Assessing the sustained effects of a water filter intervention: A 30-month longitudinal study in Rwamagana, Rwanda

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Abstract

Household water treatment and safe storage interventions can improve microbiological water quality and reduce diarrheal disease in areas lacking access to safe water. However, with few studies evaluating effectiveness of interventions delivered programmatically for more than a year post-implementation, little is known about their sustainability. We aimed to assess the longer-term use and health effects of a household-based filter with a safe storage tank delivered through Rwanda’s Community based Environmental Health Promotion Programme (CBEHPP). We undertook a 30-month longitudinal study in Rwamagana district, following 608 households across 30 villages receiving the intervention. We conducted four unannounced follow-up visits and measured filter presence, condition and use as well as drinking water quality and child diarrhea prevalence approximately 6, 15, 24, and 30 months after the delivery of the intervention. Coverage of the water filter remained high throughout the follow-up period, with 94% of households observed to have the filter by the 30-month visit. Compared to the 6-month visit, the households with filters observed to be in good condition declined from 94.0% to 84.5% at the 30 month-visit. Reported use declined over this period from 96.9% to 84.3% of households, though presence of water in the storage tank of the filter fell from 81.4% to 59.4%. Fecal contamination of point-of-use drinking water did not get worse over the follow-ups compared to the 6-month visit. Child diarrhea prevalence in the study population varied over the follow up period, from 5.7% to 3.9%, 2.9% and 5.9% at 6, 15, 24 and 30 month visits, respectively. In summary, an intervention to promote uptake and use of water filters as part of the Rwandan national environmental health program was found to show that filters were still largely present, in good condition and in use after 30 months, meaning that the intervention effects were largely maintained.
Introduction

An estimated 2 billion people use unsafe drinking water, with the majority residing in Sub-Saharan Africa, Central America, and South Asia [1, 2]. Fecally-contaminated drinking water increases the risk of enteric infections, anemia, growth faltering, and other health hazards, mostly among young children [3]. In many high-income settings, the microbial safety of drinking water is achieved using treated and well-maintained piped water systems. However, ensuring microbial safety in low-resource areas is a significant challenge due to a shortage of adaptable service models that provide comprehensive and lasting improvements to water supply.

Household water treatment and safe storage (HWTS) is an interim solution supported by the WHO and UNICEF to address the health risks of contaminated drinking water [4]. HWTS generally refers to various evidence-based methods that improve water quality at the point of consumption or use. Common methods that address fecal contamination include point-of-use (PoU) chlorination, filtration, boiling, and solar disinfection. Although the use of covered and hygienic storage containers does not actively remove contaminants, safe storage is shown to effectively protect water from further contamination [5]. HWTS is not designed to improve water quantity or access—two critical aspects of safely managed water services. However, evidence suggests that HWTS can protect populations from fecal exposure and diarrheal diseases in areas with unsafe water and could more reliably do so than basic improvements in water service delivery [6–13]. A recent systematic review published as part of the Lancet Commission on WASH concluded that water filters were highly effective water, sanitation or hygiene interventions for preventing diarrheal disease, with a pooled relative risk from 23 randomized controlled trials of 0.50 (95% CI 0.41–0.60) [13].

However, the longer-term use, and thus, sustainability of HWTS, is not well-understood. Protective health effects are mostly limited to studies evaluating studies with short durations (e.g., <12 months) [8, 11]. The diminished effect of longer-term follow-up periods was first identified in a review evaluating the impact of PoU chlorination [9]. Nearly all studies that met the inclusion criteria were short, with a median follow-up period of 30 weeks; longer trials overall showed an attenuation of the intervention’s effects on child diarrhea. A second review found that duration of follow-up was a significant predictor of the effectiveness of different types of HWTS interventions, concluding that among HWTS interventions, only ceramic filters were protective over 12 months [14].

The longer-term impact from HWTS interventions is contingent on an array of contextual factors but importantly is determined by the consistent and correct use of the technology [15–18]. Interventions are shown to need considerable behavior-change promotion to continue the use of HWTS, raising questions on whether scaling HWTS interventions is a worthwhile investment for sustained improvement of drinking water quality [9, 19, 20]. Modeling studies suggest that even slight declines in adherence will vitiate health gains if source water quality is especially poor [16, 17]. While the number of HWTS studies with extended follow-up periods (e.g., ≥12 months) has increased over the years, most indicate a decline in use and compliance over time [21–26].

Rwanda’s national environmental health program currently promotes boiling and safe storage but provides no hardware to householders [27]. A randomized controlled trial found no evidence that the program was effective in improving water quality or preventing diarrhea despite an increase in reported drinking water treatment [27]. The Government of Rwanda was interested in exploring whether filters could be added to the existing program to greater effect. We previously reported on a randomized controlled trial over 15 months that found the filter intervention described in this study to be effective in reducing fecal contamination of drinking water and the prevalence of diarrheal disease in young children (26). The filter was
delivered programmatically by implementers through the Community-Based Environmental Health Promotion Programme (CBEHPP), Rwanda’s national environmental health program. The aim of this study was to assess whether the intervention effects were sustained over 30 months, just short of the three-year design life of the filter.

Materials and methods
Study design and context
We evaluated a PoU household water filter with safe storage intervention in a longitudinal study, enrolling 608 households eligible in Rwamagana, Rwanda. We measured filter coverage, condition and use, drinking water quality, and child diarrhea prevalence at four visits over 28–32 months and assessed changes over time. The study population consisted of all the 608 intervention households that participated in a 15-month cluster-randomized controlled trial (the “RCT”) evaluating the effects of the intervention on drinking water quality and child diarrhea. Households were enrolled into the study between December 2018 and March 2019. Household respondents had to provide written consent to participate in the study. That RCT found that the filter had high uptake, and the overall intervention reduced the proportion of households with detectable *Escherichia coli* (*E. coli*) in drinking water samples by 20% (PR 0.80, 95% CI 0.74–0.87) and the proportion of children under 5 with caregiver-reported diarrhea in the previous 7 days by 49% (aPR: 0.51 95% CI: 0.35–0.73) over 13–16 months (26). Although the RCT ended approximately 15 months post-implementation, we continued monitoring of all consenting study households for another 13–16 months to assess longer-term intervention effectiveness. As follow-up was impacted by government-mandated lockdowns due to COVID-19, we were required to exercise some flexibility in follow-up periods, the reason for the range of dates reported here. The first, second, third, and fourth follow up visits occurred between October and December 2019, June and September 2020, March and June 2021, and October 2021 and January 2022, respectively. A detailed timeline of the study activities is provided in Fig 1.

![Timeline of implementation activities and data collection.](https://doi.org/10.1371/journal.pwat.0000161.g001)
**Intervention**

The intervention was the delivery and promotion of the LifeStraw® Family 2.0 filters as a part of Rwanda’s Community-Based Environmental Health Promotion Programme (CBEHPP). The LifeStraw® Family 2.0 is a PoU, container-based, water filter with an 80 μm pre-filter to remove coarse material, 20 nm hollow-fiber ultrafiltration membrane, backwash lever, and covered storage chamber with 5.5 L capacity and meets the WHO’s ‘comprehensive protection’ guideline for HWTS technologies [28]. It is estimated to be functional for three to five years without replacing parts [29].

The CBEHPP is a national scale program that organizes village-level Community Health Clubs (CHCs) to encourage safe WASH behaviors. CHCs are open to all village members and aim to meet weekly to bi-weekly. Volunteer CHC facilitators are trained to deliver a 20-module curriculum designed by the Ministry of Health. For this research, CHC facilitators were additionally tasked to deliver fully-subsidized LifeStraw® Family 2.0 filters to households meeting intervention eligibility requirements (i.e., CHC member with a child under five or pregnant person living in the household).

Catholic Relief Services and SNV-Rwanda, with their local partner African Evangelist Enterprise, were the leading implementors of the intervention and trained and supported CHC facilitators to provide household-level support. Promotional activities on the filter included a mass-distribution event with demonstrations and skits, initial household visits to teach members to use the filter, poster distribution, community meetings, a maintenance household visit ~6-months after filter distribution, and a repair and replacement process for non-functioning filters. In the first year, the implementors were additionally supported by Amazi Yego, a social enterprise with extensive experience designing and delivering programs using LifeStraw® [30]. The study period coincided the COVID-19 pandemic, beginning at Visit 2 (July 2020-September 2020) and onwards. Filter promotional activities planned during CHC sessions were interrupted beginning in March 2020, and CHC facilitators had to cancel several sessions due to pandemic restrictions. Further details on the intervention and first-year implementation are described elsewhere [30, 31].

**Eligibility and inclusion criteria**

Households that enrolled in the RCT and that were assigned to the intervention arm (i.e., 608 households) were eligible to be included in the 30-month study. To be enrolled, households had to live in the study villages, be verified eligible to receive the intervention (CHC member households who have at least one child under 5 or pregnant person living in the household at time of baseline), and have a household member that was over 18 years of age available to complete informed consent. Details on the village and household selection are described elsewhere [31]. Briefly, 60 eligible villages were randomly selected across Rwamagana district. Villages were eligible for selection if they were receiving CBEHPP programming through CRS and SNV. From these 60 villages, 30 were selected to receive the filter intervention. 1,109 households were identified to be eligible for the RCT enrolment across intervention villages. From these, 608 households were randomly selected across intervention villages. Sample size determination was based on the RCT design.

**Outcomes**

We assessed filter presence, condition and use, fecal contamination of reported drinking water and caregiver-reported diarrhea in children under 5 (S1 Table). For presence, enumerators observed the physical presence of the filter in the household. If households were observed to not have the filter, they asked additional follow-up questions on why the filter was not present.
For condition, they observed whether the filter appeared to be in “good condition” defined to include all of the following: proper assembly/missing parts, no visible cracks, adequate flow-rate, and ability to backwash/reverse flow of water. For use, respondents reported if they used the filter as a water treatment practice, and enumerators observed whether there was visible water in the storage container of the filter at the time of visit. We collected secondary parameters on reported use, including if the filter was reported to have been filled in the past 7 days from the time of visit, if at least one young child drank water treated with the filter in the last day, and if drinking water samples provided were treated with the filter. To measure microbial water quality, we asked respondents to serve drinking water as they would to a young child, whether drawn from the filter storage chamber or another supply. We sampled 100mL of this drinking water using sterile Whirl-Pak® bags containing sodium thiosulfate (Nasco, Madison, WI, USA) and kept on ice until testing for detectable _E. coli_ within 8 hours using CompactDry™ (Nissui Pharmaceutical, Tokyo, Japan) media plates and membrane filtration procedures prescribed by UNICEF [32]. We counted and recorded the number of colony-forming units (CFU) on plates. Sample processing and additional information on procedures are described elsewhere (28). Water quality results were categorized into a binary variable for detectable vs. non-detectable _E. coli_ contamination, which served as our primary outcome on drinking water quality. We also categorized _E. coli_ presence into two other binary outcomes according to WHO risk category cutoffs for moderate-to-high (≥10 CFU/100mL) and very high (≥100 CFU/100mL) contamination [33]. We estimated arithmetic and Williams means of CFU counts. The Williams mean is a geometric mean that accounts for values less than 1 by adding 1 to all values and then subtracting the geometric mean by 1 [34]. Non-detect plates were included in the mean calculation as half of their specific limit of detection. For child diarrhea, we asked respondents to report whether each under-five child in the household had diarrhea in the previous 7-days. We defined diarrhea as three or more loose stools in a 24-hour period that can take the shape of a container [35].

Household surveys were directed to the primary cooks aged 18 and over. If the primary cook was unavailable or under 18, questions were directed to another household member aged 18 and over. Survey data were collected on tablets and managed using REDCap electronic data capture tools hosted at Emory University [36]. Two authors on this manuscript (co-investigator and the study manager) had access to information that could identify individual participants during or after data collection.

**Statistical approach**

We estimated adjusted prevalence ratios (PR) and their 95% confidence intervals (CI) that compared binary outcomes on filter presence, filter use, contaminated drinking water, and child diarrhea between the first follow-up and later follow-up visits. PRs were estimated by exponenntiating coefficients derived from log Poisson regression with generalized estimating equations (GEE) using robust standard errors. Poisson regression was used due to issues of convergence commonly observed in binomial models and models with a large number of covariates [37]. We assumed an exchangeable working correlation structure, adjusting for household-level characteristics and clustering at the village level [38, 39]. Statistically significant effects were determined by using a two-sided Type I error rate of 0.05.

The main exposure variable of interest is an ordered categorical time variable corresponding to each of the four follow-up rounds, marking the range of months exposed in the original intervention arm. We adjusted for other covariates based on the literature on their potential relation to water quality or season, including socio-economic status, household size, basic drinking water access, water treatment at baseline, average monthly rainfall, and average
monthly land surface temperature. The contamination status of the source water could determine water quality outcomes as well as uptake, the condition of the filter, and child health. Households that perceive their primary water source as contaminated could be more likely to use the filter [18] and could be more likely to use one type of water source for drinking during dry seasons and another type during rainy season. Metrological conditions and household demographics could influence drinking water availability/quality [40]. Covariates considered are defined in S2 Table. Diarrhea models were additionally adjusted for the child’s sex and age in months. The exponentiated regression coefficient of the time variable provides the PRs of the outcome between exposure to 5-7-months of the intervention and proceeding follow-up periods (e.g., 5-7-months compared to 13–16, 22–25, and 28–32 months of exposure). All statistical analyses were done using Stata 16 (Stata Corporation, College Station, TX, USA).

Ethics
The protocol received ethical approval and was annually renewed by the Emory University Institutional Review Board (CR001-IRB00106424) and Rwanda National Ethics Committee (IRB 0001497). We obtained signed informed consent from the main survey respondent during study enrollment. The associated trial is registered under the Pan African Clinical Trial Registry, Trial ID = PACTR201812547047839

Results
Participant summary
608 households from the original intervention arm were eligible to be followed for over 30 months at four visits. No household was excluded from attempted follow-up. Across all visits, a total of 2,235 out of a possible 2,432 household observations (91.5%) were analyzed for uptake of the filter; 1,836 of 2,432 possible water samples analyzed (75%) to estimate fecal contamination; and 2,343 of 3,036 possible child observations (77%) were analyzed for under 5 diarrhea prevalence. Missing household observations mainly were due to lost-to-follow-up (moved away/not home at the time of visit/did not want to participate). Missing water samples were either due to household lost-to-follow-up or the household not having available drinking water at the time of visit. Missing child observations were either due to household lost-to-follow-up or if children aged out of the study eligibility or were no longer in the household (Fig 2).

Filter uptake: Presence, condition, and use over 30 months
Filter presence was relatively high across all four follow-up visits in the intervention group (Table 1 and Fig 3). At the first follow-up visit (~6 months post-implementation), 99% of households were observed to have the filter, and 94% had filters that were observed to be in good condition, i.e., no apparent issues in the assembly, leaking, storage container, tap, ability to backwash, and flow-rate.

Presence of the filter fluctuated slightly since the first follow-up visit but remained over 94% across the study duration (Table 1 and Fig 3). Compared to the first visit, the proportion of households with the filter declined by 6% at the second and fourth visits (aPR 0.94, 95% CI 0.88–0.99; aPR 0.94, 95% CI 0.91–0.96, Table 2) but was found similar at the third visit (aPR 0.98, 95% CI 0.96–1.00). Common reasons for not having the filter in the household were because the filter was reported to be broken, stolen, on loan, out for repair, taken by another family member, or because the household members no longer liked it (S3 Table).

Condition of filters declined modestly after the first visit. Compared to the first 6-months (aPR 0.91, 95% CI 0.78–1.06, Table 2). However, compared to the first 6-months,
condition declined by 7% at the third visit (~24 months post-implementation—aPR 0.93, 95% CI 0.89–0.98) and by 12% by the fourth visit (~30 months post-implementation aPR 0.88, 95% CI 0.80–0.97, Table 2). The most frequent reasons that filters were not considered to be in good condition were due to leaks, improper assembly, damaged taps, and difficulty backwashing and slow filtration (S4 Table).

Indicators of filter use declined over 30-months, particularly in the last two visits (Table 2 and Fig 3). In the first visit, 97% of households reported to use the filter for water treatment, and 81% of filters were observed to have water in the filter’s storage container.

Estimates on indicators of use were similar over 13–16 months (reported filter as water treatment: aPR 0.95, 95% CI 0.90–0.99; observed water in filter’s storage container: aPR 0.95, 95% CI 0.90–0.99, Table 2). The proportion of reported use of the filter for water treatment decreased by 5% (aPR 0.95, 95% CI 0.90–0.99) and by 14% in the fourth visit (aPR 0.86, 95% CI 0.80–0.93, Table 2). Observed water in the filter’s storage container decreased sharply afterwards. The proportion fell 14% by the third visit (aPR 0.86, 95% CI 0.76–0.98) and 31% by the fourth visit (aPR 0.69, 95% CI 0.59–0.82, Table 2). Unadjusted estimates on outcomes of
presence, condition, and use compared to 5–7 months post-implementation are provided in the supplementary information (S5 Table).

Secondary parameters measuring filter use (i.e., frequency of filling filters, child use, and water treatment of provided drinking water sample) showed similar patterns of decline over the 30 months, with the most dramatic reductions in the last half of the follow-up period (S1 Fig).

Microbial water quality over 30 months

Drinking water samples showed no clear pattern of decreasing or increasing fecal contamination over the follow-up period (Table 3). Fecal contamination rates stayed lower compared to baseline levels (Fig 4). Visit 2 had the lowest contamination rates among all rounds. In the second visit, the proportion of households with any detectable fecal contamination was lower compared to the 6-month visit (aPR 0.71, 95% CI 0.57–0.90, Table 3) compared to the 6-month visit. All other estimates in proceeding follow-up visits were comparable to the first

Table 1. Presence, condition, use, microbial risk level, and child diarrhea prevalence in the intervention group over 30 months.

<table>
<thead>
<tr>
<th>Visit</th>
<th>5–7 months since delivery</th>
<th>13–16 months since delivery</th>
<th>22–25 months since delivery</th>
<th>28–32 months since delivery</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>% (95% CI)</td>
<td>N % (95% CI)</td>
<td>N % (95% CI)</td>
<td>N % (95% CI)</td>
</tr>
<tr>
<td>Filter observed present in household</td>
<td>555 99.1 (97.9, 99.6)</td>
<td>563 97.9 (96.3, 98.8)</td>
<td>564 95.6 (93.5, 97.0)</td>
<td>543 94.3 (92.0, 96.0)</td>
</tr>
<tr>
<td>Filter observed in good condition*</td>
<td>532 94.0 (91.6, 95.7)</td>
<td>507 91.9 (89.2, 94.0)</td>
<td>504 86.3 (83.0, 89.5)</td>
<td>446 84.5 (80.9, 87.6)</td>
</tr>
<tr>
<td>Use</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reported to use filter for water treatment</td>
<td>556 96.9 (95.1, 98.1)</td>
<td>563 94.0 (91.7, 95.7)</td>
<td>563 87.7 (84.8, 90.2)</td>
<td>543 84.3 (81.0, 87.2)</td>
</tr>
<tr>
<td>Storage container of filter observed to have water in it</td>
<td>544 81.4 (77.9, 84.5)</td>
<td>545 75.0 (71.2, 78.5)</td>
<td>536 67.0 (62.9, 70.9)</td>
<td>512 59.4 (55.1, 63.6)</td>
</tr>
</tbody>
</table>

Microbial risk level of drinking water

<table>
<thead>
<tr>
<th>CFU count per 100 mL</th>
<th>N</th>
<th>Mean (95% CI)</th>
<th>N</th>
<th>Mean (95% CI)</th>
<th>N</th>
<th>Mean (95% CI)</th>
<th>N</th>
<th>Mean (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arithmetic Mean</td>
<td>448 88.9 (73.3, 104.4)</td>
<td>481 95.2 (79.0, 111.3)</td>
<td>474 100.4 (84.7, 116.2)</td>
<td>433 87.5 (71.3, 103.8)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geometric Mean</td>
<td>448 14.7 (12.2, 17.6)</td>
<td>481 13.2 (10.9, 15.9)</td>
<td>474 18.1 (15.1, 21.8)</td>
<td>433 13.7 (11.4, 16.6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diarrhea- Children Under 5</td>
<td>n*</td>
<td>% (95% CI)</td>
<td>n</td>
<td>% (95% CI)</td>
<td>n</td>
<td>% (95% CI)</td>
<td>n</td>
<td>% (95% CI)</td>
</tr>
<tr>
<td>In the last 7 days, child reported to have 3 or more loose stools in 24 hours</td>
<td>648 5.7 (4.2, 7.8)</td>
<td>569 3.9 (2.6, 5.8)</td>
<td>659 2.9 (1.8, 4.5)</td>
<td>467 5.9 (4.2, 8.6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

N denotes the number of available or non-missing household observations analyzed in the survey round for the corresponding variable

n denotes the number or available or non-missing child observations analyzed for the diarrhea outcome.

* Good condition refers to being observed to have been assembled properly, working tap, no leaking, undamaged container, adequate flowrate, and ability to backwash

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6-month visit. Unadjusted estimates of the presence of E. coli in drinking water and child diarrhea compared to 5–7 months post-implementation are presented in the supplementary information (S6 Table).

Under-5 child diarrhea over 30 months

The proportion of children under five experiencing diarrhea in the last 7 days did not change throughout the follow-up period in the intervention group (Fig 4), but remained lower than baseline levels. Visit 3 had the lowest prevalence of diarrhea (2.9%), while Visit 4 had the highest (5.9%). Table 3 reports the effects of time on diarrhea outcomes. Estimates in proceeding rounds were comparable to the first follow-up visit.

Discussion

We conducted a longitudinal study in Rwamagana District, Rwanda that aimed to assess sustainability of an advanced household water filter delivered through CHCs. While filters were still largely present in the home at the end of follow-up, there was about a 15% decline by 30 months in filters meeting the criteria for “good condition.” Reported use declined to about the same extent, with a larger decline in water actually present in the filter’s storage chamber at the time of the visit. Among those households from which we could procure a water sample for testing, or a report of child diarrhea, we found no evidence of deteriorating drinking water quality or a change in diarrhea prevalence over the follow-up period.
The intervention seemed to yield better coverage and use compared to other longer-term studies of HWS interventions. A study in Cambodia followed up with a random sample of households after 5–48 months of receiving a subsidized filter through an NGO project [41]. About 31% of the surveyed households reported using the filter. The time since receipt of the filter was identified as an important determinant of use, estimating an average declining rate of 2% per month. An independent monitoring study in Kenya of an 800,000-filter distribution campaign aimed at reaching 90% of the population found that about 50% of households

Table 2. Presence, condition, and use overtime compared to 5–7 months post-implementation.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Visit 2 (13–16 months post-implementation)</th>
<th>Visit 3 (22–25 months post-implementation)</th>
<th>Visit 4 (28–32 months post-implementation)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N*</td>
<td>PR* (95% CI)</td>
<td>PR (95% CI)</td>
</tr>
<tr>
<td>Filter observed present in household</td>
<td>2,200</td>
<td>0.94 (0.88, 0.99)</td>
<td>0.98 (0.96, 1.00)</td>
</tr>
<tr>
<td>Filter observed in good condition</td>
<td>1,967</td>
<td>0.91 (0.78, 1.06)</td>
<td>0.93 (0.89, 0.98)</td>
</tr>
<tr>
<td>Reported to use filter for water treatment</td>
<td>2,199</td>
<td>0.91 (0.80, 1.04)</td>
<td>0.91 (0.87, 0.96)</td>
</tr>
<tr>
<td>Storage container of filter observed to have water in it</td>
<td>2,115</td>
<td>0.82 (0.60, 1.12)</td>
<td>0.86 (0.76, 0.98)</td>
</tr>
</tbody>
</table>

N* denotes the total number of observations analyzed

*a Prevalence ratio (PR), 95% Confidence Interval (95% CI) and p-value derived from log-Poisson generalized estimating equations with robust standard errors to account for clustering within villages. Models condition follow-up visit, socio-economic status, household size, average monthly rainfall in previous 30 days, average monthly land surface temperature, basic water access and water treatment at baseline. Outcome is either binary filter presence, condition, reported treatment use, and storage container presence of water.

Table 3. Presence of E. coli in drinking water and child diarrhea compared to 5–7 months post-implementation.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Visit 2 (13–16 months post-implementation)</th>
<th>Visit 3 (22–25 months post-implementation)</th>
<th>Visit 4 (28–32 months post-implementation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥2 CFU/100 mL (any detectable E. coli contamination)*</td>
<td>1,816</td>
<td>0.71 (0.57, 0.90)</td>
<td>1.05 (0.95, 1.17)</td>
</tr>
<tr>
<td>≥10 CFU/100 mL (Moderate and higher E. coli contamination)*</td>
<td>1,816</td>
<td>0.64 (0.44, 0.94)</td>
<td>1.16 (0.97, 1.40)</td>
</tr>
<tr>
<td>≥100 CFU/100 mL (Very high E. coli contamination)*</td>
<td>1,816</td>
<td>0.60 (0.36, 1.00)</td>
<td>&lt;0.05 (0.80, 1.52)</td>
</tr>
<tr>
<td>In the last 7 days, child reported to have 3 or more loose stools in 24 hours*</td>
<td>2,315</td>
<td>0.32 (0.08, 1.33)</td>
<td>0.12 (0.24,1.39)</td>
</tr>
</tbody>
</table>

N* denotes the total number of observations analyzed.

*a Prevalence ratio (PR), 95% Confidence Interval (95% CI) and p-value derived from log-Poisson generalized estimating equations with robust standard errors to account for clustering within villages. Model conditions follow-up visit, socio-economic status, household size, average monthly rainfall in previous 30 days, average monthly land surface temperature, basic water access, and water treatment at baseline. Outcome is binary water quality prevalence according to risk categories.

*b PR, 95% CI and p-value derived from log-Poisson generalized estimating equations with robust standard errors to account for clustering within village. Model conditions follow-up visit, socio-economic status, household size, average monthly rainfall in previous 30 days, average monthly land surface temperature in previous 30 days, basic water access, water treatment at baseline, age in months, and sex. Outcome is binary diarrhea prevalence in children under five.
reported ever receiving the filter from the campaign and less than 20% of households reported using the filter 2–3 years since the program began (39). Water quality was found to be markedly better in water treated by the filter compared to untreated water, demonstrating that the technology did demonstrate microbiological effusiveness over the 3 years. A 12-month trial in rural Rwanda evaluating a nearly identical filter found that after delivery of 100,000 filters, presence of the filter sustained in about 92% of households and reported use observed to 53% provided drinking water samples treated by the filter by the end of the 12-month follow-up [25]. In comparison, our study observed better coverage and a higher proportion of samples treated with filter at both the 15-month and 30-month visits. Finally, a small pilot study of about 100 households preceding the large filter-campaign in Rwanda found that the filter was observed to be working in 85% of households and the odds of fecal bacteria detection were nearly 80% lower compared to matched control households 12–24 months after filter delivery [42]. Comparisons to other studies should be interpreted with caution due to the differences in scale of implementation.

Our study has certain limitations. The study design was longitudinal, and unlike the RCT, had no contemporaneous control arm. However, this approach is justified within the context of measuring the uptake and use of the filter, as such outcomes would be inherently restricted in a control group lacking access to the filter, thus rendering a direct control arm comparison impractical. While condition and the presence of water in the filter were assessed by actual observation, use and recent diarrhea relied on reports by study participants and is subject to reporting (courtesy, social desirability) bias. Although survey visits were unannounced, observational indicators are still vulnerable to reactivity bias [43]. Although the follow-up period of 30-months is longer than most studies on sustainability, the 30-month follow-up period is just

Fig 4. Effects of filter on water quality and diarrhea over 30 months among 608 intervention households.
short of the three-year projected life cycle of the filter. Future research would be valuable to measure sustainability beyond three years, when the filters are more likely to need replacement parts and maintenance. We obtained water samples or diarrhea reports at about three-quarters of the possible study visits. The missing data represents a possible source of bias that would increase as the number of samples obtained decreased over time. Pandemic interventions, such as social distancing and improved hygiene may have also influenced water quality and diarrheal outcomes, particularly during the last three follow-up visits. The results have limitations in generalizability due to the study population representing CHC members with young children or an expectant parent. This area in Rwanda also had a high prevalence of fecal contamination in household drinking water and low access to basic water at baseline [31], and results may not be generalizable in settings with better access to drinking water. Nevertheless, the findings are relevant to other settings that use CHCs, which are common service model for delivering WASH programming globally [27].

Notwithstanding these limitations, our results suggest that the intervention, delivered programmatically as part of large environmental health campaign, has the potential to achieve high uptake and sustained effects at least over 30 months. Further research should explore the costs and cost-effectiveness of adding the this component to the program in order to compare it with other public health priorities.

Supporting information

S1 Checklist. Inclusivity in global research. (DOCX)

S2 Checklist. (DOCX)

S1 Fig. Primary and secondary indicators of coverage and use of filter over 30 months. (TIF)

S1 Table. Outcomes of interest. (XLSX)

S2 Table. Independent variables and covariates of interest. (XLSX)

S3 Table. Frequency of reported reasons for not having the filter among households observed with no filter at visit 4 (28–32 months post-implementation). (XLSX)

S4 Table. Frequency of observed problems among households with filters in poor condition at visit 4 (28–32 months post-implementation). (XLSX)

S5 Table. Presence, condition, and use compared to 5–7 months post-implementation (unadjusted). (XLSX)

S6 Table. Presence of E. coli in drinking water and child diarrhea compared to 5–7 months post-implementation (unadjusted). (XLSX)
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