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Pathways for progress toward universal access to safe drinking water

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Pathways for progress toward universal access to safe drinking water

by

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Abstract

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Over two billion people globally lack access to safe water. This is both a public health problem and a violation of human rights. The United Nations Sustainable Development Goals, through its ambitious and human-rights based framework, and the safe water, sanitation, and hygiene (WASH) community, through its calls for "transformative WASH," have signaled that status quo interventions will not achieve universal safe water access goals. Rather, there is a need for new pathways toward the progressive realization of the human right to available, safe, acceptable, accessible, and affordable water for all. In Chapter 1, I present the results of a systematic review of adherence to chlorine point-of-use (POU) water treatment at the household-level, a widely promoted and inexpensive strategy for improving drinking water quality and health. While centralized chlorination of urban piped water supplies has historically contributed to major reductions in waterborne illness, sub-optimal adherence to household-level water treatment indicates that chlorine POU products are unlikely to lead to the widespread public health benefits associated with centralized treatment of piped water supplies. In Chapter 2, I present the results of an evaluation of system-level, passive chlorination technologies in small water systems in rural Nepal. These passive chlorination technologies have the potential to automatically treat water, without requiring the household-level behavior changes that are required for POU products. While these technologies have been rigorously evaluated as decentralized treatment solutions in some urban settings, little data exist on their performance in remote, rural systems, for which these technologies can serve as fully centralized chlorination systems. Over one year, we found that these technologies significantly improve the quality of water accessed by households. While service delivery models should be explored to ensure long-term sustainability, passive chlorination technologies have the potential to radically improve how rural households gain access to safe water. In Chapter 3, I present a synthesis of the literature at the intersection of gender and domestic water. The vast water and health literature is overwhelmingly focused on the consequences for child health, while focusing less attention on the health of the water carriers and managers, the women and girls who are typically the implementers of household-level treatment strategies. Yet, failing to understand the full consequences for

women and girls leaves a major gap in our accounting of the value of accessible and safe water and cannot lead to gender equality.

For Mom, Dad, Marika, and Alyssa.

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Introduction

"... the right to safe and clean drinking water and sanitation is a human right that is essential for the full enjoyment of life and all human rights..."
- United Nations General Assembly Resolution 64/292. The human right to water and sanitation (2010)

"This Agenda is a plan of action for people, planet and prosperity... We are determined to take the bold and transformative steps which are urgently needed to shift the world on to a sustainable and resilient path. As we embark on this collective journey, we pledge that no one will be left behind... [The Sustainable Development Goals] seek to realize the human rights of all and to achieve gender equality and the empowerment of all women and girls."
- United Nations General Assembly Resolution 70/1. Transforming our world: the 2030 Agenda for Sustainable Development (2015)

The global problem of unsafe water

Over two billion people globally lack access to safe water, according to estimates compiled by the Joint Monitoring Program [1]. This has long been a public health problem, with diarrheal diseases a preventable leading cause of death globally, particularly among young children. It is estimated that half a million children died from diarrheal diseases in 2015 [2]. More recently, it has been formally recognized as a human rights issue. In 2002, through the United Nations (UN) Committee on Economic, Social and Cultural Rights' General Comment 15, and then in 2010, through UN General Assembly Resolution 64/292, the UN formally recognized the human right to water [3, 4]. To motivate and monitor progress in global access to safe water and on other development priorities over the last 30 years, two sets of global development goals have been set forth.

In 1990, the UN Millennium Development Goals (MDGs) were adopted as a global development agenda with 2015 as the target date. Among the goals: reduce by half the proportion of the world without access to improved sources of water, a proxy indicator for safe access based on the construction of the water source. That goal was declared as achieved in 2010, but there still remained a significant portion of the world's population without access to safe, reliable, and affordable water. In 2015, the UN General Assembly introduced the post-MDG development framework in a resolution titled Transforming our world: the 2030 Agenda for Sustainable Development" [5]. From the very beginning, the Sustainable Development Goals (SDGs) were meant to be a radical, human-rights based agenda. The targets were more ambitious, with the stated goal of "universal access" to safely managed water – "on premises," "available when needed," and "free of fecal and priority chemical contamination" – under Goal 6, Target 1 [1] and an explicit attention to gender equality. Within the field of water, sanitation, and hygiene (WASH), there have also been calls for radical change, through transformative WASH interventions and programs [6, 7]. Recent large-scale trials have called into question the effectiveness of traditional interventions, motivating new thinking about strategies that can meaningfully reduce pathogen exposures in highly contaminated settings [8–10].

The recent language around progress within both water and development more broadly signals an openness to new ideas and pathways toward achieving safe water access, in order to improve health and to realize the human rights of all. My objective in the following chapters is to: (1) systematically review adherence to point-of-use chlorination products, currently a widely promoted low-cost water treatment strategy, but one that burdens poor households with the responsibility for water treatment; (2) evaluate passive chlorination technologies, a possible alternative to household-level chlorination where infrastructure exists; and (3) summarize the existing literature at the intersection of gender and domestic water access, highlighting specifically how women's roles are framed within the water literature, as those primarily responsible for domestic water management.

Household water treatment for low-cost safe water

In my first chapter, I report the results of a systematic review of adherence to household drinking water treatment studies using chlorine products. The dominant strategy for low-cost, safe water provision has been the promotion of point-of-use (POU) treatment at the individual household level. This includes strategies such as boiling, filtering, manually chlorinating in storage containers, and solar disinfection (SODIS). The emphasis on POU treatment was motivated because piped water access has been slow to expand, but it places the "last mile" responsibility on low-income households, primarily on women and girls. This treatment strategy has been considered an important interim solution, empowering poor households to realize the benefits of safe water until they can be reached by centrally treated and piped water infrastructure. However, in addition to the burden it places on those in poor households, POU treatment products have yet to be widely scaled.

Chlorine is cheap, effective, widely available, and provides continued post-treatment protection with a residual concentration of disinfectant, but levels of sustained use have been low in most intervention trials. Prior reviews have focused on health outcomes resulting from safe water interventions, leaving adherence as one of the least understood yet most important determinants of whether a health benefit will be realized. The main contribution of this chapter is to look beyond the efficacy of chlorine and to a systematic understanding of adoption and use practices in low-income settings. In doing so, I examine what factors influence adherence, contributing to a better understanding of the role that chlorine POU approaches can play toward achieving the ambitious goals of the SDGs.

A different pathway toward achieving universal safe water access

In my second chapter, I present an evaluation of two system-level water treatment technologies in piped water systems in rural Nepal. High-resource settings have incorporated centralized chlorination in water supplies for over a century, resulting in dramatic reductions in waterborne illness [11]. Nearly 75% of the world now accesses piped water, but where piped water supplies are available in low-resource settings, barriers to centralized treatment include reduced financial and technical capacity, especially in small, rural water supplies.

In recent years, an increased number of affordable options for automatic, in-line chlorination have emerged on the market. These low-cost technologies are installed in the pipeline or at the tank and automatically add chlorine without the use of electricity, providing an alternative to manual chlorination and lifting the burden of responsibility for treatment from individuals at the household level. Published evidence from urban trials of some of these options indicate that they are effective at improving drinking water quality and child health, and that they may be a sustainable treatment option where effective, utility-scale, centralized treatment systems have not worked [12–14]. However, little evidence exists to guide implementation of these technologies for rural piped water systems in low-resource settings, where access lags behind urban centers.

This chapter contributes the first extended field test of these in-line technologies in a remote, rural context. Through this work, I evaluate and offer a potentially transformative alternative to chlorine POU products in settings where high adherence may be unlikely and where appropriate infrastructure exists.

Gender and domestic water: intersections in a human rights-based framework

In Chapter 3, I use a gender lens to examine the literature on domestic water. Globally, the responsibilities for household water management are placed on women and girls, but their well-being, time, and labor are often neglected in the safe water literature. The high adherence to POU treatment that is required for health benefits, for example, depends primarily on the daily time and labor of women and girls. Approaches such as system-level, passive chlorination can increase gender equality by removing these daily burdens. Failing to understand the full consequences for women and girls leaves a major gap in our accounting of the value of accessible and safe water. Furthermore, it cannot lead to gender equality, a central aim of the Sustainable Development Goal Agenda. In this chapter, I contribute a synthesis of the literature of gender and domestic water access, highlighting the need for gender-transformative safe water work moving forward that addresses the underlying determinants of gendered health and access inequities.

The SDG Agenda and the limitations of this framework

Progress towards the SDGs is monitored with clearly defined indicators. I adopt these indicators in my dissertation, although I recognize there are limitations to this approach. Langford and Winkler (2005) cautioned against allowing the indicator to become the parent norm, e.g., meeting the MDG indicator still left billions without safe water [15]. This is clearly illustrated in the transition between the MDG and SDG indicators, when the number of people globally lacking safe water "grew" from 600 million to more than 2 billion, just by redefining the indicator.

Still, because of its influence in safe water work, I use the Sustainable Development Goals as a motivating framework. In doing so, I recognize also that there is safe water work that necessarily exists outside of the stable categories of *improved* and *safely managed* sources. I note that development proceeds under non-emergency situations, and that the role of the state as a human rights duty-bearer is complicated for stateless populations. I mention this literature briefly in Chapter 1, but it deserves additional mention here that, while development is the goal, a growing number of people globally access basic services in temporary settlements where relief is the immediate need.[1]

[1] My thinking about the limitations of the SDG framework has been broadly influenced by the work of Danielle Lantagne and Samira Siddique.

Chapter 1

Adherence to point-of-use chlorine products for household drinking water treatment: a systematic review

1.1 Abstract

Background: Centralized chlorination of urban piped water supplies has historically contributed to major reductions in waterborne illness. In low-income settings without effective centralized water treatment, point-of-use (POU) chlorination at the household level is a low-cost and widely promoted strategy for improving drinking water quality and health. Realizing these health benefits from POU water treatment requires correct, consistent, and sustained use, but real world evaluations of these products have often observed low levels of use. However, no prior reviews have been conducted to summarize the evidence on adherence to use of chlorine POU products.
Objectives: We conducted a systematic review of household POU chlorination studies that reported a measure of adherence. Our goals were to identify which indicators of adherence are most often used, summarize levels of adherence observed in chlorine POU studies, and understand how adherence changes over time.
Methods: We identified 35 studies of household drinking water chlorination products that met our pre-specified eligibility criteria and extracted data from 45 chlorine intervention groups with a variety of chlorine POU products and geographic locations.
Results: There is no consensus definition of adherence to household water treatment in the reviewed literature. The most common indicator of adherence was the proportion of house-

Chapter 1 is included here with the permission of my coauthors: Miki Tsuchiya, Magnifique Mukundwa, Isha Ray, and Amy J. Pickering.

hold stored water samples with free chlorine residual above 0.1 or 0.2 mg/L. Among studies that reported either free or total chlorine-confirmed adherence to chlorine POU products, use was highly variable (across all chlorine intervention groups, at last time point measured in study, range: 1.5-100%; sample size-weighted median: 47%). The median study follow-up duration was only 3 months. We identified examples of declining (n=8 intervention groups), sustained (n=10), and increasing (n=4) adherence. On average, adherence declined over time. Women were the primary respondents in the majority of studies.
Conclusions: Household water treatment with chlorine POU products has achieved high adherence in some settings, but adherence is highly variable across studies. While prior research has shown that chlorine POU products can improve health when correctly and consistently used, the reliance on individual adherence that is required for effective treatment is unlikely to lead to the widespread public health benefits historically associated with centralized treatment of piped water supplies.

1.2 Introduction

Chlorination of urban piped water supplies contributed to substantial declines in waterborne disease in major cities in the early 1900s [11]. Today the addition of chlorine-based disinfectants is a standard step in effective municipal water treatment processes [16]. For the more than 2 billion people globally who lack access to safe and effectively treated water [17], point-of-use (POU) chlorination at the household-level has been promoted as an alternative and interim strategy to realize the benefits of safe water in the absence of large-scale infrastructure [18]. However, there has been debate about whether or not evidence supports widespread investment in household water treatment [18–20], and recent large trials that included chlorine POU products found little to no impact on child health outcomes that have previously been linked to safe water consumption [8–10].

The key difference between the systems that have historically delivered enormous public health benefits and household-level chlorination strategies is that the latter relies on individuals to implement treatment. Modeling studies have concluded that high levels of correct, consistent, and sustained use of household water treatment products are required in order to realize the health benefits of such treatment [21, 22], and meta-analyses have confirmed that greater health benefits are associated with higher levels of adherence [23, 24]. Thus, an important question is whether or not these POU products can achieve high levels of correct and consistent use, or adherence to treatment.

Substantial research efforts have been made to identify ways to increase adherence [25]. However, adherence to POU treatment is not uniformly reported in the literature, despite being a critical determinant of the benefits for water quality or health. It is difficult to measure and lacks a standard definition. Use is commonly based on self-report or on an indirect measure, such as observed product presence in the home. Chlorine POU products offer a meaningful advantage for adherence measurement compared to non-chlorine POU products: the ability to measure chlorine in stored drinking water as an objective measure of current product use. In a recent large trial where adherence was measured through both self report and residual chlorine measurement, self reported adherence was higher than objectively measured adherence [26]. An important component of adherence is exclusive consumption of treated water. However, since this is less reported in the literature, and much harder to objectively verify, we focus here on product use.

In this systematic review, we aimed to summarize the evidence on adherence to use of chlorine POU products and factors associated with high adherence. Our objectives were to: (1) identify which indicators have been used to assess adherence in chlorine POU studies, (2) describe the levels of adherence observed across studies, (3) determine if and how adherence changes over time, and (4) assess the relationship between adherence and frequency of contact between study staff and participants.

1.3 Methods

We followed PRISMA guidelines (`www.prisma-statement.org/`) to develop a review protocol prior to beginning our search. The full protocol is available at `https://osf.io/ptc3m/`. Our search strategy was developed to first identify studies that included chlorine POU as a component of an intervention or program, recognizing that adherence is typically not considered a main outcome in household water treatment studies and therefore unlikely to be included in keywords, titles, or abstracts. The search terms for previous systematic reviews of household water treatment studies, which summarized evidence on health or water quality impacts, were used as a starting point and further refined for our purposes [23, 27].

We searched for "drinking water," "potable water," "tap water," "household water," or "domestic water," in combination with terms and brands associated with chlorine POU products: "chemical disinfectant," chlorin*, chlorate, chlorite, disinfec*, hypochlorite, "sodium hypochlorite," "calcium hypochlorite," "sodium dichloroisocyanurate," NaDCC, trichlor, Aquatab, Waterguard or WaterGuard, Klorin, Pur, "water quality," "free residual chlorine," or "free chlorine." We additionally included the names of all countries included in the World Bank 2019 low- and lower-middle income country categories and limited our search to articles published after January 1, 1990. We conducted database searches in PubMed/MEDLINE, Web of Science, Global Health (CABI: CAB Abstracts and Global Health), and Embase. We also hand searched the reference sections of four prior systematic reviews of household safe water interventions to ensure all relevant studies were included [23, 24, 27, 28]. In the course of screening full texts, we identified additional references that we screened for inclusion.

We downloaded search results from each database search and screened titles and available abstracts in Covidence systematic review software (`www.covidence.org`). Two authors independently reviewed each title/abstract. Inter-reviewer agreement at this stage was >97%

and reviewers discussed each screening conflict. Subsequently, full texts of articles were collected in a Google drive folder and assessed using full eligibility criteria. YC screened all full texts for inclusion, and 70% were screened by authors MT or MM. YC did data extraction for all included full-texts. Other authors partially replicated data extraction for 70% of texts, and AJP fully replicated this step for 10% of texts.

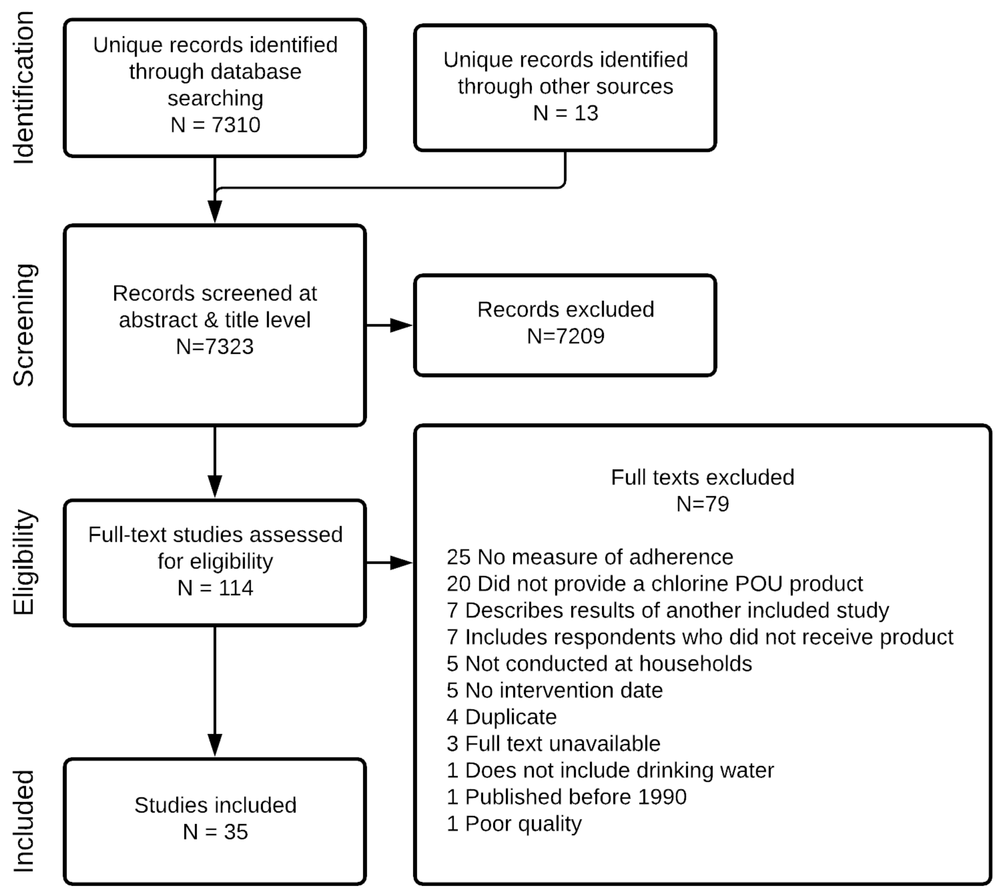

Figure 1.1: PRISMA flow diagram

Selection criteria and data extraction

Eligible studies included: (1) a clearly described drinking water intervention or program with a chlorine point-of-use product, including combined flocculant-disinfectants; (2) studies conducted in countries in World Bank low- and middle-income country categories (2019 data); (3) studies in which data were collected at households (e.g., not solely in health facilities or schools); (4) studies including a quantitative measure of adherence; and (5) an intervention or program start date. Titles and abstracts were screened for criteria 1-3; criteria 4-5 were confirmed during full text review. Cross sectional studies were eligible if the start date of the chlorination intervention could be approximated. We included all English language studies published from January 1, 1990 until our final search on March 11, 2020. Any non-English language studies identified during the hand search of prior systematic reviews were also eligible for title and abstract screening.

We extracted data related to the intervention or program design and measures of adherence. Where both self-reported and presence of chlorine are reported, we used the latter as the more objective measure. In some cases adherence was defined simply as the proportion of households with "detectable" chlorine, but we were able to infer a free chlorine residual (FCR) minimum detectable value from manufacturer information about the instruments being used. We categorized adherence as increasing if there was a 10+ percentage point increase between the first and last measure of adherence, decreasing if there was a 10+ percentage point decrease, and sustained if the change was <10 percentage points. Due to expected heterogeneity in adherence measurement and reporting, we did not plan to report a pooled summary statistic. However, we chose to make two departures from our protocol after reviewing the available data. First, we calculated median values for adherence measures that used free or total chlorine. We calculated weighted medians by multiplying the rows of observations of each group's reported adherence by its sample size prior to calculation. Second, we additionally extracted data about which individuals, if specified, were specifically targeted for product usage instruction and were the primary implementer of the intervention at the household level. Our goal was to systematically extract data identifying upon whom the non-monetary costs of household water treatment fell. Global water access data have established that women and girls are primarily responsible for water fetching [17], but less research has explicitly discussed the highly gendered household allocation of water treatment responsibilities [29, 30].

Our objective was to understand whether households use chlorine POU products if they are provided directly to them. To separate household product use from less-than-perfect implementation fidelity, which may mean products do not reach households, we excluded program evaluations that included data from households that had not received chlorine POU products. These included, for example, large scale programs that bundled chlorine POU promotion and distribution with antenatal care [31–33] and humanitarian relief efforts that distributed chlorine POU products in the aftermath of disasters that damaged water infrastructure [34–36]. We excluded studies of manual chlorine products that were installed outside of the household, which may have been associated with different barriers to and drivers of adherence (e.g., limited by availability at specific sources only, usage motivated by public peer pressure). Finally, although we did not pre-specify a method of study quality assessment, we excluded one study because the data were reported in an unusable format.

1.4 Results

Our search identified 7,323 unique results. After reviewing all available titles and abstracts, we obtained 114 full text articles to assess using full eligibility criteria (Figure 1.1). This step yielded 35 eligible texts, including 26 cluster or individually randomized controlled trials, one cross-sectional study, two program evaluations, four nonrandomized trials, one trial in which the method of intervention assignment is unspecified, and one quasi-randomized trial. Five studies had a crossover design, and studies were conducted in 16 countries. Nine studies had multiple intervention arms or were crossover trials with different chlorine POU products [37–43], or studies were conducted in more than one country [44, 45]. The results of each unique product or country arm are separately listed (Table 1.1). We pooled data from multiple arms in a single study that used the same chlorine product in the same setting but had different additional components (e.g., in combination with a safe storage container, handwashing stations, or latrines) [8, 9, 41–43, 46].

Studies were conducted in rural (n=19), urban (n=7), and periurban (n=4) settings, in addition to three studies including multiple settings, one in an internally displaced persons camp, and one with an unspecified setting description. The enrolled sample size (of chlorine POU arms) ranged from 15 households [47] to 2,737 households [8]. Nearly all provided the POU products for free for the duration of the study. The most common chlorine POU products were WaterGuard (liquid sodium hypochlorite by Population Services International), PuR (flocculant-disinfectant with calcium hypochlorite by Procter & Gamble, Cincinnati, Ohio, USA), and Aquatabs (sodium dichloroisocyanurate (NaDCC) tablets by Medentech, Wexford, Ireland).

Defining and measuring adherence

A variety of metrics were used to assess adherence to product use, and various terms were used to describe adherence, including uptake, use/usage, and compliance. The most common reported indicator of adherence was the proportion of households with stored drinking water having FCR greater than or equal to a specified threshold, typically 0.1 or 0.2 mg/L, but as high as 0.5 mg/L. The choice of threshold can significantly change conclusions about adherence. Using a threshold of 0.5 mg/L, Altmann et al. (2018) reported that 51% of households adhered to chlorine POU treatment, compared to 98% when using a threshold of 0.1 mg/L (their instrument limit of detection) [48]. A handful of studies defined adherence as "detectable" free or total chlorine without specifying a detection limit [8, 39, 41, 45, 49, 50], and one study used the smell of chlorine in stored water because no test instruments were available [51]. Two studies measured only self-reported adherence, which was defined as use "during the previous 2 weeks" [46] or undefined [37]. All others measured free or total chlorine as either a primary or secondary measure of adherence. Self-reported adherence was higher than FCR-confirmed adherence in studies that reported both (e.g., Humphrey et al. (2019) [10]; Luoto et al. (2011) [40]). Quick et al. (2002) defined compliance as "any detectable total chlorine residual," but they also measured and reported FCR. Over four time points, the percent of households with detectable total chlorine ranged from 72-95%, in contrast to 55-81% with FCR >0.2 mg/L [50]. Ten studies reported a single pooled measure of adherence across the entire study duration, but studies that reported time-point-specific measures included between one and 24 adherence measurements (across all groups, median: 3). Of the adherence results reported in Table 1.1, 17 were measured at unannounced visits, two at announced visits, 24 were not specified as either, and two were from studies that had both announced and unannounced visits. Measures of variance, such as standard deviation or range, were typically not reported with adherence results.

Table 1.1: Studies of POU chlorine products with reported adherence

Reference	Setting	Study design	# households (or other specified)**	Indicator of adherence	Last measured adherence (%)	Time point at measurement	Change in adherence (+/-/=)
Flocculant-disinfectant products: Includes PuR, PureIt, Purifier of Water, Bishan Gari (local brand in Ethiopia)							
Albert et al. 2010[37] (b)*	Kenya (rural)	RCT (crossover)	400	self-report	62	2 months	NA
Chiller et al. 2006[52] & Luby et al. 2008[53]	Guatemala (rural)	RCT	268	FCR >0.1 mg/L	44 & 1.5	10 weeks & 8.5 months	-
Colindres et al. 2007[54]	Haiti (rural)	cross sectional study	100	FCR ≥0.1 mg/L	12	1 month	NA
Crump et al. 2005[38] (a)*	Kenya (rural)	cRCT	201 family compounds	FCR >0.1 mg/L	44	pooled (5 months)	NA
Doocy and Burnham 2006[55]	Liberia (IDP camp)	RCT	200	FCR ≥0.1 mg/L	95	pooled (12 weeks)	NA
Geremew et al. 2019[39] (b)*	Ethiopia (rural)	quasi-RCT (crossover)	400	detectable free chlorine	25	2 months	=
Luoto et al. 2011[40] (c)*	Bangladesh (urban)	RCT (crossover)	600	detectable free chlorine	3	6 weeks	NA
Norton et al. 2009[56]	Bangladesh (rural)	nonrandomized trial	105 women	FCR >0.2 mg/L	43	pooled (12 weeks)	NA
Rangel et al. 2003[42] (b)*	Guatemala (rural)	RCT	60	FCR ≥0.5 mg/L	83	pooled (3 weeks)	NA
Reller et al. 2003[43] (b)*	Guatemala (rural)	RCT	199	FCR >0.1 mg/L	30	pooled (9 months)	NA
Shaheed et al. 2018[44] (a)*	Pakistan (rural)	RCT (crossover)	247	total chlorine ≥0.2 mg/L	59	8 weeks	-
Shaheed et al. 2018[44] (b)*	Zambia (urban)	RCT (crossover)	214	total chlorine ≥0.2 mg/L	18	8 weeks	-
Liquid chlorine products: Includes sodium hypochlorite, WaterGuard, Klorin/Clorin, bleach, calcium hypochlorite solution, electrochlorinator (for at-home sodium hypochlorite production)							
Albert et al. 2010[37] (a)*	Kenya (rural)	RCT (crossover)	400	self-report	76	2 months	NA
Crump et al. 2005[38] (b)*	Kenya (rural)	cRCT	203 family compounds	FCR >0.1 mg/L	61	pooled (5 months)	NA
Geremew et al. 2019[39] (a)*	Ethiopia (rural)	quasi-RCT (crossover)	400	detectable free chlorine	41	2 months	=
Humphrey et al. 2019[10]	Zimbabwe (rural)	cRCT	2035 women****	FCR >0.1 mg/L	58	12 months	NA
Luby et al. 2001[57]	Pakistan (urban)	trial (unclear if randomized)	50	FCR >0.1 mg/L	71	pooled (10 weeks)	NA

Table 1.1 continued from previous page

Reference	Setting	Study design	# households (or other specified)**	Indicator of adherence	Last measured adherence (%)	Time point at measurement	Change in adherence (+/-/=)
Luoto et al. 2011[40] (a)*	Bangladesh (urban)	RCT (crossover)	600	detectable free chlorine	11	6 weeks	NA
Macy and Quick 1998[58]	Nicaragua (rural)	nonrandomized trial	100	FCR >0.1 mg/L	52	3 months	NA
Mellor et al. 2015[59]	Guatemala (rural)	RCT	34	FCR $\geq$0.2 mg/L	65	7 months	-
Mengistie et al. 2013[60]	Ethiopia (rural)	cRCT	286	FCR $\geq$0.2 mg/L	77	12 weeks	=
Murray et al. 2020[61]	Haiti (periurban)	nonrandomized trial	60	FCR >0.1 mg/L	13	13 months	-
Null et al. 2018[8]	Kenya (rural)	cRCT	2737	detectable free chlorine	21	2 years	-
Opryszko et al. 2010[46]	Afghanistan (rural)	cRCT	607	self-report	80	1 year	NA
Potgieter et al. 2009[41] (a)*	South Africa (rural)	RCT	20	detectable free chlorine	88	3 months	=
Potgieter et al. 2009[41] (b)*	South Africa (rural)	RCT	20	detectable free chlorine	98	3 months	+
Quick et al. 1996[47]	Bolivia (urban)	RCT	15	FCR $\geq$0.1	100	9 weeks	=
Quick et al. 1999[49]	Bolivia (periurban)	RCT	64	detectable total chlorine	95	6 months	+
Quick et al. 2002[50]	Zambia (periurban)	nonrandomized trial	166	detectable total chlorine	85	13 weeks	+
Rangel et al. 2003[42] (a)*	Guatemala (rural)	RCT	20	FCR $\geq$0.5 mg/L	83	pooled (3 weeks)	NA
Reller et al. 2003[43] (a)*	Guatemala (rural)	RCT	197	FCR >0.1 mg/L	40	pooled (9 months)	NA
Sobsey et al. 2003[45] (a)*	Bangladesh (urban)	RCT	~138	detectable free chlorine	89	pooled (8 months)	NA
Sobsey et al. 2003[45] (b)*	Bolivia (periurban)	RCT	~70	detectable free chlorine	77	pooled (6 months)	NA
Sugar et al. 2017[51]	Kenya (urban)	program evaluation	392 children	smell of chlorine	97	pooled (12 months)	NA
Tablet chlorine products: Includes Aquatabs							
Altmann et al. 2018[48]	Chad***	cRCT	850 children	FCR $\geq$0.1 mg/L	98	2 months	=

Table 1.1 continued from previous page

Reference	Setting	Study design	# households (or other specified)**	Indicator of adherence	Last measured adherence (%)	Time point at measurement	Change in adherence (+/-/=)
Boisson et al. 2013[62]	India (urban/rural)	RCT	1080	FCR $\geq$0.1 mg/L	47	12 months	+
Clasen et al. 2007[63]	Bangladesh (urban)	RCT	50	FCR $\geq$0.1 mg/L	100	4 months	=
Ercumen et al. 2015[64]	Bangladesh (rural)	RCT	600	FCR $\geq$0.2 mg/L	79	1 year	-
George et al. 2016[65]	Bangladesh (urban)	cRCT	84	FCR $\geq$0.2 mg/L	94	pooled (9 days)	NA
Jain et al. 2010[66]	Ghana (periurban)	RCT	120	FCR $\geq$0.2 mg/L	83	12 weeks	=
Luby et al. 2018[9]	Bangladesh (rural)	cRCT	2086 compounds	FCR >0.1 mg/L	84	2 years	=
Luoto et al. 2011[40] (b)*	Bangladesh (urban)	RCT (crossover)	600	detectable free chlorine	10	6 weeks	NA
Pickering et al. 2015[13]	Bangladesh (urban)	cRCT	90	total chlorine >0.1 mg/L	55	10 months	-
Multiple products: Includes PuR, WaterGuard							
Blanton et al. 2010[67]	Kenya (rural)	program evaluation	662	FCR $\geq$0.1 mg/L	18	13 months	=
Granular chlorine products: Includes Klorfasil							
Tsai et al. 2020[68]	Haiti (rural)	cRCT	447	FCR $\geq$0.5 mg/L	27	180 days	-

Table note: RCT = randomized controlled trial; cRCT = cluster randomized controlled trial; FCR = free chlorine residual; IDP = internally displaced persons
*Albert et al. (2010) [37], Crump et al. (2005) [38], Geremew et al. (2019) [39], Shaheed et al. (2018) [44], Luoto et al. (2011) [40], Potgieter et al. (2009) [41], Rangel et al. (2003) [42], Reller et al. (2003) [43], and Sobsey et al. (2003) [45] had multiple eligible chlorine intervention arms which are separately listed because they have different settings or chlorine products. We pooled intervention arms with the same product, even if other intervention components differed.
** Includes sample size in chlorine arm only; *** Urban, rural, or periurban not specified and could not be inferred from main text;
**** FCR was measured in only 752 households; self-reported adherence across the entire sample was 87%.
Change in adherence: + indicates 10+ percentage point increase from first to last measure; - indicates 10+ percentage point decrease; = indicates <10 percentage point change

Observed levels of adherence across studies

Final reported adherence was highly variable and was not associated with study length (Figure 1.2). We fit a linear trendline, modeled using a generalized linear model fit to all adherence data points weighted by sample size (across all groups, pooled n=18,277). The studies reporting FCR-confirmed ($\geq$0.1 or $\geq$0.2 mg/L) adherence at any time point ranged from 1.5% [53] to 100% [47, 59, 63]. Of the studies that confirmed adherence with either free or total chlorine, eight groups had >90% adherence [41, 47–49, 51, 55, 63, 65] and two had <10% adherence at the final time point measured [40, 53]. Sugar et al (2017) also reported >90% with adherence defined as having the smell of chlorine in stored water [51]. The rest reported adherence ranging from 10-90% at the final time point measured. With the exception of Luby et al. (2018) and Null et al. (2018), which included 2 years of follow-up [8, 9], study durations were 13 months or less.

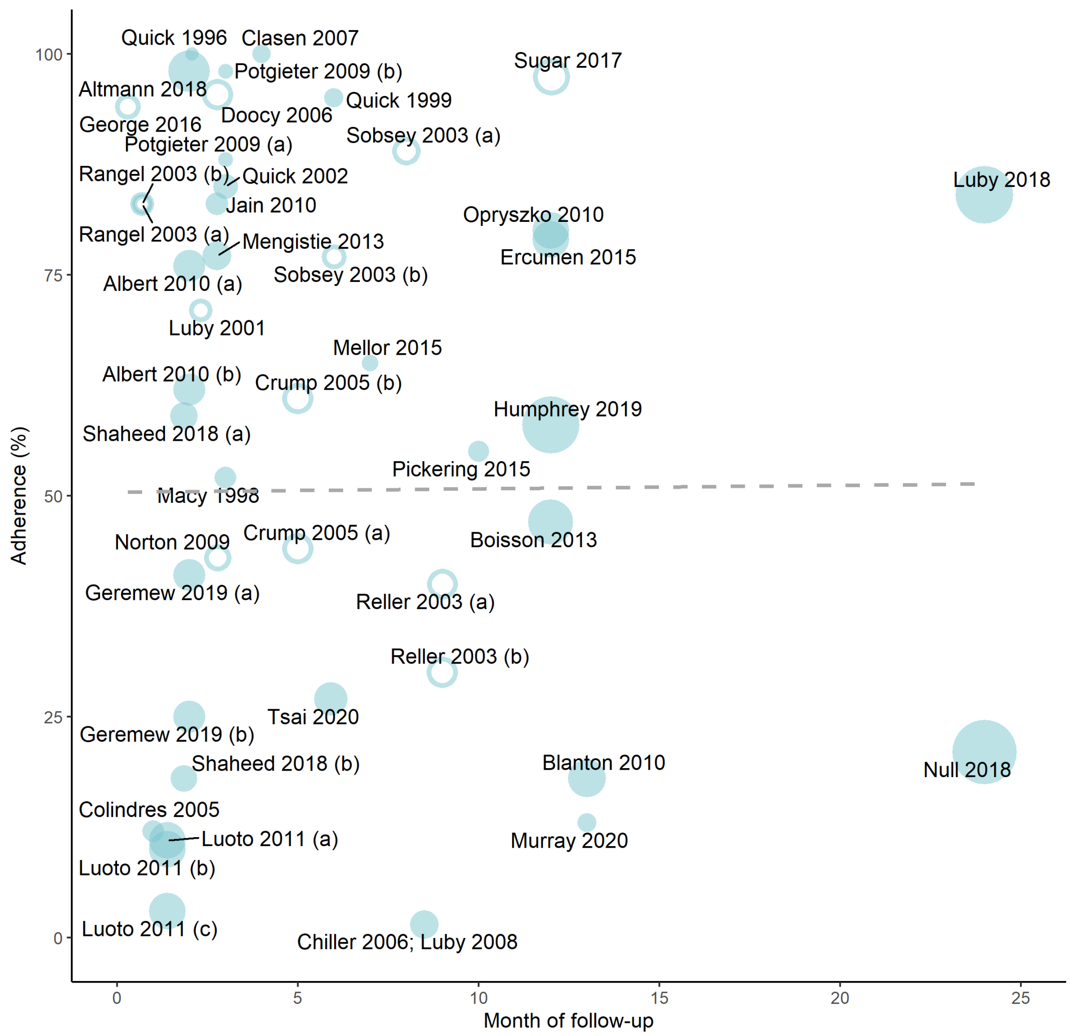

Figure 1.2: Final reported adherence

Figure note: The point sizes are scaled to indicate relative sample size (of the group(s) receiving chlorine only). Open circles indicate that the data point is reported as multiple adherence measures pooled over the months of follow-up up until the time point shown. Closed circles are a single time-point result. Opryszko et al. (2010) [46] and Albert et al. (2010)(a/b) [37] used self-reported adherence; Sugar et al. (2017) [51] used the smell of chlorine in stored water as adherence; the rest used either free or total chlorine to measure adherence.

Changing adherence over time

On average, adherence declined slightly over time, although some groups had increasing or sustained adherence. Among all studies that reported multiple time-point-specific measures of adherence, adherence increased in four chlorine intervention groups, decreased in eight groups, and was sustained in ten groups. The total pooled sample size was similar for increasing and sustained adherence studies, but there were approximately 1/3 as many observations across all decreasing adherence studies. Data at longer follow-up time points are from only a few studies. We plotted data from studies that reported one or more single-time-point adherence measurements and provided products entirely for free (Figure 1.3), which included one study with self-reported adherence [46]. The linear trendline, which we modeled using a generalized linear model fit to all adherence data weighted by group sample size (n=52,349 measures), shows a slight downward trend over time (dashed line, Figure 1.3). However, we note that data from >13 months after intervention delivery are from only two related studies (WASH Benefits Bangladesh [9]; WASH Benefits Kenya [8]).

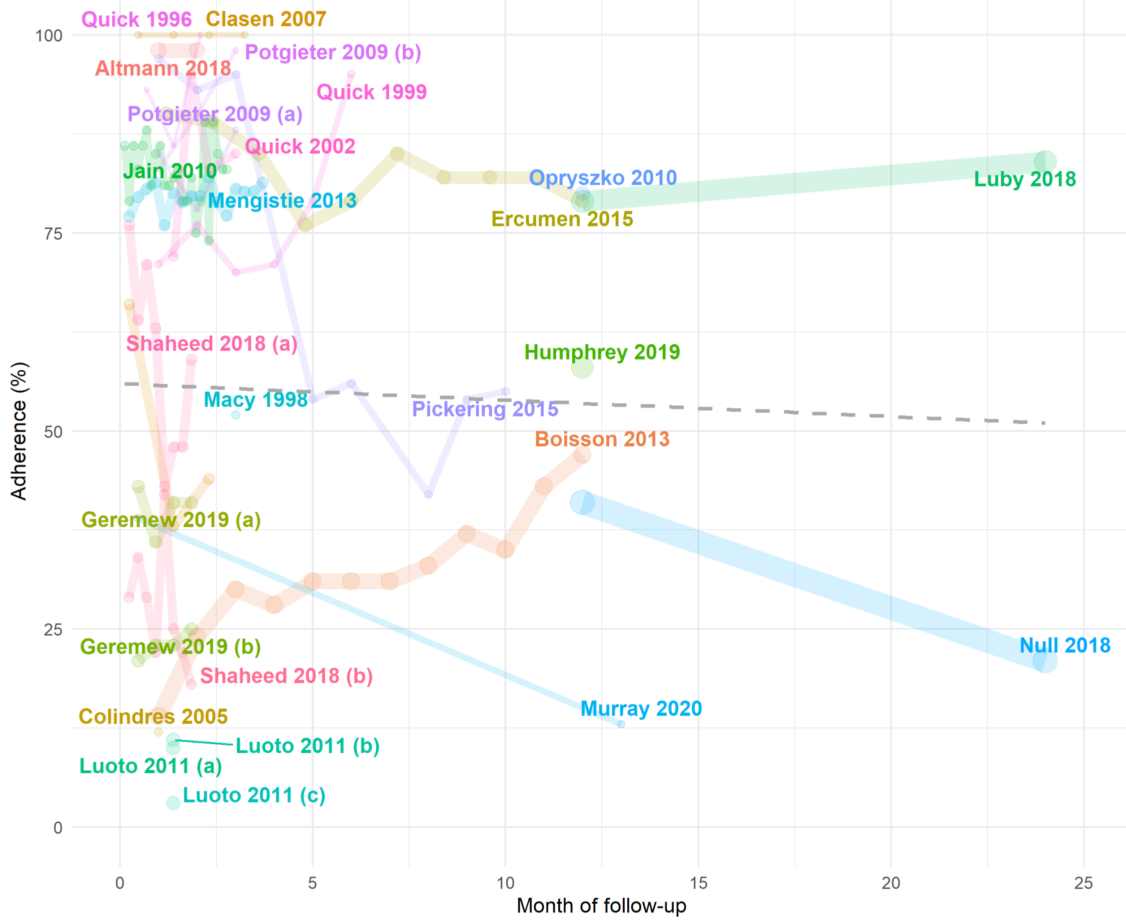

Figure 1.3: Reported product adherence over time after the start of intervention

Figure note: The line width is scaled to indicate relative sample size (of the group(s) receiving chlorine only). The studies in the graph are restricted to studies reporting one or more single-time-point measures of adherence and provided chlorine products entirely for free for the study duration. The latter restriction excludes Tsai et al. (2020) [68], Blanton et al. (2010) [67], Mellor et al. (2015) [59], and Luby et al. (2008) [53] (the final time point follow-up to Chiller et al. (2006) [52]). Among the studies included here, only Opryszko et al. (2010) [46] had only self-reported adherence.

Contact frequency between participants and study staff

Adherence was positively associated with contact frequency between study participants and study staff across studies (Figure 1.4) and within studies as well. Restricting to studies that used free or total chlorine-confirmed use, adherence ranged from a weighted median of 84% when households were visited one or more times per week by study staff, to 47% when visits were once or more per month, to 11% with less frequent visits (Figure 1.4). In a cluster randomized controlled trial in urban Dhaka [13], the intervention included biweekly promotional visits for the first half of the 10 month study, and adherence was greater than

90% when promotions were ongoing. After these visits concluded, free delivery of Aquatabs and water quality testing continued, but adherence quickly dropped by approximately 50% and remained relatively stable (42-56% from months 5-10). In a 2-year cluster randomized controlled trial in rural Kenya, Null et al. (2018) observed adherence decline by around 50% between year 1, during which households received monthly promotional visits, and year 2, when households were visited approximately every other month [8].

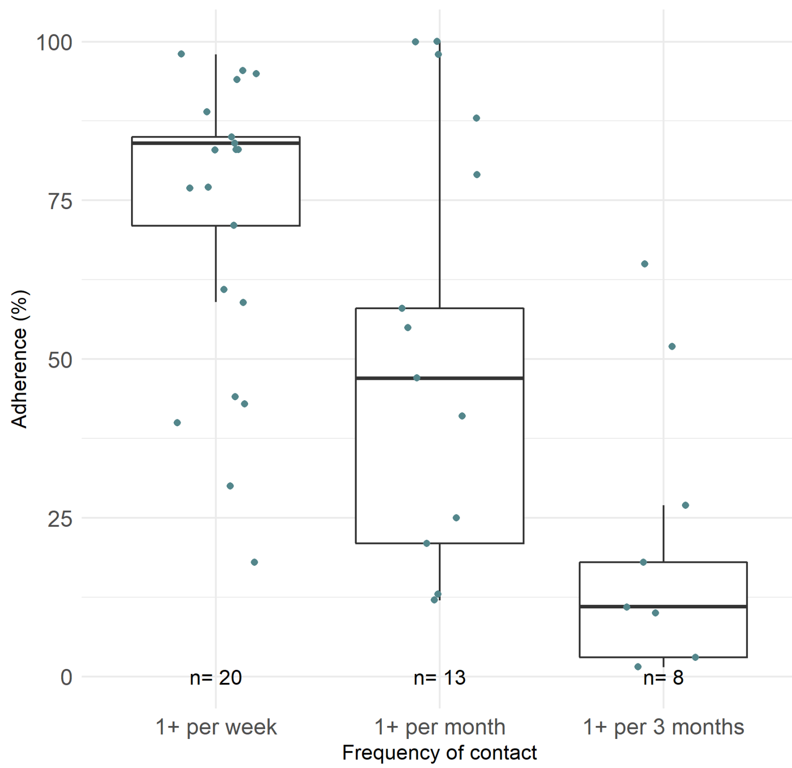

Figure 1.4: Contact frequency and final measured adherence

Figure note: Weighted box plots showing the relationship between contact frequency over the study and final measured adherence, restricted to only groups that used FCR or total chlorine to measure adherence. This excludes Opryszko et al (2010) [46], Albert et al (2010)(a/b) [37], and Sugar et al (2017) [51]. Studies were weighted by sample size and 25th, 50th, and 75th percentiles of the pooled data are displayed above. This includes studies that report single-time-point and pooled adherence measures.

Type of chlorine product and adherence

Across all groups, 22 received liquid chlorine products, including branded products such as WaterGuard and Clorin/Klorin, and generic sodium hypochlorite. One group received a locally mixed calcium hypochlorite solution [47]. Twelve groups received flocculant-disinfectant products, most commonly PuR brand, but one study in Ethiopia used a local product called Bishan Gari [39]. Nine groups received tablets, all Aquatabs brand. Tablet chlorine product interventions had the highest adherence (weighted median: 84%), followed by liquid products (weighted median: 41%), then flocculant-disinfectants (weighted median: 25%) (Appendix Figure A.1).

Barriers to use

Reasons for non-use of products, reported by respondents, were provided for only 23 of the 45 groups. This suggests that, much of the time, the reasons for low adherence are poorly understood simply because the relevant data are not systematically collected. Bad taste, smell, or appearance of treated water was identified by households in 17/23 groups (74%), and lack of time was identified in 10/23 groups (43%). Although most of the studies provided products for free, 4/23 groups (17%) identified price or availability as a barrier to repurchase and continued use. Often, however, each of these reasons was reported by a small proportion of households. Several studies emphasized reasons for use rather than non-use, reporting instead that households had a preference for treated water [13, 38, 54, 55, 66] or that households felt the time required to treat was worth it (e.g., Reller 2003 [43]).

Taste and smell concerns

The included studies suggest that taste and smell concerns can be a reason for non-use, but they are not universal barriers. In Ethiopia, the majority (66%) of households said they disliked the chlorine taste [39]. In rural South Africa, use of 3.5% sodium hypochlorite was actually slightly higher than use of 1% solution, although households in the former group did mention disliking the taste of water and the sample size was small [41]. However, in both studies that evaluated chlorine POU products in humanitarian settings, respondents reported that they preferred the taste of the chlorinated water over the untreated water [54, 55]; so did respondents in some households in non-emergency situations [66]. In urban Bangladesh, where FCR-confirmed use of Aquatabs, WaterGuard, and PuR was less than 15%, only around half of respondents said, unprompted, that taste and smell were obstacles to use [40].

The success that blinded studies have had in blinding participants to treatment assignment also suggests that taste and smell are not the overwhelming problems sometimes ascribed to chlorination. Two blinded, placebo-controlled trials with Aquatabs, Jain et al. (2010) and Boisson et al. (2013), found no difference between placebo and chlorine arm respondents in their beliefs about their group assignment. Jain et al. (2010) found that 16% of respondents overall said the tablets made their water taste better, compared to 2% and 1% reporting bad smell and taste, respectively [66]. However, Boisson et al. (2013) found higher dissatisfaction with taste and smell among the intervention group compared to the placebo group [62].

Price of chlorine POU products

All but three studies provided the chlorine POU products free to respondents for the study duration, and one text [53] reported data from households 6 months following the conclusion of the original study [52], after which households could continue to purchase the product on their own. Blanton et al. (2010) provided rural Kenyan schoolchildren with free samples of PuR to take home to parents, after which they could repurchase the widely available products in the markets [67]. In rural Haiti, Tsai et al. (2020) provided half of respondents with a free trial of Klorfasil, a granular chlorine POU product, followed by the opportunity to purchase at a subsidized price. The other half received no free trial. While over half of respondents repurchased the product, few had FCR in stored water [68]. In Mexico, Mellor et al. (2014) provided households with a free bottle of sodium hypochlorite, with the option to later purchase a 6-month supply for 3.14 USD from a local distributor [59]. In rural Guatemala, >90% of households reported that they would be willing to pay half the market price for PuR (0.14 USD to treat 10L of water), but only 1.5% had FCR in stored water [53]. Across these 4 groups, adherence ranged from 1.5% to 65%.

Gender and the time cost of chlorine POU interventions

The time required to treat was the second most reported reason for non-use by respondents, and this time burden was primarily placed on women. Women were the primary respondents in 35/45 groups, targeted for inclusion as either the primary caretaker of young children or the individual in charge of household water management. In one study in rural Afghanistan, intervention messaging was targeted to female caretakers, but nearly half of households allowed only males to participate as respondents [46]. In the remaining studies, the gender of respondents was not addressed. In Guatemala, Luby and colleagues observed very low (1.5% of stored water with FCR 8.5 months after the start of intervention) sustained use of PuR for drinking water treatment, and respondents reported lack of time as one reason for non-use. The authors observed: "Female heads of household already spent substantial time collecting water and on other innumerable household tasks required for family survival in a low-income setting. Using the flocculant disinfectant required extra steps for water treatment and extra time spent washing the filter cloths" [53]. Norton et al. (2009) provided step-by-step instructions for treatment with flocculant-disinfectant, which included a 5-minute stirring step, a 5-minute settling step, then filtering through a cloth before letting the filtered water sit for 20 minutes for disinfectant contact time. Respondents, all women, used a median 11 (range 0-48) flocculant disinfectant sachets per week. Assuming 10 minutes of active time required, from stirring to filtering, that comes to 110 (range: 0-480) minutes per week spent actively treating water. Including the 20 minute wait time, that increases to 330 (range: 0-1440) minutes weekly spent treating and waiting for water before safe use [56]. Rangel et al. (2003) reported three 30-second stirring and 5-minute waiting periods before filtering through a cloth, approximately 17 minutes of active time required. 94% of respondents were female and the reported median daily household drinking water consumption was 7 liters. Assuming once daily treatment, with each sachet treating 10 liters, that comes to 119 minutes of active time allocated to water treatment per week. Other estimates of daily household water volumes used were much higher [42]. Altmann et al. (2018) estimated that families would need to purify 40 liters of water per day, and the intervention provided sufficient tablets for 3 months of daily treatment of this volume [48]. Doocy and Burnham (2006) estimated 40 minutes as the total time required to treat water with PuR, including the stirring, filtering, and waiting steps, although this was not reported as too time consuming by participants in an internally displaced persons camp [55].

Institutional intervention settings

Although the majority of studies were in households, a handful of studies in non-household settings achieved high adherence. Three chlorine POU interventions delivered at health facilities in combination with treatment for cholera [65], severe acute malnutrition [48], and pediatric HIV care [51] resulted in adherence ranging from 94% to 99% observed at household follow-up visits. George et al. (2016) did a randomized controlled trial to evaluate a hospital-based intervention that included Aquatabs to reduce the spread of cholera from patients to household members in urban Bangladesh. When cholera patients were discharged from the hospital, they and their family members received an educational module by a trained health promoter and a cholera prevention package consisting of a 3-month supply of Aquatabs, soap, handwashing station, water storage container, and pictorial instructions. The household then received daily promotional visits for one week, in addition to 5 data collection visits from a separate team. Pooled adherence (FCR $\geq$0.2 mg/L) across all data collection visits was 94% among households who received the intervention [65]. Six to 12 months later, in structured observations, intervention households boiled drinking water 52% of the time, compared to 26% in control group households [69]. Because households may not have had access to the chlorine POU products after the intervention, we do not include the follow-up data point as the final measure of adherence (Table 1.1). However, the results suggest that the intervention may have increased use of household water treatment overall, even if not specifically of chlorine products.

Sugar et al. (2017) evaluated a program that distributed water storage containers, hypochlorite solution for drinking water treatment, soap, and insecticide treated bed nets in a program designed to reduce diarrhea and malaria among children living with HIV in periurban Kenya. Enrolled children had hospital appointments every 1-3 months. Households received announced visits approximately every 2 months over the year-long study (median: 8 visits total) from community health workers who promoted the program, provided product refills, and monitored adherence, which, for water treatment, was defined as having stored water with a chlorine odor. Adherence was 97% [51].

Altmann et al. (2018) did a cluster randomized controlled trial to evaluate the benefits of a water, sanitation, and hygiene package added to clinic-based treatment of severe acute malnutrition in Chad. Households received a safe storage container, a 3-month supply of Aquatabs, soap, a plastic cup, and pictorial instructions with hygiene messaging, plus weekly promotions during treatment visits at the health center. The 2-month intervention included 2 home visits, and 98-99% of households had FCR $\geq$0.1 mg/L at monthly visits [48].

One school-based program resulted in a moderate but sustained increase in chlorine POU product use relative to baseline. Blanton et al. (2010) evaluated a school-based program that delivered drinking water and handwashing infrastructure in schools in rural Kenya, PuR for drinking water treatment, WaterGuard for hand washing water (which kids sometimes drank), and educational comic books and samples of PuR for kids to take home to their parents. Seventy-two percent of households (n=662) reported that they practiced some form of water treatment prior to the program, although only 7% of primary caregivers had ever used either PuR or WaterGuard, and there was widespread awareness of both products through mass media. Use of either WaterGuard or PuR, as confirmed by FCR >0.1 mg/L, was 21% at four months and 18% at the 13-month follow-up. The program did not include regular household visits or products beyond an initial sample of 3 free sachets of PuR, but it was in a setting with mass media promoting the products. The main self-reported reasons for non-use were cost and a belief that the product was not needed [67].

Humanitarian intervention settings

Two included studies reported high adherence in humanitarian settings [54, 55]. Colindres et al. (2007) interviewed 100 households that had received free PuR following a 2004 tropical storm in Haiti. Before the storm caused damaging floods, 37% of households reported treating drinking water, primarily with hypochlorite powder or boiling, and PuR was not locally available prior to the flooding. Approximately one month after distribution of PuR, 22% of households reported having stored water treated with PuR when interviewed, although 92% reported that they had used PuR in the prior week. Marketing of PuR was through the radio, community demonstrations, and word of mouth from community leaders and neighbors. Although nearly all (97%) of respondents said that "PuR-treated water appears, tastes, smells, and is healthier," less than a quarter stated that they would be willing to pay the product's market price [54]. Doocy and Burnham (2006) did a 12-week trial of PuR with a water storage container in an internally displaced persons camp in Liberia. Additional free sachets were provided at weekly diarrhea monitoring visits; households were additionally visited weekly for unscheduled water quality testing. Across all weekly water testing visit measures, 95% had FCR present, with lowest adherence in the first week (90%). FCR was $\geq$0.5 mg/L in 85% of visits. The study additionally included focus group discussions with participants, who reported that they preferred the taste of the chlorinated water over untreated water and that they noticed less diarrhea in their household [55].

1.5 Discussion

In this systematic review, we found a wide range in adherence to chlorine POU product use. On average, adherence declines over time, but the relatively short follow-up in most of the included studies limits our understanding of the long-term use of chlorine POU products. Notably, our search strategy selected for closely monitored trials versus programs. The former is more likely to have a short duration and intensive promotion, given the resources required for intervention studies. Despite the relatively short follow-up periods in the included studies, an important implication is that the observed levels of adherence described here are overestimates of the adherence likely to be observed long-term in programs that cannot continue the contact frequency of high intensity interventions.

There was no standard definition of adherence to chlorine POU water treatment across studies, although the proportion of households with FCR above a threshold is most likely to capture both correct and consistent use. Although authors did not always explain the choice of FCR threshold that indicated adherence, 0.2 and 0.5 align with widely used drinking water guidelines. The Sphere Handbook, used in humanitarian response, recommends FCR $\geq$0.2-0.5 mg/L at the point of delivery for household water [70]. World Health Organization Guidelines for Drinking Water recommend that a minimum 0.2 mg/L FCR (and maximum 5 mg/L) be present at the point of delivery [71]. The threshold 0.1 mg/L aligns with the minimum detection limit of some chlorine testing instruments which use the N,N-diethyl-p-phenylenediamine (DPD) colorimetric method, by far the most common method for chlorine measurement used in the included studies. Use of FCR as a metric of adherence captures whether water is safely protected, but it underestimates usage, for which total chlorine may be a more appropriate indicator. The observation by Quick et al. (2002) that adherence measured by total chlorine is higher than that measured by free chlorine suggests that, while not all households were dosing as instructed, more households may have been consistently using chlorine than would be suggested by FCR testing only [50]. Objective measures such as FCR and total chlorine are preferable to self-reported usage, which is subject to courtesy bias and varies widely in its definition across studies. Since correct and consistent water treatment is required to realize health benefits, self-reported usage defined as, for example, "in the prior 2 weeks," is uninformative. Because of this non-standardized measurement and reporting, claims of "high" adherence, which appeared in several texts, provide little information without clearly defining the indicators that are used. When reporting adherence, single time point measurements are more informative than measures pooled over the duration of a study, due to the variability in adherence over time and because pooled measures across time points do not allow adherence to be linked to outcomes measured at single time points.

We found a positive association between contact frequency and adherence, suggesting that near-weekly contact between households and study staff may be necessary to sustain high adherence. This finding makes sense in the context of health behavior change theories [25]. Each contact with study staff, for any reason, provides households with a reminder or nudge to action [72], increasing the likelihood of habit formation, and this has important implications for health interventions. A recent article that reviewed POU safe water interventions and health impacts found that interventions with demonstrated reductions in diarrheal illness had higher frequency of contact between participants and study staff at levels often considered infeasible at large scales [7]. Efforts to replicate and scale household water treatment interventions that have been successful in trials must consider the field staff resources that were required to achieve high adherence.

We also noted higher adherence for tablet products, compared to liquid or flocculant-disinfectant products. Tablets have greater ease of use and convenience compared to liquid products [73], which may require measuring out the correct dose and which require more product for dosing use because they are typically diluted to around 1%. Flocculant-disinfectants, which require separate mixing and filtering steps, also require more effort for use than tablets. In settings where high contact frequency is possible, or in humanitarian, emergency, or outbreak situations where adherence is typically higher, these results suggest that tablet products may be more effective in achieving high levels of use, compared to liquid or flocculant-disinfectant products.

The evidence to date suggests it is unrealistic to rely solely on household-level treatment to realize the benefits of safe water at the necessary scales. The historical public health benefits of centrally treated piped water [11] are often cited as evidence of the importance of safe water interventions. However, in this utility model, in which water is effectively treated at a centralized facility and then distributed through pressurized pipe networks to in-home taps, the responsibilities for correct, consistent, and sustained use are not on individuals in households. The in-effect 100% adherence provided by effective centralized systems contrasts starkly with the adherence observed in real-world evaluations of household water treatment products. At the same time, the infrastructure limitations that first motivated household water treatment approaches are changing. Since 2000, more than one billion people have gained access to piped water [17], and passive, in-line chlorination technologies are one example of safe water solutions that are increasingly compatible with this piped infrastructure. In urban Bangladesh, where researchers have generally observed low adherence to chlorine POU product use [40, 74], a decentralized, passive chlorination technology had high acceptability and reduced child diarrhea by nearly a quarter [14]. This approach is closer to the centralized utility model in that the burden of treatment is not on individuals.

There is a non-zero demand for chlorine POU products, however, and it would be a mistake to dismiss the results of household water treatment trials as evidence that household water treatment should never be implemented. Chlorine POU provision at health facilities and in an internally displaced persons camp achieved 94% and higher adherence, suggesting that settings in which health risks are front-of-mind may motivate increased use of chlorine POU products [48, 51, 55, 65]. Even with lower sustained adherence, chlorine POU may still be a worthwhile investment in some settings. Ahuja et al. (2010) calculated that a 20-40% reduction in child diarrhea, on par with pooled effect estimates across studies with <100% adherence [23], makes chlorine POU a cost effective health intervention [75]. In Kenya, where mass media promotion of household water treatment was ongoing and products were already widely available in markets, a school-based program to provide targeted education and promotion through students resulted in a sustained, though moderate, increase in use of chlorine POU products [67]. In urban Bangladesh, around half of households continued to use freely provided Aquatabs to treat their water for several months after promotional visits ended, although water quality testing continued [13]. In some settings, the level of sustained demand is unclear, because households may not have had long-term access to the products that are so intensively promoted in shorter-term trials, although there may be other sustained and beneficial changes to household safe water behaviors [69]. While household water treatment with chlorine products may not be a cost effective approach in all settings, it can play an important supporting role in providing safe water in some settings.

One aspect that remains neglected in chlorine POU evaluations is the gendered time and labor cost of household water treatment. The time required to treat was identified as a barrier to water treatment by respondents, the majority of whom were women and targeted because of their roles as household water managers and primary caretakers of young children. The non-monetary costs, particularly on mothers, of interventions designed to improve child well-being are often unacknowledged and implicitly set to zero [76]. While the burden of water fetching on women and girls is widely acknowledged and even quantified in global statistics [17], the gendered work of household water treatment receives little attention. In settings with "innumerable household tasks required for family survival" [53], the non-monetary costs of household water treatment challenge the notion that chlorine POU treatment is simply the cost of a bottle of diluted bleach. The household burdens placed on women and girls in low-income settings are added to the everyday stresses of poverty, described by Mullainathan and Shafir (2013) [77] as a "bandwidth tax" and further discussed in relation to safe water by Ray and Smith (2021) [78]. When daily survival is a struggle, even an extra 30 minutes a day to chlorinate and wait for water can be burdensome. These are tasks that behavioral economists have alluded to as "small hassles," seemingly minor but very real barriers in the everyday lives of the poor [79]. These issues are not unique to chlorine POU products – other POU options such as boiling, solar disinfection, and filters all require time and labor for use and maintenance.

There are some limitations to our review. First, our inclusion criteria excluded some studies that are relevant for understanding the use of chlorine POU products, including large-scale programs bundled with antenatal care, disaster relief efforts, and social marketing campaigns (see Methods). Second, we did not address user preferences for chlorine POU when other POU options are available, nor did we examine (relative) adherence to other POU methods. Burt et al. (2017) did not report adherence for individual chlorine products and was therefore excluded from our review, but study respondents ranked and preferred both boiling and pot filters over WaterGuard and PuR, although self-reported adherence to all POU methods was high (average 85% and 91% across two sites) [29]. Luoto et al. (2011) observed very low adherence (<30% self-reported) across all POU products, but use was slightly higher for siphon filters compared to Aquatabs, WaterGuard, and PuR [40]. The results from these studies indicate that non-chlorine products may be preferred over chlorine products, when available, but also that if adherence to chlorine POU is very low, adherence to non-chlorine POU is likely to be similar, and vice versa.

Our review has several strengths worth noting. First, we designed a broad search strategy in order to capture the loosely defined construct of adherence to household water treatment. Although high adherence is an important determinant of health impact, it is not measured or reported in any standardized way, in contrast to the increasingly standardized primary health outcomes that are common across these studies. Our approach allowed us to systematically identify available adherence data in the literature. Second, in studies where they are available, we extracted multiple adherence data points and frequency of contact between participants and study staff. This allowed us to observe changing adherence over time within studies and to link adherence to intensity of behavior promotion and staff visits. Third, we extracted and emphasized the available data on the gendered burden of POU adherence, showing that "low-cost" chlorination products are as low cost as they are in part because no value is assigned to intra-household care work.

We were motivated to conduct this systematic review in part because recent large-scale trials that included chlorine POU interventions had small or no effects on child health outcomes that have been linked to safe water consumption. At the same time, the historical public health benefit of chlorinating water supplies is undisputed. A key difference between these two modes of water access is the reliance on systems versus households to implement the treatment, and while there is a non-zero sustained demand for chlorine POU products, the evidence to date suggests that this approach will not achieve the widespread public health benefits of system-level safe water solutions. For households that do adopt chlorine POU products, future research should examine how to ensure and measure affordable and sustained access to chlorine POU products following trials. Finally, where appropriate infrastructure exists, the safe water community should enhance efforts toward evaluating, implementing, and maintaining system-level treatment options. The effectiveness of chlorination for safe water depends as much on the mode of delivery as it does on the disinfection efficacy of the chlorine itself.

Acknowledgements

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Chapter 2

An evaluation of system-level, passive chlorination in gravity-fed piped water systems in rural Nepal

2.1 Abstract

Over 2 billion people globally lack access to safe water. In contrast to household-level treatment products that have been the dominant strategy for gaining low-cost access to safe drinking water, passive chlorination technologies have the potential to treat water and reduce the need for individual behavior change. However, few studies exist which evaluate the performance and costs of these technologies over time, especially in small, rural systems. We conducted a nonrandomized evaluation of two passive chlorination technologies for system-level water treatment in six gravity-fed, piped water systems in small communities in the hilly region of western Nepal. We monitored water quality indicators upstream of the treatment, at taps, and at households, as well as user perceptions and maintenance costs over one year. At baseline, over 80% of tap samples were contaminated with *E. coli*. After one year of system-level chlorination, only 7% of those same taps were contaminated, despite a decline in pretreatment water quality. The cost of chlorine per cubic meter of water was 0.06-0.09 USD and monitoring costs were comparable. Service delivery models should be explored to

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ensure long-term sustainability, but passive chlorination technologies have the potential to radically improve how rural households gain access to safely managed water.

2.2 Introduction

Access to safe drinking water is a human right and a public health priority [4], yet over 2 billion people globally lack access to clean, affordable, and reliably supplied water [71]. This contributes to a high global burden of diarrheal disease, estimated to be the 8th leading cause of death around the world [2]. While country-level measures of access show improving trends overall, these data mask within-country spatial inequalities. For example, rural areas lag behind urban areas in water access across all regions of the world [1].

Point-of-use (POU) drinking water treatment at the household-level has been the dominant strategy for ensuring safe drinking water where effective, centralized treatment systems do not exist [18, 27, 28]. POU treatments, such as household filters, solar disinfection (SODIS), boiling, or manually adding chlorine products, require daily behavior change and place the responsibility for treatment on individuals within households; these individuals tend to be women and girls, who are most often tasked with household water management [30]. Modeling studies have concluded that near perfect levels of correct, consistent use of POU water treatment are required to realize their health benefits, yet lower use is typically observed in real world trials of POU interventions [21, 22].

In low-resource settings where piped water infrastructure exists but centralized treatment is inadequate, passive in-line chlorination technologies are being implemented as a potential alternative to POU options, and several new technologies have been developed and tested in recent years [14]. Because of their limited treatment capacity as compared to centralized treatment infrastructure, they may be appropriate at a decentralized scale in an urban distribution network, e.g., for a small neighborhood or apartment building. However, some technologies may be suitable as a fully centralized treatment option for small, rural village water supplies. The relative simplicity of these technologies may be especially appropriate for such settings, since size and resources limit the operation and maintenance of full-scale water treatment facilities.

This chapter presents a nonrandomized evaluation of two passive chlorination technologies for system-level water treatment in six gravity-fed, piped water systems in small communities in Karnali Province, located in the hilly region of western Nepal. Approximately half of the rural population in Nepal is estimated to have access to piped water [80]. An assessment of microbial water quality during October through December in communities of this region found that 68% of water sources and 81% of household stored water samples were fecally contaminated [81]. This may be an underestimate, because fecal contamination is often higher during wet seasons, typically June through September in Nepal [82]. Yet, according to the 2016 Nepal Demographic and Health Survey, only 12% of rural households treat water prior to drinking [80]. Although passive chlorination technologies are compatible with rural piped water system infrastructure, few studies to date have evaluated these technologies in small rural piped systems. We present here a year-long evaluation of the impact of these system-level technologies on system and household water quality nested within a rural water safety intervention.

2.3 Methods

Study setting and design

The REACH-Nepal parent study was a collaboration between researchers at the Swiss Federal Institute of Aquatic Science and Technology (Eawag) and the NGO Helvetas-Nepal working in 33 rural communities. The intervention included construction of field laboratories, water system upgrades, and water quality monitoring with centralized data management. Local NGO workers were trained to manually chlorinate the gravity-fed piped water supply at reservoir tanks in 4 treatment communities, and bleaching powder was provided for free. However, no enrolled communities consistently practiced manual chlorination of their drinking water supplies. In this sub-study, we evaluated two chlorination technologies that could be installed at the system-level to automatically chlorinate the piped water supply. We selected two adjacent communities from the pool of 21 treatment communities enrolled in the parent study. These two communities were selected because they had six geographically clustered reservoir tanks, which made repeated sampling and monitoring logistically feasible by a small field team. All water distribution systems had a similar design, each of which included a spring source, a 2.5-5 m^3 concrete reservoir tank, and a gravity-fed piped distribution system to outdoor taps (Figure 2.1). Each tap served multiple households. On average, each system had nine taps serving 22 households. Two reservoir tanks shared the same spring source; the remaining four had separate spring sources. Each community had a water users committee to manage the water supply, as well as community members designated as village maintenance workers, who were responsible for small system repairs.

Passive chlorination technologies

We selected passive chlorination technologies based on their compatibility with existing infrastructure and their availability in Nepal (imported by distributors located in Kathmandu and Pokhara). We purchased all chlorinators and refills at the local market price. We hypothesized that they would be similar in terms of disinfection efficacy, with similar chlorine tablet erosion mechanisms, but that they would have different costs and labor time required for maintenance, which would affect the feasibility of each option for wider implementation in similar communities. The first technology is marketed as the Aquatabs Flo (Medentech, Wexford, Ireland). It is an "end-line" erosion chlorinator that consists of a small cartridge, filled with solid tablets of trichloro-s-triazinetrione (also known as trichlor), that is twisted

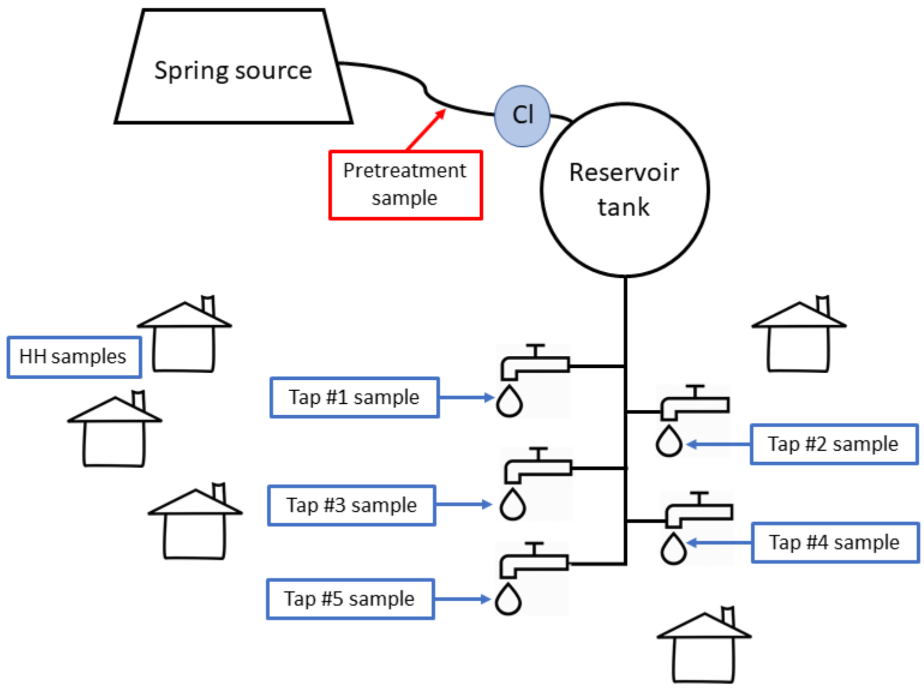

Figure 2.1: System layout and sampling locations

onto an accompanying adapter at the outflow of a pipe (Figure 2.2). As water moves through the cartridge, it slowly dissolves and mixes with the tablets through slots in the cartridge channel. There are two ways to adjust dosing. First, increased mixing, and higher dosing, can be achieved by lowering a plastic screw to partially block the channel. Second, upstream of the device, the pipe can be split into two branches to adjust the proportion of water that flows through versus bypassing the cartridge. The advertised cartridge capacity is 180 m^3 dosed with 1 mg/L chlorine. The device is refilled by swapping out the entire cartridge.

The second technology is marketed as the PurAll 100 (Easol Ltd., Maharashtra, India). It is an "in-line" T-shaped erosion chlorinator that consists of a rectangular box with a vertical tube containing a cartridge stacked with trichlor tablets and it is installed in the pipeline (Figure 2.2). As water moves through the box, it slowly dissolves and mixes with the chlorine tablets through slots at the bottom of the cartridge tube. As tablets dissolve, new tablets drop down in the tube. To adjust the dosing, the pipe is split into two branches upstream of the chlorinator and valves are used to change the proportion of water through the device or bypass. The advertised cartridge capacity is 2,500 m^3 dosed with 1 mg/L chlorine. The device is refilled by unscrewing the top of the tube and swapping out the entire cartridge nested inside.

Technologies were purposively assigned based on system size, with the higher-capacity PurAll

100 chlorinator assigned to the larger systems, which we refer to as systems 1B, 2B, and 3B. We refer to systems assigned to the Aquatabs Flo as systems 1A, 2A, and 3A. During initial site visits, we asked a few community members about prior chlorine experience and provided chlorinated water samples to assess taste and smell acceptability. The responses suggested similar taste and smell acceptability found in other settings [83]. Thus, to avoid households rejection of the chlorinators due to taste and/or smell of chlorine, we initially adjusted dosing to target 1 mg/L at the tap.

Figure 2.2: Chlorination technologies after installation

Figure note: (left) Aquatabs Flo technology installed at the inlet to a reservoir tank. Pretreatment samples were collected from the unchlorinated bypass. (right) The PurAll 100 technology installed in-line just upstream of a reservoir tank. Pretreatment samples were collected from a sampling tap, visible just upstream of the device.

Data collection and outcomes of interest

Household water quality and user acceptability

We conducted three rounds (Figure 2.3) of household surveys to assess pre- and post-installation user acceptability, chlorination impacts on household water quality, and water management practices that could influence quality. We collected baseline data from November-December 2018, midline data in May 2019, and endline data in December 2019. At each round, we sampled household stored drinking water and conducted interviews that included questions on household water access, water treatment and storage practices, and perceptions of water quality and safety. We identified households from water system planning documents that listed participating households, then randomly ordered them using Microsoft Excel random number generator and approached them in that order. One adult who made

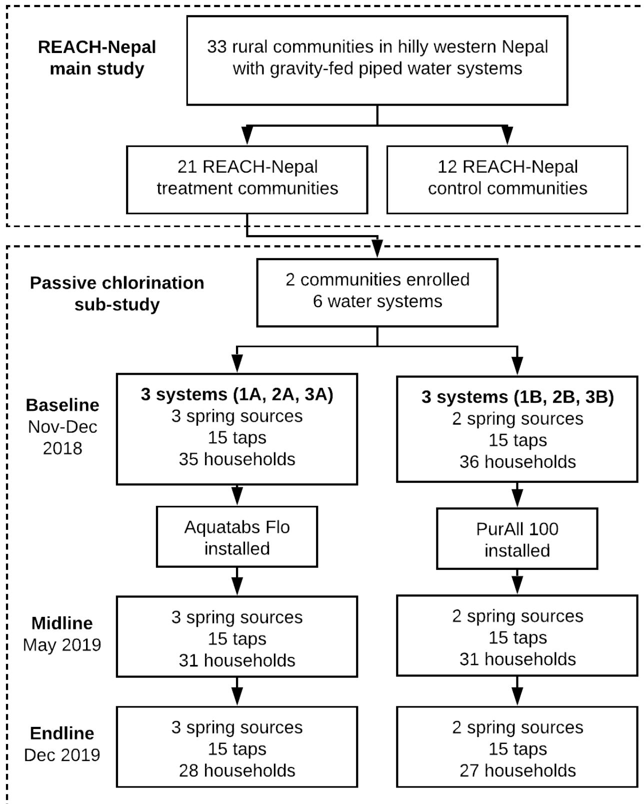

Figure 2.3: Study flow chart

Figure note: We define a system as a reservoir tank and its associated piped distribution system with shared taps accessed by households.

decisions about water management was enrolled in each household until 15 households per system had been enrolled or until all available households had been approached, whichever occurred first. On subsequent visits to each household, we attempted to interview the same individual; if they were unavailable, we obtained consent from and interviewed another eligible adult with water management responsibilities. Surveys were conducted in Nepali by native Nepali speakers using tablets with Open Data Kit (ODK) open-source mobile survey software (`opendatakit.org`).

Technology performance monitoring

To evaluate the effectiveness of each technology, we closely monitored free chlorine residual (FCR), *E. coli*, and total coliforms in the distribution systems. We randomly selected five taps across each system, downstream of the reservoir tank. Each was assigned a unique tap ID and sampled throughout the study. At each sampling time point, one pretreatment sample was collected upstream of each chlorination device. From February to November 2019, over seven visits to each system, trained NGO staff collected and processed a pretreatment sample, samples from the closest and farthest taps geographically from the reservoir tank, and a stored drinking water sample from one household near one of the two selected tap locations. Results were recorded on tablets using ODK. From December 2018 to November 2019, two community members were hired and trained to measure FCR 1-2 times per week at one tap at each system.

Implementation requirements

We documented the time required for monitoring and maintaining devices during this study. We kept a record of all chlorine refills, starting when chlorination began in late December/early January 2018 until the last refills were recorded in October/November 2019, before endline data collection in December 2019. We installed locally purchased mechanical flow meters at the inlet to each reservoir tank to track the total volume (m^3) treated per technology installation.

Sample collection and microbial testing

We collected pretreatment samples at either a non-chlorinated bypass pipe at the reservoir tank (Aquatabs Flo) or from a sampling tap installed just upstream from the chlorinator (PurAll 100) (Figure 2.1, Figure 2.2). For tap samples, we turned on taps for 30 seconds prior to collecting each sample. Household water samples were collected directly from drinking water storage containers. We measured free and total chlorine at the sampling location. For regular FCR monitoring by trained community members, some measurements were taken using a Lovibond low-range pool tester, which has a range of 0.1-3.0 mg/L Cl_2 (Tintometer Inc., Sarasota, FL). All other free and total chlorine measurements were collected with a LaMotte DC1500 digital colorimeter and DPD tablets (LaMotte Co., Chestertown, PA), which has a range of 0.03-4.0 mg/L. Samples for *E. coli* and total coliforms were collected in 100 mL Whirl-Pak Thio-bags (Nasco, Fort Atkinson, USA) and filtered through 47 mm diameter, 0.45 μm pore size cellulose filters (MilliporeSigma, Burlington, MA) using a filtration funnel with a manual vacuum pump (DelAgua, UK) and placed on Nissui Compact Dry EC plates (Nissui Pharmaceuticals, Japan) at a mobile field lab. Samples were typically processed within 2 hours on-site. Filtration funnels were sterilized with methanol vapor, and sterile water was produced daily by filling a sterilized baby bottle with boiled tap water and sodium thiosulfate to neutralize residual chlorine from the community water supply. Processed samples were transported to a central field lab installed at the home of a village maintenance worker, where plates were incubated at 35$\pm$2°C for 24 hours in a locally custom-built, solar powered incubator and counted for *E. coli* and total coliforms. Additional details on equipment construction and methods are described elsewhere [84, 85]. One negative control and one duplicate sample were processed daily for quality assurance.

Data analysis

We cleaned data in STATA version 13 and did analysis in R version 4.0.2. Data and replication scripts are available at `https://osf.io/mrtfb/`. CFU counts exceeding 300 were above the method limit of detection, and we assigned these a value of 300 for statistical analysis. We assigned a value of 0.5 to 0 counts prior to log transformation. To convert costs to USD, we used a January 1, 2020 exchange rate of 1 USD = 114.34 Nepali rupees (NPR). Confidence intervals were calculated with standard errors clustered by system. (See Appendix for additional details).

Ethics

All surveyed households gave verbal informed consent. Prior to enrollment, all households in the communities were invited to an outdoor meeting where the research team and NGO staff explained the purpose and planned activities of the study; 49 community members attended. The study protocol received ethical approval from the Nepal Health Research Council (Reg. no. 24/2018) as part of ongoing Eawag research activities, from Eawag's internal ethical review committee (Protocol no. 1609_20180227) and from the Committee for the Protection of Human Subjects at the University of California, Berkeley (2018-08-11354).

2.4 Results

We collected data from 71 households at baseline, 62 households at midline, and 55 households at endline. Reasons for loss to follow up included migration out of the community, attending a funeral or wedding away from the community, and the birth of a baby. We attempted to follow-up with missing households but were unable to do so in some cases. Overall, the average age of respondents was 39.4 years (range: 18-71), and respondents had lived in the community an average of 26.1 years (range: 1-71) (Appendix Table B.1). Nearly all (97%) households owned at least one solar panel, which was the only electricity option for most households. Respondents were asked what they thought were the main concerns for the community and allowed to name multiple, without prompting options. The top concern across all respondents was electricity supply, followed by healthcare services and education. Water supply services were named as a concern by 11% and 22% in Aquatabs Flo and PurAll 100 communities, respectively.

All households reported that the piped water supply was their primary drinking water source in both wet and dry seasons. The majority (67/71) of households reported monthly payments for water supply from shared taps ranging from 10-20 NPR (0.08-0.17 USD). Across both wet and dry seasons, 59% of respondents reported that they had experienced intermittently supplied water (i.e., <24 hours of availability per day), mainly during the dry season. Aquatabs Flo communities reported more hours of water availability compared to PurAll 100 communities during both the wet season (23.7 versus 14.0 hours per day) and the dry season

(20.1 versus 11.6 hours per day). Across all households, roundtrip water collection time was on average 6.8 minutes (range: 2-40 minutes). The majority of households collected water at taps in containers (61%), with the rest of households using either a flexible pipe they pushed onto the tap to pipe water directly into their home (23%) or a combination of the two methods (17%). All households owned animals, with chickens, goats, and cows common in the community, and the majority of households (85%) used the piped water supply for their animals' drinking water as well. Eighteen of the 71 households (25%) said they kept animals inside their home.

At baseline, 87% of tap samples were positive for *E. coli* with an average 0.63 $\log_{10}$ CFU/100 mL (Table 2.2) and similar contamination was observed across system samples, with an slight increase of 0.14 (95% confidence interval (CI): -0.95 to 1.24) $\log_{10}$ CFU/100 mL *E. coli* between pretreatment and tap samples. At midline, 80% of pre-treatment samples were positive for *E. coli*, 73% of taps had FCR >0.1 mg/L, and 13% of tap samples had *E. coli* present. Three of the four contaminated samples had FCR >0.1 mg/L, although all would be considered low risk (1-10 CFU/100 mL *E. coli*). There was an average reduction of 0.95 (95% CI: -1.85 to -0.03) $\log_{10}$ CFU/100 mL *E. coli* between pretreatment and tap samples. At endline, 80% of pretreatment samples were positive for *E. coli*, over 90% of tap samples had FCR >0.1 mg/L, and 7% (n=2) of taps had *E. coli* present. Both contaminated samples had FCR >0.1 mg/L and would be considered low and medium risk (11-100 CFU/100 mL *E. coli*). There was an average reduction of 1.15 (95% CI: -2.25 to -0.05) $\log_{10}$ CFU/100 mL *E. coli* between pretreatment and tap samples.

User perception and water management behaviors

Household water treatment behaviors remained unchanged throughout the study. At baseline, the majority of households (87%) reported treating their water in the prior 7 days, either by boiling (17%) and/or with a ceramic candle filter (82%). 73% of the samples collected from these ceramic water filters were positive for *E. coli* prior to installation of the chlorinators. At midline and endline, respectively, 79% and 82% of households reported treating their water in the prior 7 days. Across all household visits, most stored drinking water samples were collected from ceramic water filters with taps (77% at baseline, 81% at midline, 73% at endline).

Over 90% of respondents reported that the taste of water was "good" at all survey rounds (Appendix Table B.3). However, there was a change in perceived smell, with 87% of respondents identifying either a chlorine or chemical/medicine smell at endline compared to 16% at midline. We increased dosing following the midline survey visit, during which we had observed low dosing. The increased chlorine smell did not translate to an increased perception of drinking water safety. When asked how safe the main drinking water source was for drinking, all respondents across all survey rounds responded either neutrally ("Neither safe nor risky") or positively ("Quite safe" or "Very safe"). However, the percent of neutral responses increased notably to 36% at endline, up from 2% at midline. Despite the change in smell of water, the study's community outreach at the start, and multiple visits to the household during which the study was explained, only 67% of respondents said "yes" at endline when asked if the drinking water was treated in any way at the system level. Of these respondents, all correctly said that the treatment included chlorination.

Table 2.1: Water quality results at each survey round

	Aquatabs Flo			PurAll 100			Combined		
	Baseline	Midline	Endline	Baseline	Midline	Endline	Baseline	Midline	Endline
Pre-treatment (RVT)	n=3	n=3	n=3	n=2	n=2	n=2	N=5	N=5	N=5
E. coli present (proportion)	0.67 (0.58)	1.00 (0.00)	0.67 (0.58)	0.50 (0.71)	0.50 (0.71)	1.00 (0.00)	0.60 (0.55)	0.80 (0.45)	0.80 (0.45)
Total coliform present (proportion)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)
E. coli $\log_{10}$ (CFU/100 mL)	0.43 (0.71)	1.17 (0.24)	0.83 (1.20)	0.57 (1.22)	0.09 (0.55)	1.02 (0.77)	0.48 (0.79)	0.74 (0.68)	0.91 (0.94)
Total coliform $\log_{10}$ (CFU/100 mL)	2.48 (0.00)	2.48 (0.00)	2.48 (0.00)	2.42 (0.08)	2.29 (0.27)	2.48 (0.00)	2.45 (0.05)	2.40 (0.17)	2.48 (0.00)
Free chlorine >0.1 mg/L (proportion)	-	0.00 (0.00)	0.00 (0.00)	-	0.00 (0.00)	0.00 (0.00)	-	0.00 (0.00)	0.00 (0.00)
Taps	n=15	n=15	n=15	n=15	n=15	n=15	N=30	N=30	N=30
E. coli present (proportion)	1.00 (0.00)	0.00 (0.00)	0.13 (0.35)	0.73 (0.46)	0.27 (0.46)	0.00 (0.00)	0.87 (0.35)	0.13 (0.35)	0.07 (0.25)
Total coliform present (proportion)	1.00 (0.00)	0.27 (0.46)	0.20 (0.41)	1.00 (0.00)	0.33 (0.49)	0.00 (0.00)	1.00 (0.00)	0.30 (0.47)	0.10 (0.31)
E. coli $\log_{10}$ (CFU/100 mL)	1.05 (0.58)	-0.30 (0.00)	-0.19 (0.35)	0.20 (0.49)	-0.10 (0.39)	-0.30 (0.00)	0.63 (0.68)	-0.20 (0.29)	-0.25 (0.25)
Total coliform $\log_{10}$ (CFU/100 mL)	2.40 (0.13)	0.09 (0.83)	-0.06 (0.56)	2.33 (0.16)	0.06 (0.77)	-0.30 (0.00)	2.37 (0.14)	0.07 (0.79)	-0.18 (0.41)
Free chlorine >0.1 mg/L (proportion)	-	0.67 (0.49)	1.00 (0.00)	-	0.80 (0.41)	0.87 (0.35)	-	0.73 (0.45)	0.93 (0.25)
Free chlorine residual (mg/L)	-	0.50 (0.41)	0.66 (0.44)	-	0.65 (0.62)	2.46 (1.42)	-	0.57 (0.52)	1.56 (1.38)
Households	n=34	n=31	n=28	n=36	n=31	n=27	N=70	N=62	N=55
E. coli present (proportion)	0.76 (0.43)	0.65 (0.49)	0.29 (0.46)	0.78 (0.42)	0.45 (0.51)	0.30 (0.47)	0.77 (0.42)	0.55 (0.50)	0.29 (0.46)
Total coliform present (proportion)	0.91 (0.29)	0.90 (0.30)	0.75 (0.44)	0.92 (0.28)	0.71 (0.46)	0.44 (0.51)	0.91 (0.28)	0.81 (0.40)	0.60 (0.49)
E. coli $\log_{10}$ (CFU/100 mL)	1.06 (0.97)	0.42 (0.84)	0.03 (0.75)	0.68 (0.78)	0.43 (0.99)	-0.06 (0.45)	0.86 (0.90)	0.43 (0.91)	-0.02 (0.62)
Total coliform $\log_{10}$ (CFU/100 mL)	1.81 (0.99)	1.74 (0.94)	0.90 (1.13)	1.67 (0.93)	1.04 (1.15)	0.42 (0.99)	1.74 (0.96)	1.39 (1.10)	0.66 (1.08)
Free chlorine >0.1 mg/L (proportion)	-	0.23 (0.43)	0.32 (0.48)	-	0.32 (0.48)	0.67 (0.48)	-	0.27 (0.45)	0.49 (0.50)
Free chlorine residual (mg/L)	-	0.09 (0.14)	0.11 (0.13)	-	0.25 (0.60)	1.19 (1.63)	-	0.17 (0.44)	0.64 (1.26)

Table note: All values are mean (SD). CFU = colony forming units. At baseline, we were unable to collect a household stored water sample from one respondent, because she was unable to enter her home while she was menstruating. This practice of seclusion, called *chhaupadi*, is becoming less common in rural Nepal.

Technology performance monitoring

During monitoring visits, the majority of pretreatment samples were contaminated with *E. coli* (Figure 2.5). Only three pretreatment samples across all monitoring visits had 0 CFU/100 mL *E. coli*. With the exception of visit round three, during which two Aquatabs Flo installations were observed to have empty chlorine cartridges, all tap samples had 0 CFU/100 mL *E. coli*, indicating that both technologies were effective over time. Recontamination in the household to levels equal to or greater than pretreatment contamination was observed in system 2A. This may reflect unsafe water handling practices at the selected household(s), but we did not collect household data to verify this during monitoring visits. In all other systems, even where post-collection recontamination occurred, household stored water quality was better than pretreatment water quality.

FCR >0.1 mg/L was present at the majority of closest and farthest taps, although free chlorine declined considerably after household collection and storage (Figure 2.4). In system 1B during round one, observed FCR was higher in the household stored water than in either of the taps, although no households reported chlorinating at the household level during surveys. No data on household treatment practices or storage time was collected during monitoring rounds, but it is possible a household may have collected and safely stored water at an earlier time with higher dosing. During round three in system 2A, the household sample had 0 CFU/100 mL *E. coli* despite contamination observed at taps. The water may have been effectively treated at the household level or of higher quality at the system level when it was collected.

During regular free chlorine monitoring over the 11 months (12 Dec 2019-28 Nov 2019), an average of 90 (range: 69-97) measurements were collected from taps in each system (Appendix Table B.2). In Aquatabs Flo systems, 74-86% of tap samples had FCR >0.1 mg/L compared to 90-100% of taps in PurAll 100 systems.

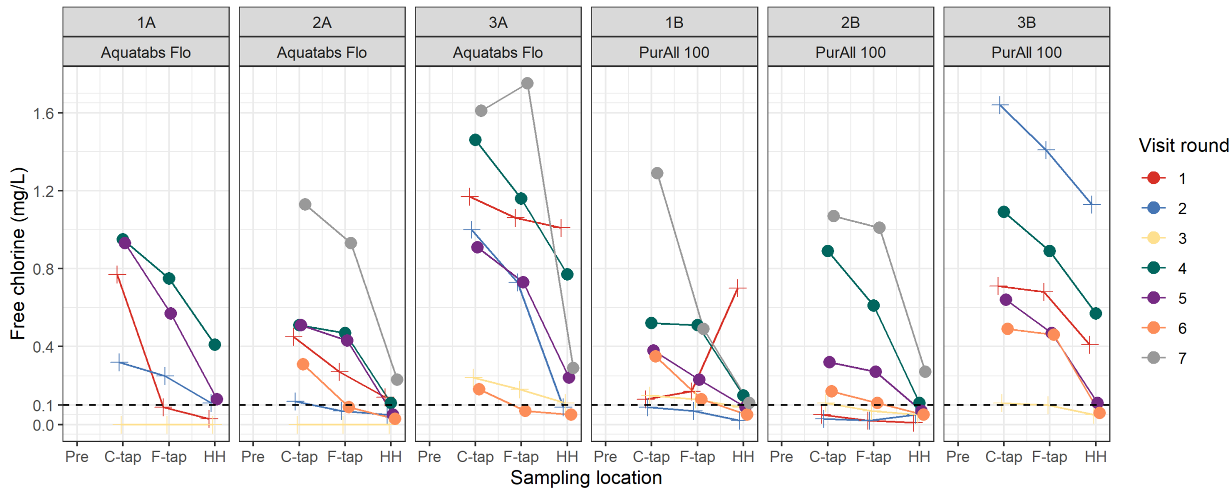

Figure 2.4: Free chlorine (mg/L) across 7 monitoring visits from Feb-Nov 2020

Figure note: For each round of sampling, the line connects the specified observed water quality parameter from the tap closest to the chlorinator, tap farthest from the chlorinator, and one household nearby one of the selected taps. Each point represents a single water sample. The dashed line indicates detectable free chlorine at 0.10 mg/L. Closed circles indicate rounds after the midline survey round, when dosing was adjusted higher; plus signs indicate rounds before.

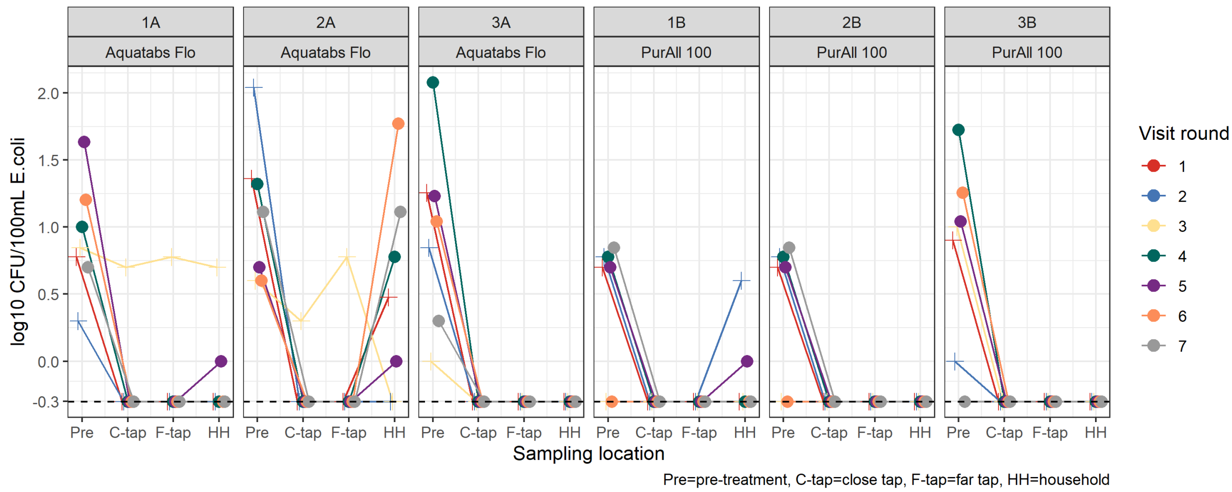

Figure 2.5: *E. coli* ($\log_{10}$ CFU/100 mL) across 7 monitoring visits from Feb-Nov 2020

Figure note: For each round of sampling, the line connects the specified observed water quality parameter from the pretreatment sampling location, tap closest to the chlorinator, tap farthest from the chlorinator, and one household nearby one of the selected taps. Each point represents a single water sample. The dashed line indicates -0.3 $\log_{10}$, which reflects a linear scale value of 0.5 assigned to non-detect plate counts, or 0 CFU/100 mL (i.e., meeting microbiological standards for "safely managed"). Closed circles indicate rounds after the midline survey round, when dosing was adjusted higher; plus signs indicate rounds before. Each point represents a single water sample. Because systems 1B and 2B share a source and technology installation (with a shared upstream sampling tap), their pretreatment results reflect the same samples. All tap and household samples are unique to their respective systems.

Observed chlorinator maintenance and costs

We observed instances of incorrect dosing from both technologies during the study. At the April monitoring visit, chlorine cartridges were empty at two of the installations. During the rainy season, a landslide damaged the intake pipe at the source for system 2A and disrupted service. Subsequently, the flow rate in this system was low, resulting in low dosing. At the endline visit to system 3B, we observed high dosing (4.0 mg/L, the upper limit of detection) at the PurAll 100 installation because a non-return valve downstream of the chlorinator was non-functional; the cause appeared to be built-up sediment. This high dosing resulted in more rapid depletion of the chlorine cartridge. The other PurAll 100 installation had a rapid sand filter installed upstream of the chlorinator; this infrastructure upgrade was planned prior to and installed during the chlorination technology trial but was likely helpful in preventing sediment build up in the chlorinator.

The average installation costs of each device, including all required pipe fittings but excluding both labor and chlorine, was 5290 NPR (46 USD) for the Aquatabs Flo and 75675 NPR (662 USD) for the PurAll 100 (Table 2.2). The Aquatabs Flo devices were easily screwed onto to the end of pipes at tanks, while the PurAll 100 devices had more hardware and required cutting the pipe upstream of the tank. Costs will vary for other installations of the same technologies. For example, some installations of the Aquatabs Flo in tanks require a second float valve to close a bypass line in tanks that may otherwise fill above the level of the cartridge. Members of the research team supervised initial installation of the Aquatabs Flo, which was installed by the NGO staff with assistance from community members, and the PurAll 100, which was installed by an NGO technician with assistance from community members. Each installation took less than 2 hours, but each PurAll 100 installation required several people to assist. In contrast, the Aquatabs Flo installations required only 1-2 people. Following installation of the technologies, achieving the correct chlorine dose required multiple visits to each installation by members of the research team, who trained and initially supervised dosing adjustments by the NGO staff.

We calculated the cost of chlorine per cubic meter of treated water to be 0.09 USD for the Aquatabs Flo installations and 0.06 USD for the PurAll 100 installations. In total, there were 27 cartridges completed at Aquatabs Flo installations and 5 at PurAll 100 installations (Appendix Table B.4). Combining total volume treated across all installations for each technology over the year, on average the systems treated 308 m^3/cartridge (advertised capacity: 180 m^3/cartridge) for Aquatabs Flo and 2485 m^3/cartridge (advertised capacity: 2500 m^3/cartridge) for PurAll 100 (Table 2.2, Appendix Table B.4). Flow meters continued to be monitored after the last recorded refill, but no additional refill events were recorded during the study period. Since there was no way to quantify partially completed cartridges, only fully completed cartridges are included in Table 2.2 calculations.

We calculated labor costs for monitoring, per cubic meter of treated water, to be 0.07 USD for the Aquatabs Flo and 0.05 USD for the PurAll 100. Since monitoring tasks are equally spread across each system in our study, we allocated costs accordingly. NGO staff and trained community members were all able to install refill cartridges. The two trained local community members conducting regular free chlorine monitoring were each paid for 1.5 days of work per week, for a total of 156 person-days per year (52 weeks x 3 person-days/week) to monitor 6 systems. Each round of monitoring for *E. coli* and total coliforms required 3 days, including travel to the field site, for sample collection and processing by an NGO staff member, for a total of 21 person-days over the year (7 visit rounds x 3 person-days/visit) (Table 2.3). Technology distributors sent chlorinator supplies to the NGO office, which was located a few hours by car from the study site, via bus from Pokhara and Kathmandu. To avoid supply disruptions during the study, we maintained a supply of refills at the home of one village maintenance worker.

Table 2.2: Observed average installation, refill, and monitoring costs, by technology

	Aquatabs Flo	PurAll 100
Completed cartridges	27	5
Total volume treated (m^3)	8318	12,427
Average volume (m^3) treated/cartridge	308	2485
Installation costs		
Time required per installation	<1 hour (with 1-2 people)	<2 hours (with 3+ people)
Hardware cost per installation*	5290 NPR (46 USD)	75675 NPR (662 USD)
Refill costs		
Local cost per refill cartridge	3200 NPR (28 USD)	18000 NPR (157 USD)
Average cost chlorine only per m^3 treated water	0.09 USD	0.06 USD
Monitoring costs		
Labor costs for monitoring per m^3 treated water (as observed in our study)	0.07 USD	0.05 USD

Table note: Systems 1B and 2B share a spring source and a single chlorinator installation upstream of their respective reservoir tanks. The total volume value for 1B+2B combines flow meter readings from both tanks. In total there are 5 installations across 6 systems. *Includes local costs of all required pipe fittings and parts, excluding labor and chlorine.

Table 2.3: Observed chlorine and labor cost calculations over entire study period

Free chlorine residual monitoring	156 person-days/year x 700 NPR/person-day = 109,200 NPR (955 USD)
Water quality monitoring	21 person-days/year x 1000 NPR/person-day = 21,000 NPR (184 USD)
Total cost of chlorine	Aquatabs Flo: 27 cartridges x 3200 NPR/cartridge = 86,400 NPR (755 USD)
	PurAll 100: 5 cartridges x 18000 NPR/cartridge = 90,000 NPR (787 USD)

Community members voiced concerns about the security of chlorinators, specifically the PurAll 100, which was installed just upstream of the reservoir tank. The Aquatabs Flo, installed inside the tank at the inlet pipe, was secure because access to tanks required keys that were kept only by village maintenance workers. To protect PurAll 100 installations from vandalism or animals, community members initially covered the devices with branches. Later the NGO constructed concrete enclosures for the devices; these added an unspecified cost to the installations.

2.5 Discussion

We found that two passive chlorination technologies effectively improved drinking water quality over the course of one year in small gravity-fed rural drinking water systems with variable flow rates. At baseline, over 80% of tap samples were contaminated with *E. coli*. One year later, the majority of those taps were safe water sources, with only 7% of taps positive for *E. coli*. Pretreatment samples collected upstream of the chlorination technologies verified that upstream water quality did not improve over the course of the study. Instead, the improved water quality observed at taps and households was due to effective system-level chlorination.

Passive, system-level chlorination resulted in higher coverage of safely managed water without any behavior change required from, or observed in, individual households. Most households in these communities continued to use ceramic candle filters, which were convenient as covered storage containers, but which were not effective at treatment. Since these filters were ineffective on average, and because households were transporting their water from taps in various containers and hoses, we expected and observed a decline in water quality between taps and household storage containers [86]. While 93% of taps had FCR >0.1 mg/L at endline, this was true of only 49% of household stored water samples. While recontamination is the most likely explanation for the decline in FCR, it is also possible that some household filters contained activated carbon, which removes chlorine, or that the chlorine reacted with metal transport or storage containers, eliminating FCR by the time we measured the stored water. Regardless, household water quality was still improved compared to pretreatment water quality, and this risk reduction may be important for health even if a protective chlorine residual is not maintained during storage. A study with the Aquatabs Flo in urban Dhaka, Bangladesh, found that passive chlorination reduced child diarrhea by nearly a quarter, though free chlorine was detected in only 45% of household stored drinking water samples [14].

Although households had safer water, we found that system-level chlorination may not eliminate recontamination when households must collect and transport their water to their homes. The World Health Organization recommends a minimum 0.2 mg/L FCR at the point of delivery in piped water systems [71]. However, even when this minimum was met or exceeded, we continued to observe contaminated water in households. The taps in our study were close to households, with an average roundtrip collection time of 6.8 minutes, but recontamination risks would be even greater with longer collection trips. Until households receive reliable and safe water piped into their homes, the promotion of safe transport and storage containers in combination with system-level chlorination may be necessary.

Over the course of our study, the cost of labor to monitor and maintain systems was comparable to the cost of chlorine, on a per cubic meter of treated water basis. Although maintenance costs vary by setting (e.g., higher in a remote setting with limited road access), they are non-negligible and are crucial for long-term sustainability. Rayner et al. (2016) found that low sustained effectiveness of passive, system-level chlorination in Haiti after two years was due to chlorine supply chain issues and lack of management and maintenance accountability [87]. In this study in rural Nepal, community water management structures were already in place from prior NGO involvement in water projects, and village maintenance workers were in charge of small repairs. However, when a landslide damaged the intake pipe at the spring source of one system, it remained unfixed for months, and the change in flow rate required chlorinator dosing adjustments. We also observed first-hand the unpredictable supply chain for these imported technologies. Installations for the PurAll 100 were delayed because the hardware arrived weeks later than expected. The small piped water systems in our study communities were effectively treated with passive chlorination, but the NGO was necessary to deliver the chlorine supply and provide regular maintenance support. In other words, our results suggest that the provision of consistently-safe water supplies in low-income, small systems such as these requires the support of a service-style delivery model [78].

Our study makes several contributions to the safe water technology literature. First, the year-long, intensive monitoring of the technology installations captures their performance across seasons. We were able to closely track the volume of treated water and refill frequency, to calculate a precise cost of chlorine per cubic meter of treated water, and to roughly estimate the ongoing maintenance costs of both systems. We show that, even when financial costs are no barrier, as in these fully funded installations, external organizations may continue to play a key role in sustaining community-based treatment systems over the long term.

Our study has some limitations. First, the characterization of untreated water quality is based on a single upstream sample for each system at each visit. Water quality is dynamic over time and often declines as it moves through piped systems. However, we observed relatively stable upstream contamination (Figure 2.5), suggesting that pretreatment samples served as a reasonable proxy for untreated system water quality. Our sample size was relatively small, albeit intensively monitored, and the systems had similar infrastructure and source water quality, so our results may have limited generalizability. This is especially true for our cost calculations, although we provide all details of our calculations so that different assumptions for the price of labor and time can be evaluated.

Since the start of this study, additional chlorination technologies have become available, but limited distribution to and within countries, both of the proprietary technologies and the chlorine tablets themselves, limit the more widespread use of passive chlorination technologies at a low cost. Future research should explore service models that allow communities to easily access chlorine refills. This technology evaluation provides evidence to guide and support the implementation of system-level, passive chlorination technologies, even in low-income, rural communities that are considered challenging settings for successful implementation and maintenance of water infrastructure. Years of research on safe water solutions have established that adoption of household water treatment products is an unrealistic pathway to universal safe drinking water [20, 53, 88], precisely because it relies on sustained health behavior change. Continuing to rely on household water treatment as a primary strategy toward low-cost, universal safe water access will leave many behind. In both dense urban and remote rural communities, passive chlorination technologies can improve drinking water quality, without requiring behavior change from individuals in households. These passive treatment approaches, where the supply chain can be maintained, have the potential to radically improve how poor households gain access to safe water.

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Chapter 3

Water and development: a gender perspective

3.1 Abstract

In this chapter we review the state of access to water for domestic use through a gender lens, focusing specifically on the literature addressing (1) the negative health and well-being impacts of inadequate access to safe water, and (2) the effects of women's participation in water allocation and management decisions. While "gender" refers to the socially constructed roles and identities of girls, women, boys, men and non-binary people, the literature on water and gender is mainly concerned with women and girls, on whom inadequate water access places a disproportionate burden. For example, the literature shows that the education of young girls suffers if fetching water is a daily duty. Studies on women's participation in water-related decisions in the community are mixed with respect to their effects on equity, access, and empowerment. The vast water and health literature is overwhelmingly focused on the consequences for child health, while focusing less attention on the health of the water carriers and managers. Yet, failing to understand the full consequences for women and girls leaves a major gap in our accounting of the value of accessible and safe water.

The more recent literatures on water and health have gone beyond a focus on infectious diseases to include the psychosocial stress consequences of unreliable or inadequate water supplies. These stresses are acknowledged to fall on women in particular. A small literature exists on the health impacts of carrying heavy loads of water, made all the more difficult when the womans body may be undernourished to begin with. We find that, in keeping with the spirit of the Sustainable Development Goals, intersectionality with respect to gen-

Chapter 3 is included here with the permission of my coauthor, Isha Ray.

der, class, ability and race, has started to inform research, especially in the field of political ecology. Political ecology has also drawn attention to structural inequalities and their consequences for water access, a perspective that is “upstream” of public health’s concerns with health impacts. Research on participation is being augmented with studies of leadership and decision-making, both within communities as well as within the water sector. Household economics studies have analyzed the gendered burden of paying for safe water, especially as the pressure for cost recovery has grown within urban water policy. Research has also expanded beyond its original focus on drinking water to include domestic water (i.e., access to water for cooking, sanitation, and basic hygiene), all of which particularly concern women’s well-being.

Finally, access is being defined beyond the household to prioritize safe water availability in schools and in health-care facilities, both of which serve vulnerable populations. Both are also institutional settings with a majority female workforce. These are significant and growing new directions that acknowledge the breadth and complexities of the gender and water world; they do not simply call for gender-disaggregated data but take water research towards the recognition of gender justice as a foundation for water justice for all.

3.2 Introduction: Why gender and water?

The iconic image of development needs unmet is that of a woman carrying water on her head or balanced against her hips, often with the scorching sun above. She is often smiling (for reasons unknown) but sometimes her face shows the fatigue and stress that must accompany this chore. This image indeed represents the reality for more than 20% of households globally, because there is no water nearby, and because social expectations dictate that women and girls bear the burden of this domestic chore. Recognizing this reality, the Sustainable Development Goals (SDGs), the human-rights based framework of global anti-poverty and development goals, identifies both gender equality and universal access to water, sanitation, and hygiene (WASH) as priorities for the years 2015-2030. In contrast to the Millennium Development Goals (MDGs), the SDGs promote intersectoral cooperation to achieve their aims. The literature on gender and water is informed by a wide range of disciplines, but much of the research still remains siloed within fields and sub-fields. An earlier review [30] concluded that the sparsity of gender disaggregated data and a lack of consensus on how to theorize gender and development has created difficulties in identifying clear policy recommendations for development goals on women and water.

Our review is both guided and constrained by the dominant framings of gender within the WASH literature. Water access has been a global development priority since at least the 1970s, and the research on gender and water is situated within globally-evolving contexts and sectoral trends. Beginning in the 1970s, the women in development (WID) approach framed investment in women as “smart economics” [89, 90]. The gender and development

(GAD) approach of the 1980s framed gender roles as context-specific, with dynamic gender relations, rather than "women," as key to understanding the connections between women, water and development. "Gender" framed as binary and heteronormative is a reflection of the development field more broadly [91]. The majority of the WASH literature either treats gender as a neutral category (i.e., it does not explicitly address it), or focuses on women for their instrumental value (e.g., their ability to fetch water, to care for ill family members, or to nurture young children) rather than for their intrinsic worth. This has important implications for how women's access to water is valued within a mainstream development discourse in which calculations of costs and benefits influence investments in water and sanitation.

Our objective is to provide a summary of the current literature on women and domestic water, and to call out some of the gaps that remain, in this era of ambitious goals for both safe water access and gender equality. We choose to focus on domestic water, rather than economic uses of water such as irrigation for farming income. Access to water for such economic uses is not explicitly considered within the Human Right to Water and does not have its own target under the Sustainable Development Goals; these are the two frameworks we are drawing on in this chapter. Widely accepted guidelines for water quality and quantity needs are also based on domestic uses – drinking (and cooking), sanitation, and hygiene [92, 93]. However, we acknowledge the important literature on rural women and water for irrigation [94]; this literature meaningfully casts women as farmers and producers as opposed to (only) as reproducers and caregivers.

3.3 Part 1: Toward improved access and gender equality

This section reviews the evolution of the literature on the state of access to safe drinking water, on the negative health impacts of inadequate access to safe water, and on the effects of womens participation in water allocation and management. We focus on studies from approximately 1990 - 2010, about five years away from the end of the Millennium Development Goals era, during which the global community aimed to halve the proportion of the population without access to safe water, relative to 1990 baseline levels. In 2010, the MDG drinking water targets were declared as met. More recent works have taken a broader view of drinking water and health, a more intersectional approach to gender overall, and considered water use and access in relation to climate change; these aspects will be addressed in Part Two.

Frameworks for gender and water

By the mid-1970s, it had become clear to scholars, policy-makers and activists that development and modernization were not rising tides that were lifting all boats. Rural women in particular were still spending many hours a week collecting water and fuel. Women were also the de facto managers of water in their households, and often in their communities. Thus the rights to access, as well as make decisions over, water resources were gradually recognized as key to the fulfillment of development aspirations as well as to gender equality [30].

In 1992 the International Conference on Water and Environment was held in Dublin, Ireland. The meeting culminated in four guidelines for the global water sector, collectively known as the Dublin Principles:

- Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment;
- Water development and management should be based on a participatory approach, involving users, planners, and policy makers at all levels;
- Women play a central part in the provision, management and safeguarding of water; and
- Water has an economic value in all its competing uses and should be recognized as an economic good.

This framework linking women, water, participation, and development was augmented in 2000 at the United Nations Millennium Summit, which subsequently gave rise to eight Millennium Development Goals (MDGs). Of these, Goal 3 (Promote gender equality and empower women) and Goal 7, Target C (Halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation) were most relevant to the quest of greater access to safe water for women. The MDGs quickly became the primary framework through which development policy was made, development assistance was meted out, and development progress was compared; this last entailed regular assessments of which countries were "on pace" to meet specific MDGs and which were "failing" (e.g., Easterly (2009) [95]).

Taken together, the Dublin Principles and the MDGs implied that increased access to safe water and greater women's participation in water management should result in (i) improved child health, which was a direct benefit to women because they are so often the primary caregivers in the family and community, and (ii) more control in women's hands over how water in the household and community was managed and used. The global development community hoped that water access, health and participation could deliver greater autonomy and improved well-being for women in the Global South. From the start, however, there were debates within feminist scholarship on whether "woman-centered" water policies would increase women's well-being or merely their workloads [96, 97]. These debates pushed back against simplistic and essentializing notions of women's roles in water management, and, by extension, in the development process.

The final major framework for women and water in the early 2000s was the United Nations declaration that safe water was a human right. General Comment 15 explicitly declared that there was a right to safe, accessible and affordable water for all [4]. That safe water was a human right had been argued earlier [98], but the UN General Comment made this "official" for the community of nations, with particular attention to the rights of traditionally powerless groups and individuals. In principle, rights-holders are individuals rather than households or communities. In practice, however, measures of water access are tracked by households, though equitable water (or any service) allocation intra-household is always determined by the power balance between its (adult) members [99]. We return to this point later in this review. Taken together, the Dublin Principles, the MDGs and the Human Right to Water functioned as the inspiration and justification for many of the women-and-water policies at the domestic and community scales through the MDG era.

Access

The UNICEF and World Health Organization Joint Monitoring Program (JMP) definition of *improved* versus *unimproved*, based on whether the construction of the water point protects the source from contamination, became the most widely used indicator of safe water access as the metric for progress toward the MDGs. *Improved* sources include taps or standpipes, borewells/tubewells, protected dug wells, protected springs, or collected rainwater. *Unimproved* sources are unprotected wells or springs, vendor-provided water, tanker trucks, bottled water (due to quantity and price limitations), or surface water [100]. By 2002, the JMP estimated that over 80% of the world population used improved drinking water sources, with the lowest proportion of population coverage in Sub-Saharan Africa, but the greatest total numbers lacking access (i.e., using unimproved sources) in Asia [101].

During this era, research on the gendered burden of water focused primarily on "time poverty" and its consequences, with women and girls contributing significantly more to "household time overhead" through domestic chores such as water-fetching and caregiving for family members with water-related illness [102]. Global data showed that women and girls were primarily responsible for water management in most but not all settings (see Hawkins & Seager (2010) [103], in Mongolia, for an exception).

Economic accessibility, or affordability, was the least clearly defined criterion of access, although it is generally described as an acceptable percent of income spent on water supply. Although affordability is a logical requirement for access, and various international agencies have set affordability thresholds (e.g., 3% of income by UNDP, 5% by the World Bank), the lack of data for global monitoring led this criterion to be deleted from the MDG target for safe water access [104]. These thresholds, however, do not include the unpaid, and mainly women's, work of collecting, treating, and storing water; thus the financial costs of domestic water likely underestimate its true cost in lower-income settings.

Water access was (and continues to be) measured as a household attribute, with very little data on intra-household disparities in use, and comparable, accurate, and consistently-collected data on domestic water use has been rarely available [105]. Of the 45 countries that reported water access metrics to the JMP early in the MDG era, there was a wide range of definitions, with various acceptable thresholds for quantity, distance, and/or time to water source [106]. The 1992 baseline and 2002 midline JMP reports during the MDG era included data disaggregation by urban versus rural setting, but not disaggregation by gender.

Health

Diarrheal disease is the greatest water-related health burden and is the basis for economic estimates of the health costs of unsafe water access [107, 108]. Diarrhea was the fifth and seventh leading cause of death in 1990 and 2010, respectively, but with an especially heavy toll on children under 5 [109]. Mortality in this age group declined enormously during this time, but morbidity remained high, with children in developing countries experiencing several episodes of diarrhea on average each year [110]. Women and girls are primarily responsible for providing home-based care during these episodes; the WHO even developed "Mother's Cards", an informational sheet reminding mothers how to treat diarrheal illness in their young children [111]. Promotion of home-based management of diarrhea using oral rehydration therapy (ORT) focused on educating mothers about how to prepare and use it [112].

Since 1972, the Bradley Classification has served as a way to broadly define four categories of water-related disease: waterborne (e.g., diarrheal diseases such as typhoid and cholera), water-washed (e.g., trachoma), water-based (e.g., schistosomiasis), and water-related with an insect vector (e.g., malaria) [113]. Far less attention in safe water research was paid to non-diarrheal disease outcomes, although epidemiologic studies assessed the higher burden they placed on the women as household water managers and fetchers. Compared to men, women experience far higher rates of trachoma, the leading preventable cause of blindness; and caring for children is associated with greater incidence of trachoma [114]. Schistosomiasis, spread in freshwater bodies used for chores such as washing clothes, infects women in far higher numbers; female genital schistosomiasis can lead to poor pregnancy outcomes, infertility, and potentially increased risk of HIV infection [115, 116]. Outside of these categories of water-related disease, womens increased risk of spinal injuries from regularly carrying 20 kg loads of water on their heads or potential dangers such as drowning or snake bites as they ventured out to collect and use water were acknowledged but not well measured [117, 118]. The time burdens could impact seemingly unrelated health outcomes as well; in rural South Africa, time spent fetching water significantly reduced the use of prenatal care [119].

Although the MDG safe water goal was declared met in 2010 [120], the use of improved sources, as defined by the JMP, did not necessarily mean the water was safe from pathogens [121]. Additional recontamination during water transport and storage in the home could result in consumption of unsafe water even with access to a safe source [86]. To improve drinking water quality and protect it in the home, low-cost household water treatment (HWT) technologies and safe storage strategies were developed and widely promoted during the MDG era [122]. This was seen as a faster and cheaper safe water solution than could be achieved through construction of centrally treated and piped drinking water systems, and it was a way to empower households to take control over their own safe water access. Since women and girls are primarily responsible for household water management, they became the de facto target population for promotion and use of household water treatment, which includes boiling, filtering, chlorinating, or using solar disinfection to treat drinking water. In fact, the relatively "low-cost" in-home safe water solutions were low cost in part because of the unpaid labor of (primarily) women and girls that went into maintaining them [78].

Participation

Since the 1970s, there has been broad agreement in policy and (mainstream) academic circles on the need to include women in water planning and decision-making. This was the dominant view for water management at the community-scale, but perhaps less so for national or transboundary water management. Dublin Principle 3 in 1992 cemented womens participation as a core value for the international water community. Many reasons were proffered: women's participation in water management was said to lead to more efficient and sustainable water use (e.g., Mason & King (2001) [123]); women arguably knew domestic priorities best and often also the local water sources best, and therefore they should be the loci of decision-making [124]; and women's participation in water management could increase self-confidence and status in the household and community (e.g., Van Wijk-Sijbesma (1985) [125]).

Project reports during this period suggested that the inclusion of women in decision-making over the use of water could, but did not always, lead to better access and more control over local water resources [126–128]. Supporters of Dublin Principle 3 argued that water projects without women's participation could neither be equitable nor be a vehicle for empowerment; dissenters pointed out that participation could be "token" and that the empirical evidence did not make clear on what terms women's participation actually improved access and control [30]. Low-level engagement could not sway water decision-making the way more active involvement could, but low-level (and low-influence) engagement that left actual authority in men's hands was common (e.g., Prokopy (2004) [129]). In some cases women were expected to act as "natural" protectors and caretakers who could manage community water resources without compensation (e.g., Jackson (1993) [130]), so participation based on women's water knowledge and traditional responsibilities could increase women's workload without increasing their well-being [97].

By the end of the MDG era, there was no consensus on whether women's health would measurably improve with better management of water; and several reports had indicated that participation of community members who were not women can also be effective for efficient and sustainable water management (e.g., Prokopy (2004) [129]). Feminist scholars pointed out (not for the first time) that project data was so rarely disaggregated by gender that the impacts of women's participation on their own lives or on the outcomes of a water project were almost inevitably unknown (e.g., Kleemeier (2000) [131]; Zwarteveen (1998) [132]). Scholars and practitioners also argued that equitable access to water for women meant water not just for drinking and health alone, but also for domestic needs such as caring for animals, laundry, and family hygiene [133]. Thus women could be more willing to manage and safeguard their water resources, and could benefit more from participation, if they had access to water for their full range of needs. This more expansive notion of drinking water became the normative definition within the "drinking water" access goal of the SDG era.

Part 1 Conclusions

Understanding how women's access to safe and reliable water and how women's health and participation mutually reinforce one another demands gender-disaggregated data from households and communities. The human right to water framework in particular demands a behind-the-scenes examination of water access within the household, though this remains rare in development research and practice even today (see Part Two). As the international development community moved away from the MDGs and into the SDG era, the calls for disaggregated data on key indicators, and even for new indicators altogether, became more widespread. Research on water and development from 2010 to the present has been more attuned to the gendered nature of all aspects of water access, but, as we show in the following sections, the practice of water policy has yet to catch up with the research frontiers.

3.4 Part 2: Toward universal access and gender justice

By 2010, global water communities of both research and practice were looking ahead to the post-MDG era for frameworks within which to conceptualize sustainable and accessible water for all. The MDGs had already been critiqued for aiming for less than universal access [15], and for becoming, in practice, a way to label countries as being "on pace" or "failing" to meet their targets [134]. Two frameworks for action came to dominate this period. First, the eight MDGs gave way to 17 Sustainable Development Goals [135]. Second, the Human Right to Water framework rose to new prominence; this was not a new concept [4, 98], but it was explicitly adopted as a guiding framework for safe and adequate water provision only in 2010 [3]. Both frameworks are highly compatible in that they emphasize universal access with particular attention to the poorest and most vulnerable. SDG 6, echoing the right to water, explicitly calls for "clean water and sanitation for all" [135]. Adjacent concepts that emphasize reliability as well as safety and adequacy, such as household water (in)security, have also begun to emerge [136]. These frameworks, unlike the older literatures, have collectively shown that the failure to meet the human right to water is not a feature of low-income countries alone; failures can be found in marginalized communities in otherwise wealthy and well-served countries such as the United States [137–139].

Broadly reflecting the new(er) frameworks, recent work on gender, water and development is redefining several older concepts to slowly, but surely, give greater recognition to specifically gendered perspectives. These re-definitions are particularly evident in the research on access and health. For instance, within the SDG targets, the JMP explicitly interprets "drinking water" to also include water needed for "cooking, food preparation, and personal hygiene" [71]. This is a potentially gender-equitable change as domestic water is a traditionally "female" domain. New experimental studies on safe have shown the challenges of achieving measurably better health outcomes using household safe water technologies [6, 21]. At the same time, water-related health research is expanding beyond its conventional focus on gastro-intestinal diseases to the health impacts of waiting for and fetching water, as well as the psychosocial stresses from inadequate household water access. Water for hygiene is prominent in this line of research. These changes can also be seen as gender-inclusive. Attention to occupational and mental health has opened up the unitary household as a unit of analysis and has encouraged researchers to consider a disaggregated model of the household in which intra-household inequalities are revealed and studied. In addition, led by JMP efforts, research on drinking water has gone beyond the household to investigate access in shared facilities, particularly schools and healthcare facilities.

The participation strands of the water literature have started to focus more on women's leadership rather than on participation alone. Participation in water-related activities has frequently been critiqued as tokenistic, so newer studies are investigating the access and equity impacts of women's leadership at all levels of the domestic water and sanitation sector. Finally, drawing on decades of feminist research, as well as on the interlocking-goals premise of the SDGs, a small literature has started to see women and water through an intersectional lens, highlighting the co-existence of gender, race, age, ability, and class within the same body. We elaborate on these aspects in the following sections.

Redefining access

While the MDG eras binary categorization of improved versus unimproved focused on water quality, the SDGs introduced a ladder of water service levels. The highest rung is safely managed water, defined as from an improved water source which is located on premises, available when needed and free of faecal and priority contamination [71]. The rights-based discourse of the SDG framework and the Human Right to Water brought a normative description of access to the fore, specifically that domestic water must be "...sufficient, safe, acceptable, physically accessible, and affordable" [4]. This notion of deep access beyond simply the presence of infrastructure highlights the important distinctions between modes of access, toward a more multidimensional understanding of access and its often gendered consequences [140, 141].

For example, time costs for water, primarily borne by women and girls, can accrue from walking 30 minutes to and back from a tubewell or from waiting at home for a water tanker truck to arrive. Both are considered improved sources in the SDG era, yet the different modes of access lead to different hardships and benefits for household and personal well-being. In rural Zambia, households that gained access to reliable piped water accrued significant weekly time savings (primarily to women and girls) and increased their households food security through household gardens [142]. In Morocco, households that upgraded from public taps to private household taps used the saved time for leisure and socializing [143]. In Brazil, women reported they would use time savings to sleep, rest, or care for their children [144]. Empirical data from Ghana quantified the time savings benefits for girls education, with attendance increasing significantly when water fetching time was reduced [145]. However, a small set of studies, reflecting long-standing feminist critiques of "woman-friendly" policies, suggested that more reliable access to water did not always reduce women's work; waiting to collect water could attenuate the benefits of more accessible water [146], or women might not have autonomy over the use of their saved time.

Once safe water systems were constructed, water safety plans – risk assessment and management strategies – became a widely promoted systems maintenance approach to ensure continued safe water access [147, 148]. One World Health Organization water safety planning field guide emphatically stated, "Do not forget to involve women!" as they are best able to identify risks because of their roles as primary water collectors and managers [149]. Household water treatment (which renders safe water provision a domestic chore) continued as the dominant strategy for ensuring safe water at the point of consumption, although research in this era focused less on developing new technologies and more on motivating correct and consistent use of existing technologies [150]. A handful of studies on passive, in-line chlorination technologies have begun to offer an alternative to manual household water treatment. These have potential to reduce burdens on women, both by reducing the burden of treatment and by effectively reducing incidence of diarrhea among their young children [14, 151]. Affordability has remained a poorly defined aspect of water access, although the data show that the poorest paid disproportionately more for service, often having to gain access through informal means [104].

Finally, while measurement of access focused primarily on physical proximity to and quality of water supply, insights from feminist political ecology further unpacked the complex social relationships and rules that mediate daily access to and control of water resources [152–154]. This literature builds on critiques of the shift toward privatization and commodification of water, a system which freely benefits from women's labor through "gendered ideologies of caring and domesticity" [155] and simultaneously marginalizes women who may not control the household budget for purchasing water or water treatments. This is not to deny that, in some cases, some women have benefited from corporate-meets-community modes of water supply [156]. Yet, as climate change threatens potable water sources (e.g., through droughts that leave wells dry or floods that spread fecal contamination), it is women who will simultaneously bear the greatest burden and have the fewest resources to adapt.

New evidence on water and health

Research continued to focus primarily on water-related pathogens, evaluating the impacts of safe water on the physical health of children and involving mothers mainly through their instrumental role as caregivers. Sorenson et al. (2011) write that despite the central role of women in safe household water management, when it comes to health research, the "water fetchers are almost secondary to the water itself" [157]. The focus remained largely on child health, as WASH researchers worked to understand specific transmission pathways and the particular pathogens responsible for disease outcomes in children [158], as well as the links between nutrition, diarrhea, and child growth and development [159, 160]. However, research on womens health has begun to recognize women's unique health challenges, beyond "maternal and child health" and "sexual and reproductive health," which had been the dominant framings of women's health in prior decades [161].

The results of three large randomized controlled trials, evaluating the impacts of WASH on child diarrhea and growth, showed no impacts of water treatment, though sanitation and hygiene interventions reduced diarrhea in one setting [8–10]. The trials enrolled pregnant women so that infants would receive the interventions from birth, and the expected success of the trials relied on these women as the primary caregivers and implementers of the household-level water treatment, hand hygiene, and sanitation interventions. The mostly null primary results of these trials have motivated the idea of "transformational" or "transformative" WASH, concluding that traditional WASH interventions are insufficient to reduce pathogen exposure in highly contaminated settings and suggesting that more comprehensive WASH improvements, at scales beyond the household level, may be required to improve health [6, 7]. Notably, relatively little data was collected on the mothers.

Although safe water access has mainly been considered an LMIC (low-and-middle-income country) issue, the "universal access" mandate of the SDG era brought greater attention to water and health in marginalized communities in high-income countries as well. Some chemical contaminants of concern (e.g., lead in Flint, Michigan [162]; nitrates in Californias Central Valley [163]) can be particularly consequential for pregnant women or infants. Finally, frameworks have emerged within the health literature for gender-transformative approaches to health promotion, not simply "gender accommodating" but rather an attempt to transform harmful gender norms to eliminate the underlying social determinants of gendered health inequities [164]. Given the enormous role of gender norms in water- and sanitation-related behaviors and burdens, researchers have advocated for a gender-transformative approach (as distinct from "transformative" WASH) within WASH programs [165].

Women's health: cumulative physical burdens on women's bodies

The integrated framework of the SDGs parallels an increasing attention to the "linked burdens" faced by women through their lived experiences [166]. The focus of water and health studies has overwhelmingly remained on diarrheal diseases and children, but more research has begun to connect water access with the multiple burdens on women's bodies. Pregnancy is one such burden. Data across multiple countries show that water fetching by women and girls is associated with reduced use of antenatal care [119, 167]. Women in western Kenya associate pregnancy complications with carrying heavy water loads [168], and women in Uganda have described how pregnant women, tired but still expected to fetch water, would fall behind on chores and end up with less food and water for themselves at a time when they have increased caloric and water needs [169]. HIV is yet another burden. People living with HIV (PLHIV) are more susceptible to infections from water-related pathogens, yet their care requires greater volumes of water for hygiene and medication [170]. In sub-Saharan Africa, where water scarcity is greatest, the majority of new HIV infections are among women, who are simultaneously responsible for the home-based care of ill household members [171].

Globally, the data clearly show women and girls do the majority of water fetching [172], yet the physical health consequences of this enormous burden are not well quantified. The musculoskeletal pain or injuries that can result from carrying heavy loads of water on heads, hips, or backs are not reflected in global estimates of morbidity and mortality due to inadequate water [157]. In Brazil, women reported that carrying heavy loads on their heads could cause wounds, even bleeding [144]. Thirteen percent of households across 21 LMICs reported a water-fetching injury, including from falls, accidents, animal bites, simply from using the water source, and even physical confrontations when attempting to access water; women were more likely to report an injury [173]. Researchers have pointed to a continued sparsity of data on sexual assault against women during water fetching [157, 169]; however, studies in Nepal and Kenya have linked water insecurity with intimate partner violence, a gendered pattern that has been reported under scarcity of other household resources such as food [168, 174].

Broadening to psychosocial health

Current research on water and health has broadened beyond water-related diseases to consider mental health and stress from lack of adequate, accessible and affordable water, with an emphasis on women rather than children. Early work from "squatter" settlements in Bolivia showed that inadequate access to water and water conflicts produced emotional distress in women, many of whom expressed fear of running out when water shortages resulted in overt interpersonal conflicts [175]. Both men and women reported water-related stress during severe shortages in Mozambique, with women feeling that they could not be good wives when there was no water in the house [176]. Similar associations of womens mental distress and water scarcity have been found in rural Ethiopia [177]. Survey results of urban households in

India with piped but unpredictable and intermittent water services found (mainly) women reporting that they frequently had low-level worry about water arriving on time [178]. Studies have argued that mental health stressors from water insecurity are similar to those from food insecurity: anxiety from, and coping with, insecure supplies are necessary in both cases, and similar methods of measurement could prove useful [177, 179].

Other than anxiety, the emotions of indignity and shame from unsafe WASH have given rise to a rich ethnographic literature. Low-income women face stress and fear of sexual assault when seeking safe sanitation or carrying water over distances [180]; women find themselves torn between fetching water from outside sources and taking care of home and family [176]; and girls struggle with shame when they are in school, without WASH supplies, when they are menstruating ([181], see below). Overall, multi-country multi-disciplinary reviews have confirmed that women carry disproportionate psychosocial burdens when they do not have adequate and accessible water supplies, but that these aspects are not always "counted" and operationalized as health impacts [182, 183].

Water-induced stress is not an exclusively LMIC phenomenon. The environmental justice literature has repeatedly shown that poor communities in the USA also experience these stresses. For example, respondents in a Letcher County (Kentucky, USA) study with coal mining pollution in the water supply reported shame and low self-esteem because they smelled bad and had dirty clothes in church and at school [184]. Flint (Michigan, USA) residents whose water service had been cut off similarly reported the "ripple effect, mentally and physically," of shame at being unable to pay their bills, having to shower at other people's homes, or their children smelling bad and being embarrassed at school [185]. Most of these respondents were women. More broadly, the development literature has leaned on insights from cognitive science to pay more attention to poverty itself as an underlying stressor. This connection has led researchers to argue that basic services, such as water and sanitation, have to be made not only affordable, but also secure and reliable, for low-income households worldwide [77]. Relieving stress and mental tension through more readily accessible water supplies can thus be seen as improving both public health and gender equality [78].

Water for hygiene

Here, we discuss hygiene in the "traditional" sense (i.e., handwashing and bathing), as well as in the specific subfield of menstrual hygiene management (MHM). While the MDGs included indicators for water and sanitation, the SDG includes hygiene related indicators as well – specifically for handwashing facilities and sanitation facilities that pay "special attention to the needs of women and girls" [135].

The SDG indicators include the presence of handwashing stations with soap and water. Evidence shows that handwashing can significantly reduce diarrheal disease [186, 187], yet an estimated quarter of the global population lacks hand hygiene facilities at home [188].

Numerous studies and campaigns have encouraged mothers to wash their hands at critical times (e.g., before preparing food) to reduce illness in their children [189, 190]. Curtis et al. (2009) found that a desire to nurture children could be an effective motivator for mothers to wash their hands [191]. During the COVID-19 pandemic, handwashing was heavily promoted to prevent the spread of SARS-CoV-2 [192] in LMICs as well as high income countries, although it was pointed out that women and girls in LMICs could be more exposed because of their water fetching roles, such as while waiting at crowded water points or touching frequently used taps or handpumps [193].

Notably, SDG 6, Target 2 acknowledges gendered sanitation and hygiene needs (SDGs). While much of the work in the subfield of MHM focuses on the design of safe, private toilets, adequate MHM requires access to water for washing and bathing, in addition to water for cleaning reusable menstrual products. For example, a handful of studies have evaluated the acceptability of reusable menstrual cups, which may offer a more financially and environmentally sustainable alternative to repeated purchases of disposable pads, but which require water for proper cleaning [194]. Poor water access has been linked to increased urogenital infections [195], and researchers applying a life-course perspective have pointed out that women need water to manage vaginal bleeding for reasons other than menstruation, such as miscarriage or cancers [196]. For menstruators, including transgender and non-binary persons, a lack of latrines with water access poses a significant barrier to gender equality, by restricting mobility and full participation in public life. This lack of appropriate latrine access has been the main entry point through which the needs of transgender individuals have received recognition in the water and sanitation literature [197].

Beyond the household: water in shared spaces

In the SDG era, water access goals expanded beyond the household, including public spaces in the normative definition of “universal access” [71]. In 2019, the UN Special Rapporteur on the Human Rights to Drinking Water and Sanitation released a report clearly laying out how multiple SDG objectives rely upon equitable access to water in public spaces [198], a fact acknowledged in General Comment 15, which stated that water “is a prerequisite for the realization of other human rights” [4]. Although public spaces should expansively cover all spheres on life beyond the household [198], specific SDG targets for quality health-care services (Target 3.8) and gender sensitive and inclusive learning environments (Target 4.A) have motivated particular attention to healthcare facilities and schools [199]. We note that these institutional settings leave out some of the most vulnerable populations, for example, women experiencing homelessness or incarcerated populations.

Schools

In the SDG era, the JMP is tasked with tracking progress in schools toward a “basic” service level for drinking water, sanitation, and hygiene [200]. In their 2020 progress report, the JMP reported that nearly 600 million children lacked water at school, with regional estimates of basic water service coverage in schools as low as 44% in sub-Saharan Africa [201]. Prior research has shown that safe water provision in schools can reduce both absenteeism and illness across genders [202], but the lack of water to manage menstruation takes a particular toll on girls' attendance. McMahon et al. (2011) found that Kenyan schoolgirls would go home to manage their periods, often missing multiple days of class; the lack of toilets and water for personal hygiene at school made period management difficult and shame-inducing [181]. "Basic" water access on school premises is not enough for gender inclusion – water must also be reliably accessible to girls inside latrines [203, 204]. We note that the timing of these impacts is important – school absence on account of a period is relevant mainly for secondary school attendance, and educational research has shown that additional years of school, beyond primary education, are associated with girls being better able to articulate and advocate for their rights [205].

Healthcare facilities

Starting in the SDG era, the JMP is tasked with monitoring progress on WASH goals in healthcare facilities, with an aim toward a "basic" service level [206]. Not only are healthcare facilities spaces where women access necessary medical care, they are also important workplaces for women. Although drastically underrepresented in leadership positions, women make up an estimated 70% of the global health workforce [207]. During the MDG era, there was a big push toward health facility deliveries, rather than home births, with the expectation that this would reduce the high rates of maternal mortality in LMICs [208]. Yet maternal mortality remained high and vastly unequal across settings: 16 maternal deaths per hundred thousand live births in high income countries versus 230 in LMICs on average [209].

By 2018, 76% of births were in health facilities, but poor hygiene conditions continue to compromise potential benefits and can dissuade mothers from delivering at facilities [209, 210]. Approximately 10% of pregnancy-related deaths globally are due to sepsis [211], and water has long been recognized as crucial for infection control and prevention. In Nepal, where infection is a leading cause of neonatal death, neonatal mortality was reduced by 41% when both birth attendants and mothers washed their hands with soap and water [212]. In rural Rwanda, even a single day of water shortages at a healthcare facility more than doubled the likelihood of infection among women following cesarean sections [213]. WHO guidelines recommend 100 liters/intervention as the minimum water quantity required in a maternity unit [214], yet an estimated half of all healthcare facilities in LMICs lack piped water [215]. Women about to give birth may even be required to bring their own water [216]. Finally, apart from the physical infrastructure, there is increasing recognition of health facilities as strategic settings to educate new mothers in water-related health behavior change, for example by bundling antenatal care with promotion of household water treatment [150].

Beyond participation, towards leadership

Based on Dublin Principle 3 – “Women play a central part in the provision, management and safeguarding of water” – the early literature called for attention to women’s leadership as well as (general) participation. Participation, loosely defined, could range from intense participation, to significant unpaid project work [217], to token (and silent) attendance at meetings [129]. Moving more firmly beyond participation and towards leadership, the newer literature is still small, but growing. At times the literature on this theme walks a fine line between analysis and advocacy. Among the more optimistic findings, Chattopadhyay and Duflo (2004), drawing on a natural experiment in rural India, found that women political leaders, such as Village Council leaders, tend to increase investments in infrastructure and basic services, such as roads and drinking water [218]. Another study, based on the same experimental conditions, reported that gastro-intenstinal health outcomes improved in villages with women leaders who invested in better access to drinking water [219]. There is some evidence that gender-equalizing basic services-oriented priorities are also reflected when more women are represented in national-level leadership [220]. Nonetheless, even when women are in leadership positions, many cultural and educational barriers exist to translating these positions into effective or changed practices. Constant negotiations between expected duties at home and expected duties at work make even women leaders in the WASH sector less influential in decision-making [221]. Despite gender-aware national policies and greater awareness of the need for women’s leadership in urban and rural water systems, women routinely find themselves occupying lower-rung positions in the water sector [221, 222] and actually excluding themselves from public or prominent positions in order to remain socially acceptable [223]. On the other hand, researchers have documented cases where women in leadership positions in community-based water governance successfully enhanced their skills and self-confidence, even when project outcomes per se did not measurably improve [224].

Mainstreaming efforts have been only partially successful, and mandatory inclusion rules imposed by NGOs and donors do not take into account social barriers and constraints, even when these are well known [225, 226]. These observations have led some scholars to argue that women as a single category may not be the right categorization with respect to water and gender. Women’s leadership possibilities in practice depend on class, marital status, age, asset base and race; therefore, the potential for, and impact of, womens leadership in the water sector are not homogeneous across, or even within, study sites. For instance, poor and marginalized men as well as women can be excluded from decision-making authority [223]; and land tenure and land title may determine who gets a voice in water users’ associations, thus placing women at a disadvantage, as reported from countries as different as Argentina and Ethiopia [227, 228]. A rich ethnography from the water wars of Cochabamba, Bolivia, documents the courageous leadership and resistance of respected women but finds that these same women resorted to homophobic taunts to shame their menfolk into confronting state-sanctioned violence [229]. In sum: this body of work shows that women’s leadership in water cannot be treated as an apolitical and comforting “good-for-everyone” policy. Many facets, and many enabling and disabling conditions, determine the prospects for women's leadership and potential to effect transformative change. These nuances – with a few exceptional case studies – remain under-researched within WASH [230].

Water and intersectionality

The awareness of gender as but one characteristic among many others, all of which collectively determine women's capacities and opportunities in the (water) world, has led to a small literature analyzing women's experiences in the water sector as not simply gendered, but intersectional. Intersectionality recognizes that women (and all genders) hold multiple simultaneous identities: race, indigenous status, socio-economic status, marital status, ability status, and so on [231]. These identities intersect to make women's water access more or less available, or participation and leadership more or less feasible. If multiple marginalities are represented in one individual, as with low-caste women in India, for instance, their experiences with respect to water access may be even more challenging [232, 233]. For example, Sultana (2020), based on an ethnographic study of Dhakas largest slum, has argued that struggles for and claims to water are, in effect, struggles for and claims to urban citizenship [234] (see also Appadurai (2001) [235]). She finds that the exclusion of women from equal participation as citizens, and thus as deserving of reliable water as "proper" citizens are, is exacerbated by poverty and migrant status. In a completely different context, a study on the WASH sector in Kenya found married women managers to be doubly disadvantaged in their careers: On the one hand, if they worked late, their husbands and sons constantly called them, and on the other hand, if they were young, their bosses were reluctant to promote them for fear of future pregnancies [221]. Intersectionality is not invariably about a constellation of "disadvantages." An insightful study of community organizers against water privatization in Bolivia showed the nuances of intersectionality: Indigenous status was often a marginalizing factor with respect to the state, but, within the community, respected women (*supermadres*) became powerful rallying forces and leaders in the movement to preserve water access [229].

Disability is yet another intersect with gender. The SDGs have argued that disability is a cross-cutting vulnerability across several goals and targets. The WHO estimates that approximately 15% of the global population faces some form of disability [236]. Disability prevents easy access to WASH facilities, especially to sanitation, but is also associated with longer times to fetch water from public water sources [237], and with greater difficulties in accessing enough water not just for survival but for maintaining productive employment [238]. These are examples of gender, age, disability, and low-income status co-occurring; pain, incontinence and other discomforts are also experienced by women fetching water in such circumstances [239]. Cross-country comparative research has found that even when households with disabled members do not have lower access than other households, disabled members within their households are disadvantaged [240]. This finding provides yet another confirmation of the need for disaggregated WASH access data, instead of data that uses the unitary household as a unit of analysis.

The socially-constructed and intersectional nature of women's experiences have led United Nations agencies to call for bundled investments in water, sanitation and household energy as urgent priorities for health, sustainability, and gender equality [241]. At the same time, feminist scholars such as Cornwall and Rivas (2015) have argued that broader alliances with social justice movements, based on principles of inclusion and non-discrimination beyond gender, may be more effective and politically salient than an exclusively gender-centric framework for realizing the potential of women's inclusion and leadership in key sectors [226]. These calls for broader coalitions appear philosophically aligned with the work of feminist geographers and political ecologists, who, working through the lens of water access, have argued that gender itself is socially constructed through access to water, control of water resources, and through its intersections with social status, home ownership, land tenure, and employment status [242, 243].

Part 2 Conclusions

The SDG service ladder, the human right to water, and the gradual recognition of intersectional identities have motivated an increasingly multidimensional understanding of access beyond simply infrastructure coverage. The health literature continues to focus primarily on diarrheal disease and child health, but research has begun to unpack causal pathways to identify cost-effective, impactful interventions. Null results from large-scale randomized controlled trials of traditional water quality improvement strategies are opening up a larger conversation about the need for "transformative" or "transformational" WASH, a concept that calls for ambitious interventions to improve health. It is yet to be seen how gender norms are incorporated into "transformative WASH" programs, a concept that is distinct from "gender-transformative," although research on the cumulative burdens on women - both physical and psychosocial - are generating a more nuanced understanding of the true toll of the lack of water access on women and society overall.

With "special attention" to the needs of women and girls in the SDG sanitation and hygiene targets, the sub-field of menstrual hygiene management has gained attention, and the expansion of WASH goals into schools and healthcare facilities has directly linked basic infrastructure with women's and girls' education and participation in public life. WASH programs are using formalized rules and benchmarks to encourage women's leadership, often used synonymously with "empowerment," in water planning; yet, significant barriers remain to meaningful participation and leadership. Finally, the intersectionality of multiple identities held by those who access or struggle to claim access to water is increasingly acknowledged, recognizing that gendered burdens can be mitigated or exacerbated by factors such as race, class, caste, gender identity, or marital status.

3.5 Conclusion

The human-rights based SDGs have put forth ambitious goals for universal water access and gender equality by 2030. It is still true that data are collected by the single unit of "the" household as opposed to by gender, though the need for disaggregated data is now widely acknowledged in almost all health and development research. The expansion of water access goals beyond the household recognizes the importance of creating inclusive spaces for women and girls to safely participate in public life. While barriers remain to the realization of gender equality in the water sector, we find that the research literature has internalized the need not only for gender-equal access to water, but for water as a potential vehicle for human rights and dignity in diverse political contexts. The recent literature on water and development has, to a significant extent, moved beyond a discussion of women as a single category towards a more relational – and complex – understanding of gender in the water domain. Yet, through the instrumentalization of women and the undervaluation of their labor, the global water agenda continues to undervalue the benefits of safe water for women, despite acknowledging their central role in providing and protecting water. Research on gender and water, particularly in the social sciences, is taking an intersectional turn, however, acknowledging the co-existence of multiple marginalities within the same body. If justice calls for fairness in interacting with specific groups on their own terms, giving value to their perspectives and positionalities, then we can say that the water and development community is (slowly) moving towards a recognition of gender justice in the pursuit of water for all.

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Conclusion

From these three chapters, I have concluded that: (1) chlorine POU products can play a limited role in increasing safe water access, although suboptimal and declining adherence makes it unlikely to achieve the historical benefits of chlorinated urban piped water systems, (2) passive chlorination technologies are effective for system-level water treatment in small rural piped systems, with the potential to radically change how low-income, rural communities can gain access to safe water, and (3) that the safe water literature is slowly but surely moving toward gender justice, recognizing that the burdens and opportunities for women and girls must be acknowledged in order to achieve justice for all in safe water access. Through this work, I hope to have contributed to the cumulative knowledge required to move closer to universal safe water access.

There are a number of possible future research directions that are motivated by this work. In Chapters 1 and 2, I focused on chlorination because of the low cost and wide availability of chlorine products, in addition to the historical benefits attributed to chlorination and its standard use in municipal treatment systems globally. However, I did not closely examine the role of non-chlorine products, for which users in experimental studies have at least a slight preference [29, 37, 40]. Future work examining adherence to non-chlorine POU products can identify whether there are additional settings in which those POU approaches may be scaled. To ensure the long-term sustainability of passive chlorination systems, future research should examine the design of service delivery models to ensure maintenance and chlorine refill delivery. Finally, to ensure that gender equality is a component of safe water work moving forward, additional research must appropriately incorporate the burdens and benefits for women and girls into valuations of safe water approaches.

However, I note that lack of safe water access is not a technological problem, and achieving universal safe water access will require much more than simply developing and implementing more effective technologies. Ribot and Peluso (2009) define access as the "ability to derive benefits from things." They use the term "bundle of powers" (contrasted with a "bundle of rights") as the combination of mechanisms within a given social and political-economic context that determine whether and how an individual may benefit from resources [244]. In other words, those without power are the ones without access. In the dominant safe water literature, these are poor households, especially rural women and girls, but also transgender people, those in religious or ethnic minority groups, or refugees.

These are the ones “left behind” during the MDG era and before, and the ones that are now prioritized in the human-rights based framework of the SDGs. I offer findings through which the current paradigm of household-level water treatment can be improved and made more equitable with a shift toward passive treatment technologies, but to truly achieve universal safe water access will require transformative changes at the community, state, and international levels.

Bibliography

1. Joint Monitoring Programme. *Safely managed drinking water - thematic report on drinking water 2017* tech. rep. (World Health Organization, UNICEF, 2017).
2. Troeger, C. *et al.* Estimates of the global, regional, and national morbidity, mortality, and aetiologies of lower respiratory infections in 195 countries, 1990–2016: a systematic analysis for the Global Burden of Disease Study 2016. *Lancet Infect. Dis.* **18,** 1191–1210 (2018).
3. UN. *The human right to water and sanitation: resolution/adopted by the General Assembly (A/RES/64/292)* 2010.
4. UN. *General comment no. 15 (2002), The right to water (arts. 11 and 12 of the International Covenant on Economic, Social and Cultural Rights)* 2002.
5. United Nations. *(A/RES/70/1) Transforming our world: the 2030 Agenda for Sustainable Development* 2015.
6. Cumming, O. *et al.* The implications of three major new trials for the effect of water, sanitation and hygiene on childhood diarrhea and stunting: a consensus statement. *BMC Med.* **17,** 173 (2019).
7. Pickering, A. J. *et al.* The WASH Benefits and SHINE trials: interpretation of WASH intervention effects on linear growth and diarrhoea. *Lancet Glob Health* **7,** e1139–e1146 (2019).
8. Null, C. *et al.* Effects of water quality, sanitation, handwashing, and nutritional interventions on diarrhoea and child growth in rural Kenya: a cluster-randomised controlled trial. *The Lancet Global Health* **6,** e316–e329 (2018).
9. Luby, S. P. *et al.* Effects of water quality, sanitation, handwashing, and nutritional interventions on diarrhoea and child growth in rural Bangladesh: a cluster randomised controlled trial. *Lancet Glob Health* **6,** e302–e315 (2018).
10. Humphrey, J. H. *et al.* Independent and combined effects of improved water, sanitation, and hygiene, and improved complementary feeding, on child stunting and anaemia in rural Zimbabwe: a cluster-randomised trial. *Lancet Glob Health* **7,** e132–e147 (2019).
11. Cutler, D. & Miller, G. The role of public health improvements in health advances: the twentieth-century United States. *Demography* **42,** 1–22 (2005).

12. Amin, N. *et al.* Field trial of an automated batch chlorinator system at shared water points in an urban community of Dhaka, Bangladesh. *Journal of Water, Sanitation and Hygiene for Development* **6,** 32–41 (2016).

13. Pickering, A. J. *et al.* Differences in Field Effectiveness and Adoption between a Novel Automated Chlorination System and Household Manual Chlorination of Drinking Water in Dhaka, Bangladesh: A Randomized Controlled Trial. *PLoS One* **10,** e0118397 (2015).

14. Pickering, A. J. *et al.* Effect of in-line drinking water chlorination at the point of collection on child diarrhoea in urban Bangladesh: a double-blind, cluster-randomised controlled trial. *Lancet Glob Health* **7,** e1247–e1256 (2019).

15. Langford, M. The United Nations Concept of Water as a Human Right: A New Paradigm for Old Problems? *Int. J. Water Resour. Dev.* **21,** 273–282 (2005).

16. White, G. C. *White's handbook of chlorination and alternative disinfectants* (Wiley, 2010).

17. UNICEF & World Health Organization. *Progress on household drinking water, sanitation and hygiene 2000-2017: special focus on inequalities* tech. rep. (2019).

18. Mintz, E., Bartram, J., Lochery, P. & Wegelin, M. Not just a drop in the bucket: expanding access to point-of-use water treatment systems. *Am. J. Public Health* **91,** 1565–1570 (2001).

19. Clasen, T. *et al.* Comment on "Household Water Treatment in Poor Populations: Is There Enough Evidence for Scaling up Now?" *Environ. Sci. Technol.* **43,** 5542–5544 (2009).

20. Schmidt, W.-P. & Cairncross, S. Household Water Treatment in Poor Populations: Is There Enough Evidence for Scaling up Now? *Environmental Science & Technology* **43,** 986–992 (2009).

21. Brown, J. & Clasen, T. High Adherence Is Necessary to Realize Health Gains from Water Quality Interventions. *PLoS One* **7,** e36735 (2012).

22. Enger, K. S., Nelson, K. L., Rose, J. B. & Eisenberg, J. N. S. The joint effects of efficacy and compliance: a study of household water treatment effectiveness against childhood diarrhea. *Water Res.* **47,** 1181–1190 (2013).

23. Arnold, B. F. & Colford Jr, J. M. Treating water with chlorine at point-of-use to improve water quality and reduce child diarrhea in developing countries: a systematic review and meta-analysis. *Am. J. Trop. Med. Hyg.* **76,** 354–364 (2007).

24. Clasen, T. F. *et al.* *Interventions to improve water quality for preventing diarrhoea* 2015.

25. Dreibelbis, R. *et al.* *The Integrated Behavioural Model for Water, Sanitation, and Hygiene: a systematic review of behavioural models and a framework for designing and evaluating behaviour change interventions in infrastructure-restricted settings* 2013.

26. Parvez, S. M. *et al.* Achieving optimal technology and behavioral uptake of single and combined interventions of water, sanitation hygiene and nutrition, in an efficacy trial (WASH benefits) in rural Bangladesh. *Trials* **19,** 358 (2018).

27. Wolf, J. *et al.* Impact of drinking water, sanitation and handwashing with soap on childhood diarrhoeal disease: updated meta-analysis and meta-regression. *Trop. Med. Int. Health* **23,** 508–525 (2018).

28. Fewtrell, L. *et al.* Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: a systematic review and meta-analysis. *Lancet Infect. Dis.* **5,** 42–52 (2005).

29. Burt, Z. *et al. User preferences and willingness to pay for safe drinking water: Experimental evidence from rural Tanzania* 2017.

30. Ray, I. Women, Water, and Development. *Annu. Rev. Environ. Resour.* **32,** 421–449 (2007).

31. Loharikar, A. *et al.* Long-term impact of integration of household water treatment and hygiene promotion with antenatal services on maternal water treatment and hygiene practices in Malawi. *Am. J. Trop. Med. Hyg.* **88,** 267–274 (2013).

32. Matanock, A. *et al.* Integrating Water Treatment into Antenatal Care: Impact on Use of Maternal Health Services and Household Water Treatment by Mothers-Rural Uganda, 2013. *Am. J. Trop. Med. Hyg.* **94,** 1150–1156 (2016).

33. Sheth, A. N. *et al. Impact of the Integration of Water Treatment and Handwashing Incentives with Antenatal Services on Hygiene Practices of Pregnant Women in Malawi* 2010.

34. Lantagne, D. S. & Clasen, T. F. Use of household water treatment and safe storage methods in acute emergency response: case study results from Nepal, Indonesia, Kenya, and Haiti. *Environ. Sci. Technol.* **46,** 11352–11360 (2012).

35. Lantagne, D. & Clasen, T. Effective use of household water treatment and safe storage in response to the 2010 Haiti earthquake. *Am. J. Trop. Med. Hyg.* **89,** 426–433 (2013).

36. Mong, Y. *et al.* Impact of the safe water system on water quality in cyclone-affected communities in Madagascar. *Am. J. Public Health* **91,** 1577–1579 (2001).

37. Albert, J., Luoto, J. & Levine, D. End-user preferences for and performance of competing POU water treatment technologies among the rural poor of Kenya. *Environ. Sci. Technol.* **44,** 4426–4432 (2010).

38. Crump, J. A. *et al.* Household based treatment of drinking water with flocculant-disinfectant for preventing diarrhoea in areas with turbid source water in rural western Kenya: cluster randomised controlled trial. *BMJ* **331,** 478 (2005).

39. Geremew, A. *et al.* Consistent point-of-use water chlorination among households using unimproved water sources and treatment preference in Eastern Ethiopia. *Int. J. Environ. Health Res.* **29,** 686–701 (2019).

40. Luoto, J. *et al.* What point-of-use water treatment products do consumers use? Evidence from a randomized controlled trial among the urban poor in Bangladesh. *PLoS One* **6,** e26132 (2011).

41. Potgieter, N., Becker, P. J. & Ehlers, M. M. Evaluation of the CDC safe water-storage intervention to improve the microbiological quality of point-of-use drinking water in rural communities in South Africa. *Water SA* **35** (2009).

42. Rangel, J. M., Lopez, B., Mejia, M. A., Mendoza, C. & Luby, S. A novel technology to improve drinking water quality: a microbiological evaluation of in-home flocculation and chlorination in rural Guatemala. *J. Water Health* **1,** 15–22 (2003).

43. Reller, M. E. *et al.* A randomized controlled trial of household-based flocculant-disinfectant drinking water treatment for diarrhea prevention in rural Guatemala. *Am. J. Trop. Med. Hyg.* **69,** 411–419 (2003).

44. Shaheed, A. *et al.* Adherence to Point-of-Use Water Treatment over Short-Term Implementation: Parallel Crossover Trials of Flocculation–Disinfection Sachets in Pakistan and Zambia. *Environ. Sci. Technol.* **52,** 6601–6609 (2018).

45. Sobsey, M. D., Handzel, T. & Venczel, L. Chlorination and safe storage of household drinking water in developing countries to reduce waterborne disease. *Water Sci. Technol.* **47,** 221–228 (2003).

46. Opryszko, M. C. *et al.* Water and hygiene interventions to reduce diarrhoea in rural Afghanistan: a randomized controlled study. *J. Water Health* **8,** 687–702 (2010).

47. Quick, R. E. *et al.* Narrow-mouthed water storage vessels and in situ chlorination in a Bolivian community: a simple method to improve drinking water quality. *Am. J. Trop. Med. Hyg.* **54,** 511–516 (1996).

48. Altmann, M. *et al.* Effectiveness of a Household Water, Sanitation and Hygiene Package on an Outpatient Program for Severe Acute Malnutrition: A Pragmatic Cluster-Randomized Controlled Trial in Chad. *Am. J. Trop. Med. Hyg.* **98,** 1005–1012 (2018).

49. Quick, R. E. *et al.* Diarrhoea prevention in Bolivia through point-of-use water treatment and safe storage: a promising new strategy. *Epidemiol. Infect.* **122,** 83–90 (1999).

50. Quick, R. E. *et al.* Diarrhea prevention through household-level water disinfection and safe storage in Zambia. *Am. J. Trop. Med. Hyg.* **66,** 584–589 (2002).

51. Sugar, N. R. *et al.* Integrating Household Water Treatment, Hand Washing, and Insecticide-Treated Bed Nets Into Pediatric HIV Care in Mombasa, Kenya: Impact on Diarrhea and Malaria Risk. *J. Acquir. Immune Defic. Syndr.* **76,** 266–272 (2017).

52. Chiller, T. M. *et al.* Reducing diarrhoea in Guatemalan children: randomized controlled trial of flocculant-disinfectant for drinking-water. *Bull. World Health Organ.* **84,** 28–35 (2006).

53. Luby, S. P., Mendoza, C., Keswick, B. H., Chiller, T. M. & Hoekstra, R. M. Difficulties in bringing point-of-use water treatment to scale in rural Guatemala. *Am. J. Trop. Med. Hyg.* **78,** 382–387 (2008).

54. Colindres, R. E., Jain, S., Bowen, A., Mintz, E. & Domond, P. *After the flood: an evaluation of in-home drinking water treatment with combined flocculent-disinfectant following Tropical Storm Jeanne — Gonaives, Haiti, 2004* 2007.

55. Doocy, S. & Burnham, G. Point-of-use water treatment and diarrhoea reduction in the emergency context: an effectiveness trial in Liberia. *Trop. Med. Int. Health* **11,** 1542–1552 (2006).

56. Norton, D. M. *et al.* Flocculant-disinfectant point-of-use water treatment for reducing arsenic exposure in rural Bangladesh. *Int. J. Environ. Health Res.* **19,** 17–29 (2009).

57. Luby, S. *et al.* A low-cost intervention for cleaner drinking water in Karachi, Pakistan. *Int. J. Infect. Dis.* **5,** 144–150 (2001).

58. Macy, J. T. & Quick, R. E. Evaluation of a novel drinking water treatment and storage intervention in Nicaragua. *Rev. Panam. Salud Publica* **3,** 135–136 (1998).

59. Mellor JE, Kallman Erin, Oyanedel-Craver Vinka & Smith James A. Comparison of Three Household Water Treatment Technologies in San Mateo Ixtatán, Guatemala. *J. Environ. Eng.* **141,** 04014085 (2015).

60. Mengistie, B., Berhane, Y. & Worku, A. *Household Water Chlorination Reduces Incidence of Diarrhea among Under-Five Children in Rural Ethiopia: A Cluster Randomized Controlled Trial* 2013.

61. Murray, A. L. *et al.* Evaluation of consistent use, barriers to use, and microbiological effectiveness of three prototype household water treatment technologies in Haiti, Kenya, and Nicaragua. *Sci. Total Environ.* **718,** 134685 (2020).

62. Boisson, S. *et al.* Effect of household-based drinking water chlorination on diarrhoea among children under five in Orissa, India: a double-blind randomised placebo-controlled trial. *PLoS Med.* **10,** e1001497 (2013).

63. Clasen, T., Saeed, T. F., Edmondson, P., Boisson, S. & Shipin, O. *Household water treatment using sodium dichloroisocyanurate (NaDCC) tablets: A randomized, controlled trial to assess microbiological effectiveness in Bangladesh* 2007.

64. Ercumen, A. *et al. Effects of Source- versus Household Contamination of Tubewell Water on Child Diarrhea in Rural Bangladesh: A Randomized Controlled Trial* 2015.

65. George, C. M. *et al.* Randomized Controlled Trial of Hospital-Based Hygiene and Water Treatment Intervention (CHoBI7) to Reduce Cholera. *Emerg. Infect. Dis.* **22,** 233–241 (2016).

66. Jain, S. *et al.* Sodium Dichloroisocyanurate Tablets for Routine Treatment of Household Drinking Water in Periurban Ghana: A Randomized Controlled Trial. *Am. J. Trop. Med. Hyg.* **82,** 16–22 (2010).

67. Blanton, E. *et al.* Evaluation of the role of school children in the promotion of point-of-use water treatment and handwashing in schools and households–Nyanza Province, Western Kenya, 2007. *Am. J. Trop. Med. Hyg.* **82,** 664–671 (2010).
68. Tsai, F.-J., Wu, M. & Lin, C.-P. Does a Free-Trial Approach Increase Purchase and Use of a Household Water Treatment and Safe Storage Product in Rural Haiti? *Am. J. Trop. Med. Hyg.* **102,** 518–525 (2020).
69. George, C. M. *et al.* Sustained Uptake of a Hospital-Based Handwashing with Soap and Water Treatment Intervention (Cholera-Hospital-Based Intervention for 7 Days [CHoBI7]): A Randomized Controlled Trial. *Am. J. Trop. Med. Hyg.* **94,** 428–436 (2016).
70. Sphere Association. *The Sphere Handbook: Humanitarian Charter and Minimum Standards in Humanitarian Response* (Geneva, Switzerland, 2018).
71. World Health Organization. *Guidelines for drinking water quality: fourth edition incorporated the first addendum* (Geneva, 2017).
72. Thaler, R. H. & Sunstein, C. R. *Nudge: Improving Decisions about Health, Wealth and Happiness* (Penguin Books, 2009).
73. Clasen, T. & Edmondson, P. Sodium dichloroisocyanurate (NaDCC) tablets as an alternative to sodium hypochlorite for the routine treatment of drinking water at the household level. *Int. J. Hyg. Environ. Health* **209,** 173–181 (2006).
74. Najnin, N. *et al.* Impact of adding hand-washing and water disinfection promotion to oral cholera vaccination on diarrhoea-associated hospitalization in Dhaka, Bangladesh: evidence from a cluster randomized control trial. *Int. J. Epidemiol.* **46,** 2056–2066 (2017).
75. Ahuja, A., Kremer, M. & Zwane, A. P. Providing Safe Water: Evidence from Randomized Evaluations. *Annu. Rev. Resour. Econ.* **2,** 237–256 (2010).
76. Evans, D. K., Jakiela, P. & Knauer, H. A. The impact of early childhood interventions on mothers. *Science* **372,** 794–796 (2021).
77. Mullainathan, S. & Shafir, E. *Scarcity: Why Having Too Little Means So Much* (Macmillan, 2013).
78. Ray, I. & Smith, K. R. Towards safe drinking water and clean cooking for all. *Lancet Glob Health* **9,** e361–e365 (2021).
79. Bertrand, M., Mullainathan, S. & Shafir, E. Behavioral Economics and Marketing in Aid of Decision Making among the Poor. *Journal of Public Policy & Marketing* **25,** 8–23 (2006).
80. Ministry of Health Nepal, New ERA & ICF. *Nepal Demographic and Health Survey 2016* tech. rep. (Ministry of Health, Nepal, Kathmandu, Nepal, 2017).

81. Daniel, D., Diener, A., van de Vossenberg, J., Bhatta, M. & Marks, S. J. Assessing Drinking Water Quality at the Point of Collection and within Household Storage Containers in the Hilly Rural Areas of Mid and Far-Western Nepal. *Int. J. Environ. Res. Public Health* **17** (2020).

82. Kostyla, C., Bain, R., Cronk, R. & Bartram, J. Seasonal variation of fecal contamination in drinking water sources in developing countries: a systematic review. *Sci. Total Environ.* **514,** 333–343 (2015).

83. Crider, Y. *et al.* Can you taste it? Taste detection and acceptability thresholds for chlorine residual in drinking water in Dhaka, Bangladesh. *Sci. Total Environ.* **613-614,** 840–846 (2018).

84. Schertenleib, A. *et al.* Construction of a Low-cost Mobile Incubator for Field and Laboratory Use. *J. Vis. Exp.* (2019).

85. Tosi Robinson, D. *et al.* Assessing the Impact of a Risk-Based Intervention on Piped Water Quality in Rural Communities: The Case of Mid-Western Nepal. *Int. J. Environ. Res. Public Health* **15** (2018).

86. Wright, J., Gundry, S. & Conroy, R. Household drinking water in developing countries: a systematic review of microbiological contamination between source and point-of-use. *Trop. Med. Int. Health* **9,** 106–117 (2004).

87. Rayner, J., Yates, T., Joseph, M. & Lantagne, D. Sustained effectiveness of automatic chlorinators installed in community-scale water distribution systems during an emergency recovery project in Haiti. *J. Water Sanit. Hyg. Dev.* **6,** 602–612 (2016).

88. Luoto, J. *et al.* Learning to dislike safe water products: results from a randomized controlled trial of the effects of direct and peer experience on willingness to pay. *Environ. Sci. Technol.* **46,** 6244–6251 (2012).

89. Chant, S. & Sweetman, C. Fixing women or fixing the world? 'Smart economics', efficiency approaches, and gender equality in development. *Gender & Development* **20,** 517–529 (2012).

90. Razavi, S. & Miller, C. *From WID to GAD: Conceptual shifts in the women and development discourse* tech. rep. (United Nations Research Institute for Social Development, United Nations Development Programme, 1995).

91. Jolly, S. Why is development work so straight? Heteronormativity in the international development industry. *Dev. Pract.* **21,** 18–28 (2011).

92. Gleick, P. H. Basic Water Requirements for Human Activities: Meeting Basic Needs. *Water Int.* **21,** 83–92 (1996).

93. Howard, G. *et al. Domestic water quantity, service level and health (2nd edition)* tech. rep. (World Health Organization, 2020).

94. Zwarteveen, M. Z. Water: From basic need to commodity: A discussion on gender and water rights in the context of irrigation. *World Dev.* **25,** 1335–1349 (1997).

95. Easterly, W. How the Millennium Development Goals are Unfair to Africa. *World Dev.* **37,** 26–35 (2009).

96. Cleaver, F. Incentives and informal institutions: Gender and the management of water. *Agric. Human Values* **15,** 347–360 (1998).

97. O'Reilly, K. "Traditional" women, "modern" water: Linking gender and commodification in Rajasthan, India. *Geoforum* **37,** 958–972 (2006).

98. Gleick, P. H. The human right to water. *Water Policy,* 487–503 (1998).

99. Alderman, H., Chiappori, P.-A., Haddad, L., Hoddinott, J. & Kanbur, R. Unitary versus collective models of the household: is it time to shift the burden of proof? *World Bank Res. Obs.* **10,** 1–19 (1995).

100. WHO/UNICEF. *Progress on Drinking Water and Sanitation (2014 update)* tech. rep. (World Health Organization, UNICEF, 2014).

101. WHO/UNICEF. *Meeting the MDG Drinking Water and Sanitation Target: A Mid-Term Assessment of Progress* tech. rep. (World Health Organization, UNICEF, 2004).

102. *Gender, Time Use, and Poverty in Sub-Saharan Africa* (eds Wodon, Q. & Blackden, C. M.) (The World Bank, 2006).

103. Hawkins, R. & Seager, J. Gender and Water in Mongolia. *Prof. Geogr.* **62,** 16–31 (2010).

104. Hutton, G. *Monitoring "Affordability" of water and sanitation services after 2015: Review of global indicator options* tech. rep. (Submitted to the United Nations Office of the High Commission for Human Rights, 2012).

105. Gleick, P. H. Water Use. *Annu. Rev. Environ. Resour.* **28,** 275–314 (2003).

106. Aiga, H. & Umenai, T. Correspondence: Standardisation of the definition of access to safe water. *Lancet* **361,** P2156 (2003).

107. Hutton, G., Haller, L. & Bartram, J. Global cost-benefit analysis of water supply and sanitation interventions. *J. Water Health* **5,** 481–502 (2007).

108. Prüss, A., Kay, D., Fewtrell, L. & Bartram, J. Estimating the burden of disease from water, sanitation, and hygiene at a global level. *Environ. Health Perspect.* **110,** 537–542 (2002).

109. Lozano, R. *et al.* Global and regional mortality from 235 causes of death for 20 age groups in 1990 and 2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet* **380,** 2095–2128 (2012).

110. Kosek, M., Bern, C. & Guerrant, R. L. The global burden of diarrhoeal disease, as estimated from studies published between 1992 and 2000. *Bull. World Health Organ.* **81,** 197–204 (2003).

111. WHO/UNICEF. *IMCI adaptation guide: A guide to identifying necessary adaptations of clinical policies and guidelines, and to adapting the charts and modules for the WHO/UNICEF course* (2002).

112. WHO. *The management and prevention of diarrhoea: Practical guidelines* World Health Organization (1993).

113. White, G. F., Bradley, D. J. & White, A. U. Drawers of water: domestic water use in East Africa. 1972. *Bull. World Health Organ.* **80,** 63–62 (2002).

114. West, S. K., Munoz, B., Turner, V. M., Mmbaga, B. B. & Taylor, H. R. The epidemiology of trachoma in central Tanzania. *Int. J. Epidemiol.* **20,** 1088–1092 (1991).

115. Kjetland, E. F. *et al.* Association between genital schistosomiasis and HIV in rural Zimbabwean women. *AIDS* **20,** 593–600 (2006).

116. Nour, N. M. Schistosomiasis: health effects on women. *Rev. Obstet. Gynecol.* **3,** 28 (2010).

117. Faveau, V. & Blanchet, T. Deaths from injuries and induced abortion among rural Bangladesh women. *Social science and medicine* **29,** 1121–1127 (1989).

118. Geere, J. L., Hunter, P. R. & Jagals, P. Domestic water carrying and its implications for health: a review and mixed methods pilot study in Limpopo Province, South Africa. *Environ. Health* **9,** 52 (2010).

119. McCray, T. M. An issue of culture: the effects of daily activities on prenatal care utilization patterns in rural South Africa. *Soc. Sci. Med.* **59,** 1843–1855 (2004).

120. WHO/UNICEF. *Progress on Drinking Water and Sanitation (2012 update)* tech. rep. (World Health Organization, UNICEF, 2012).

121. Bain, R. *et al.* Fecal contamination of drinking-water in low- and middle-income countries: a systematic review and meta-analysis. *PLoS Med.* **11,** e1001644 (2014).

122. Sobsey, M. D. *Managing water in the home: accelerated health gains from improved water supply* tech. rep. (World Health Organization, 2002).

123. Mason, A. D. & King, E. M. *Engendering development through gender equality in rights, resources, and voice (English). A World Bank policy research report* tech. rep. (World Bank Group, Washington, D.C., 2001).

124. Shiva, V. *Staying Alive: Women, Ecology and Development* (Zed Books, 1989).

125. Van Wijk-Sijbesma, C. in *Participation of women in water supply and sanitation: roles and realities.* (IRC, 1985).

126. Cleaver, F. Maintenance of rural water supplies in Zimbabwe. *Waterlines* **9** (1991).

127. Hoffman, L. Women handpump mechanics in Kenya. *Waterlines* **11,** 19–21 (1992).

128. Wood, M. A handpump for Africa: the Afridev experience. *Waterlines* **11** (1993).

129. Prokopy, L. Women's participation in rural water supply projects in India: is it moving beyond tokenism and does it matter? *Water Policy* **6,** 103–116 (2004).

130. Jackson, C. Doing what comes naturally? Women and environment in development. *World Dev.* (1993).

131. Kleemeier, E. The Impact of Participation on Sustainability: An Analysis of the Malawi Rural Piped Scheme Program. *World Dev.* **28,** 929–944 (2000).

132. Zwarteveen, M. Z. Identifying gender aspects of new irrigation management policies. *Agric. Human Values* **15,** 301–312 (1998).

133. Goff, M. & Crow, B. What is water equity? The unfortunate consequences of a global focus on 'drinking water'. *Water Int.* **39,** 159–171 (2014).

134. Fukuda-Parr, S., Greenstein, J. & Stewart, D. How Should MDG Success and Failure be Judged: Faster Progress or Achieving the Targets? *World Dev.* **41,** 19–30 (2013).

135. UN. *A/RES/70/1. Transforming our world: the 2030 Agenda for Sustainable Development* 2015.

136. Jepson, W. E., Wutich, A., Colllins, S. M., Boateng, G. O. & Young, S. L. Progress in household water insecurity metrics: a cross-disciplinary approach. *WIREs Water* **4,** e1214 (2017).

137. Balazs, C. & Ray, I. The Drinking Water Disparities Framework: On the Origins and Persistence of Inequities in Exposure. *Am. J. Public Health* **104,** 603–611 (2014).

138. Heaney, C. D. *et al.* Public Infrastructure Disparities and the Microbiological and Chemical Safety of Drinking and Surface Water Supplies in a Community Bordering a Landfill. *J. Environ. Health* **75,** 24–36 (2013).

139. Meehan, K. *et al.* Exposing the myths of household water insecurity in the global north: A critical review. *WIREs Water* **7,** e1486 (2020).

140. Obeng-Odoom, F. Beyond access to water. *Dev. Pract.* **22,** 1135–1146 (2012).

141. Subbaraman, R. *et al.* Multidimensional Measurement of Household Water Poverty in a Mumbai Slum: Looking Beyond Water Quality. *PLoS One* **10,** e0133241 (2015).

142. Winter, J. C., Darmstadt, G. L. & Davis, J. The role of piped water supplies in advancing health, economic development, and gender equality in rural communities. *Soc. Sci. Med.* 113599 (2021).

143. Devoto, F., Duflo, E., Dupas, P., Parienté, W. & Pons, V. Happiness on Tap: Piped Water Adoption in Urban Morocco. *American Economic Journal: Economic Policy* **4,** 68–99 (2012).

144. Silva, B. B., Sales, B., Lanza, A. C., Heller, L. & Rezende, S. Water and sanitation are not gender-neutral: human rights in rural Brazilian communities. *Water Policy* **22,** 102–120 (2020).

145. Nauges, C. & Strand, J. *Water Hauling and Girls' School Attendance: Some New Evidence from Ghana* (The World Bank, 2013).

146. Gross, E., Günther, I. & Schipper, Y. Women Are Walking and Waiting for Water: The Time Value of Public Water Supply. *Econ. Dev. Cult. Change* **66,** 489–517 (2018).

147. Bartram, J. *et al. Water safety plan manual: step-by-step risk management for drinking-water suppliers* World Health Organization & International Water Association (2009).

148. WHO. *Guidelines for Drinking-water Quality* World Health Organization (2004).

149. WHO. *Water safety plan: a field guide to improving drinking-water safety in small communities* World Health Organization Regional Office for Europe (2014).

150. Wood, S., Foster, J. & Kols, A. Understanding why women adopt and sustain home water treatment: Insights from the Malawi antenatal care program. *Soc. Sci. Med. Part Special Issue: Challenges to changing health behaviours in developing countries* **75,** 634–642 (2012).

151. Caruso, B. A. & Sinharoy, S. S. Gender data gaps represent missed opportunities in WASH. *The Lancet Global Health* **7,** e1617 (2019).

152. Sultana, F. Suffering for water, suffering from water: Emotional geographies of resource access, control and conflict. *Geoforum. Themed Issue: New Feminist Political Ecologies* **42,** 163–172 (2011).

153. Truelove, Y. (Re-)Conceptualizing water inequality in Delhi, India through a feminist political ecology framework. *Geoforum. Themed Issue: New Feminist Political Ecologies* **42,** 143–152 (2011).

154. Udas, P. B., Roth, D. & Zwarteveen, M. Informal privatisation of community taps: issues of access and equity. *Local Environ.* **19,** 1024–1041 (2014).

155. Nagar, R., Lawson, V., McDowell, L. & Hanson, S. Locating Globalization: Feminist (Re)readings of the Subjects and Spaces of Globalization. *Econ. Geogr.* **78,** 257–284 (2002).

156. Cheng, D. Contestations at the last mile: The corporate–community delivery of water in Manila. *Geoforum* **59,** 240–247 (2015).

157. Sorenson, S. B., Morssink, C. & Campos, P. A. Safe access to safe water in low income countries: water fetching in current times. *Soc. Sci. Med.* **72,** 1522–1526 (2011).

158. Kotloff, K. L. *et al.* Burden and aetiology of diarrhoeal disease in infants and young children in developing countries (the Global Enteric Multicenter Study, GEMS): a prospective, case-control study. *Lancet* **382,** 209–222 (2013).

159. Arnold, B. F. *et al.* Cluster-randomised controlled trials of individual and combined water, sanitation, hygiene and nutritional interventions in rural Bangladesh and Kenya: the WASH Benefits study design and rationale. *BMJ Open* **3** (2013).

160. Humphrey, J. H. *et al.* The Sanitation Hygiene Infant Nutrition Efficacy (SHINE) Trial: Rationale, Design, and Methods. *Clin. Infect. Dis.* **61 Suppl 7,** S685–702 (2015).

161. Langer, A. *et al.* Women and Health: the key for sustainable development. *Lancet* **386,** 1165–1210 (2015).

162. Hanna-Attisha, M., LaChance, J., Sadler, R. C. & Champney Schnepp, A. Elevated Blood Lead Levels in Children Associated With the Flint Drinking Water Crisis: A Spatial Analysis of Risk and Public Health Response. *Am. J. Public Health* **106,** 283–290 (2016).

163. Balazs, C., Morello-Frosch, R., Hubbard, A. & Ray, I. Social disparities in nitrate-contaminated drinking water in California's San Joaquin Valley. *Environ. Health Perspect.* **119,** 1272–1278 (2011).

164. Pederson, A., Greaves, L. & Poole, N. Gender-transformative health promotion for women: a framework for action. *Health Promot. Int.* **30,** 140–150 (2015).

165. Caruso, B. A. *et al.* Understanding and defining sanitation insecurity: women's gendered experiences of urination, defecation and menstruation in rural Odisha, India. *BMJ Glob Health* **2,** e000414 (2017).

166. Caruso, B. A., Sevilimedu, V., Fung, I. C.-H., Patkar, A. & Baker, K. K. Gender disparities in water, sanitation, and global health. *Lancet* **386,** 650–651 (2015).

167. Geere, J. L., Cortobius, M., Geere, J. H., Hammer, C. C. & Hunter, P. R. Is water carriage associated with the water carrier's health? A systematic review of quantitative and qualitative evidence. *BMJ Glob Health* **3** (2018).

168. Collins, S. M. *et al.* 'I know how stressful it is to lack water!' Exploring the lived experiences of household water insecurity among pregnant and postpartum women in western Kenya. *Glob. Public Health* **14,** 649–662 (2019).

169. Pommells, M., Schuster-Wallace, C., Watt, S. & Mulawa, Z. Gender Violence as a Water, Sanitation, and Hygiene Risk: Uncovering Violence Against Women and Girls as It Pertains to Poor WaSH Access. *Violence Against Women* **24,** 1851–1862 (2018).

170. West, B. S., Hirsch, J. S. & El-Sadr, W. HIV and H20: Tracing the connections between gender, water and HIV. *AIDS Behav.* **17,** 1675–1682 (2013).

171. The Lancet HIV. For the HIV epidemic to end so must gender inequality. *Lancet HIV* **6,** e411 (2019).

172. Geere, J. L. & Cortobius, M. Who carries the weight of water? Fetching water in rural and urban areas and the implications for water security. *Water Alternatives* **10,** 513–540 (2017).

173. Venkataramanan, V. *et al.* In pursuit of 'safe' water: the burden of personal injury from water fetching in 21 low-income and middle-income countries. *BMJ Global Health* **5,** e003328 (2020).

174. Choudhary, N., Brewis, A., Wutich, A. & Udas, P. B. Sub-optimal household water access is associated with greater risk of intimate partner violence against women: evidence from Nepal. *J. Water Health* **18,** 579–594 (2020).

175. Wutich, A. & Ragsdale, K. Water insecurity and emotional distress: coping with supply, access, and seasonal variability of water in a Bolivian squatter settlement. *Soc. Sci. Med.* **67,** 2116–2125 (2008).

176. Van Houweling, E. "A Good Wife Brings Her Husband Bath Water": Gender Roles and Water Practices in Nampula, Mozambique. *Soc. Nat. Resour.* **29,** 1065–1078 (2016).

177. Stevenson, E. G. J. *et al.* Water insecurity in 3 dimensions: an anthropological perspective on water and women's psychosocial distress in Ethiopia. *Soc. Sci. Med.* **75,** 392–400 (2012).

178. Kumar, T., Post, A. E. & Ray, I. Flows, leaks and blockages in informational interventions: A field experimental study of Bangalore's water sector. *World Dev.* **106,** 149–160 (2018).

179. Wutich, A. & Brewis, A. Food, Water, and Scarcity: Toward a Broader Anthropology of Resource Insecurity. *Curr. Anthropol.* **55,** 444–468 (2014).

180. Sahoo, K. C. *et al.* Sanitation-related psychosocial stress: A grounded theory study of women across the life-course in Odisha, India. *Soc. Sci. Med.* **139,** 80–89 (2015).

181. McMahon, S. A. *et al.* 'The girl with her period is the one to hang her head' Reflections on menstrual management among schoolgirls in rural Kenya. *BMC Int. Health Hum. Rights* **11** (2011).

182. Bisung, E. & Elliott, S. J. Psychosocial impacts of the lack of access to water and sanitation in low- and middle-income countries: a scoping review. *J. Water Health* **15,** 17–30 (2016).

183. Wutich, A., Brewis, A. & Tsai, A. Water and mental health. *WIREs Water* **7,** e1461 (2020).

184. Blakeney, A. B. & Marshall, A. Water quality, health, and human occupations. *Am. J. Occup. Ther.* **63,** 46–57 (2009).

185. Amirhadji, J. *et al. Tapped Out: Threats to the Human Right to Water in the Urban United States* tech. rep. (2013).

186. Curtis, V. & Cairncross, S. Effect of washing hands with soap on diarrhoea risk in the community: a systematic review. *Lancet Infect. Dis.* **3,** 275–281 (2003).

187. Freeman, M. C. *et al.* Hygiene and health: systematic review of handwashing practices worldwide and update of health effects. *Tropical Medicine & International Health* **19,** 906–916 (2014).

188. Brauer, M., Zhao, J. T., Bennitt, F. B. & Stanaway, J. D. Global Access to Handwashing: Implications for COVID-19 Control in Low-Income Countries. *Environmental Health Perspectives* (2020).

189. Nizame, F. A. *et al.* Handwashing before food preparation and child feeding: a missed opportunity for hygiene promotion. *Am. J. Trop. Med. Hyg.* **89,** 1179–1185 (2013).

190. Scott, B. E., Schmidt, W. P., Aunger, R., Garbrah-Aidoo, N. & Animashaun, R. Marketing hygiene behaviours: the impact of different communication channels on reported handwashing behaviour of women in Ghana. *Health Educ. Res.* **23,** 392–401 (2008).

191. Curtis, V. A., Danquah, L. O. & Aunger, R. V. Planned, motivated and habitual hygiene behaviour: an eleven country review. *Health Educ. Res.* **24,** 655–673 (2009).

192. WHO. *Recommendations to Member States to improve hand hygiene practices to help prevent the transmission of the COVID-19 virus (Interim guidance)* World Health Organization (2020).

193. Freeman, M. C. & Caruso, B. A. Comment on "Global Access to Handwashing: Implications for COVID-19 Control in Low-Income Countries". *Environ. Health Perspect.* **128** (2020).

194. Van Eijk, A. M. *et al.* Menstrual cup use, leakage, acceptability, safety, and availability: a systematic review and meta-analysis. *Lancet Public Health* **4,** e376–e393 (2019).

195. Das, P. *et al.* Menstrual Hygiene Practices, WASH Access and the Risk of Urogenital Infection in Women from Odisha, India. *PLoS One* **10,** e0130777 (2015).

196. Sommer, M. *et al.* Beyond menstrual hygiene: addressing vaginal bleeding throughout the life course in low and middle-income countries. *BMJ Glob Health* **2** (2017).

197. Human Rights Council. *A/HRC/21/42: Report of the Special Rapporteur on the human right to safe drinking water and sanitation: Catarina de Albuquerque* tech. rep. (UN General Assembly, 2012).

198. Human Rights Council. *A/HRC/42/47. Human rights to water and sanitation in spheres of life beyond the household with an emphasis on public spaces* tech. rep. (UN General Assembly, 2019).

199. Chatterley, C. *et al.* Institutional WASH in the SDGs: data gaps and opportunities for national monitoring. *Journal of Water, Sanitation and Hygiene for Development* **8,** 595–606 (2018).

200. WHO/UNICEF. *Drinking Water, Sanitation and Hygiene in Schools: Global baseline report 2018* tech. rep. (World Health Organization, UNICEF, 2018).

201. WHO/UNICEF. *Progress on drinking water, sanitation and hygiene in schools: Special focus on COVID-19* tech. rep. (World Health Organization, UNICEF, 2020).

202. Jasper, C., Le, T. & Bartram, J. Water and Sanitation in Schools: A Systematic Review of the Health and Educational Outcomes. *Int. J. Environ. Res. Public Health* **9,** 2772–2787 (2012).

203. Jewitt, S. & Ryley, H. It's a girl thing: Menstruation, school attendance, spatial mobility and wider gender inequalities in Kenya. *Geoforum* **56,** 137–147 (2014).

204. Mahon, T. & Fernandes, M. Menstrual hygiene in South Asia: a neglected issue for WASH (water, sanitation and hygiene) programmes. *Gender & Development* **18,** 99–113 (2010).

205. Unterhalter, E. *The MDGs, girls' education and gender equality* tech. rep. (UN Women, Mexico City, Mexico, 2013).

206. WHO/UNICEF. *WASH in health care facilities: Global Baseline Report 2019* tech. rep. (World Health Organization, United Nations Children's Fund, 2019).

207. ILO. *Improving Employment and working conditions in health services: Report for discussion at the Tripartite Meeting on Improving Employment and Working Conditions in Health Services* tech. rep. (International Labour Organization, 2017).

208. Campbell, O. M. R. & Graham, W. J. Strategies for reducing maternal mortality: getting on with what works. *Lancet* **368,** 1284–1299 (2006).

209. Velleman, Y. *et al.* From joint thinking to joint action: a call to action on improving water, sanitation, and hygiene for maternal and newborn health. *PLoS Med.* **11,** e1001771 (2014).

210. Bouzid, M., Cumming, O. & Hunter, P. R. What is the impact of water sanitation and hygiene in healthcare facilities on care seeking behaviour and patient satisfaction? A systematic review of the evidence from low-income and middle-income countries. *BMJ Global Health* **3,** e000648 (2018).

211. Say, L. *et al.* Global causes of maternal death: a WHO systematic analysis. *The Lancet Global Health* **2,** e323–e333 (2014).

212. Rhee, V. *et al.* Impact of Maternal and Birth Attendant Hand-washing on Neonatal Mortality in Southern Nepal. *Arch. Pediatr. Adolesc. Med.* **162,** 603–608 (2008).

213. Robb, K. A. *et al.* Variability of water, sanitation, and hygiene conditions and the potential infection risk following cesarean delivery in rural Rwanda. *J. Water Health* **18,** 741–752 (2020).

214. Adams, J., Bartram, J. & Chartier, Y. *Essential environmental health standards in health care* tech. rep. (World Health Organization, 2008).

215. Cronk, R. & Bartram, J. Environmental conditions in health care facilities in low- and middle-income countries: Coverage and inequalities. *Int. J. Hyg. Environ. Health* **221,** 409–422 (2018).

216. Belizan, M. *et al.* Contraception and post abortion services: qualitative analysis of users' perspectives and experiences following Zika epidemic in Honduras. *BMC Womens. Health* **20,** 199 (2020).

217. Van Koppen, B., Cossio Rojas, V. & Skielboe, T. Project politics, priorities and participation in rural water schemes. *Water Alternatives* **5** (2012).

218. Chattopadhyay, R. & Duflo, E. Women as policy makers: Evidence from a randomized policy experiment in India. *Econometrica* **72,** 1409–1443 (2004).

219. Dongre, A. A. Female Political Leadership and the Prevalence of Water Borne Diseases: Evidence from a Natural Experiment in India. *SSRN* (2010).

220. Jalal, I. *Women, Water, and Leadership* tech. rep. (Asian Development Bank, 2014).

221. WSUP. *Gender representation in Kenyan sanitation institutions* tech. rep. (Water & Sanitation for the Urban Poor, 2020).

222. Adams, E. A., Juran, L. & Ajibade, I. 'Spaces of Exclusion' in community water governance: A Feminist Political Ecology of gender and participation in Malawi's Urban Water User Associations. *Geoforum* **95,** 133–142 (2018).

223. Sultana, F. Community and participation in water resources management: gendering and naturing development debates from Bangladesh. *Trans. Inst. Br. Geogr.* **34,** 346–363 (2009).

224. Das, P. Women's Participation in Community-Level Water Governance in Urban India: The Gap Between Motivation and Ability. *World Dev.* **64,** 206–218 (2014).

225. Cairns, M. R., Workman, C. L. & Tandon, I. Gender mainstreaming and water development projects: analyzing unexpected enviro-social impacts in Bolivia, India, and Lesotho. *Gend. Place Cult.* **24,** 325–342 (2017).

226. Cornwall, A. & Rivas, A. From 'gender equality and 'women's empowerment' to global justice: reclaiming a transformative agenda for gender and development. *Third World Q.* **36,** 396–415 (2015).

227. Agarwal, B. *A Field of One's Own: Gender and Land Rights in South Asia* (Cambridge University Press, 1995).

228. Imburgia, L., Osbahr, H., Cardey, S. & Momsen, J. Inclusive participation, self-governance, and sustainability: Current challenges and opportunities for women in leadership of communal irrigation systems. *Environment and Planning E: Nature and Space* (2020).

229. Laurie, N. Gender Water Networks: Femininity and Masculinity in Water Politics in Bolivia: Gender in water politics in Bolivia. *Int. J. Urban Reg. Res.* **35,** 172–188 (2011).

230. Dery, F., Bisung, E. & Dyer, M. Understanding empowerment in water, sanitation, and hygiene (WASH): a scoping review. *Journal of Water, Sanitation & Hygiene for Development* **10** (2019).

231. Crenshaw, K. Demarginalizing the intersection of race and sex: A black feminist critique of antidiscrimination doctrine, feminist theory and antiracist politics. *Univ. Chic. Leg. Forum,* 139 (1989).

232. Cleaver, F. & Hamada, K. 'Good' water governance and gender equity: a troubled relationship. *Gender & Development* **18,** 27–41 (2010).

233. Joshi, D. Caste, Gender and the Rhetoric of Reform in India's Drinking Water Sector. *Economic and Political Weekly* **46,** 56–63 (2011).

234. Sultana, F. Embodied Intersectionalities of Urban Citizenship: Water, Infrastructure, and Gender in the Global South. *Ann. Assoc. Am. Geogr.* **110,** 1407–1424 (2020).

235. Appadurai, A. Deep democracy: urban governmentality and the horizon of politics. *Environmental & Urbanization* **13,** 23–43 (2001).

236. WHO. *World Report on Disability* tech. rep. (World Health Organization, World Bank, 2011).

237. Banks, L. M. *et al.* Are current approaches for measuring access to clean water and sanitation inclusive of people with disabilities? Comparison of individual- and household-level access between people with and without disabilities in the Tanahun district of Nepal. *PLoS One* **14,** e0223557 (2019).

238. Wrisdale, L., Mokoena, M. M., Mudau, L. S. & Geere, J. Factors that impact on access to water and sanitation for older adults and people with disability in rural South Africa: An occupational justice perspective. *Journal of Occupational Science* **24,** 259–279 (2017).

239. White, S., Kuper, H., Itimu-Phiri, A., Holm, R. & Biran, A. A Qualitative Study of Barriers to Accessing Water, Sanitation and Hygiene for Disabled People in Malawi. *PLoS One* **11,** e0155043 (2016).

240. Mactaggart, I. *et al.* Access to water and sanitation among people with disabilities: results from cross-sectional surveys in Bangladesh, Cameroon, India and Malawi. *BMJ Open* **8,** e020077 (2018).

241. UN Women. *World Survey on the Role of Women in Development 2014: Gender Equality and Sustainable Development* tech. rep. (United Nations, 2014).

242. Harris, L., Kleiber, D., Goldin, J., Darkwah, A. & Morinville, C. Intersections of gender and water: comparative approaches to everyday gendered negotiations of water access in underserved areas of Accra, Ghana and Cape Town, South Africa. *Indian J. Gend. Stud.* **26,** 561–582 (2017).

243. O'Reilly, K., Halvorson, S., Sultana, F. & Laurie, N. Introduction: global perspectives on gender–water geographies. *Gend. Place Cult.* **16,** 381–385 (2009).

244. Ribot, J. C. & Peluso, N. L. A theory of access. *Rural Sociology* **68,** 153–181 (2009).

Appendix A

Appendix to Chapter 1

Crossover trials

To report adherence measures for crossover trials, we use the method in Albert et al. (2010) [37], which pools all households over the duration they experience each product. For example, in Geremew et al. (2019) [39], we combine results from Group 1 crossover period 1 with Group 2 crossover period 2 to calculate adherence to a single product for all households over the duration of one crossover period. Depending on the order that households were assigned products, they may have experienced another chlorine product just prior.

Trials with multiple arms using the same chlorine product

Where studies have multiple arms that use the same chlorine POU product, we report in Table 1.1 an adherence calculation pooling data across those arms. If possible, we use the number of units (e.g., households, children) measured at each time point so that each arm is appropriately weighted even if there is differential attrition between arms.

Follow-up studies

Luby et al. (2008) [53] was a follow-up study to Chiller et al. (2006) [52]; we include the follow-up adherence as the last measured adherence in the sample. George et al. (2016) [69] was a 6-12 month follow-up study to George et al. (2016) [65]. However, because it is unclear whether households had access to Aquatabs, which were provided for free in the original trial, we use only adherence as measured in the original trial.

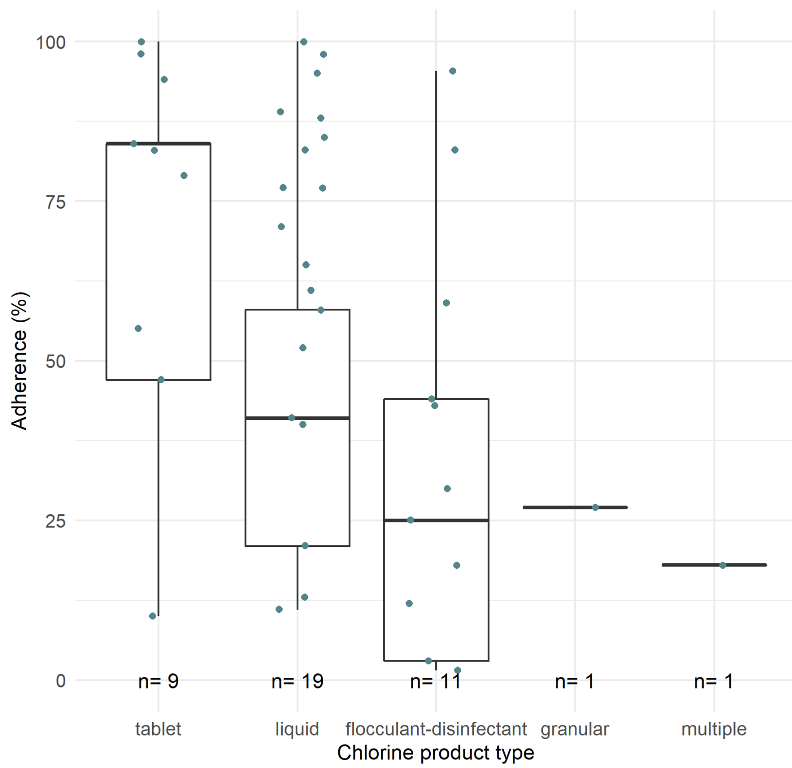

Figure A.1: Type of chlorine product and final measured adherence

Figure note: Weighted box plots showing the relationship between the type of chlorine product and final measured adherence, restricted to only groups that used FCR or total chlorine to measure adherence. This excludes Opryszko et al (2010) [46], Albert et al (2010)(a/b) [37], and Sugar et al (2017) [51]. Studies are weighted by sample size to calculate the 25th, 50th, and 75th percentiles displayed above. This includes studies that report single-time-point and pooled adherence measures.

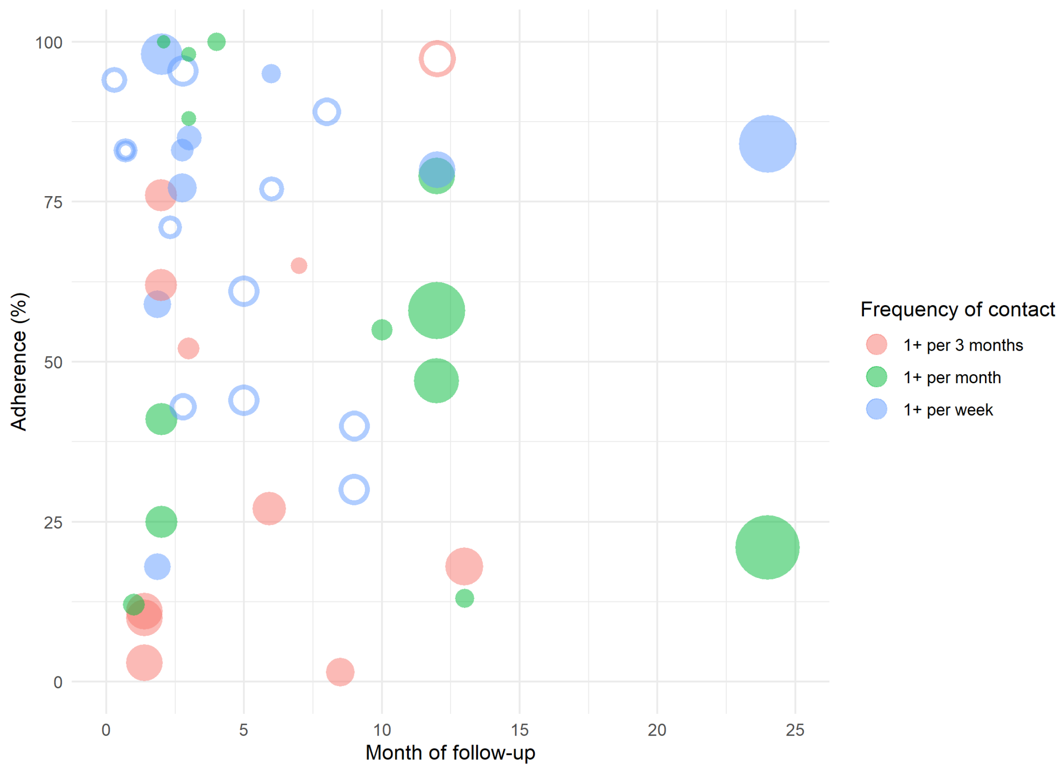

Figure A.2: Final measured adherence over time by frequency of contact with study staff

Figure note: The point sizes are scaled to indicate relative sample size (of the group(s) receiving chlorine only). Open circles indicate that the data point is reported as multiple adherence measures combined over the months of follow-up up until the time point shown. Closed circles are a single time-point result. This plot includes all groups listed in Table 1.1

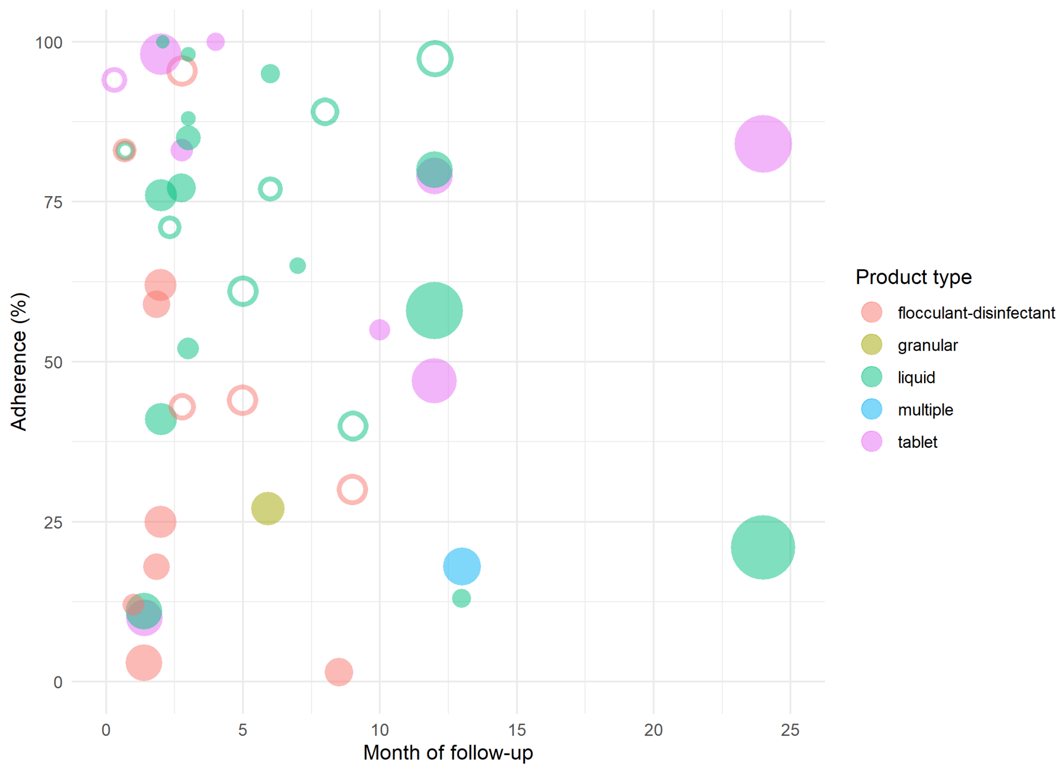

Figure A.3: Final measured adherence over time by type of chlorine POU product

Figure note: The point sizes are scaled to indicate relative sample size (of the group(s) receiving chlorine only). Open circles indicate that the data point is reported as multiple adherence measures combined over the months of follow-up up until the time point shown. Closed circles are a single time-point result. This plot includes all groups listed in Table 1.1

Figure A.4: Final measured adherence over time by study location

Figure note: "Institution" includes schools and health care facilities; "Humanitarian" includes an internally displaced persons camp and post-disaster relief. The point sizes are scaled to indicate relative sample size (of the group(s) receiving chlorine only). Open circles indicate that the data point is reported as multiple adherence measures combined over the months of follow-up up until the time point shown. Closed circles are a single time-point result. This plot includes all groups listed in Table 1.1

Figure A.5: Final measured adherence over time by study setting

Figure note: The point sizes are scaled to indicate relative sample size (of the group(s) receiving chlorine only). Open circles indicate that the data point is reported as multiple adherence measures combined over the months of follow-up up until the time point shown. Closed circles are a single time-point result. This plot includes all groups listed in Table 1.1

Appendix B

Appendix to Chapter 2

Data analysis

To confirm that our feasibility-based sample size was sufficient, we did an *a priori* sample size calculation, clustered at the system level, to determine the minimum number of households per system required to detect a difference in the proportion of households with FCR >0.1 mg/L of 0.60, as compared to an assumed comparison proportion of zero households with chlorine, using an intracluster correlation of 0.10, power equal to 0.80, and alpha equal to 0.05. Only two households per system would be required under this scenario.

Differences in pretreatment versus tap samples at each round were estimated using linear regression and standard errors clustered at the system level, using the *estimatr* R package.

Lab negative controls

40 negative control samples in total were processed during the study. For each negative control we processed 100 mL of sterile water, prepared by boiling tap water with sodium thiosulfate to neutralize any chlorine and then pouring it into a boiled baby bottle. This sterile water was used to moisten compact dry plates during sample processing, and the baby bottle was capped when not immediately in use. 39/40 negative controls had 0 *E. coli* or total coliforms present. One negative control on Nov 20, 2018 had 1 *E. coli* CFU/100 mL and 2 total coliforms CFU/100 mL. To determine whether the bottle nipple or water had been contaminated, we processed two more negative controls from the same bottle. Both had 0 *E. coli* and total coliforms.

Household storage time

At baseline, household stored drinking water had been collected an average of 6.8 hours (range: 0.5-24) prior to sampling. At midline, an average of 7.5 hours (range: 1-24). At endline, an average of 7 hours (range: 1-96).

Monthly monitoring data

During monitoring visits, all negative control lab samples had zero *E. coli* and total coliforms. Some monitoring samples were missing survey entries, resulting in complete *E.coli* data but some missing chlorine measurements. Nine household and tap samples are missing free chlorine measurements, but their *E.coli* and total coliform results are available. Observations with missing data are excluded when calculating summary statistics.

E. coli contamination in the presence of free chlorine residual

We collected a small number of samples that were positive for *E. coli* even in the presence of free chlorine residual. There are two likely explanations. First, there may have been contamination during sample collection due to failure to practice sterile methods. More likely, there may have been contamination immediately upstream from or at the tap and insufficient chlorine contact time to inactive *E. coli*. Sodium thiosulfate in the Whirlpak Thio-bags immediately neutralizes chlorine residual and would limit chlorine contact time in both cases.

Table B.1: Household baseline characteristics

	Technology A (n=35) Mean (SD)	Technology B (n=36) Mean (SD)	Combined (N=71) Mean (SD)
Household			
Respondent age, years	38.5 (14.0)	40.2 (14.4)	39.4 (14.1)
Years lived in community	22.5 (17.1)	29.6 (17.4)	26.1 (17.5)
No formal schooling completed (%)	62.9 (49.0)	63.9 (48.7)	63.4 (48.5)
Completed primary education (%)	17.1 (38.2)	8.3 (28.0)	12.7 (33.5)
Completed secondary education or higher (%)	20.0 (40.6)	27.8 (45.4)	23.9 (43.0)
Number HH members	5.2 (1.8)	4.8 (2.1)	5.0 (1.9)
Number HH members under 5 years	0.6 (0.8)	0.6 (0.8)	0.6 (0.8)
Assets			
Owns 1+ radio (%)	42.9 (50.2)	52.8 (50.6)	47.9 (50.3)
Owns 1+ television (%)	2.9 (16.9)	5.6 (23.2)	4.2 (20.3)
Owns 1+ solar panel (%)	100.0 (0.0)	94.4 (23.2)	97.2 (16.7)
Owns 1+ mobile phone (%)	97.1 (16.9)	88.9 (31.9)	93.0 (25.8)
Owns 1+ fridge (%)	2.9 (16.9)	0.0 (0.0)	1.4 (11.9)
Owns 1+ watch (%)	71.4 (45.8)	75.0 (43.9)	73.2 (44.6)
Main community concerns			
Healthcare services (%)	60.0 (49.7)	61.1 (49.4)	60.6 (49.2)
Sanitation and hygiene (%)	2.9 (16.9)	41.7 (50.0)	22.5 (42.1)
Transportation and roads (%)	20.0 (40.6)	55.6 (50.4)	38.0 (48.9)
Security and crime (%)	0.0 (0.0)	2.8 (16.7)	1.4 (11.9)
Electricity service (%)	91.4 (28.4)	80.6 (40.1)	85.9 (35.0)
Unemployment (%)	25.7 (44.3)	52.8 (50.6)	39.4 (49.2)
Education (%)	51.4 (50.7)	55.6 (50.4)	53.5 (50.2)
Support for agriculture (%)	22.9 (42.6)	30.6 (46.7)	26.8 (44.6)
Water supply services (%)	11.4 (32.3)	22.2 (42.2)	16.9 (37.7)
Water access and use			
Household is involved in community water supply system (%)	48.6 (50.7)	16.7 (37.8)	32.4 (47.1)
Piped water availability, wet season (hours/day)	23.7 (1.5)	14.0 (8.8)	18.8 (8.0)
Piped water availability, dry season (hours/day)	19.7 (6.1)	11.6 (7.5)	15.6 (7.9)
Other domestic water source use, prior 6 months (%)	17.1 (38.2)	0.0 (0.0)	8.5 (28.0)
Current roundtrip water collection time (minutes)	11.3 (10.0)	5.1 (2.3)	8.2 (7.8)
I collect in containers that I carry (%)	57.1 (50.2)	63.9 (48.7)	60.6 (49.2)
I connect a flexible pipe from the tap to my home (%)	22.9 (42.6)	22.2 (42.2)	22.5 (42.1)
I use both containers and a flexible pipe to my home (%)	20.0 (40.6)	13.9 (35.1)	16.9 (37.7)

Table B.1 continued from previous page

	Technology A (n=35) Mean (SD)	Technology B (n=36) Mean (SD)	Combined (N=71) Mean (SD)
Animal water source is piped water supply (%)	54.3 (50.5)	66.7 (47.8)	60.6 (49.2)
Animal water source is another source (%)	14.3 (35.5)	16.7 (37.8)	15.5 (36.4)
Animal water source is both piped water and another source (%)	31.4 (47.1)	16.7 (37.8)	23.9 (43.0)
Number water sources over past year, all purposes	1.6 (0.6)	1.7 (0.5)	1.6 (0.5)
Water treatment, prior 7 days	85.7 (35.5)	88.9 (31.9)	87.3 (33.5)
Boiling	31.4 (47.1)	2.8 (16.7)	16.9 (37.7)
Filtration with a tabletop filter	74.3 (44.3)	88.9 (31.9)	81.7 (39.0)
Every day	77.1 (42.6)	72.2 (45.4)	74.6 (43.8)
Half of the time or more	8.6 (28.4)	13.9 (35.1)	11.3 (31.8)

Table B.2: Regular free chlorine residual monitoring results

	System ID	N	Proportion tap samples with FCR >0.1 mg/L
Aquatabs Flo	1A	92	0.86
	2A	69	0.83
	3A	97	0.74
PurAll 100	1B	96	0.90
	2B	93	0.91
	3B	93	1.00

Table B.3: User perceptions of water safety and acceptability

	Baseline N=71	Midline N=62	Endline N=55
How is the taste?			
Good	1.00 (0.00)	0.92 (0.27)	0.91 (0.29)
Chlorine	-	0.05 (0.22)	0.09 (0.29)
Chemical	-	0.03 (0.18)	-
How is the smell?			
Good	0.97 (0.17)	0.84 (0.37)	0.13 (0.34)
Chlorine	-	0.11 (0.32)	0.85 (0.36)
Chemical/medicine	-	0.05 (0.22)	0.02 (0.13)
How is the appearance?			
Clear/good	0.87 (0.34)	0.97 (0.18)	1.00 (0.00)
Dirty/cloudy	0.01 (0.12)	0.03 (0.18)	-
How safe do you think your main drinking water source is for drinking?			
Very safe	0.21 (0.41)	0.95 (0.22)	0.27 (0.45)
Quite safe	0.76 (0.43)	0.03 (0.18)	0.36 (0.49)
Neither safe nor risky	0.03 (0.17)	0.02 (0.13)	0.36 (0.49)

Table B.4: Observed refill requirements by system

	Aquatabs Flo			PurAll 100	
System ID	1A	2A	3A	1B+2B	3B
Total volume treated (m^3)	2547	2047	3724	6796	5631
Cartridges completed	8	9	10	2	3
Days elapsed from installation to last recorded refill	335 days	325 days	330 days	292 days	327 days
Volume (m^3) treated per cartridge	318	227	372	3398	1877

Table B.5: Pre-installation average flow rate (L/min) and chlorine measurements (mg/L)

System	Tank inlet	Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Tap 6
1	7.0	2.2	0.7	4.4	10.8	6.8	7.9
2	6.5	3.4	5.5	10.0	4.6	4.4	
3	6.3	6.3	7.5	12.9	0.3		
4	6.6	3.5	1.8	2.3	9.5	7.7	

Table note: Prior to installation of the chlorinator devices, we visited 4 of the systems to collect in-depth flow rate measurements and confirm absence of chlorine. To measure flow rate, we recorded time to fill a 500 mL graduated cylinder; we repeated 3 times and calculated the average. All 9 water samples tested at these points had <0.1 mg/L free and total chlorine.

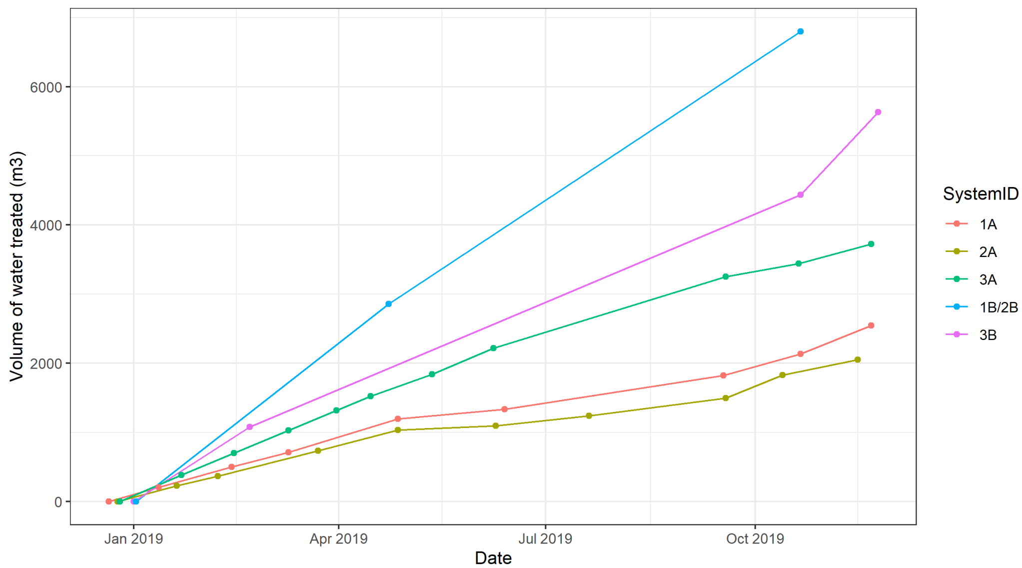

Figure B.1: Total volume of water treated at all systems over time

Figure note: Data were recorded from mechanical flow meters. Points indicate refills events. Systems 1B and 2B share a spring source and single installation upstream of their respective reservoir tanks. We continued to monitor volume through December 2019, but no additional refills events were recorded after the points shown here.

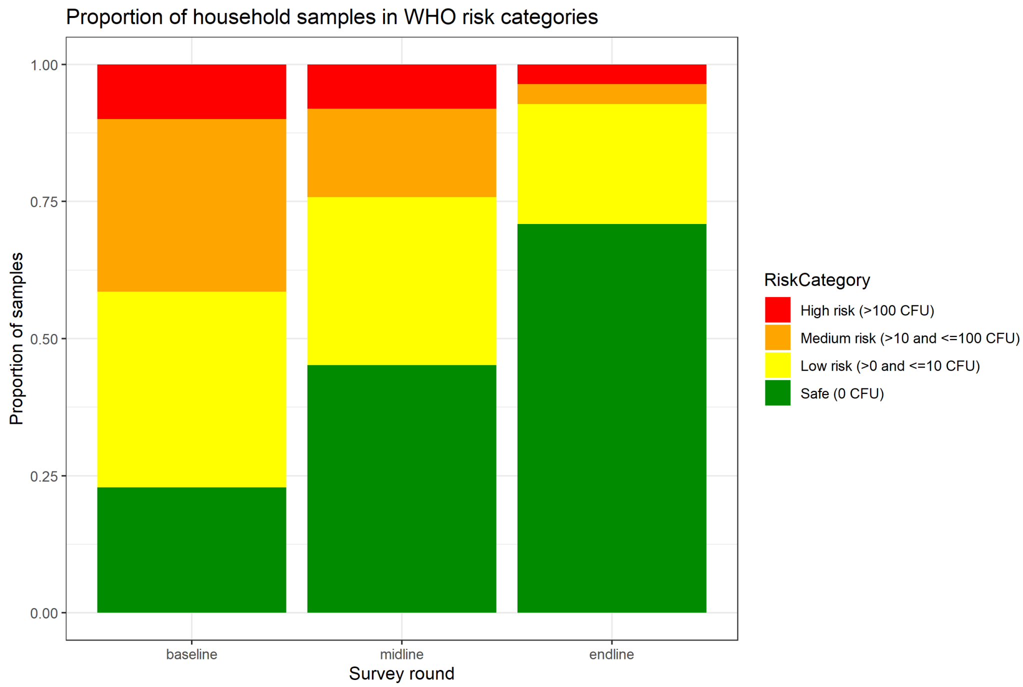

Figure B.2: Proportion of household samples in WHO risk categories

Figure note: Risk categories based on World Health Organization guidelines. Safe, or meeting guidelines, is 0 CFU E.coli/100 mL; low risk is 1-10 CFU; medium risk is 11-100 CFU; high risk is >100 CFU.