initially intended to collect a follow-up stool sample in round 4, to measure reinfection in these household members. However, given the low response rate for stool collection, and low infection rate and intensity in round 2 samples, we decided to forgo the follow-up measure. We used formalin ether concentration and microscopy to quantify worms and ova for hookworms (*A. duodenale* and *N. americanus*), *Ascaris lumbricoides*, *Hymenolepis nana*, and *Tricuris trichura*[144]. Three slides were examined for each sample, with all positives and 10% of negatives examined in duplicate. The mean of measurements was used to estimate eggs per gram (epg) of feces and to quantify worm burden.

Statistical analysis

Using Monte Carlo simulation to estimate the log odds of child diarrheal disease (the primary outcome) we determined a sample size of 45 villages per study arm and 26 children per village, assuming 8.8% diarrhea prevalence, 0.20 effect size, 80% power, 0.05 significance level and 10% loss to follow-up, as previously reported[137].

We used logistic regression to estimate intervention association with prevalence of diarrheal disease, ARI, bruising/scrapes, and STH infection, accounting for clustering of observations within households and villages, and linear regression to estimate association with height-for-age (HAZ), weight-for-age (WAZ), and weight-for-height (WHZ) z scores. The same model structures were used to estimate intervention association with WaSH infrastructure coverage, access and use. Two level models were estimated using Gauss-Hermite quadrature with 12 integration points; three level models were estimated using Laplace approximation. Profile likelihood confidence intervals were estimated to limit potential bias from assumptions of asymptotic normality.

Missing household-level covariate data were handled with multi-level multiple imputation (R pan, version 1.4, and mitml, version 0.3-4, packages)[145,146]. The imputation model was run for 20 iterations, included all household-level covariates included in regression models, and was adjusted for clustering at the village level. Imputations were used in all following analyses[147].

We used principal components analysis (R psych package, version 1.6.12) to construct a household wealth index from 15 variables, including household assets, housing characteristics, agricultural land ownership, and below poverty line status[148,149]. We used mixed Pearson, tetrachoric and polychoric correlation to handle the inclusion of binary, categorical and continuous variables, and extracted the component which explained the most variability as the wealth index[150].

Adjusted models were fit with an *a priori* determined set of village, household and individual-level covariates. Adjusted models of WaSH coverage, access and use included household wealth, religion, caste/tribe status, head of household's education, primary caregiver's education, and village access road quality. In addition to these variables, adjusted models of health outcomes included the individual's age and sex. All regressions were repeated using the original, unimputed data, as a sensitivity check. All analyses were completed in R (version 3.3.2).

Ethics

The study protocol was approved by the London School of Hygiene and Tropical Medicine, London, U.K (No. 9071) and the Kalinga Institute of Medical Sciences of KIIT University, Bhubaneswar, India (KIMS/KIIT/IEC/053/2015) ethics committees. Anonymized data were provided to Emory University, Atlanta, U.S. under a data transfer agreement and analysis was approved by the Emory University IRB (IRB00079717). This study was registered at ClinicalTrials.gov (NCT02441699).

RESULTS

Characteristics of the study population

A total of 1123 households (1530 children under 5 years) in the intervention villages, and 1275 households (1771 children under 5 years) in the control villages were enrolled over the four study rounds (Fig 1). Of 11,523 possible observations for children under five, 9550 were available and included in the analysis, an average of 26.5 child observations per village per round. This equates to 17.1% loss to follow-up for children under five (and 10.4% for all household members) over the course of the study, but was similar across study arms.

Intervention and control villages were well balanced on pre-intervention village-level characteristics used in the matching process[137]. After intervention implementation, trends in village, household, and individual-level sociodemographic characteristics were still generally similar across intervention and control villages (Table 5.1). However, there were differences in household wealth and house construction, with intervention households less poor and living in better constructed houses.

Coverage, availability and use of water, hygiene and sanitation facilities

Access to a household improved toilet was almost five times higher in intervention villages than in control villages (85.0% v. 17.7%), as was access to an enclosed bathing room in the household (82.1% v. 12.1%) (Table 5.2). Access to household piped water and presence of a designated hand-washing station with water and cleansing agent available were also both substantially higher in intervention villages than control.

The intervention was positively associated with improvements in round trip time to water source, though average time saved was only 5.85 minutes (95% CI: -7.78, -3.94) per trip (Table 3). However, the intervention was associated with lower odds of water availability, i.e. no interruptions in reported availability (aOR: 0.21, 95% CI: 0.11, 0.40), although almost 10% of households in both intervention and control villages reported some interruption in their preferred drinking water source.

Household improved sanitation use was also substantially higher in intervention than control villages (60.7% v. 31.5%) (Table 5.3). Toilet use by elders (60 years and older), adult men and women (18 and 59 years), and older children (5-17 years) were all over 50 percentage points higher in intervention than control villages (Table 5.2). Prevalence of improved child feces disposal was substantially higher in intervention than in control villages (34.8% v. 6.1%).

Health outcomes

The 7-day diarrhea prevalence for children under five was slightly lower in intervention villages compared to control (5.3% v. 4.9%), however, there was no association with the intervention (aOR: 0.98, 95% CI: 0.77, 1.25) (Tables 5.4 and 5.5). Among all household members, prevalence of diarrhea was even lower, with no association with the intervention.

The 7-day prevalence for ARI in children under five was similar in intervention and control villages (9.3% v. 10.3%), and was not associated with the intervention for either children under five or all household members (aOR: 1.03, 95% CI: 0.84-1.25; and aOR: 1.08, 95% CI: 0.94-1.24) (Table 5.5). There was also no intervention effect on prevalence of bruising/scrapes, collected as a negative control for self-reported health outcomes, for either children under five or all household members.

Prevalence of any soil-transmitted helminthiasis among children under five was higher in control villages compared to the intervention (6.8% v. 3.9%), and there was evidence the intervention had a protective effect on infection with any STH (aOR: 0.44, 95% CI: 0.18, 1.00)(Tables 5.4 and 5.5). Prevalence of any STH infection in all household members was higher in control villages than intervention (11.5% v. 8.6%), but was not associated with the intervention. No *A. lumbricoides* and few *T. trichiura* infections were found in either study arm. The helminth burden was primarily due to infection with hookworms or *H. nana*, with hookworms the most prevalent across both study arms. For both study arms, STH burden falls into the lowest WHO classification with low cumulative STH prevalence and low intensity of infection[151]. Reported use of an antihelminthic in the previous six months among household members who provided stool samples was similar between study arms (13.6% control v. 14.4% intervention).

A smaller proportion of children under five were stunted in intervention villages compared to control (33.3% v. 40.4%); and, the intervention was positively associated with increased HAZ in children under five (+0.17 HAZ, 95% CI: 0.03, 0.31) (Table 5.5). The association between the intervention and HAZ in children under two was similar in magnitude to that in children under five, but was not as strong. While a smaller proportion of children under five were underweight or wasted in intervention villages than control, there was no intervention association with either WAZ or WHZ (Table 5.3).

Sensitivity analyses

A sensitivity analysis was conducted for all water, sanitation and hygiene coverage, availability and use models, and all health models, comparing use of the multi-level imputed data with the unimputated data containing missing covariate values. We found no meaningful difference in adjusted estimates.

DISCUSSION

Our matched-cohort study assessed the impacts of a combined water and sanitation intervention in rural India. In contrast to interventions that involve only community-level water supplies and/or partial community sanitation coverage, the Gram Vikas MANTRA intervention was designed to provide piped water at each home and ensure every household had an improved toilet and bathing room. The intervention was associated with substantial increases in piped water coverage and small reductions in time spent collecting water. It increased access to and use of improved sanitation, including for child feces disposal, and reduced the proportion of household members reporting practicing open defecation. The intervention was also associated with increased coverage of household hand-washing stations and bathing rooms. In these respects, the intervention was effective in accomplishing the target outputs of many WaSH initiatives. However, intermittent availability of preferred water sources and subsequent high levels of drinking water storage provided a possible source of continued exposure to enteric pathogens. It is possible the increase in household piped water coverage mainly indirectly impacted child health through increasing toilet use, instead of the expected direct impact if the piped system provided microbiologically high-quality water.

Notwithstanding these overall gains in WaSH coverage, availability, and use, the health impacts of the intervention were mixed. There was no evidence the intervention was protective against diarrheal disease, the primary study outcome. However, prevalence was low in both study arms. Our results are consistent with the findings of recent randomized controlled trials of sanitation interventions in both rural India under the Total Sanitation Campaign and in Mali under the Community-Led Total Sanitation approach [6,7,53]. There was no evidence the intervention was protective against acute respiratory infection despite increases in water and hand-washing station coverage; this may be attributed to remaining exposure pathways not affected by the WaSH intervention.

On the other hand, our results were suggestive of a protective effect against soil-transmitted helminthiasis in children under five, though we may have had insufficient power to detect an effect, given the lower than expected prevalence. This is in contrast with previous trials in India, but consistent with other evidence on the impact of sanitation, particularly in the context of increases in piped water coverage[47,52]. Future analyses of intervention impact on environmental fecal contamination and on the pathways through which the intervention impacted health could further elucidate this.

The intervention was effective in improving HAZ in children under five; we found a similar magnitude gain to that reported in the Mali evaluation, which found similar reductions in reported open defecation[53]. However, unlike in the Mali evaluation, the effect in our study was not driven primarily by children under two years[53]. This could be due in part to different patterns of growth faltering in Mali and India: in India, children's HAZ decreases more dramatically and remains lower in the second through fifth years of life[31]. In addition, since our study began after intervention completion, there was the opportunity for children to be born into less fecally contaminated environments, benefit from the intervention from birth, and thus have sustained nutritional benefits past the key developmental window of 6-24 months. The sustained impact on HAZ for children under five may be due in part to the increased sanitation coverage and use achieved by the intervention or to the combined effects of sanitation and household-level piped water.

There are several important limitations to this study. First, due to the long implementation period necessary for the intervention, intervention status was not randomly assigned. While intervention and control arms were well balanced after matching, there is still the possibility of imbalance on unobserved variables. To limit confounding, a set of *a priori* determined potential confounders were included in all models, although estimates are still subject to potential residual confounding. Second, WaSH behaviors, diarrheal disease and acute respiratory infection were collected using self- and caregiver reports—a method known to be subject to measurement bias[94,152]. However, we found no difference in our negative control outcome, indicating any potential measurement bias for self-reported outcomes was not differential by study arm.

This study provides evidence that a combined intervention, where provision of household water connections is contingent on community sanitation coverage, can substantially increase piped water coverage, decrease open defecation and improve child nutritional outcomes in India. Given previous evidence that increasing sanitation use, even with high coverage, is especially difficult in rural India, this study provides evidence to support combining household piped water with sanitation access[6,7,14].

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Competing Interests. None declared.

Contributions from authors. TC, HHC and HR designed the study, with contributions from SSS. HR and SSS developed data collection tools. HR, SSS, BT and PR were involved in training. HR and PR oversaw field work. HR analyzed the data and drafted the manuscript. All authors contributed to editing and revising the manuscript.

Figure 5.1. Profile of the study population across four rounds of data collection. The total number of individuals included at each stage of enrollment, follow-up and analysis are on the left in the intervention and control columns. The subset of the total population that is under 5 years is in right in dashed boxes.

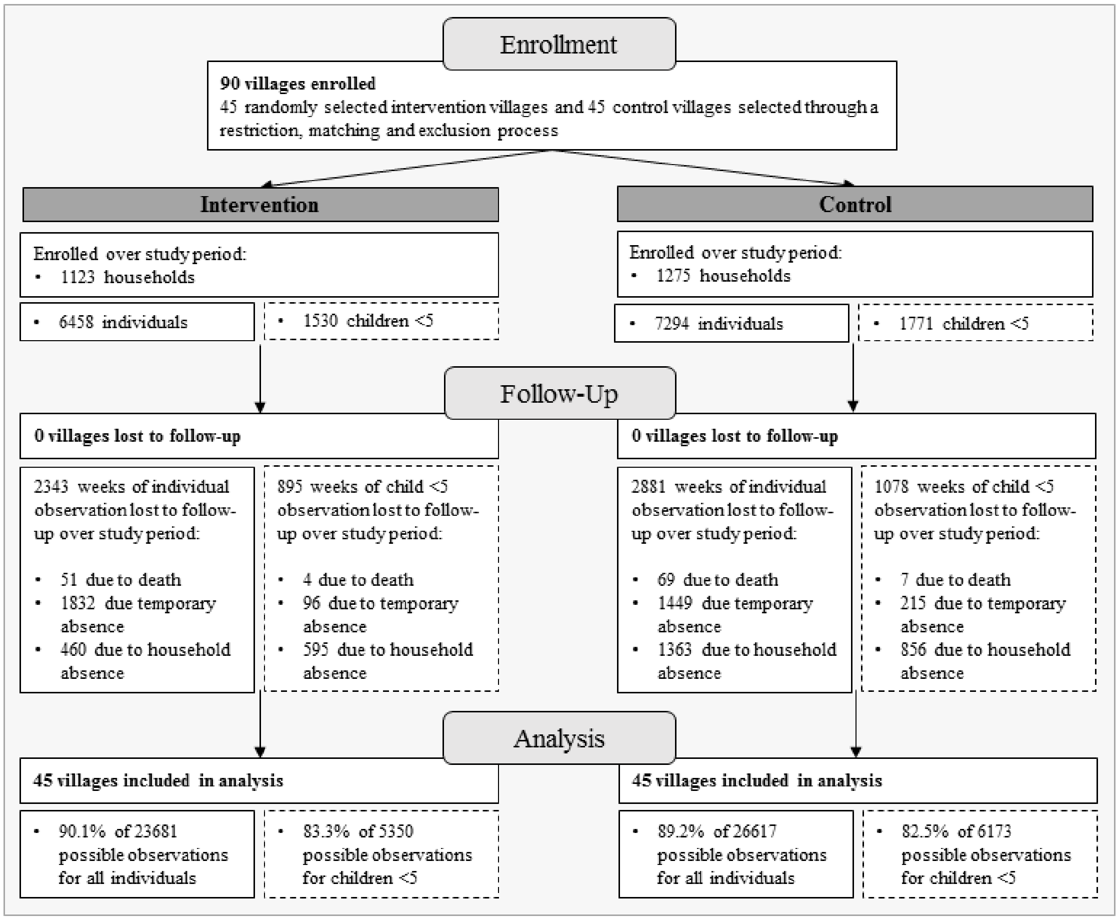

Table 5.1. Sociodemographic characteristics of the study population.

	Control % (n)	**Intervention** % (n)	**p-value**
Village characteristics	n=45	n=45	
Village size (households), $\bar{x}$ (sd)	157.3 (135·0)	124.0 (92.5)	0.176
Access road paved	91.1% (45)	88.9% (45)	0.726
Household characteristics	n=1275	n=1123	
Caregiver education ≥ 5 years	48.0% (612)	57.0% (640)	0.102
Head of household education ≥ 5 years	38.0% (485)	42.3% (475)	0.203
Caste/Tribe			0.147
Scheduled caste	23.7% (255)	13.6% (133)	
Scheduled tribe	15.0% (161)	12.2% (120)	
Other backward caste	39.7% (426)	41.5% (407)	
Other caste	21.6% (232)	32.7% (321)	
Religion			0.632
Hindu	98.8% (1035)	96.7% (902)	
Christian	1.2% (13)	2.8% (26)	
Other	0% (0)	0.5% (5)	
Own home	96.6% (1012)	94.1% (878)	0.058
Agricultural land owned (acres), $\bar{x}$ (sd)	0.6 (1.59)	0.5 (1.31)	0.761
House type			0.002
Pucca: concrete walls and roof	63.0% (645)	75.3% (699)	
Semi-pucca: concrete walls or concrete roof	12.5% (128)	12.9% (120)	
Kucha: neither walls nor roof are concrete	24.5% (251)	11.8% (109)	
Standardized wealth index, $\bar{x}$ (sd)	0.8 (0.46)	1.0 (0.46)	0.026
Wealth quintile[†]			0.015
Poorest	25.3% (233)	14.9% (125)	
Poor	20.3% (187)	19.2% (162)	
Middle	20.6% (190)	19.4% (163)	
Rich	18.0% (166)	22.5% (189)	
Richest	15.8% (146)	24.1% (203)	
Individual characteristics	n=7395 all ages n=1797 cu5	n=6357 all ages n=1502 cu5	
Sex, female (all ages)	52.3% (3802)	52.0% (3345)	0.719
Sex, female (children under 5)	49.0% (860)	49.2% (748)	0.887
Age, years (all ages) $\bar{x}$ (sd)	24.2 (20.43)	25.0 (20.60)	0.082
Age, months (children under 5) $\bar{x}$ (sd)	28.5 (17.72)	29.4 (17.68)	0.218

Wald p-values are adjusted for clustering at village level for household characteristics, and at village and household levels for individual characteristics

[†] Wealth quintile captures the proportion of households in each quintile of the standardized wealth index

Table 5.2. Household water, sanitation and hygiene coverage, access and use characteristics across all study rounds, unless otherwise noted.

	Number of observations	Control % (n)	Intervention % (n)	p-value
Water, sanitation and hygiene coverage				
Improved toilet[†]	2105	17.7% (198)	85.0% (837)	<0.001
Improved water[†]	2388	72.0% (913)	92.1% (1031)	<0.001
Household piped water[†]	2388	8.0% (102)	72.7% (813)	<0.001
Hand-washing station	6048	61.7% (1934)	85.3% (2487)	<0.001
Water available	7529	61.5% (2409)	83.1% (2998)	<0.001
Soap/detergent available	7528	25.1% (982)	48.9% (1764)	<0.001
Ash/sand available	7528	37.3% (1463)	27.2% (981)	<0.001
Bathing room	1902	12.1% (121)	82.1% (739)	<0.001
Water access				
Interruption in water availability, any	7807	7.1% (291)	16.5% (609)	<0.001
≥ 24 hours in previous 2 weeks	7806	4.3% (177)	9.5% (353)	<0.001
Anytime in the previous 24 hrs [‡]	3888	6.4% (198)	15.2% (421)	<0.001
Time to water source (min)	5766	10.2 (11.5)	3.5 (6.7)	<0.001
Water storage, any	7805	99.5% (4099)	97.7% (3601)	<0.001
Water storage, safe	7786	20.6% (849)	22.6% (831)	<0.001
Narrow mouthed container (< 6 cm)	7681	24.7% (1009)	26.0% (913)	<0.001
Covered container	7682	83.0% (3398)	86.2% (3094)	<0.001
Improved sanitation use				
Household use, all ages, $\bar{x}$ (sd)	5890	12.9% (28.8%)	59.3% (36.0%)	<0.001
Toilet use, ≥60 yrs	3023	17.8% (279)	76.2% (1107)	<0.001

Toilet use, men 18-59 yrs	5395	15.0% (428)	74.5% (1900)	<0.001
Toilet use, women 18-59 yrs	5833	18.2% (561)	79.5% (2182)	<0.001
Toilet use, 5-17 yrs	3904	16.8% (351)	76.4% (1387)	<0.001
Child feces disposal, <5 yrs	5367	8.8% (250)	39.2% (989)	<0.001

p-values are adjusted for clustering at village level

† Reported once for each household

‡ Data available rounds 2-4

Table 5.3. Effect of the intervention on water, sanitation and hygiene coverage, access and use.

		Unadjusted		Adjusted	
	Number of observations	OR (95% CI)	p-value	OR (95% CI)	p-value
Water, sanitation and hygiene coverage					
Improved sanitation	2105	51.16 (30.38, 93.51)	<0.001	65.76 (39.96, 116.76)	<0.001
Improved water	2388	12.29 (3.12, 57.48)	<0.001	11.03 (2.70, 50.05)	0.001
Household piped water	2388	69.41 (21.87, 220.37)	<0.001	65.93 (20.76, 209.34)	<0.001
Hand-washing station	6048	6.15 (3.16, 12.43)	<0.001	5.01 (3.07, 8.47)	<0.001
Water access					
Water availability	7807	0.21 (0.11, 0.41)	<0.001	0.21 (0.11, 0.40)	<0.001
Time to water source (min) †	5766	-6.11 (-8.15, -4.06)	<0.001	-5.85 (-7.78, -3.94)	<0.001
Improved sanitation use					
Household use, all ages†	5890	0.45 (0.39, 0.51)	<0.001	0.41 (0.37, 0.46)	<0.001
Child feces disposal, <5 yrs	6706	82.01 (50.15, 144.82)	<0.001	37.98 (24.99, 64.36)	<0.001

† Effect estimate, not odds ratio

Table 5.4. Prevalence of health outcomes in children under two years, children under five years, and all household members. Prevalence across all study rounds is shown for self-reported health, prevalence at round 2 (Oct 2015- Jan 2016) is shown for soil-transmitted helminth infection, and prevalence at round 3 (Feb-June 2016) is shown for nutrition and control outcomes.

	Number of observations	**Control** % (n)	**Intervention** % (n)	**p-value**
Children under 2 years				
Nutrition outcomes				
HAZ, $\bar{x}$ (sd)	655	-1.67 (1.20)	-1.35 (1.33)	0.013
Stunted (HAZ<-2)	655	38.0% (136)	30.0% (89)	0.070
Severely stunted (HAZ<-3)	655	15.1% (54)	9.1% (27)	0.311
WAZ, $\bar{x}$ (sd)	685	-1.49 (1.11)	-1.21(1.22)	0.038
Underweight (WAZ<-2)	685	30.3% (115)	21.6% (66)	0.054
Severely underweight (WAZ<-3)	685	10.3% (39)	5.9% (18)	0.384
WHZ, $\bar{x}$ (sd)	659	-0.76 (1.09)	-0.67 (1.05)	0.244
Wasted (WHZ<-2)	659	12.2% (44)	8.4% (25)	0.413
Severely wasted (WHZ<-3)	659	1.7% (6)	0.7% (2)	0.130
Children under 5 years				
Self-reported health				
Diarrhea	8875	5.3% (251)	4.9% (199)	0.557
Acute respiratory infection	8964	9.3% (127)	10.3% (122)	0.959
Soil-transmitted helminth infection				
Any STH prevalence	775	6.8% (28)	3.9% (14)	0.044
Ascaris lumbricoides prevalence	775	0.0% (0)	0.0% (0)	1.000
Trichuris trichiura prevalence	775	0.0% (0)	0.0% (0)	1.000
Hymenolepis nana prevalence	775	1.5% (6)	1.1% (4)	0.659
Hymenolepis nana intensity (epg), $\bar{x}$ (sd)	775	2.4 (13.72)	1.1 (9.32)	0.270
Hookworm prevalence	775	5.3% (22)	2.8% (10)	0.095
Hookworm intensity (epg), $\bar{x}$ (sd)	775	1.8 (24.04)	0.4 (3.62)	0.115
Nutrition outcomes				
HAZ, $\bar{x}$ (sd)	1826	-1.77 (1.12)	-1.48 (1.17)	<0.001
Stunted (HAZ<-2)	1826	40.4% (402)	33.3% (277)	0.063
Severely stunted (HAZ<-3)	1826	14.0% (139)	7.9% (66)	0.356
WAZ, $\bar{x}$ (sd)	1893	-1.61 (1·08)	-1.36 (1.11)	0.019
Underweight (WAZ<-2)	1893	34.8% (362)	26.5% (226)	0.030
Severely underweight (WAZ<-3)	1893	9.8% (102)	6.2% (53)	0.602

WHZ, $\bar{x}$ (sd)	1829	-0.85 (1.03)	-0.75 (1.06)	0.146
Wasted (WHZ<-2)	1829	12.3% (123)	10.3% (86)	0.808
Severely wasted (WHZ<-3)	1829	1.5% (15)	1.0% (8)	0.303
Control				
Bruising/scrapes	2172	3.8% (45)	3.5% (35)	0.738
All household members				
Self-reported health				
Diarrhea	40436	2.8% (593)	2.4% (485)	0.092
Acute respiratory infection	40999	4.3% (254)	6.6% (241)	0.678
Soil-transmitted helminth infection				
Any STH prevalence	1452	11.5% (86)	8.6% (61)	0.273
Ascaris lumbricoides prevalence	1452	0.0% (0)	0.0% (0)	1.000
Trichuris trichiura prevalence	1452	0.0% (0)	0.0% (1)	0.997
Trichuris trichiura intensity (epg), $\bar{x}$ (sd)	1452	0.0 (0)	0.0 (0.1)	0.318
Hymenolepis nana prevalence	1452	1.9% (14)	1.6% (11)	0.714
Hymenolepis nana intensity (epg), $\bar{x}$ (sd)	1452	3.8 (66.2)	0.78 (9.7)	0.238
Hookworm prevalence	1452	9.7% (72)	7.2% (51)	0.366
Hookworm intensity (epg), $\bar{x}$ (sd)	1452	5.8 (24.2)	3.7 (18.4)	0.333
Control				
Bruising/scrapes	10091	1.7% (93)	1.5% (70)	0.276

p-values adjusted for clustering at village and household levels

Table 5.5. Effect of the intervention on health in children under two years, children under five years, and all household members

	Number of observations	Unadjusted		Adjusted	
		OR (95% CI)	p-value	OR (95% CI)	p-value
Children under 2 years					
Nutrition outcomes					
Height-for-age z score[†]	655	0.31 (0.04, 0.57)	0.026	0.17 (-0.04, 0.38)	0.110
Weight-for-age z score[†]	685	0.23 (-0.03, 0.49)	0.077	0.08 (-0.11, 0.28)	0.390
Weight-for-height z score[†]	659	0.07 (-0.13, 0.27)	0.481	0.00 (-0.17, 0.18)	0.958
Children under 5 years					
Self-reported health					
Diarrhea	8875	0.93 (0.73, 1.18)	0.557	0.98 (0.77, 1.25)	0.855
Acute respiratory infection	8964	1.00 (0.84, 1.18)	0.959	1.03 (0.84, 1.25)	0.363
Soil-transmitted helminth infection					
STH infection, any‡	777	0.49 (0.20, 1.08)	0.077	0.44 (0.18, 1.00)	0.049
Nutrition outcomes					
Height-for-age z score[†]	1826	0.26 (0.06, 0.46)	0.011	0.17 (0.03, 0.31)	0.015
Weight-for-age z score[†]	1893	0.22 (0.01, 0.42)	0.038	0.13 (-0.01, 0.27)	0.068
Weight-for-height z score[†]	1829	0.08 (-0.07, 0.24)	0.288	0.04 (-0.09, 0.16)	0.587
Control					
Bruising/scrapes	2172	0.93 (0.59, 1.45)	0.737	0.88 (0.55, 1.41)	0.601
All household members					
Self-reported health					
Diarrhea	40409	0.85 (0.72, 1.01)	0.063	0.86 (0.74, 1.03)	0.122
Acute respiratory infection	40999	1.03 (0.90, 1.18)	0.688	1.08 (0.94, 1.24)	0.288

Soil-transmitted helminth infection					
STH infection	1452	0.69 (0.40, 1.16)	0.161	0.72 (0.42, 1.19)	0.192
Control					
Bruising/scrapes	10091	0.89 (0.42, 1.88)	0.764	0.86 (0.41, 1.39)	0.660

† Effect estimate, not odds ratio

‡ Household religion excluded from adjusted model due to lack of variability

Chapter 6. The effect of a combined household piped water and sanitation intervention on fecal contamination of source water, household drinking water and children's hands: a matched cohort study in Odisha, India[3]

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[3] This chapter is a manuscript prepared for submission to a peer-reviewed journal. The structure, length and format are in keeping with journal requirements.

ABSTRACT

Enteric pathogens are transmitted through several environmental pathways, and require combination of interventions to fully interrupt transmission. We assessed whether an intervention, where household piped water connection is contingent on full community toilet coverage, reduced fecal environmental contamination. We collected survey data and samples from 45 intervention and 45 matched control villages in four rounds from June 2015-Oct 2016. Source water (n=1583) and drinking water (n=2044) were assayed for *E. coli*, *Shigella* spp., and *V. cholerae*, and children's hands (n=976) for *E. coli* and *Shigella* spp. There was no association between the intervention and either prevalence or concentration of *E. coli*. in source water, drinking water, or on hands. The intervention substantially reduced the prevalence of *S. dysenteria* and *S. flexneri* in source water (aRR: 0.59, 95% CI: 0.35, 0.97); however, there was no association with prevalence of *Shigella* spp. in drinking water or on hands. Although the intervention was associated with high toilet use and coverage of household piped water connections, it had a limited impact on fecal contamination of waters and hands. Future interventions should focus on continuous provision of piped water and adequate chlorine residual in the distribution system, to reduce reliance on household drinking water storage.

INTRODUCTION

Diarrheal diseases, soil-transmitted helminthiasis, and subclinical conditions such as environmental enteric dysfunction, account for a substantial burden of disease worldwide, and are associated with fecal environmental contamination[21,60]. Environmental transmission of enteric pathogens from feces to hosts is through multiple pathways. These pathways were first popularly conceptualized in the F-diagram, where pathogens in a single individual host’s feces are transmitted through fingers, flies, fluids, fields/fomites, and foods to a second individual, and has since grown in complexity[153]. Water, sanitation and hygiene (WaSH) interventions are each capable of interrupting multiple transmission pathways, with sanitation and hygiene interventions providing primary barriers, and water protections providing a secondary barrier to transmission. Sanitation interventions should interrupt fecal contamination of the environment as well as decrease breeding locations for flies, while water interventions should prevent contamination of water and food supplies. To fully interrupt transmission of feces in the environment, interventions need to be combined.

While there is evidence of WaSH interventions improving child health, several recent randomized controlled effectiveness trials have found limited or no protective effect on diarrheal diseases, undernutrition, and other child health outcomes[6,7]. This has raised questions about the extent to which these programs have reduced exposure to enteric pathogens—a fundamental link in the theory of change of WaSH interventions that is rarely investigated. There is limited evidence of water, sanitation, and hygiene interventions effectively reducing fecal contamination of the environment. A 2016 systematic review found no effect of sanitation interventions on source or stored drinking water quality (9 studies), or on fecal contamination of hands (5 studies). Results greatly varied between studies, though the overall quality of the evidence was considered very poor[154]. Three recent randomized controlled sanitation trials, two in India and one in Mali, have shown limited impact on fecal indicator bacteria in source or household stored water, or on hands[6,7,53]. However, the two trials in India were targeted at the household and reached low levels of community coverage of improved sanitation (<50% of households). Improvements in environmental fecal contamination may require complete community level sanitation coverage and use.

There is little evidence of water interventions providing consistent improvements in fecal contamination in rural settings. While interventions that provide protections at the water source, such as protected wells, boreholes and public taps, have been shown to improve water quality at the point of collection, water is quickly re-contaminated during collection and storage[9,155,156]. Interventions that instead focus on water protections at the point-of-use within the household have had mixed effects on health[157,158]. This may be attributed to the dependence of many interventions on consistent behaviors, e.g. safe water storage and appropriate treatment, instead of community-level infrastructure, such as networked water supply with access on the household premises.

This study was nested within a matched cohort evaluation of a sanitation and household-level piped water intervention implemented at the community level. Measures of environmental fecal contamination were intermediate outcomes along the intervention to health pathways of the main evaluation. The main health outcomes have been previously reported (Reese *et al*, under review). This study describes the effects of the combined piped water and sanitation intervention on fecal indicator bacteria and selected bacterial pathogens present in: 1) sources where households report collecting drinking water, 2) drinking water in the household, and 3) on children’s hands.

MATERIALS AND METHODS

Study design

This study is part of a matched cohort evaluation to assess the effectiveness of a water and sanitation intervention in rural Ganjam and Gajapati districts within Odisha, India. Forty-five control villages were matched to 45 randomly selected intervention villages through a restriction, genetic matching, and exclusion process, as described elsewhere[137]. Matching was effective in balancing the intervention and control study arms on all variables used in the matching process[137]. Households with a child under age 5 were eligible for enrollment. If more than 40 households were eligible in a village, 40 were randomly selected. Data were collected from June 2015-October 2016 in four study rounds, each approximately four months apart.

Intervention

The MANTRA program (Movement and Action Network for the Transformation of Rural Areas) was implemented by the Indian NGO, Gram Vikas. The intervention consisted of: 1) a household pour-flush toilet with dual soak-away pits, 2) an attached bathing room, and 3) household piped water connections in the toilet, bathing room, and the kitchen. Access to the piped-water system was contingent on full community coverage of household toilets. The intervention details are described elsewhere[137].

Ethics

The male and/or female head of the household provided written informed consent for the household. The study was reviewed and approved by the Ethics Committee of the London School of Hygiene and Tropical Medicine, U.K (No. 9071) and Institute Ethics Committee of the Kalinga Institute of Medical Sciences of KIIT University, Bhubaneswar, India (KIMS/KIIT/IEC/053/2015).

Water, sanitation and hygiene measures

We collected data in each of the four study rounds from a randomly selected subset of households with a child under 5 years, across all intervention and control villages. Household surveys were administered to the primary caregiver in Odia and collected data on household sociodemographic characteristics, WaSH infrastructure, and household and individual behaviors. Field workers conducted spot check observations of WaSH infrastructure and conditions, including household water storage container type, covered status, and implement used to retrieve drinking water; presence of water and soap at the designated handwashing station; and presence of animal or human feces in the household compound. Field workers recorded reported water treatment for drinking water. In addition, in round 4, field workers measured chlorine residual in source and stored water samples using a colorimeter and the DPD method (Tintometer Inc. Sarasota, Fl; 0-4.0 mg/L detection range, precision ±0.2 mg/L). Two source water samples from each village, including one piped water sample if available, were also tested in round 4 for nitrates and fluoride using a colorimeter (Tintometer Inc. Sarasota, Fl; NO_3^-: 0-1.0 mg/L detection range, precision ±0.1 mg/L; F^-: 0.2-2mg/L detection range, precision ±0.09

mg/L). Before collecting hand rinse samples from children under 5, field workers noted whether children's palms and finger pads appeared visibly soiled.

Sample collection and processing

We collected samples of the source water and drinking water for each household four times, once in each study round, and child hand rinse samples two times, in rounds 2 and 4. If a household randomly selected for sampling was absent, field workers collected samples from the nearest enrolled household to the right. All samples were collected in sterile Whirl-Pak bags (Nasco Modesto Salida, Ca). Field workers collected drinking water samples (500mL) by asking the primary caregiver, usually the mother, to provide water as she would if her child were thirsty, and pour the water from the glass or cup into the Whirl-Pak bag. Source water samples (500mL) were collected from the location identified as the primary source for drinking water by the study household; if multiple households identified the same source, only a single source water sample was collected. If the source was a tap or pump, it was flushed for 30 seconds before sample collection. Surface water samples were collected by dipping the open Whirl-Pak bag into the water from the access location most often used for collecting drinking water. Field workers collected hand rinse samples of the youngest child under 5 by placing the child's hands one at a time into a Whirl-Pak bag pre-filled with 300mL of sterile PBS, and gently massaging each hand from the outside of the bag for 20 seconds. Rinses of children's hands were collected as a proxy of the child's exposure, and to provide a more general assessment of fecal contamination of the household environment, captured on a child's hands during play behavior, beyond drinking water.

Samples were stored on ice during transport, and analyzed within 6 hours of collection using membrane filtration. We assayed source and drinking water for *Escherichia coli*, a WHO recommended fecal indicator bacteria, as well as *Vibrio cholerae* (round 1 only) and *Shigella* spp., both important waterborne pathogens. We assayed hand rinse samples for *E. coli* and *Shigella* spp. Samples assayed for *E.coli* were vacuum-filtered through a 0.45µm mixed cellulose esters filter (Millicore Corporation, Billerica, MA), plated on m-Coli Blue 24 (Millipore Corporation, Billerica, MA), and incubated at 35° C for 24 hours according to U.S. Environmental Protection Agency Method 10029[109]. Samples assayed for *V. cholerae* were vacuum-filtered through a 0.45µm mixed cellulose esters filter, and enriched in alkaline peptone water (HiMedia Labs Pvt. Ltd.) incubated at 35° C overnight. Positive samples were streaked on thiosulfate citrate bile salts sucrose agar (HiMedia Labs Pvt. Ltd.), and incubated at 35° C for 24 hours[107]. Samples field presumptive positive for *Vibrio* spp. after plating were subjected to biochemical tests and then confirmed using agglutination with antisera for *V. cholerae* O1 and O139 serogroups. Samples assayed for *Shigella* spp. were vacuum-filtered through a 0.22µm mixed cellulose esters filter (Millicore Corporation, Billerica, MA), plated on xylose lysine desoxycholate agar (HiMedia Labs Pvt. Ltd.) for *Shigella* spp. and incubated at 35° C for 24 hours[108]. Samples that were field presumptive positive for *Shigella* spp. after plating were subjected to biochemical tests and then confirmed using agglutination with antisera for *S. flexneri* and *S. dysenteria* serogroups[108].

One laboratory blank per laboratory technician per day, one laboratory positive control per target microbe per week, and one field blank per field sample collection team per day were processed for laboratory quality control. Field workers collected field blanks by opening a Whirl-Pak pre-filled with 300mL sterile PBS in the field, as if collecting a hand rinse sample. For each sample, we processed the direct sample and a 1:10 dilution. Detection limits were 0-200 CFU per 100mL for source and stored water samples, and 0-200 CFU per two hands for hand rinses.

Statistical analysis

We calculated the concentration for each sample as the average of the two dilutions, substituting the value of 200 CFU, the upper detection limit, for counts above the detection limit. We tabulated prevalence of field presumptive positive *Vibrio* spp. and *Shigella* spp., and confirmed positive *V. cholerae* o1, *V. cholerae* O139, *Shigella dysenteria*, and *Shigella flexneri*. Confirmed positive *V. cholerae* and *Shigella* spp. were considered positive if serotype positive, and negative if serotype negative or field negative. Field presumptive positive samples which were not serotyped were excluded from confirmed positive prevalence and further analyses.

We assessed the association between *E. coli* concentration and intervention status using negative binomial regression to account for overdispersion with a random effect to account for observations clustered within villages. An additional random effect to account for observations clustered within households was considered but not included due to the low average number of observations per household. We assessed the association between confirmed positive *Shigella dysenteria* and *flexneri* (combined), and confirmed positive *V. cholerae* O1 and O139 (combined), and intervention status using Poisson regression with robust standard errors, and including a random effect for village.

For all models, we adjusted for the following *a priori* determined set of potential confounders: household caste/tribe, religion, women's education, and wealth quintile, for source and drinking water samples, and additionally adjusted for child sex and age for hand rinse samples. Wealth quintile was calculated through principal components analysis of 15 variables, including household assets, housing characteristics, agricultural land ownership, and below poverty line status (Reese *et al,* under review). We assessed effect modification of the intervention by rainfall by including an interaction with a dummy variable for rainy v. dry season in adjusted models. Odisha, India typically has a southwest monsoon season from June to September, in which it receives the majority of its rainfall and environmental contamination may increase. Data processing was completed in R version 3.3.2 and regressions in STATA version 15 (StataCorp, College Station, Tx)[159].

RESULTS AND DISCUSSION

We collected environmental samples from 840 total households over the four rounds: 533 households in round 1, 469 in round 2, 531 in round 3, and 549 in round 4. From these households, we collected 1583 source water samples, 2044 stored drinking water samples, and 976 rinses of children's hands (Figure 1).

Depending on sample type, 3-9% of observations were missing assay results due to an insufficient quantity of sample collected, or turbid samples resulting in plates with too much particulate matter to accurately count. However, missing assay results were not differential by intervention arm. In addition, a lower proportion of source water samples were collected each round in intervention villages than control (68% v. 84% of total households selected for sampling). This is likely due to the reliance on piped water and the frequency of water system intermittencies in intervention villages. If the networked water system was off at the time of the field worker visit, it was not possible to collect source water samples for those households that reported the piped system as their primary source. In addition, assay results for *E. coli* from six villages in round 4 were excluded due to contamination of negative controls.

The parent matched cohort study population was well-balanced on pre-intervention characteristics; however, there were some differences after intervention completion[137]. Intervention households were wealthier (18% v. 30% in the poorest quintile) than control households (Table 6.1).

Source water

A greater proportion of intervention households than control used a piped water source on the household premises (67% v. 7%), with fewer intervention than control households using a public piped water source (4% v. 16%)(Table 6.2). Over 29% of control households relied on an unprotected well, unprotected spring, or surface water, compared to only 12% of intervention households. Similar to the water source used for drinking water, a greater proportion of intervention households reported using a piped water source on the household premises for other uses, including cooking, bathing and toilet use. We tested piped water sources (n=15), when available at the time of sample collection, and none had detectable chlorine residual (Table 6.5). Fluoride and nitrates were detected in the majority of source water samples in both study arms (F: 92% v. 100%, and NO3: 76% v. 79%), though levels did not exceed the WHO guidelines (Table 6.5)[160].

Over 80% of source water samples were positive for *E. coli* in both study arms (Table 6.3). Average *E. coli* concentration was similar between study arms (4.8×10^1 cfu/100ml in the intervention v. 5.2×10^1 cfu/100ml in the control) (Figure 6.2). There was no intervention association with prevalence (aRR: 0.96, 95% CI: 0.84, 1.09) or concentration of *E. coli* (0.65, 95% CI: 0.38, 1.10) adjusting for sociodemographic variables (Table 6.4). However, after including an interaction term for rainy season and intervention, the intervention was associated with increased *E. coli* concentration in the rainy season, (1.49, 95% CI: 1.01, 2.20), while the intervention in the dry season was associated with lower *E. coli* concentration (0.55, 95% CI: 0.29, 1.01) (Table 6.7). A smaller proportion of source water samples were positive for *S. dystenteriae* or *S. flexneri* in intervention communities compared to control (12.2% v. 9.7%, *S. dysenteriae* and *S. flexneri* combined). Of these, most samples were positive for *S. dysenteriae*. The intervention had a substantial protective effect on prevalence of *S. dysenteria* and *S. flexneri* in source water, adjusting for sociodemographic variables (aRR: 0.59, 95% CI: 0.35, 0.97)(Table 6.4). A slightly larger proportion of intervention source water samples were positive for

V. cholerae O1 compared to the control; however, there was no difference by study arm (aRR: 1.21, 95% CI: 0.46, 3.14).

Drinking water

A greater proportion of intervention households reported treating their drinking water compared to control (47.9% v. 36.7%), with boiling the most common method across both study arms (Table 6.2). Only 7 households, all in the same intervention village, had total chlorine detected in their stored water at time of sample collection, and none had detectable free chlorine residual (Table 6.5). Regardless of intervention status, the majority of households stored their drinking water (98.0% intervention v. 99.7% control households). Over 80% of households in both study arms covered stored water containers, with approximately a quarter using a container with a narrow mouth to limit post-collection water contamination (Table 6.2). Few households in the intervention or control arms (19% v. 16%) poured water from the container, or used another method to retrieve water which limits contamination, when asked for a sample of the drinking water.

The majority of drinking water samples from both intervention and control households were positive for *E. coli* (95% v. 91%) (Table 6.3). Average *E. coli* concentration was similar between study arms (4.8×10^1 cfu/100ml in the intervention v. 6.1×10^1 cfu/100ml in the control). There was no intervention association with either prevalence (aRR: 0.98, 95% CI: 0.94, 1.03) or concentration of *E. coli* (0.94, 95% CI: 0.69, 1.28) adjusting for sociodemographic variables (Table 6.4). Approximately 10% of stored drinking water samples were positive for *S. dystenteriae* or *S. flexneri* in both study arms (9.8% v. 10.4%, *dysenteriae* and *flexneri* combined). There was no intervention association with prevalence of *S. dysenteria* and *S. flexneri* in stored drinking water (aRR: 1.07, 95% CI: 0.76, 1.49). Approximately a quarter of drinking water samples in both study arms were positive for *V. cholerae* O1; there was no difference by study arm (aRR: 1.21, 95% CI: 0.78, 1.87) (Tables 6.3 and 6.4).

Hands

We observed soap or detergent (56% v. 25%), and water (78% v. 60%) at a designated location for handwashing in greater proportion of intervention households compared to control (Table 6.2). We observed that almost half of children in both study arms had visibly soiled hands, with dirt equally likely to be on finger pads and palms. There was no intervention association with soiled hands (aRR: 0.92, 95% CI: 0.78, 1.08) (Table 6.6). However, after including an interaction term for rainy season and intervention, the intervention was associated with a reduced risk of visibly soiled hands in the dry season (aRR: 0.82, 95% CI: 0.68, 0.98), while the intervention increased risk of visibly soiled hands in the rainy season, though not significantly (aRR: 1.31, 95% CI: 0.99, 1.72) (Table 6.7).

The majority of children's hands from both intervention and control households were positive for *E. coli* (90% v. 92%) (Table 6.3). Average *E. coli* concentration was similar between study arms (4.1×10^1 cfu/hands in the intervention v. 5.2×10^1 cfu/hands in the control) (Figure 6.2). There was no intervention association with either prevalence (aRR:

0.99, 95% CI: 0.93, 1.04) or concentration of *E. coli* (0.82, 95% CI: 0.59, 1.15) adjusting for sociodemographic variables (Table 6.4). Approximately 10% of children's hands were positive for *S. dystenteriae* or *S. flexneri* in both study arms (10.9% v. 11.0%, *S. dysenteriae* and *S. flexneri* combined), and there was no association with the intervention (aRR: 0.92, 95% CI: 0.64, 1.34).

Observation of feces in household compound

While animal or suspected human feces were observed in almost a third of households, the intervention had no effect on observation of any feces in the household compound (aRR: 0.90, 95% CI: 0.67, 1.22) (Table 6.6).

Discussion

The combined piped-water and sanitation intervention had little effect on fecal contamination of the household environment. In source waters, the intervention improved *Shigella* contamination, but had no effect on *E. coli* or *V. cholerae* contamination, although there is some evidence that seasonality may moderate the impact of the intervention. This could in part be due to low exclusive use of household piped sources in intervention communities, diluting the potential intervention effect if adherence had been higher. Although two thirds of intervention households used the piped water connection as their primary source, 10% reported using an unimproved source. Although the intervention most commonly employed a gravity-fed system into a community containment tank with the spring protected at the source, contamination could have been introduced either through microbe ingress when water pressure drops during the daily or biweekly interruptions in piped water access experienced by over 15% of intervention households, or through biofilm formation on the walls of the containment tank or within the pipe distribution system itself, with no or insufficient chlorination to last throughout the system[161]. In addition, there was no evidence that the piped water was chlorinated at the WHO recommended minimum level (0.5 mg/L chlorine)[160].

The intervention did not reduce fecal contamination of drinking water, the majority of which was stored within the household regardless of the proximity of the water source. Since there were limited intervention impacts on fecal contamination of source waters, there would only be improvements in stored water quality if sufficient and consistent water treatment and safe water storage were practiced. The provision of household-level piped water access in intervention communities should have theoretically eliminated, or at least substantially reduced, the need to store drinking water within the household. The majority of intervention households still stored water (98%), perhaps due to cultural practices or concerns about water availability. In addition, the intervention focused on providing quality drinking water at the point-of-use in the household, and did not include contingencies for water storage to reduce post-collection contamination. Although over a third of households in both study arms report treating drinking water, the most common method was boiling, which is not effective at preventing recontamination.

The intervention had mixed impacts on fecal contamination of children’s hands. While the intervention did not reduce *E. coli* or *Shigella* contamination of children’s hands in models adjusted for sociodemographic characteristics, it increased the risk of *E. coli* contamination on children’s hands during the rainy season when adjusting for effect modification by season. This mixed impact by season in intervention households may be attributed in part to flooding of the household compound, not uncommon in the rainy season, coupled with pour flush toilets with soak-away pits located in close proximity to the household. Although use of the improved toilets may be high regardless of season, flooding of the soak-away pits has the potential to coat the household compound in fecal contamination, which a young child may become exposed to through normal crawling behaviors. Future analyses should assess fecal contamination of soil from the household compound to provide a broader evaluation of environmental contamination that may be less susceptible to diurnal variability than hand contamination.

There were several limitations to this study. First, hand contamination is highly variable over the course of a day, and dependent on the activity the individual was doing immediately before the sample was collected[162]. Since it was not feasible to standardize the time of hand rinse collection across all households, this introduces additional noise into already highly variable data. We also measured observation of hand cleanliness as proxy measure for fecal contamination. However, this measure is likely also associated with similar diurnal changes as microbial contamination. Hand rinse samples were collected twice during the study period, water samples were collected up to four times for each household across the 16 month study period. This allowed for temporal variation in fecal contamination influenced by season. However, since household fecal contamination levels may vary even within the same day, the single collection per study round may not fully capture variability[163,164].

Another limitation is the use of *E. coli* as a fecal indicator bacteria. While *E. coli* is a standard non-human specific indicator of fecal contamination, the limitations of this indicator are well-established[110–112]. *E. coli* is not consistently correlated with enteric pathogens, and is associated with animal as well as human feces. Given that almost half of all households owned livestock (46% in both intervention and control), it's possible that livestock feces may have contributed to fecal contamination of the household environment, also contributing to *E. coli* prevalence. Despite its limitations, *E. coli* is used internationally as an indicator bacteria to assess the microbiological contamination of water, and a systematic review provided evidence of an association with diarrheal diseases[111]. In addition, to better characterize likely human fecal contamination of the household environment, *Vibrio cholerae* and *Shigella* were selected based on prevalence in southern Asia, evidence of public health importance, and field laboratory limitations[113–115]. Although the use of both a standard fecal indicator bacteria and two enteric pathogens strengthened the quality of evidence provide by this study, future studies should use molecular techniques as a complement to culture based methods. In addition, this study focused only on bacterial pathogens and did not measure potential effects on viral or protozoan pathogens.

In addition, samples which were positive for *V. cholerae* O1 were not further tested for cholera toxin, a component essential for the toxigenicity of *V. cholerae* O1. Since there is evidence of non-toxigenic *V. cholerae* in environmental waters, especially marine and estuarine waters, there is the possibility that the *V. cholerae* O1 detected in this study was not toxigenic and therefore not a health concern. However, a large number of samples that were presumptive positive for *Shigella* spp. and *Vibrio* spp. were not serotyped, and were therefore excluded from further analysis. In addition, both *S. sonnei*, a serogroup we did not test for in this study, and non-agglutinable *Shigella*, are becoming more prevalent in India[113]. Thus, our estimates of both confirmed *Shigella* spp. and *V. cholerae* were likely conservative.

Lastly, this study was part of a larger matched cohort study, with households randomly selected for measurement of environmental outcomes. While the matched cohort study was well-balanced after matching, there is the possibility of confounding. To limit the possibility of confounding, we adjusted for household wealth, caste/tribe status, religion, and the primary caregiver’s education in all models, and additionally child age and sex in hand rinse models. However, due to the observational nature of the study, it is possible that there is still some residual confounding.

Figure 6.1. Environmental sample observations by sample type and assay across the four study rounds.

	E. coli	*Shigella spp.*	*Vibrio cholerae*
Round 1 *June – September 2015*	Source water (N=395) Drinking water (N=521)	Source water (N=366) Drinking water (N=448)	Source water (N=394) Drinking water (N=507)
Round 2 *October 2015 – January 2016*	Source water (N=361) Drinking water (N=479) Hands (N=471)	Source water (N=335) Drinking water (N=427) Hands (N=459)	
Round 3 *February – June 2016*	Source water (N=416) Drinking water (N=524)	Source water (N=404) Drinking water (N=481)	
Round 4 *July – October 2016*	Source water (N=413) Drinking water (N=538) Hands (N=525)	Source water (N=410) Drinking water (N=529) Hands (N=503)	

Figure 6.2. *E. coli* concentration in source water, drinking water, and on hands, by study arm over the four rounds of data collection.

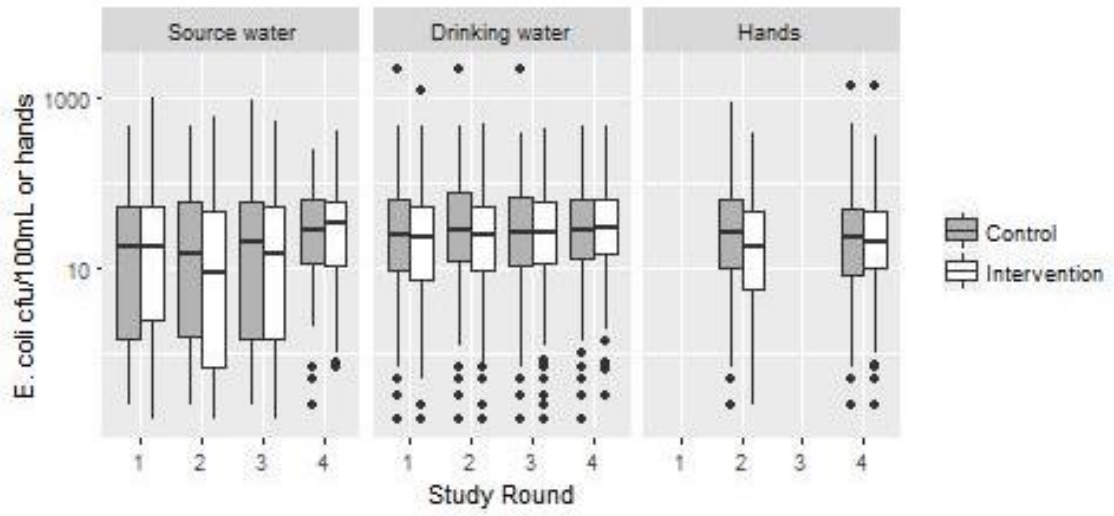


Table 6.1. Sociodemographic characteristics of study households selected for environmental sampling (n=840), and children selected for hand rinse sampling (n=685).

	Number of households	**Control** % (n)	Number of households	**Intervention** % (n)	p-value
Household characteristics					
Caregiver education ≥ 5 years	441	47.2% (208)	399	58.6% (234)	0.133
Caste/Tribe	363		349		0.138
Scheduled caste		19.8% (72)		11.5% (40)	
Scheduled tribe		19.8% (72)		20.6% (72)	
Other backward caste		38.8% (141)		36.7% (128)	
Other caste		21.4% (78)		31.2% (109)	
Religion, Hindu	364	98.4% (358)	342	96.2% (329)	0.389
Wealth quintile†	315		311		0.053
Poorest		29.5% (93)		18.0% (56)	
Poor		19.4% (61)		19.0% (59)	
Middle		19.4% (61)		19.9% (62)	
Rich		16.5% (52)		21.5% (67)	
Richest		15.2% (48)		19.5% (67)	
Individual characteristics					
Child sex, female	349	45.8% (160)	329	46.2% (152)	0.812
Age (months), $\bar{x}$ (sd)	353	34.7 (16.2)	329	34.1 (16.5)	0.360

p-values adjusted for clustering at the village level

† Quintiles for the standardized wealth index

Table 6.2. Community, household, and individual characteristics, by village intervention status.

	Number of observations	Control % (n)	Number of observations	Intervention % (n)	p-value
Community characteristics					
Village improved toilet coverage, $\bar{x}$ (sd)	178	20.3 (21.5)	174	86.2 (12.3)	<0.001
Village improved toilet use, $\bar{x}$ (sd)	136	12.0 (14.7)	136	56.6 (20.0)	<0.001
Household characteristics					
Water source (drinking)	1084		998		<0.001
Piped on premises		7.9% (86)		67.3% (672)	
Other improved		63.8% (692)		21.5% (215)	
Unimproved		28.2% (306)		11.1% (111)	
Water source (other purpose)	836		782		<0.001
Piped on premises		8.5% (71)		71.1% (556)	
Other improved		55.1% (461)		16.0% (125)	
Unimproved		36.4% (304)		12.9% (101)	
Interruption in water availability, any	1082	6.2% (67)	998	16.6% (166)	<0.001
Anytime in previous 24 hours	1082	4.9% (40)	998	15.5% (115)	<0.001
≥ 24 hours in previous 2 weeks	1082	3.8% (41)	998	9.0% (90)	0.021
Water storage					
Covered	1079	83.1% (897)	975	83.7% (816)	0.803
Narrow mouth (< 6cm)	1079	24.7% (266)	974	27.2% (265)	0.309
Poured/directly from tap	1059	16.1% (170)	969	19.0% (184)	0.128
Reported water treatment, any	1084	37.3% (404)	998	46.5% (464)	0.014
Boil		34.1% (370)		43.7% (436)	0.010
Chlorinate		0.6% (6)		0.1% (1)	0.274
Strain through a cloth		7.0% (76)		6.9% (69)	0.996
Other		1.0% (7)		3.6% (20)	0.325
Handwashing station, with soap and water	1058	22.0% (233)	979	58.0% (411)	<0.001

Soap/detergent available		24.9% (259)		55.6% (430)	<0.001
Water available		60.4% (628)		78.3% (759)	<0.001
Proportion of people >5 yrs using improved toilets, $\bar{x}$ (sd)	838	15.09 (33.8)	782	72.6 (40.2)	<0.001
Child feces disposal	735	7.1% (57)	799	34.3% (252)	<0.001
Feces observed in compound, any	557	32.0% (178)	522	27.0% (141)	0.350
Oxen, cattle	557	23.9% (133)	522	15.7% (82)	0.029
Goats, sheep	557	8.8% (49)	522	7.9% (41)	0.813
Poultry	557	8.6% (48)	522	9.2% (48)	0.804
Human, monkey	557	0.9% (5)	522	1.7% (9)	0.276
Individual characteristics (hand rinse samples only)					
Soiled hands, palms or finger pads	450	56.2% (253)	418	48.8% (204)	0.120
Palms	503		453		0.389
Visible dirt		25.0% (126)		24.1% (109)	
Unclean		29.2% (147)		24.7% (112)	
Clean		45.7% (230)		51.2% (232)	
Finger pads	502		454		0.148
Visible dirt		26.3% (132)		23.8% (108)	
Unclean		30.7% (154)		25.3% (115)	
Clean		43.0% (216)		50.9% (231)	

p-values adjusted for clustering at the village level for village characteristics, and adjusted at village and household levels for household and individual characteristics

Table 6.3. *E. coli*, *Shigella* spp. and *V. cholerae* detection in source water, drinking water and on children's hands.

	Control % positive (n)			**Intervention** % positive (n)		
E. coli						
Source water	81.4% (726)			80.1% (536)		
Drinking water	95.0% (1005)			90.9% (882)		
Child's hands	91.9% (465)			89.9% (414)		
***Shigella* spp.**	presumptive *Shigella spp.*	*S. dystenteria*	*S. flexneri*	presumptive *Shigella spp.*	*S. dystenteria*	*S. flexneri*
Source water	61.3% (519)	11.8% (101)	0.4% (4)	60.3% (388)	8.2% (53)	0.5% (3)
Drinking water	57.1% (550)	9.1% (89)	0.7% (7)	56.8% (507)	10.1% (91)	0.3% (3)
Child's hands	74.9% (370)	10.8% (54)	0.2% (1)	73.5% (325)	10.9% (49)	0.0% (0)
***Vibrio* spp.**	presumptive *Vibrio spp.*	*V. cholerae* O1	*V. cholerae* O139	presumptive *Vibrio spp.*	*V. cholerae* O1	*V. cholerae* O139
Source water	47.4% (101)	13.3% (21)	0.0% (0)	57.1% (101)	12.7% (15)	0.0% (0)
Drinking water	55.7% (146)	23.7% (55)	0.0% (0)	61.5% (150)	23.2% (44)	0.7% (1)

Table 6.4. Intervention effect on *E. coli* prevalence and concentration (cfu/100ml or hands), prevalence of *Shigella* spp., and prevalence of *V. cholerae* spp.

	Unadjusted			Adjusted		
	Number of observations	RR (95% CI)	p-value	Number of observations	RR (95% CI)	p-value
E. coli						
Concentration ‡						
Source water	1520	0.79 (0.50, 1.25)	0.307	1185	0.65 (0.38, 1.10)	0.110
Drinking water	1970	0.89 (0.66, 1.19)	0.433	1545	0.94 (0.69, 1.28)	0.676
Child’s hands	915	0.83 (0.60, 1.17)	0.294	703	0.82 (0.59, 1.15)	0.255
Prevalence						
Source water	1520	0.99 (0.87, 1.12)	0.871	1185	0.96 (0.84, 1.09)	0.527
Drinking water	1970	0.96 (0.91, 1.00)	0.074	1545	0.98 (0.94, 1.03)	0.471
Child’s hands	915	0.97 (0.91, 1.04)	0.380	703	0.99 (0.93, 1.04)	0.591
S. dysenteria and flexneri						
Prevalence						
Source water	1489	0.68 (0.42, 1.10)	0.116	1165	0.59 (0.35, 0.97)	0.039
Drinking water	1853	1.07 (0.76, 1.51)	0.695	1455	1.07 (0.76, 1.49)	0.713
Child’s hands	947	0.99 (0.66, 1.47)	0.945	731	0.85 (0.59, 1.24)	0.405
V. cholerae O1 and O139						
Prevalence						
Source water†	268	0.91 (0.42, 1.98)	0.814	187	1.21 (0.46, 3.14)	0.699
Drinking water	411	1.00 (0.65, 1.55)	0.998	280	1.21 (0.78, 1.87)	0.402

† Household religion and caste/tribe status were excluded from adjusted model due to lack of variability

‡ All concentration analyses report the percent change in expected *E. coli* cfu/100ml or hands, not the risk ratio

Table 6.5. Chlorine concentration in source and drinking waters, and nitrate and fluoride concentration in source water, by intervention status.

		Control		Intervention	
	Number of observations	$\bar{x}$ (sd)	% positive (n)	$\bar{x}$ (sd)	% positive (n)
Source water					
Chlorine (mg/l)					
Total Chlorine	15	0 (0)	0% (0)	0 (0)	0% (0)
Free Chlorine	15	0 (0)	0% (0)	0 (0)	0% (0)
Fluoride (mg/l)	91	0.82 (0.06)	100% (53)	0.77 (0.05)	92.1% (35)
Nitrates (mg/l)	91	0.53 (0.05)	79.2% (42)	0.56 (0.05)	76.3% (29)
Drinking water					
Chlorine (mg/l)					
Total Chlorine	321	0.0 (0.0)	0.0% (0)	0.04	4.3% (7)
Free Chlorine	321	0.0 (0.0)	0.0% (0)	0.0% (0.0)	0.0% (0)

Table 6.6. Intervention effect on indicators of fecal contamination.

	Unadjusted			Adjusted		
	Number of obs	RR (95% CI)	p-value	Number of obs	RR (95% CI)	p-value
Soiled hands	2379	0.89 (0.74, 1.08)	0.255	1817	0.92 (0.78, 1.08)	0.307
Feces observed in compound	2408	0.92 (0.66, 1.26)	0.592	1939	0.90 (0.67, 1.22)	0.511

Table 6.7. Intervention effect on indicators of fecal contamination, *E. coli* prevalence and concentration, and prevalence of *Shigella* spp., moderated by season.

		Intervention effect – dry season		Intervention effect – rainy season	
	Number of observations	RR (95% CI)	p-value	RR (95% CI)	Interaction p-value
Soiled hands	1817	0.82 (0.68, 0.98)	0.034	1.31 (0.99, 1.72)	0.057
Feces observed in compound	1939	0.84 (0.61, 1.18)	0.323	1.13 (0.75, 1.69)	0.565
E. coli					
Concentration[‡]					
Source water	1185	0.55 (0.29, 1.01)	0.053	1.49 (1.01, 2.20)	0.047
Drinking water	1545	0.90 (0.65, 1.26)	0.549	1.09 (0.93, 1.28)	0.284
Child’s hands	703	0.77 (0.54, 1.09)	0.145	1.17 (0.85, 1.62)	0.341
Prevalence					
Source water	1185	0.95 (0.80, 1.13)	0.571	1.01 (0.88, 1.14)	0.930
Drinking water	1545	0.97 (0.92, 1.02)	0.264	1.03 (0.99, 1.08)	0.120
Child’s hands	703	0.95 (0.91, 1.02)	0.084	1.08 (1.00, 1.17)	0.039
S. dysenteria and *flexneri*					
Prevalence					
Source water	1165	0.59 (0.32, 1.09)	0.093	0.98 (0.36, 2.64)	0.967
Drinking water	1455	1.06 (0.71, 1.58)	0.788	1.07 (0.57, 1.99)	0.836
Child’s hands	731	0.78 (0.51, 1.18)	0.236	1.89 (0.48, 7.45)	0.362

[‡] Concentration analyses report the percent change in expected *E. coli* cfu/100ml or hands, not the risk ratio

Chapter 7. Conclusion

Summary of findings

This dissertation describes the effectiveness of a matched cohort evaluation of a combined WaSH intervention implemented in rural Odisha, India, which involves household-level piped water connections contingent on full community sanitation coverage. Aim 1, covered in Chapter 5, assessed the association between the intervention and water, sanitation and hand-washing station coverage, availability, and use. Aim 2, covered in Chapter 6, assessed the association between the intervention and fecal contamination of source water, drinking water, and children's hands. Aim 3, also covered in Chapter 5, assessed the association between the intervention and diarrheal diseases, acute lower respiratory infections, soil-transmitted helminth infections, and undernutrition characterized by low height-for-age, weight-for-age, and weight-for-height for children under 5 years.

In Chapter 4, we provide a description of the intervention and the overarching study for the three dissertation aims. The MANTRA water and sanitation intervention was implemented by Gram Vikas, an NGO based in Odisha, India. The program approach follows a three-phase process over an average of three years. During the first, or Motivational, phase, Gram Vikas assesses village interest and progress towards a set of Gram Vikas requirements, including the commitment of every household to participate, creation of a village corpus fund, and development of village guidelines for maintenance and use of future water and sanitation infrastructure. In the second, or Operational, phase of the intervention, each household constructs a pour-flush toilet with two soak-pits and an attached bathing room, through a combination of household and Gram Vikas resources. At the same time, a water tank and piped water distribution system protected at the source and connected to every household, is constructed through a similar collaborative process. All households must construct a toilet and bathing room for the village to progress into the final, or Completed, phase of the intervention, in which the water system is turned on. Notably, this three-phase process only allows each household access to piped water once every household in the village has a toilet and bathing room.

This study used a matched cohort study design to assess the effectiveness of the completed MANTRA intervention as implemented in Ganjam and Gajapati districts in Odisha, India. Study intervention villages were randomly selected from a list of villages with completed interventions provided by Gram Vikas. Control villages were matched to the randomly selected intervention villages through a multi-step restriction, genetic matching, and exclusion process. This resulted in balance between the 45 intervention and 45 matched control villages on all pre-intervention sociodemographic characteristics used in the matching process. We conducted surveys and observations, and collected stool and environmental samples between June 2015-October 2016 in households with a child under five.

In Chapter 5, we assessed the association of the intervention with WaSH coverage, availability and use, as well as with child health. Multi-level logistic regression was used to estimate intervention association with prevalence of diarrheal disease, ARI, bruising/scrapes, and STH infection, while linear regression was used to estimate association with HAZ, WAZ, and WHZ. The same model structures were used to estimate association with WaSH coverage, availability, and use. Models were adjusted for clustering of observations within households and villages, as relevant, and adjusted for an a priori determined set of village, household and individual-level covariates. Multi-level multiple imputation was used to handle missing household-level covariate data. The imputation was run for 20 iterations and was used in the remainder of analyses. Compared to controls, intervention villages had higher improved toilet coverage as well as increased toilet use by adults and for child feces disposal. However, use of a toilet for child feces disposal was still very low compared to adult toilet use even in intervention villages (35% v. 74%). The intervention was also associated with increased access to piped water on the household premises, and a designated hand-washing station with available water and cleansing agent. However, almost all households in both study arms storing drinking water, and only a quarter followed safe storage practices (using a covered, narrow mouthed container). There was no intervention association with prevalence of diarrheal diseases or respiratory infection; even though, unlike in previous rigorous evaluations in India, there were substantial increases in improved sanitation use[6,7]. However, children in intervention villages had substantially lower odds of helminthiasis (OR: 0.44, 95% CI: 0.18, 1.00) and improved HAZ (+0.17, 95% CI: 0.03-0.31) compared to the control. This was a similar magnitude increase in HAZ to that seen in the Pickering *et al* study, although our study showed sustained impacts to age 5[53]. Our study provides new evidence that a combined WaSH intervention can substantially reduce open defecation and improve child nutritional outcomes and STH infection in rural India. Together with previous evidence, the findings do not support an association between improvements in sanitation and water coverage, and diarrheal diseases in children under five in rural, low-resource settings, though they do provide evidence of an association with increases in HAZ and reductions in STH infections. Further research is needed to assess the different mechanisms through which these mixed impacts on health occur.

In Chapter 6, we assessed the association of the intervention with fecal contamination of source water, drinking water, and children's hands. Multi-level Poisson regression with robust standard errors was used to estimate intervention association with prevalence of *E.coli*, *Shigella flexneri and dystenteria* (combined), and *V. cholerae,* while negative binomial regression was used to estimate association with *E. coli* concentration. Models were adjusted for clustering of observations within villages, and adjusted for an a priori determined set of household and individual-level covariates. The majority of all samples in both study arms were positive for *E. coli*. There was no association between the intervention and either prevalence or concentration of *E. coli*. in source water, drinking water, or on hands. The intervention substantially reduced the prevalence of *S. dysenteria* and *S. flexneri* (combined) in source water; however, there was no association with prevalence of *Shigella* spp. in drinking water or on hands. There was also no association with prevalence of *V. cholerae* in source or drinking waters. These results are in line with previous findings that water quality declines after collection from the source[155]. Given the similarity in drinking water storage practices between the intervention and control study arms, any direct health benefit from improvements in water quality at the source may have been negated by post-collection contamination during drinking water storage.

Further analysis will help determine whether the on-premise piped water supply had indirect impacts on health, potentially through increasing use of the pour-flush toilets (Table 7.1). Future on-premise piped water interventions should focus on ensuring consistent water availability, and maintaining the WHO recommended 0.2-0.5 mg/l chlorine residual level within the distribution system, reducing the need for storing drinking water[160]. Additional research is needed to determine if there are cultural determinants of drinking water storage behaviors that would not be affected by changes in water availability and quality.

Reflections on study limitations and the potential for improvements

There are several limitations to the study used in this dissertation. Some of these limitations have been discussed previously within earlier chapters, but are discussed in more detail below.

Selection of households

There was a high level of variability in the number of eligible households between study villages. Some villages had as few as three households with a child under 5, while other villages had over a hundred eligible households. This not only reduced the ability to equally capture within cluster variability and assess community level characteristics, but increased the possibility of losing a cluster during follow-up due to absence of only a few children. While we were powered to detect the expected change in primary outcome, diarrheal disease, in the future, I would include variability in cluster size to power calculations[165].

In addition, selection of households with a child under five years, although the target population for the main evaluation, reduced our ability to assess the influence of WaSH coverage and behaviors for those households directly proximate to each child's household on the child's health, in future analyses. However, in villages with over 40 eligible households, study households were selected using systematic random sampling to improve the geographic distribution of households within the village. Future analyses of community and sub-community effects on household or individual measures rely on the assumption that households with a child under 5 are similar in behaviors and exposures to non-study households. These analyses would also be strengthened by assessing and adjusting for spatial autocorrelation.

Matched design

Since it was not feasible to use a randomized controlled study design, but instead a matched cohort design, this study is subject to the usual limitations of observational studies including the potential for residual confounding. There is limited internal validity compared to a randomized controlled trial since the intervention was not randomly allocated. In addition, the criteria used to select intervention villages reduced the external validity of this study, providing a form of sampling bias by restricting villages included in the study to those that fit the restriction criteria and were similar to intervention communities.

While the matching process resulted in balance between the intervention arms, this study is reliant on the quality of the matching data. The matching process relied on data from two national level surveys, the 2001 census and the Below Poverty Line (BPL) Survey from 2003. These data were aggregated village estimates, and had a limited number of applicable variables to use. In addition, village BPL Survey data were only available from the associated district office, not a centralized source. Although we were able to obtain data from the Ganjam district office, there were complexities trying to work with the Gajapati office, and we eventually relied on scraping the website to obtain these publicly available data. Though the Gajapati data included all blocks within the district, it is possible there were differences in the data obtained from the district office compared to that available from their website. However, it is unlikely this would be differential across intervention and control study villages.

After matching, some villages were excluded from selection due to logistical constraints, including being located more than a 3-hour journey from the field office. Several intervention villages were excluded from the study because the village was not accessible via car and required a long hike up the mountainside (> 3-hour total travel time). With the remoteness of these villages, it is quite impressive that Gram Vikas was able to successfully implement their intervention. Given previous evidence of a negative association between diarrheal diseases and village remoteness, it's possible the intervention may have been more or less successful in remote villages[166]. We adjusted for village accessibility (access road type) for infrastructure and health outcomes as a proxy for remoteness in the selected villages, however future research should further consider the effectiveness of community level interventions in remote versus highly accessible villages.

Retrospective design

The several year time lapse between intervention completion and the beginning of the evaluation process prevents baseline comparison between study arms or assessment of immediate intervention impacts. However, it does allow for a biologically plausible length of time for die-off of even the most persistent pathogens in the environment, and provides time for children to have be born into this environment. In addition, it allows for the assessment of longer-term sustained impacts; most evaluations of WaSH interventions assess intervention impacts shortly after implementation and provide no evidence of longer-term effects.

Since the implementation process involved the community opting into the intervention, there is the potential for communities with greater collective efficacy choosing to participate in the intervention or potentially having more a more effective intervention. This evaluation was conducted retrospectively, so it was not possible to measure collective efficacy at baseline, nor, given the reliance on previously collected data for the matching process, to match on collective efficacy. Future analysis of collective efficacy measured during study follow-up could provide some indication of whether a community's collective efficacy is associated with intervention effectiveness.

In addition, since we were reliant on a retrospective design, a process evaluation to assess intervention implementation, and a contemporaneous accounting of implementation costs for the cost and cost-effectiveness analysis was not possible.

Intervention approach

The single arm combined intervention approach used by Gram Vikas limited our ability to assess the impact of the individual water or sanitation components, or to determine whether there is a synergistic effect of the combined intervention. However, a future analysis of the direct and indirect intervention effects on health through water and sanitation coverage, availability, and use could provide some limited evidence of the indirect impacts through the program theory of change.

Water distribution system

We did not examine water quality along the water distribution system to determine relative effectiveness of the intervention process at each stage, including both structural and operational factors. Several factors could influence the quality of water coming directly from the tap within the household. First, structural factors include adequate protection at the source, and use of a microbiologically and chemically uncontaminated source. While Gram Vikas devoted resources in initial selection of a water source, occasionally requiring use of a source located several kilometers away from the benefiting community, we did not assess quality at the point where water enters the system due to logistical constraints. Second, the transmission main from water source to the community reservoir, and the distribution system from the reservoir to the households, are susceptible to infiltration of contaminants and biofilm formation. Third, the water stored in the community water reservoir is also susceptible to biofilm formation. Given the high prevalence of fecal contamination even in on-premise piped waters in our study, further research of networked water supply systems in low-resource rural settings should include assessment of microbiological water quality, as well as indicators of biofilm formation, at multiple points within the distribution system.

Operational factors including slow water velocity within the distribution system, changes in water pressure, long water detention times in the water tower, and hydraulic conditions within the distribution system which allow sediment to accumulate, all influence water quality. We measured water intermittencies (self-reported interruptions in water availability at any time in the previous 24 hours, and for more than a day in the previous two weeks) in all study communities, providing a broad measure of these operational characteristics. While this indicated issues with water velocity and water pressure, it is not specific enough to allow detailed identification of issues. In addition, we did not assess the maintenance and repair procedures within each village which may also have influenced water quality. This includes adequate regular disinfection of the reservoir, repair and replacement of damaged pipes, and appropriate flushing and disinfection processes following any pipeline repairs. Further research assessing priority operational measures as well as barriers to use within rural low-resource settings is of programmatic interest given the SDG focus on provision of piped water sources.

The intervention distribution system was engineered to fit the geographic limitations and population needs of each community; there was no simple systematic and consistent methodology we could use across all 45 intervention communities to assess the water distribution system. Since the implementing NGO, Gram Vikas, was not able to provide even model system blueprints, we decided obtaining blueprints for each village from the corresponding block administrative office (an administrative level below district) was not logistically feasible. Without a more detailed assessment of the distribution system, this study was not able to isolate the specific deficiencies of the intervention, aside from the need for improved water availability and increased chlorine residual, and thus has limited ability to provide additional evidence for programmatic improvements.

Measurement methods

There is a need for more sensitive and objective measures for behaviors, exposures, and health outcomes. We relied primarily on self-reported behaviors (water treatment, toilet use, child feces disposal), and self-reported health outcomes (diarrheal diseases and respiratory infections). Use of sensors, such as passive latrine use monitors (PLUMs), in a subset of household could have a provided more objective measures for behaviors[152]. For self-reported health outcomes, we used the prevalence of bruising or scrapes as a negative control outcome, and found no evidence of differential reporting bias. But, there is still the possibility of non-differential inflation or deflation of reported values. The reliance on self-reported diarrheal disease provides an estimate only of symptomatic disease during the short window captured within the recall period. The future planned analysis of seroprevalence for a panel of enteric pathogens will provide a more specific assessment, especially given previous evidence of association between reported diarrheal disease and *Giardia intestinalis* and *Cryptosporidium parvum* point seroprevalence within a water quality intervention[167].

Another limitation is the reliance on the fecal indicator bacteria, *E. coli*, to assess fecal contamination of waters and hands. An indicator specific to human feces or a panel of enteric pathogens could have been assessed in a subset of households, providing more objective and specific exposure measures. While the use of culture based methods provided assurance that detected bacteria were viable, use of a ddPCR or another quantitative molecular method would have provided more specific and precise estimates for a broader group of enteric pathogens. In addition, the data collection process for this study did not allow temporally linking exposure data (WaSH infrastructure and behaviors, fecal contamination of water and hands, etc.) and health outcomes. Both exposure and outcome data were collected the same day, and thus attribution of association assumes the exposure was continuous. Future studies should consider collection of exposure measures within the incubation period for common pathogens prior to collecting outcomes, although this may be logistically difficult and cost prohibitive in field settings.

Quality control and data loss

The discrepancies in identifiers for household observations across rounds and environmental samples across labs made data processing very time consuming and led to some data loss. Barcoding households, sample collection containers, petri dishes, and chain of custody forms used to document sample transfer between laboratories would have streamlined the process. In addition, the ODK platform used to collect data for all household surveys, observations, and sample collection has built-in barcode support, making this a very feasible improvement.

In addition, there were issues with incomplete implementation of chemical water assessment. Although we intended to test source water for chlorine residual in all villages, we only had results for 15. There were several barriers to this including: 1) data loss due to incorrect sample identification, as discussed above, 2) inability to test water due to lost materials (affected several villages before additional materials could be ordered), 3) water source unavailable during the field visit, for community or household piped water sources, and 4) the primary water source is not relevant for chemical disinfection, such as use of surface waters. Although there was negligible reported use of chlorination, and no detection of chlorine residual in those samples we were able to analyze, testing source waters in all villages would have provided much stronger evidence to support this conclusion.

There were also issues with contamination in the field lab and with sample transfer between laboratories. Low level contamination (median 10 cfu/100mL) of plates within the field laboratory over several days resulted in data loss for that round for all village samples processed those days. A large number of samples that were presumptive positive for *Shigella* spp. and *Vibrio* spp. were not transferred to the lab to be serotyped, and were excluded from further analysis resulting in substantial data loss. The proportion of presumptive positive samples transferred for serotyping also differed substantially between study rounds, limiting our ability to assess seasonality, and included the unplanned transfer and serotyping of some negative samples. Both *S. sonnei*, a serogroup we did not test for in this study, and non-agglutinable *Shigella*, are becoming more prevalent in India[114]. Multiple imputation (MI) for missing confirmed positive *Shigella* and *V. cholerae* outcome data could have been used to improve the power of subsequent analyses; however, there is evidence that use of MI for estimation of relative risks produces biased estimates regardless of the approach used[168].

Policy and program recommendations

This study occurred within the context of almost two decades of Government of India programming to eliminate open defecation. Previous government initiatives include the Total Sanitation Campaign (1999-2012), Nirmal Bharat Abhiyan (2012-2014), and the current campaign, Swachh Bharat Abhiyan (2014-2019). There are only minor differences between the objectives of these programs: each sought to provide sanitation coverage across rural India through a demand-driven, community-led framework[169].

While objectives were similar between the government programs, implementation was not. The TSC provided small subsidies as incentives for household toilet construction for below poverty line (BPL) households, and included a strong information, education and communication (IEC) software component. However, there was a substantial gap between program objectives and implementation. The focus on monitoring sanitation coverage, and in some cases, subsidy distribution as a proxy for coverage, likely contributed to the general poor quality and/or incomplete construction that affected over 30% of household toilets, according to a Comptroller and Auditor General of India (CAG) audit[170]. In addition, the CAG audit, as well as policy research not affiliated with the Indian government, determined that both the TSC and the NBA were subject to poor coordination between administrative levels, widespread lack of fund disbursement at all levels, as well as misappropriation of funds that were disbursed[171,170]. The TSC was rebranded as Nirmal Bharat Abhiyan (NBA) in 2012, with an increased focus on creating community demand for sanitation, but had minimal differences in implementation[171].

The NBA was then restructured into Swachh Bharat Abhiyan (SBA) in 2014, with urban and rural programs addressed separately. It expanded incentives for household toilets to both BPL and select above poverty line (APL) households, and included a focus on construction of school and anganwadi toilets[169]. In addition, the subsidy allotted for household toilet construction was increased, with the aim to encourage water provision at the toilet, and there was an emphasis on community engagement throughout the implementation process. In addition, there is an increased focus on monitoring sanitation use, not only coverage. Due to these factors, there is reason to believe that the SBA may prove more effective than previous program iterations.

As discussed previously within this dissertation, two independent evaluations of the TSC found little improvements in toilet use, and no improvements in health[6,7]. There has been no rigorous evaluation, to date, of the effectiveness of the newest program, the SBA, on child health. In contrast, this dissertation has shown that the Gram Vikas intervention has been effective at substantially increasing toilet coverage and use, and in improving select health outcomes. Given the mixed success of this program, future programming in rural India should build upon the framework used by Gram Vikas (community-level mobilization, and the combination of on-premise piped water access and high-quality household toilets), with some additional improvements. Based on this dissertation, the simplest and likely most effective remaining infrastructure improvements would be ensuring quality water at the tap, regardless of intermittencies. An automatic chlorine dosing system could be installed at the community reservoir, with the dosage calibrated to provide an adequate free chlorine residual through the maximum time that drinking water is generally stored. This method would require some preliminary assessment of drinking water storage practices, likely water system intermittencies, and chlorine concentration taste-tests for the target populations to determine an appropriate and acceptable chlorine dose. In addition to the hardware, some behavioral programming could target increased toilet use by children and adult men, and for child feces disposal, as well as decreased use of drinking water storage, and improved storage practices (narrow-mouthed, covered container with a tap) for other water purposes.

Recommendations for future research

This dissertation has provided additional evidence of the effectiveness of community level sanitation interventions, but there are still further research gaps including opportunities within the current study framework. Future planned analyses within the Gram Vikas study are listed in Table 7.1; a few are described in more detail below.

Given the strong effect of the intervention on WaSH coverage and use, but the heterogenous effects on child health, there is a need to further assess the pathways through which these impacts may occur. Structured equation modeling can be used to examine the pathways through which the combined intervention impacted child health outcomes to: 1) separate direct from indirect impacts, and 2) determine where there were breakages in the theory of change. Further assessment will provide a stronger evidence base for program development in similar low-resource rural settings (Table 7.1). In addition, given the distribution of community sanitation coverage (35%-100% of households in intervention villages v. 0%-86% of households in control villages) and sanitation use (0%-93% of individuals in intervention villages v. 0%-66% of individuals in control villages) this study provides the opportunity to further examine the potential of a dose-response relationship between community sanitation and health outcomes (Table 7.1). In addition, it offers the possibility to assess the relative contributions of individual, household, and community behaviors as well as the potential moderating effect of each level. While previous research has explored the effects of community, and sub-neighborhood sanitation contributions to health, there is still a need for a stronger evidence base to inform program and policy development[55,172,173].

According to measures of toilet coverage and use, the sanitation intervention was successful in improving community level sanitation. However, the substantially lower use of improved sanitation for disposal of child feces compared to use by household members over age 5 suggests that there are different determinants for these two populations. Increasing safe child feces disposal to the same level as adult toilet use likely requires a directed behavioral component. Further research should examine determinants of safe child feces disposal as separate from adult use of improved sanitation. In addition, the benefits of provision of piped water connections at the household should be further explored, beyond direct impacts on infectious disease prevalence. There is still a dearth of evidence on the benefits of on-premise piped water connections in low-income rural settings.

Table 7.1. Planned future analyses within the Gram Vikas MANTRA study framework. An asterisk denotes those analyses I am leading or mentoring.

Topic	Description of planned analyses
Health	
Environmental enteric dysfunction	1) Determine an EED factor solution for this study, 2) assess the effect of the intervention on each EED marker and factor solution, 3) assess EED markers/factor solution as mediators for HAZ, and 4) assess association between fecal environmental contamination and EED
Seroconversion for enteric pathogens	Determine the effect of the intervention on seroprevalence and seroconversion for enteric pathogens
Direct and indirect effects of the intervention on health *	Assess the direct and indirect effects of the intervention on child health via WaSH coverage, WaSH access/availability and WaSH use, including the intersecting contributions of the three water, sanitation and hygiene pathways
Determinants for ALRI and diarrhea *	Assess individual, household, community, and environmental risk factors for ALRI and diarrheal diseases
Determinants of STH infection *	Assess individual, household, community, and environmental risk factors for STH infection
Spatial determinants of undernutrition *	1. Assess association of household and community coverage and use of sanitation with undernutrition, and 2. determine whether there is sub-community clustering of sanitation coverage and use, and the association with undernutrition
Intervention, dietary diversity, and undernutrition	Assess whether the intervention acts through improved crop production and/or livestock ownership, to improve dietary diversity, and decrease undernutrition
Community sanitation effects on health *	1. Assess potential for threshold or dose-response relationship between of sanitation coverage/use and health, and 2) assess household and community WaSH behaviors as mediators of individual health
Environmental fecal contamination	
Determinants of fecal environmental contamination *	Assess individual, household, community, and environmental risk factors for fecal contamination of source water, drinking water, and children's hands
QMRA*	1. Quantitative microbial risk assessment for hands/drinking pathways by intervention and control study arm, 2. compare theorized and measured exposures between study arms, and 3. assess differences in exposure by child age and season

Fecal sludge management	
Fecal sludge management	Describe fecal sludge management practices within the intervention
Collective efficacy	
Collective efficacy: factor solution	Determine a collective efficacy factor solution
Collective efficacy: intervention effectiveness	Determine the effect of collective efficacy on WaSH coverage, use and health in the intervention
Collective efficacy: exploratory	Assess collective efficacy 'themes' in formative research cognitive interviews
Cost and cost-effectiveness	
Cost and cost-effectiveness	1. Determine the intervention cost, and 2. calculate incremental cost-effectiveness ratios for disease-specific DALYs averted and other averted social opportunity costs
Menstrual hygiene management, sanitation insecurity, and well-being	
MHM and urogenital health	1. Determine the effect of the intervention on MHM, and 2. determine MHM effect on urogenital health
Women's empowerment, food security and growth	1. Determine the effect of the intervention on women's empowerment and food security, and 2. assess women's empowerment as a mediator between intervention status and growth
Sanitation security, MHM and well-being	Determine the effect of the intervention on sanitation insecurity and mental health
Sanitation insecurity, well-being and urogenital infection	1. Assess the association between sanitation insecurity and anxiety/well-being, and 2. determine direct and indirect effects of sanitation insecurity on urogenital infection via anxiety/well-being

Appendix A. Description of outcome measurement

Table A.1. Description of the methods and measurements used to define outcomes.

Outcome	Method	Measures	Description
WaSH coverage, availability and use outcomes			
Improved sanitation coverage	Survey and observation	Does your household have access to a toilet facility? Currently, what kind of toilet facility do members of your household usually use? [confirmed with observation] Where is your toilet facility located? [confirmed with observation]	Improved sanitation defined according to the JMP categories
Toilet use and household toilet use	Survey	Currently, what kind of toilet facility do members of your household usually use? Currently, where do household members usually defecate? Elder members (more than 60 years)? Male adults (18 to 59 years)? Female adults (18 to 59 years)? Children 5 to 17 years?	Improved toilet use dichotomized for each age/sex category Household toilet use reported at the proportion of all household members who report using an improved toilet (including use of improved child feces disposal for children under 5) out of all household members present during that round
Improved child feces disposal	Survey	The last time your youngest child under 5 defecated, where did they defecate? The last time your youngest child under 5 defecated, what was done to dispose of the stools?	Safe child feces disposal defined according to current research and WHO/UNICEF recommendations. Clarification on defecation location informed by previous research
Improved water source coverage	Survey and observation	What is the main source of drinking water for members of your household? [confirmed with observation] Currently, what is the main source of water used by your household for other purposes such as cooking, bathing and handwashing? What is that water source used for?	Improved water source defined according to JMP categories
Time to water source	Survey	Where is that water source located? How long does it take to go there, get water, and come back?	Total reported round trip time in minutes

Interruptions in water source availability	Survey	In the past two weeks, was the water from this source not available for at least one full day? Was this water source unavailable in the past 24 hours?	Reported interruption in availability dichotomized as either interruption
Drinking water storage	Survey and observation	Do you have a container where you store drinking water? [Observe type of water container.] [Observe presence of container cover.]	Any storage dichotomized as reported and observed storage
Drinking water treatment	Survey and assay	What do you usually do to make the water safer to drink? Anything else? [Total and free chlorine residual]	Reported water treatment Chlorine residual from drinking water sample
Handwashing station coverage	Survey and observation	Can you please show me where members of your household most often wash their hands (post-defecation and all other times)? [Observe the presence of water at the place for hand washing.] [Observe the presence of soap, detergent, or other cleansing agent at the place for hand washing.]	Handwashing station coverage dichotomized for observed designated location with water and cleansing agent visible
Fecal environmental contamination			
Water quality and hand contamination	Assay	*E. coli* by M-ColiBlue, *Shigella* spp. and *V. cholerae* by culture and serological confirmation for source water, drinking water and rinses of children's hands	*E. coli* concentration reported as cfu/100 mL or hands, and dichotomized as ≥1 cfu/100 mL or hands Presumptive positive and confirmed positive *Shigella* and *V. cholerae* dichotomized as ≥1 cfu/100 mL or hands
Health outcomes			
Diarrheal disease	Survey	At any time in the past 7 days, has [HH member] had diarrhea (loose motion more than 3 times per day)?	Reported 7-day prevalence of diarrheal disease
ALRI	Survey	At any time in the past 7 days, has [HH member] had an illness with a cough? At any time in the past 7 days, as [HH member] had fast, short, rapid breaths or difficulty breathing?	Reported 7-day prevalence of cough or difficulty breathing due to chest congestion

		Was the fast or difficult breathing due to a problem in the chest or to a blocked or runny nose?	
STH infection	Assay	Formalin ethyl acetate sedimination[97] and microscopy for ova and worms for hookworms, *Ascaris lumbricoides*, and *Tricuris trichura*, and *H. nana*	Dichotomized as any STH infection
HAZ, WAZ, and WHZ	Measurement and survey	Supine length measured using a length board for children under 24 months old; standing height measured using a stadiometer for children over 24 months old Weight measured using a digital scale Birth date and survey date captured from survey	Calculated as z-scores using WHO standards[30]

Appendix B. Description of intervention infrastructure

The hardware component of the Gram Vikas intervention included a: 1) networked water supply system with a community water tower as the reservoir (Figure B1), 2) a pour-flush toilet with dual soak-away pits, and 3) an attached bathing room. In each community the water was generally sourced from a protected spring and used gravity-fed system or was sourced from a dug well or borehole and used a pumping system. Since the water system was engineered to fit village characteristics including hydrology, geology and population requirements of each village, Gram Vikas was not able to provide a common design. However, the toilet and bathing room complex was standard across villages (Figures B2 and B3).

Figure B1. Community water tower with reservoir above, and community meeting room below.

Figure B2. Toilet with dual soak-away pits (left) and attached bathing room (right). There is a connection to the networked water system in each room.

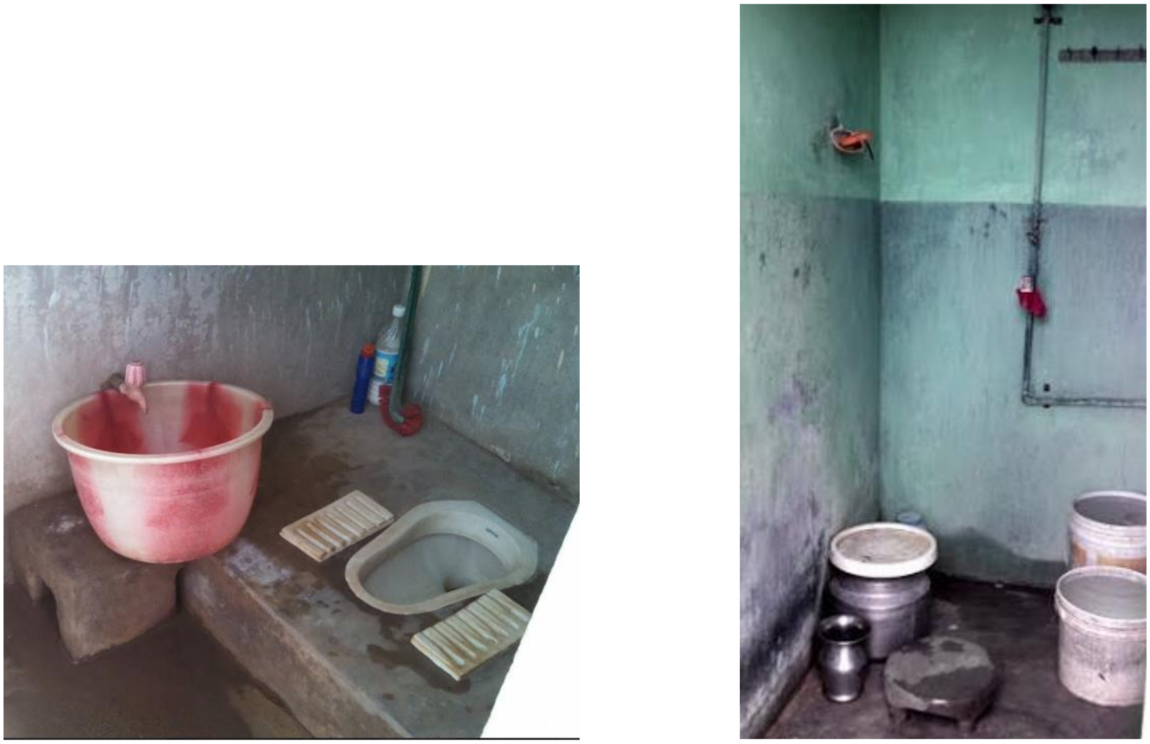
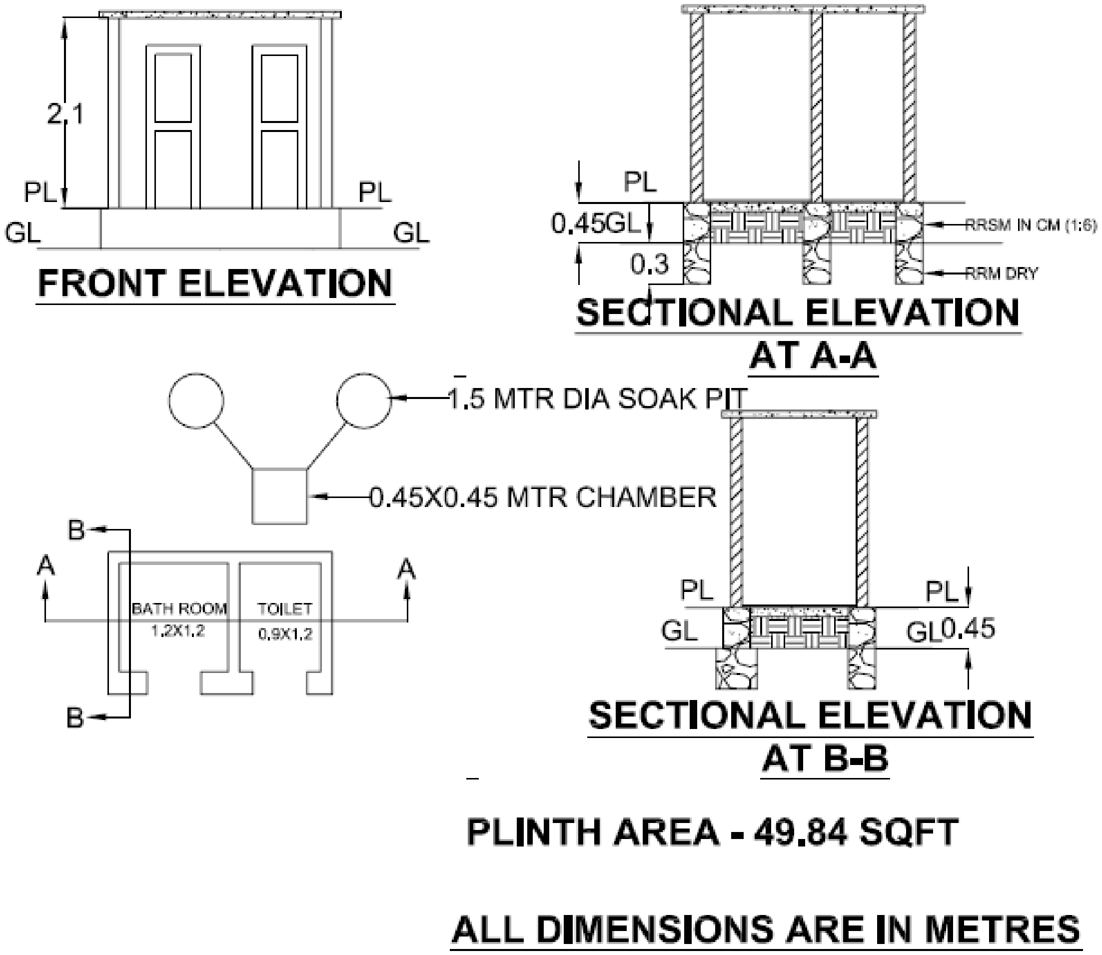


Figure B3. Standard design for Gram Vikas toilet and bathing room.



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