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Intermittent slow sand filtration for preventing diarrhoea among children in Kenyan households using unimproved water sources: randomized controlled trial

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Summary

OBJECTIVE Measure effectiveness of intermittent slow sand filtration for reducing child diarrhoea among households using unimproved water sources in rural Kenya.

METHODS A randomized controlled trail was conducted among populations meeting a high-risk profile for child diarrhoea from drinking river water in the River Njoro watershed. Intervention households (30) were provided the concrete BioSand Filter and instructed on filter use and maintenance. Control households (29) continued normal practices. Longitudinal monthly monitoring of diarrhoea (seven-day daily prevalence recall) and of influent, effluent, and drinking water quality for fecal coliform was conducted for 6 months.

RESULTS Intervention households had better drinking water quality than control households (fecal coliform geometric mean, 30.0 CFU *vs.* 89.0 CFU/100 ml, $P < 0.001$) and reported significantly fewer diarrhoea days (86 days over 626 child-weeks) compared to controls (203 days over 558 child-weeks) among children up to 15 (age-adjusted RR 0.46; 95 % CI = 0.22, 0.96). Greater child diarrhoea reduction due to the intervention (age-adjusted RR 0.23, 95 % CI = 0.10, 0.51) was observed among the sub-group using unimproved water sources all of the time.

CONCLUSION Intermittent slow sand filtration, a non-commercial technology, produces similar observed effects on child diarrhoea as commercial POU products, adding to the range of effective options for poor populations (chlorination, ceramic filtration, solar disinfection, flocculation/disinfection).

keywords: bioSand filter, Kenya, child diarrhoea, point-of-use water treatment, household drinking water quality, randomized controlled trial

Introduction

Diarrhoeal diseases continue as the second leading cause of child death in the world, accounting for around 1.9 million child deaths per year (Boschi-Pinto *et al.* 2008), of which approximately 38% are in Africa (Bryce *et al.* 2005). Inadequate water quality and quantity, with lack of basic sanitation and poor hygiene, create risk conditions for endemic transmission of pathogens in developing countries that account for over 85% of the global diarrhoea disease burden (Pruess *et al.* 2002). With 1/5th of the world's population still dependent on unimproved water sources (WHO/UNICEF 2006), the on-going challenge of reducing endemic childhood diarrhoea has prompted new efforts to develop and promote options for treating water at the point of use (POU) (Sobsey 2002).

Low cost household water treatment (HHWT) and safe storage to improve water quality in the home in developing countries are thought to reduce childhood diarrhoea by 25–35% (Fewtrell *et al.* 2005; Clasen *et al.* 2006). Among promoted HHWT technologies, intermittent slow sand filtration, known also as the Manz or BioSand Filter (BSF), is considered a promising option (Sobsey *et al.* 2008). For poor populations without improved water supplies, the BSF has advantages of robust and durable design, simple user operation and maintenance with no recurring purchases, high flow rate (3–60 l/h) sufficient for domestic and drinking needs, ability to treat highly turbid waters, and local fabrication resulting in affordability (US $15–25/unit) (Fewster *et al.* 2004; CAWST 2008; Sobsey *et al.* 2008). Under controlled conditions, the BSF removed 100% of *Giardia lamblia* cysts, 99.98% of *Cryptosporidium* oocysts, 95–99% of bacteria, variable and lower amounts of virus, while reducing turbidity to below 2 NTU (Buzunis 1995; Palmateer *et al.* 1999; Stauber *et al.* 2006; Baumgartner *et al.* 2007; Elliott *et al.* 2008; Tiwari 2008).

Despite the BSF's estimated use by over a half million people, relatively little attention has been given to its effectiveness in reducing childhood diarrhoea. The first randomized controlled trial of the BSF, undertaken in an urban setting in the Dominican Republic, was recently completed. Stauber *et al.* (2009) report a significant improvement in drinking water quality and all-age reduction in diarrhoea incidence. More field trials of the BSF are needed to confirm positive BSF performance and health impacts in different settings and sub-populations.

The purpose of this study was to add to the evidence base by evaluating the health effect of the BSF on child diarrhoea in poor rural Kenyan households at high risk for childhood diarrhoea diseases from using unimproved polluted water sources for drinking.

Methods

Study area and population

The trial comprised households living in the River Njoro watershed (RNW), spanning Nakuru and Molo Districts, Kenya, endemic for diarrhoea diseases and having poor water supply conditions typical of much of Kenya (Tiwari & Jenkins 2008). Encompassing 280 km^2 and over 300 000 inhabitants, the RNW contains forests, grasslands, large- and small-scale agriculture, and a mixture of major urban, slum, peri-urban, and rural settlements. Fecal pollution from point and non-point sewerage, livestock, agricultural, and direct human sources along its 50 km length is widespread, resulting in high average turbidity and fecal coliform levels frequently exceeding 100 000 CFU/100 ml (Jenkins 2008). Water supply infrastructure is relatively scarce, concentrated in the lower and parts of the middle watershed; usage is further limited by barriers of cost, distance, in-operation, and rationing, common to many water systems in sub-Saharan Africa. Rainwater harvesting and storage, an important RNW household source, is used to varying degrees depending on a household's resources. As a result, over 50% of watershed residents depend directly on fetching river water for some or all of their domestic water needs.

A survey of households collecting river water in 2004 found double the rate of reported 2-week childhood diarrhoea period prevalence among households drinking river water (22%) compared to households who, while also using river water for domestic needs, drank piped water (9%), roof-collected rainwater (8%), and borehole water (13%) (Tiwari & Jenkins 2008). Treating river water by any means was extremely rare. Drinking untreated river water was associated with poverty as measured by lower income, having a thatched roof, having mud walls or floors, lower mother's education, and living near the river.

This study was conducted for the SUMAWA (Sustainable Management of Watersheds) project in collaboration with the Nakuru District Office of the Kenyan Ministry of Health (KMOH). SUMAWA is a multi-disciplinary, multi-institution project of the Global Livestock Collaborative Research Support Program, supported by USAID funds, based at Egerton University in the RNW. SUMAWA works on water resource development and management problems at the watershed scale with a focus on public health and poverty reduction.

Participant recruitment

Households deemed at high-risk for water-borne childhood diarrhoea through drinking river water were identified and recruited for trial inclusion in two steps. First, a subset of 11 high diarrhoea endemic sub-communities (neighbourhoods) was identified in the middle and upper RNW from clinic case registries, and river water use verified. Then, within them, households were identified and screened for eligibility using the existing high risk profile: having at least one child under the age of 3; using river water as a primary or secondary drinking water source; having a monthly income less than Ksh 4000 (US $65) for the upper and less than Ksh 6000 (US $97) for middle watershed areas; living in hatched roof homes with mud floors; living near the river; mother having less than an 8th grade education, and stable residence for the next 12 months. Follow-up to obtain informed consent resulted in 50 enrolled and eligible households. To reach the target sample size of 60 households, eligibility was relaxed to allow the youngest child's age requirement to increase from 3 to 4 years, resulting in final enrolment of 60 qualifying households (Figure 1).

Randomization

Prior to randomization, a baseline survey was administered and mother's and father's informed consent obtained. Enrolled households were stratified by river section into 10 strata, according to the household's river watering point location, to account for fecal pollution trends along the river's length (Jenkins 2008). Households were randomly assigned within each strata, to intervention (BSF users) or control (continue usual water use practices) groups. Upon assignment, one control household dropped out, leaving 29 in the control arm.

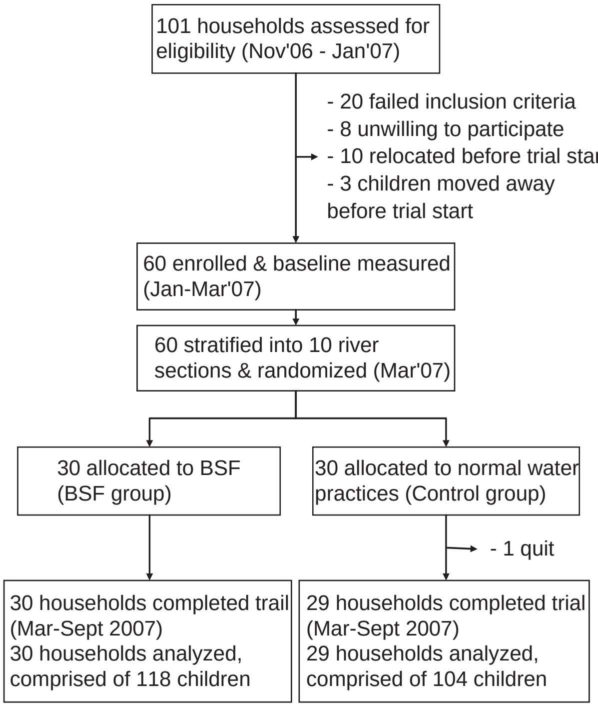

Figure 1 Flow diagram through phases of randomized trial.

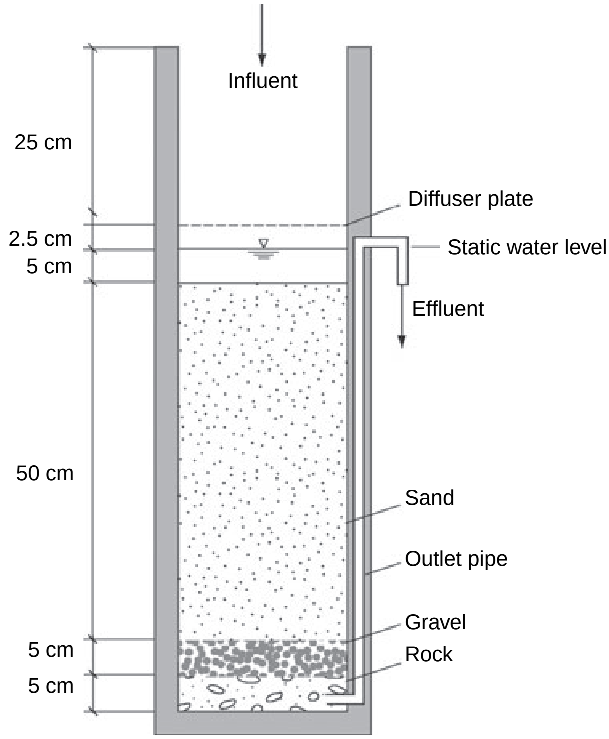

Figure 2 Schematic of intermittent slow sand filter.

Intervention

BushProof's concrete circular BSF design was used in this study (0.95 m tall, 36 cm diameter, 2.5 cm wall thickness) (Mol & Fewster 2007). Contents consisted of 5 cm of rocks, 5 cm of gravel, and 50 cm of river sand (0.15 mm d_{10}, 2.4 uniform coefficient) (Figure 2). Users were advised to operate the BSF with minimum 8 hours pause between treatment of successive 20 l batches. Residence time and sand size significantly affect BSF performance (Baumgartner *et al.* 2007; Tiwari 2008).

Four local artisan/masons were trained to build, install, maintain, and educate mothers on the BSF, and collect water samples. Technicians visited intervention homes weekly during month one to check on proper filter functioning and use. Later, when flow rates became too slow, technicians instructed BSF mothers on filter maintenance using the wet harrowing method to restore flow rates. Intervention households were advised to use BSF treated river water in place of untreated river water for all domestic purposes, including drinking, bathing, laundry, washing clothes, watering animals, etc. They were also instructed not to use BSF treated water for drinking during the 2-week biological maturation period, and not instead of improved water sources if these were customarily drunk (i.e. borehole water or rainwater). BSF households were also encouraged to continue their normal drinking water treatment practices on treated BSF drinking water. The control arm was instructed to continue their normal water use practices.

Outcome measures

Monthly monitoring of BSF performance, drinking water quality, and 7-day diarrhoea prevalence was conducted from April to September 2007 using two teams. All households were visited once per month by two technicians to collect a sample of drinking water for laboratory analysis. Poor households with unreliable access to improved water supplies in the study area use as many as three different sources of drinking water over the course of a week, depending on availability, preference, needs, and cost. Thus, both source and treatment were recorded for each collected drinking water sample. During the same visit, BSF influent and effluent water samples were collected in intervention homes and each sample's water source recorded. Without knowledge of arm assignment, another team of two enumerators under supervision of the KMOH visited all households once a month to administer a short questionnaire on reported diarrhoea symptoms of all children (≤15 years) and adults during the preceding week. At each visit, three oral rehydration packets and instructions were provided. Two additional visits to intervention households were made in June and August by a third team, to administer a questionnaire on perceptions, difficulties, attitudes, acceptability, and filter usage patterns.

Water quality sample collection and analysis

Water samples were collected in sterile Pyrex 250 ml glass collection bottles, and immediately placed inside a cool box (4–10 °C). Samples were transported to Egerton University and analysed within 6 h of collection. Fecal coliform was enumerated as thermotolerant coliform according to the membrane filtration technique outlined in the International Organization of Standardization: Method 9308-1 (ISO 1990). Water quality analysis and BSF performance results are the subject of work reported elsewhere (Jenkins *et al.* 2009).

Longitudinal diarrhoea prevalence

Diarrhoea was defined as the passing of three or more loose stools within a 24-h period. Mothers were asked whether each child in the household had had diarrhoea during the previous 7 days, and if so, the number of days of diarrhoea, allowing calculation of the longitudinal prevalence, an outcome measure shown to be more closely correlated with adverse outcomes than incidence (Morris *et al.* 1996). Intermittent monitoring to estimate longitudinal prevalence, approximately once a month, was selected based on evidence of its relative efficiency (logistics and power) over more costly and intrusive continuous monitoring (Schmidt *et al.* 2007).

Statistical analysis

A sample size of 60 households (minimum six visits) was estimated as adequate to detect a 50% reduction in weekly diarrhoea prevalence among children in intervention households with 95% confidence, based on an assumed baseline weekly diarrhoea prevalence of 16%, at least one child under 5 per household, and 80% statistical power. Number of diarrhoea days for each child at each visit was analysed as counts using a random effects Poisson regression model, adjusted and accounting for household-level clustering and repeated measures. The prevalence risk ratio of diarrhoea among children up to 15 years, and under 5 was computed. Child ages were grouped into levels: <6, ≥6–24, ≥24–60, ≥60–120, and >120 months. Adult prevalence risk ratio, based on total adult diarrhoea days reported over the six observation weeks, was analysed at household level, applying the appropriate offset. Statistical analysis was performed using StataIC version 10 (Stata Corporation, College Station, TX, USA).

Ethics

The University of California, Davis' Institutional Review Board Administration reviewed and approved the study in December 2006. Trained personnel obtained informed consent from both the male and female household head in January-March 2007, following the approved protocol. No compensation was paid to subjects. At trial end subjects were given the opportunity to purchase the BSF at a reduced price of US $4.86 (production cost US $22.91).

Results

Household characteristics

The trial population consisted of 222 children (≤15 years age) and 165 adults (>15 years age) from 59 households. Control households had 101 children at baseline, plus two newborns and one child that moved in, for a total of 104. BSF households had 118 children. Of the maximum possible number of diarrhoea observations (623 and 705 child-weeks for control and intervention arms, respectively), 90% and 89% of control and intervention observations, respectively, were collected.

Control and intervention household characteristics and baseline reported diarrhoea prevalence (Table 1) were broadly similar though important differences in age distribution within the under 5 population were observed. There was also some indication that diarrhoea at baseline in children under 5 was higher in the intervention group, however, baseline 1-week diarrhoea reporting was collected over a 3-month period spanning dry and wet seasons and therefore difficult to compare.

BSF performance and water quality outcomes

Mean fecal coliform reduction achieved by the BSF in intervention households (1.25 log or 94.4%) was comparable to prior controlled laboratory testing results with river water (1.30 log or 95.0%), although variability in the 30 field filters was substantially higher than in the two laboratory filters (Jenkins *et al.* 2009). Significant BSF water quality improvements achieved during the trial (influent vs. effluent fecal coliform geometric mean CFU/100 ml: 653 ± 5.34 *vs.* 36.4 ± 8.90) were evaluated using World Health Organization drinking water quality risk categories (WHO 2006), and showed that the low or

Table 1 Baseline characteristics of the participating population by treatment group

Characteristics	Overall	Control	BSF
Demographics			
Total households	59	29	30
Total participants	387	181	206
<6 months	15	9	6
≥6–24 months	34	16	18
≥24–60 months	65	30	35
Children under age 5	114	55	59
≥60–120 months	77	35	42
≥120–180 months	31	14	17
Children age 5–15	108	49	59
Adults (>15 years old)	165	77	88
Mean household size	6.6	6.2	6.9
Mother's education ≤ Primary (1–8)	51	26	25
Mother's education > Primary	8	3	5
Income ≤ US $65/month	56	27	29
Income > US $65/month	3	2	1
Home structure			
Mean no. of rooms/household	2.7	2.8	2.6
Mud/wood walls	57	28	29
Floor material – mud	51	25	26
Floor material – concrete	8	4	4
Sanitation and hygiene practices			
No latrine on compound	10	5	5
Traditional pit latrines	42	19	23
VIP latrine	7	5	2
Animal feces on premises	28	12	16
Report hand washing after defecating	37	17	20
Report hand washing before eating/feeding child	27	18	11
Report hand washing after farming	36	19	17
Reported water practices & usage			
Amount for drinking, l	5	4.5	5.5
Amount for non-drinking, l	72	66.6	77.3
Drink river or unprotected spring	59	29	30
Drink rainwater	57	28	29
Drink groundwater (improved source)	16	7	9
Report boiling drinking water	21	10	11
Report chlorinating drinking water	1	0	1
Mean distance to river water source, m	913.4	917.9	909
Drinking water extraction – pouring	38	16	22
Drinking water extraction – dipping	21	13	8
Drinking water storage container lid	37	18	19
Baseline diarrhoea reported†			
Mean number of days with diarrhoea in proceeding 7 days per child			
<5 years old	0.41	0.15	0.63
5–15 years old	0.1	0.1	0.09
Percent of children with diarrhoea in proceeding 7 days			
<5 years old	9.7	6.4	12.5
5–15 years old	5.1	5.3	5

All values are reported at the household level except participant totals, which are reported by group, and daily and weekly diarrhoea prevalences, which are reported per child.
†The reported baseline diarrhoea prevalence rates were computed using the GEE Poisson regression with random effects adjusted for age and clustering at the household level and below.

no risk (1–10 or 0 CFU/100 ml) sample fraction improved from just 3% for the influent to 27% for the effluent, while the very high risk (>1000 CFU/100 ml) sample fraction was reduced to 7% (effluent) from 43% (influent) (Tiwari 2008). Epidemiological evidence on the relationship between water quality and water-borne childhood diarrhoea in low income populations has shown elevated risk when drinking water is highly contaminated (e.g. *E. coli* above 1000 CFU/100 ml) but is less clear for water quality improvements below this threshold (Moe *et al.* 1991).

Drinking water geometric mean fecal coliform concentration was significantly better in intervention households (30.0 CFU/100 ml, 95% CI: 21.3, 42.1; $n = 175$) than in control households (88.9 CFU/100 ml, 95% CI: 58.7, 135; $n = 173$) ($P < 0.001$). Only one control drinking water sample was treated (BSF treated drinking water from an intervention household). While intervention and control households had similar quality ground- and rain-sourced drinking water, intervention homes' BSF treated river-sourced drinking water had statistically lower fecal coliform concentration than control homes' untreated river-sourced drinking water (Tiwari 2008). No significant recontamination was detected when comparing BSF effluent samples with BSF drinking water samples (Tiwari 2008).

A plot of the geometric mean fecal coliform count in drinking water samples from intervention (clear triangles) and control (black triangles) homes at each visit (Figure 3) illustrates how drinking water quality fluctuated in control households over the trial period, but steadily improved (declining trend) in intervention households. BSF bacterial removal has been shown to increase as the filter matures biologically with increased usage/time (Elliott *et al.* 2008) and may explain steady improvement in BSF household drinking water quality. Seasonal variations in river water quality, and water source switching, specifically use of relatively clean rain water for drinking by nearly all households in late June, and by those households with rainwater storage during July and August, account for much of the observed temporal variation in control household quality.

Better drinking water quality in intervention over control households was notably more pronounced among trial households in the upper watershed compared to those in the middle (Figure 4). Upper watershed households had no improved water sources to use and very limited rainwater storage, and therefore, used river water (or equally

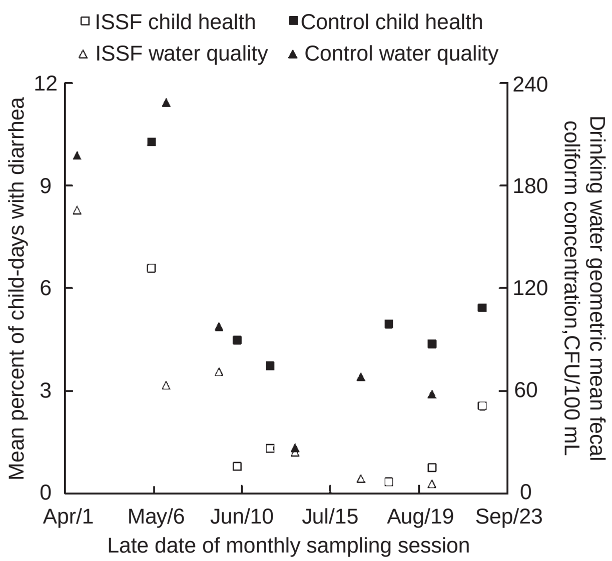

Figure 3 Daily child diarrhoea prevalence rate (squares) and drinking water quality (triangles) for intervention (clear) and control (black) groups at each visit.

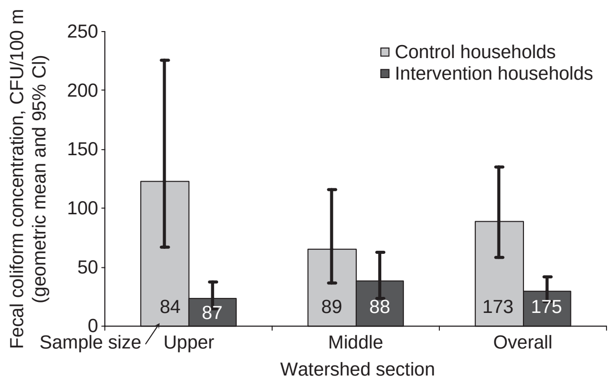

Figure 4 Comparison of fecal coliform concentration in drinking water from control and intervention households.

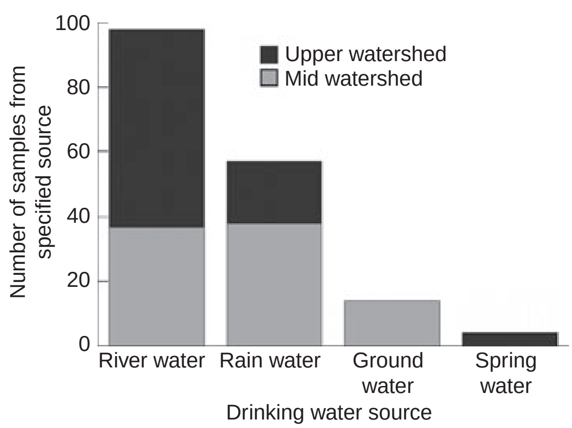

Figure 5 Drinking water sample sources in trial households by watershed position.

contaminated spring water) for drinking much more often compared to middle watershed households (Figure 5).

Diarrhoea prevalence

Figure 3 shows children in households with BSF filters (clear squares) had considerably lower daily diarrhoea prevalence than children in control homes (black squares) at each visit during the six-month trial. Both total child-days and total child-weeks with diarrhoea (daily and weekly prevalences) over the trial were higher in control than intervention households (Table 2). Among all-age children, daily prevalence in the intervention group was 2.0% compared to 5.2% in the control group. Controlling for repeated measures and clustering, unadjusted (for age) relative risk for daily prevalence was 0.38 (95% CI = 0.18, 0.82). Observed difference in weekly prevalence was greater (3.8% intervention; 17.0% control).

Diarrhoea prevalence was sensitive to child age (Table 2) and child ages were by chance not evenly distributed among the two groups (Table 1). Thus, child age was controlled for when estimating the intervention-attributable relative risk. Age-adjusted estimated relative risk for daily diarrhoea, controlled for repeated measures at the child-level and household clustering, was 0.46 (95% CI = 0.22, 0.96, $P = 0.038$) for all children and 0.49 (95% CI = 0.24, 1.02, $P = 0.057$) for children under age 5 years.

Age-adjusted relative risk was analysed separately by watershed position to examine potential effects of differing access to and use of improved water sources (Table 3). A greater reduction in child diarrhoea due to use of the BSF to treat river water was observed in households located in the upper watershed (RR = 0.23, 95% CI = 0.10, 0.51), where they depend on river water for drinking all or most of the time, than in the middle watershed (RR = 0.81, 95% CI = 0.24, 2.69) where improved public sources (deep borehole) and rainwater storage were more likely to be available and these sources drunk. However, the test for interaction between intervention group and watershed position was not significant ($P = 0.28$).

Table 3 Child (all ages) diarrhoea daily prevalence relative risk for BSF intervention treatment

Watershed position	Relative risk (95 % CI) age-adjusted	*P*-value
Upper	0.23 (0.10, 0.51)	<0.001
Middle	0.81 (0.24, 2.69)	0.731
Overall	0.46 (0.22, 0.96)	0.038

As expected, diarrhoea was less frequently reported in adults than children. Adults in the intervention group had lower daily (0.44%) and weekly (0.95%) prevalence rates than the control group (daily: 0.63%, weekly: 1.73%), however, differences were not statistically significant (RR = 0.82, 95% CI = 0.09, 7.12).

Discussion

The study found use of the BSF to treat river water was associated with a 54% reduction in child diarrhoea days slightly higher than the average reduction (44%) described in the literature (Clasen *et al.* 2006) and similar to that observed for the BSF in the Dominican Republic trial (47%) for all ages (Stauber *et al.* 2009). Health impacts of the BSF may be substantially greater among households lacking access to any improved water source in the upper watershed than in middle watershed households who had access to an improved water source (as defined by the WHO/Unicef Joint Monitoring Program (2006)), although the test for interaction was not significant. Adjusted risk results show that a child in a home drinking untreated river water has a 2.2 times greater risk of having diarrhoea on any given day than one in a home drinking BSF-treated river water. This

Table 2 Child days and weeks with diarrhoea among control and intervention households

Age group	Group	Child-days with diarrhea	Child-weeks with diarrhea	Child-weeks of observation	Relative risk (daily prevalence) (age-adjusted)
All children	BSF	86	24	626	0.46
	Control	203	95	558	95% CI: 0.22, 0.96
	Overall	289	119	1184	
< 5 years	BSF	69	17	285	0.49
	Control	166	74	288	95% CI: 0.24, 1.02
	Overall	235	91	573	
5 – 15 years	BSF	17	7	341	0.59
	Control	37	21	270	95% CI: 0.16, 2.21
	Overall	54	28	611	

effect may be conservative, given the possibility of higher baseline diarrhoea rates listed in Table 1 among under-five children in the BSF group.

Economical, ethical, and logistical concerns introduced several limitations. Sample size was relatively small. While recalls beyond 2 days might be considered unreliable (Boerma *et al.* 1991), this study used a 7 day recall of diarrhoea. On the other hand, very short recalls require more frequent visits that risk participant fatigue and greater biases to study results in a non-placebo controlled trial. The trial was not placebo controlled primarily because of difficulties and costs associated with producing a reliable placebo filter. Thus, some portion of the observed health impact might well be attributed to a placebo effect. Bias is regarded as a considerable problem in water, sanitation and hygiene trials, highlighted by the observation that blinded POU trials have shown little evidence for a reduction in diarrhoea (Clasen *et al.* 2006; Schmidt & Cairncross 2009). At the least, this study demonstrates that non-commercial POU methods can result in similar observed effect sizes as unblinded studies of commercial POU products, even if the latter are microbiologically more effective.

Point of use water treatment acceptance and long-term adoption has been a challenge (Stanton *et al.* 1992; Makutsa *et al.* 2001). In contrast, the BSF had relatively quick and easy acceptance and a high rate of post-trial purchase adoption (90% intervention and 69% control households). Besides improved health, BSF users were pleased with the ease of filter operation, cost savings, quantity of treated water, and improved smell, temperature, and taste, in contrast to most other POU methods which sometimes lack any non-health benefits (Clasen *et al.* 2006; Schmidt & Cairncross 2009). Availability of building materials and simplicity make production and sale of the BSF a feasible local enterprise, adding to its sustainability.

This study extends the health impacts evidence base for the BSF to include a rural African population, providing additional support for adding intermittent slow sand filtration to the current range of established POU treatment technologies (chlorination, ceramic filtration, solar disinfection and flocculation/disinfection), each appropriate in specific situations and contexts. This trial suggests that the BSF may be more effective for improving health among low-income households with no or limited access to improved water sources. Equally important, the long-term health and economic benefits due to sustained use of the BSF are likely to be realized, as the BSF was easily incorporated into daily life, end-of-trial purchase was high, perception of the BSF was positive, and no further materials, resources, or skills are needed for households to continue using and maintaining their BSF for many years.

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