VOLUME 18 NO 1 PP 65–74 JANUARY 2013

Relative benefits of on-plot water supply over other 'improved' sources in rural Vietnam

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Abstract

OBJECTIVE Access to improved water sources is rapidly expanding in rural central Vietnam. We examined one NGO-led piped water supply programme to assess the drinking water quality and health impacts of piped water systems where access to 'improved' water sources is already good.
METHODS This longitudinal, prospective cohort study followed 300 households in seven project areas in Da Nang province, Vietnam: 224 households who paid for an on-plot piped water connection and 76 control households from the same areas relying primarily on 'improved' water sources outside the home. The 4-month study was intended to measure the impact of the NGO -led water programmes on households' drinking water quality and health and to evaluate system performance.
RESULTS We found that: (i) households connected to a piped water supply had consistently better drinking water quality than those relying on other sources, including 'improved' sources and (ii) connected households experienced less diarrhoea than households without a piped water connection (adjusted longitudinal prevalence ratio: 0.57 (95% CI 0.39–0.86, $P = 0.006$) and households using an 'improved' source not piped to the plot: (adjusted longitudinal prevalence ratio: 0.59 (95% CI 0.39–0.91, $P = 0.018$).
CONCLUSIONS Our results suggest that on-plot water service yields benefits over other sources that are considered 'improved' by the WHO/UNICEF Joint Monitoring Programme.

keywords water quality, diarrhoeal disease, water supply

Introduction

The interconnected and persistent problems of unsafe drinking water, inadequate sanitation and poor hygiene contribute to a massive global burden of diarrhoeal disease that disproportionately affects the poor, the elderly, the young and those already suffering from other diseases or malnutrition. According to data published by the WHO (2008), diarrhoeal diseases are a leading cause of death in children under five in Vietnam, having accounted for an estimated 14% of all deaths in that age group in 2004. The rapid expansion of water and sanitation infrastructure coverage currently underway there is expected to reduce this burden of disease. Indeed, access to 'improved' water sources has increased from 52% of households in 1990 to 77% in 2000, 92% in 2006 and 95% in 2010 (WHO/UNICEF 2012), but diarrhoeal diseases remain a problem in Vietnam (Bui *et al.* 2008).

Although one of the Millennium Development Goals is to 'halve, by 2015, the proportion of people without sustainable access to safe drinking water', access to 'safe' water is not commonly measured, partly because there is no consensus international definition of what constitutes safe water. The WHO has recommended 1×10^{-6} DALYs per person per year as the risk-based target for all drinking water exposures, but in practice, this is difficult to measure. Other safe water criteria, such as the absence of detectable *E. coli* or total coliform in 100-ml samples, are commonly applied, but their utility and universal applicability are in question, partly due to the fact that microbial indicator monitoring data do not seem to correlate well with health risks (Moe *et al.* 1991; Brown *et al.* 2008). To simplify matters, the UNICEF/WHO Joint Monitoring Programme (JMP) tracks 'improved' water sources (rather than 'safe' water sources), and the definition of what constitutes access to these sources varies. According to the JMP, improved water sources are (i), a piped water connection into dwelling, plot or yard; (ii), access to a public tap or standpipe; (iii), a borehole, tube well or protected dug well; (iv), a protected spring; or (v), harvested rainwater. These improved sources represent lower-risk options that may be less likely to become contaminated with faecal matter than 'unimproved' sources such as surface water, shallow/unprotected wells or springs and vended water. In this study, the phrase 'piped water' refers to a piped water connection into dwelling, plot or yard.

A major focus of government, NGOs, and increasingly, private sector-led programmes is scaling up access to water and sanitation improvements in the rapidly developing economies of South-East Asia. As of January 2012, the NGO East Meets West (EMW) has installed on-plot metered piped water connections serving an estimated 375 000 people in 213 communities in Vietnam, with support from multiple donors and following a community-based development model. Most schemes have been in villages with mean incomes of approximately US$1 per day, per person, as identified in a needs assessment conducted by EMW, and are based on the goal of reaching financial sustainability although minimum subsidies or unsubsidised models for this critical infrastructure. In support of EMW's goal of exploring innovative methods for scaling up access to water and sanitation service delivery, we conducted a post-implementation assessment to evaluate a large-scale implementation of community piped water systems in rural central Vietnam. Objectives of this assessment included determining whether: (i) water systems consistently delivered safe drinking water to users and (ii) on-plot access to piped water systems provided health and other advantages over access to other available water sources, including 'improved' water sources.

Methods

This observational study had two phases: (i) an initial cross-sectional sampling and recruitment phase (1 month) and (ii) a longitudinal data collection phase (4 months). There were a total of four visits to each of 300 households, including those with a domestic piped water connection and control households without domestic water connections across seven community project areas. We collected interview data and household water samples for microbial and other analyses.

Sites, eligibility and recruitment

We worked with EMW to select study sites and gain access to study areas. Communities were randomly chosen from EMW projects in low-income settings. We randomly selected households initially from EMW and local government-supplied household lists of connected and unconnected households. Eligible villages for inclusion in the EMW piped water programme (i) were rural communities near Da Nang, in Quang Nam Province; (ii) included a minimum of 200 households; (iii) were relatively poor as determined by an EMW-administered needs assessment, with limited social and economic stratification; and (iv) exhibited demand for the system and were willing to contribute to construction via in-kind labour or cash. Eligible villages were selected by EMW for water systems based on both need and demand metrics in pre-surveys. Of more than 8000 households identified in the project areas at the time of this study, we visited randomly selected households from separate lists (connected and unconnected) in a cluster-randomized order to introduce the study and determine eligibility. Eligible households within villages were in local government or EMW records and within the official geographical boundaries of selected villages.

Selected households were in seven communities served by nine water supply projects. Systems were constructed between 2002 and 2008, were managed either by a cooperative (private) or a 'people's committee' (public), and employed similar conventional water treatment technology. Two systems used sedimentation followed by slow sand filtration (without disinfection). Seven systems used calcium hypochlorite pre-chlorination, chemical coagulation/flocculation with alum, followed by rapid sand filtration. A variety of source waters were used, primarily surface water. No final disinfection was employed by any system.

All survey data were collected from the primary caregiver, who acted as the study's point of contact with the household. Native speakers of Vietnamese from the region with experience in household survey techniques led all communication with households. We stressed that participants could quit the study at their request with no consequences at any point without having to give any reason. All recruitment, informed consent procedures and study documentation were reviewed and approved by the University of North Carolina – Chapel Hill Institutional

Review Board and by local Vietnamese authorities before use in this study.

Estimates of diarrhoeal disease morbidity in rural Vietnam were near 10% for a 2-week recall period in 2003 (Tang *et al.* 2003). We used a baseline estimate of 10% in the sample size calculations. Based on systematic reviews by Esrey and Habicht (1986), Esrey *et al.* (1985), Clasen *et al.* (2007), mean reductions of diarrhoeal diseases as a result of access to a household connection to piped drinking water and sanitation were assumed to be 30–60%. We based the sample size calculation on the detection of a risk ratio of 0.70. We calculated the required sample size for this study as a minimum of 350 individuals (in each group) to detect a 30% difference in proportions (risk ratio = 0.70) between the study groups with 80% power and $\alpha = 0.05$, using the methods for analysis of binary outcomes in multiple groups with repeated observations as described by Diggle *et al.* (2002). We estimated that 70 households would be the minimum needed for each group. Calculations account for limited clustering within households and clustering in individuals over time (Killip *et al.* 2004; Leon 2004). We recruited 300 households in total: 224 households connected to a piped water supply system and 76 unconnected households within project areas, selected randomly from each group.

Data collection and management

Each household was visited once upon recruitment and then three more times over three months. Initial household interviews were extensive (1 h) with subsequent brief follow-ups (15 min each) to monitor changing covariates, including water quality and water handling practices. Data for each household were recorded for water use and handling practices; sanitation access and behaviour; other water, sanitation and hygiene practices; and other covariates. A broad range of data on water, sanitation and hygiene (WSH) were collected. We estimated the variability between study groups in measured quantities via Welch's *t*-test in part to identify possible confounding variables (Welch 1947).

Diarrhoeal disease data and analysis

In longitudinal diarrhoeal disease surveillance of all household members, we asked each household respondent to provide a 1-week recall of diarrhoeal illness for herself and all members of her household. Diarrhoea was defined as three or more loose or watery stools in a 24-h period, and dysentery was defined as stool with the presence of blood, following WHO definitions.

We estimated diarrhoeal disease burdens using longitudinal prevalence, or the proportion of total observed person-time with the outcome in individuals (Schmidt *et al.* 2007; Morris *et al.* 1996;. Longitudinal prevalence ratios (LPRs) were computed for individuals in households with a piped water connection against a control group of individuals without one via a Poisson extension of generalised estimating equations (GEE), adjusting for clustering of diarrhoeal disease outcomes within households and within individuals over time (Liang & Zeger 1986; Zeger & Liang 1986). The GEE model assumed that missing observations were missing completely at random (MCAR; Little & Rubin 2002). All statistical analyses were performed in Stata software (Stata Corporation, College Station, TX, USA). All potential measured confounders, including water use and handling practices, socioeconomic status and sanitation and hygiene-related factors, were assessed in the analytical model through a series of stepwise regression analyses with both forward selection and backward elimination. Confounders were identified based on an *a priori* change-in-estimate-of-effect criterion of 10%.

Water quality data and analysis

Drinking water samples were collected from all households in the study at each visit. Households were sampled for at least two types of water: stored household water from control households or water as delivered via the household/yard tap for other households and stored, treated drinking water (usually, boiled water) if available. If households used another source or treatment step for drinking water at the time of the visit, a sample of that water was also collected. Samples were kept on ice and transported by air to the laboratory in Ho Chi Minh City (arriving by 09:00 the morning following sampling), where analysis was performed as soon as possible, in all cases within 24 h of sample collection. Total coliforms (TC) and *Escherichia coli* were the microbial indicators used in this study, using membrane filtration or IDEXX Colilert®, consistent with methods described in *Standard Methods for the Examination of Water and Wastewater* (Eaton *et al.* 2005), with concentrations reported as colony-forming units (cfu) or most probable number (MPN) per 100 ml, respectively.

Results

Demographic and socioeconomic data

Groups being compared were assessed for differences in demographics or socioeconomic status, and some of the important measured variables are shown in Table 1.

Table 1 Key socioeconomic and WSH-related measures

	Domestic service	No domestic service
Households	224	76*
Mean persons per household	5.2	4.9
Per cent female	51	57*
Homeownership,%	72	49*
Single-parent household,%	9.0	16*
Mean land owned or rented, *soa*	1600 (95% CI 1300–1800)	1200 (95% CI 900–1400)
Bedrooms in house, mean	2.0	2.1
Mean electricity bill per month, USD	3.94 (95% CI 3.47–4.47)	3.82 (95% CI 3.12–4.53)
Education of primary caregiver, %		
No school	1.8	1.5
Primary school	17	17
Some secondary school	55	52
Secondary school	19	20
Some university/technical or more	6.8	11
Education of household head, %		
No school	1	1
Primary school	33	20
Some secondary school	21	23
Secondary school	32	38
Some university/technical or more	13	18
House construction wealth indicators, %		
Sheet metal roof	34	41
Earth floors	3.6	12
Thatch or bamboo walls	1.8	6.6
Access to a latrine, %	98	99
Hand washing reported 'always' at critical points (unprompted), %	63	58
Report hand washing with soap (unprompted), %	61	57
Soap available in house at time of visit (visually confirmed by interviewer), %	81	75
Water use per month (from metering or user estimate, litres)	5200 (95% CI 4500–5800)	~3000 (mean of small number that could be reliably estimated)*
Price paid for water per month, USD	0.78 (95% CI 0.69–0.87)	0.90 (95% CI 0.32–1.5)
Unsafe water storage (possibility for recontamination), %	51	39
Unsafe water collection observed from stored containers, %	44	32
Uncovered water storage containers, %	8.6	9.2
Litres treated/day	7.0 (95% CI 6.6–7.5)	6.0 (95% CI 5.4–6.6)*
Boiling, %	99	98
Settling†, %	36	17*
Ceramic filter, %	8.7	7.9
Cite health as primary motivation for household water treatment, %	43	58

*significant difference at $\alpha = 0.05$, Welch's *t*-test.
†Settling was also practised in order to allow dissipation of volatile chlorine among connected households.

These were measured as covariates in the analysis to examine the potential associations between dependent variables (diarrhoeal disease, household drinking water quality) and primary independent variables (water source, system parameters). Data suggest that control households were somewhat poorer (as indicated by key wealth-related variables) than those investing in EMW piped water programmes. We therefore used wealth indicators in a subsequent confounding analysis.

Water sources and user satisfaction

Households were asked to name their most important (usually, not the only) source of water during the wet and dry seasons (Table 2). They were then asked to report observations about the taste and colour of water sources, and any problems they may have experienced. All respondents reported intermittent service in the piped water supply (Table 3).

Household water handling and treatment

A variety of data on water collection, storage and handling practices were recorded for each household (Table 1). All households were observed to have one or more water storage containers. The data collection team noted whether one or more containers were uncovered at the time of the household visit and whether water was collected from storage containers via a tap or by pouring ('safe collection') or by dipping cups, hands or some other utensil into the water ('unsafe collection'). No significant differences in water storage or handling were observed between the two groups.

Water treatment data are summarised in Tables 1 and 3. Self-reported water treatment of some household water by boiling or other means was near universal in both groups: 99% of respondents in households connected to a water supply system reported boiling most or all drinking water, while 98% of unconnected households did. Most households (91% in the connected group, 92% in the unconnected group) had stored, boiled water on hand at the time of follow-up visits. Households connected to a piped water supply system reported treating more water daily: 7.0 l/day (95% CI 6.6–7.5), *vs* 6.0 l/day (95% CI 5.4–6.6) among control households, a statistically significant difference. Boiling water reduced microbes by 99–99.9% on average across all samples. Apart from drinking, 62% of all households reported using boiled water for making formula or preparing food and 61% for washing or hygiene. Detectable indicator microbes were still present in stored, boiled water (Table 3). No clear association was detected between the practice of boiling and reported diarrhoeal disease when controlling for study group and covariates. Additionally, other water treatment methods were reported by households, including allowing collected water to settle over time to reduce turbidity and chlorine taste/smell and filtration using commercially available point-of-use ceramic filters (Table 1). Respondents were asked to state motivations for treating drinking water. Without prompting with suggested answers, 43% of connected respondents gave health or wellness reasons for treating drinking water, while 58% of those from unconnected households did.

Water quality

Drinking water quality as measured by microbial counts of TC and *E. coli* differed between those having access to household piped water connections and those relying on other sources. As shown in Table 3, the geometric mean piped water *E. coli* counts (not including those samples that were treated by boiling) were 16 (95% CI 13–18) bacteria/100 ml compared with 63 (95% CI 47–84) bacteria/100 ml among control households and 36 (95% CI 31–42) bacteria/100 ml among those from 'improved' sources. The geometric mean piped water total coliform counts were 310 (95% CI 260–370) bacteria/100 ml compared 1600 (95% CI 1200–2100) bacteria/100 ml among unconnected households and 1200 bacteria/100 ml (95% CI 1,100–1400) in the subset of households using 'improved' sources. For both measures, the piped water supply systems delivered statistically meaningful improvements in water quality over alternative sources serving the area as indicated by samples collected at the household level. Microbial counts from water systems that used pre-chlorination were not significantly different from systems that did not employ this treatment step (Table 3). Sixty per cent of household drinking water samples in households using piped water were ≤ 10 cfu/100 ml *E. coli* compared with 43% of drinking water samples from all unconnected households and 49% of samples from 'improved' sources.

Table 2 Water sources by season and overall satisfaction of sources available, by group

Group	Primary source of drinking water: Wet season	Primary source of drinking water: Dry season
Household connection to piped water supply	Piped water (96%), borehole (3%), other protected well meeting definition of improved (1%)	Piped water (98%), borehole (1%), other protected well meeting definition of 'improved' (1%)
Control households not connected to a piped water supply	Borehole (70%), other protected well meeting definition of improved (8.7%), rainwater (0.82%), unimproved sources (22%)	Borehole (73%), other protected well meeting definition of 'improved' (8.6%), 'unimproved' sources (19%)

Table 3 Summary of water quality data across study groups

	Domestic service		No domestic service	
	All households connected to a piped water supply	Subset of households connected to systems with pre-treatment chlorination	All households unconnected to a piped water supply	Subset of unconnected households reporting primary use of 'improved' sources
Untreated household water (all sources, n = 1256)				
Geometric mean *E. coli* per 100 ml (cfu or MPN), (95% CI)	16 (13–18)	15 (12–18)	63 (47–84)	40 (28–54)
% total samples with $\leq$ 10 *E. coli* per 100 ml (cfu or MPN), %	61	60	44	49
% total samples with $\leq$1 *E. coli* per 100 ml (cfu or MPN), %	24	22	30	33
Geometric mean TC per 100 ml (cfu or MPN), (95% CI)	310 (260–370)	370 (150–880)	1600 (1200–2100)	1200 (1100–1400)
Arithmetic mean turbidity, all sources (NTU), (95% CI)	2.1 (1.9–2.3)	1.1 (0.71–1.8)	2.2 (1.0–3.3)	2.4 (1.8–3.0)
Stored, boiled household water samples (all sources, n = 1225)				
Geometric mean *E. coli* per 100 ml (cfu or MPN), (95% CI)	11 (8.4–16)	31 (16–62)	17 (9.7–28)	14 (11–19)
% total samples with $\leq$10 *E. coli* per 100 ml (cfu or MPN), %	86	84	85	87
% total samples with $\leq$1 *E. coli* per 100 ml (cfu or MPN), %	75	72	77	80
Geometric mean TC per 100 ml (cfu or MPN), (95% CI)	50 (38–66)	81 (47–140)	100 (63–170)	88 (68–110)
Other household water use data				
% with boiled water in household at time of visit, %	91	90	92	91
Arithmetic mean $\log_{10}$ reduction of *E. coli*, boiled household drinking water, (95% CI)	0.71 (0.63–0.78)	0.68 (0.64–0.72)	1.1 (1.0–1.3)	1.2 (1.1–1.3)
Arithmetic mean $\log_{10}$ reduction of total coliform, boiled household drinking water, (95% CI)	1.5 (1.3–1.6)	1.3 (1.3–1.4)	1.9 (1.7–2.1)	2.1 (2.0–2.2)
% reporting intermittent service, %	100	100	–	–
Percentage of samples positive for residual free chlorine (0.01 mg/l detection limit) determined by testing at point of sampling, %	0	0	0	0

System performance and water quantity

No disinfectant (free chlorine) residual was detected at the household level in any samples, with all samples for free chlorine detection processed in the field immediately after collecting the drinking water sample. Approximately 16% of households connected to a piped water supply reported that they could ever taste chlorine in the water. All connected households reported occasional to frequent intermittent service, a mean of 1.8 times per month. When asked about the quantity of water available, 68% of households connected to a piped water supply responded that the quantity supplied all daily needs of the household, while only 1.3% of control households did.

Data presented in Table 1 show that respondents connected to piped water supply systems used significantly more water, which may be associated with better hygiene. In terms of meeting daily water needs, respondents indicated in interviews that they valued the convenience of a household tap for several reasons. Our data indicate that households without water connections paid approximately twice as much per m^3 for half to a third less water, although our cost data for unconnected households were incomplete. Mean water use from connected households was approximately 5200 l/month (95% CI 4500–5800), according to metering data, *vs* an estimated 3000 l/month for unconnected households. The mean cost per litre for connected households was US$0.00015 compared with US$0.003 for unconnected households who reportedly paid for access to water.

Sanitation and hygiene

A summary of key sanitation and hygiene data are presented in Table 1. Both groups had relatively good access to sanitation – the most common variety was a pour-flush latrine – and hand washing practices and access to soap were similar. These parameters and other related factors were measured as covariates in the analysis of diarrhoeal disease impact.

Diarrhoeal disease

A summary of cases identified by group is presented in Table 4. A total of 154 cases were detected in both groups: 103 among those with access to an on-plot water supply, and 51 among those without. The unadjusted LPR was 0.66 (95% CI 0.47–0.91, $P = 0.012$) when using all unconnected households as the control group, and 0.68 (95% CI 0.48–0.98, $P = 0.037$) when comparing the group with piped water to the subset of households using 'improved' sources only. After adjusting for the limited observed clustering in households and in individuals over time, the LPR for diarrhoeal disease in the previous 7 days was estimated to be 0.59 (95% CI 0.40–0.87, $P = 0.008$), indicating a protective effect of a piped water connection. Comparing households with piped water to only those control households with 'improved' water sources also revealed a statistically significant effect: the LPR was determined to be 0.60 (95% CI 0.39–0.93, $P = 0.021$). This study was not sufficiently powered to detect differences in subgroups (e.g. under 5 s). In the backward elimination procedure for covariates to include in the GEE model, no adjustments for confounding were necessary based on the *a priori* criterion of a 10% change in mean estimate of effect. Because the presence of a household connection could also be associated with better health, greater wealth and other factors that may be associated with reduced risk of disease, we also adjusted estimates by measured variables that seemed to capture this difference between the groups: household income and home ownership. The resulting LPR was 0.57 (95% CI 0.39–0.86, $P = 0.006$) when comparing households with piped water to all other sources, and 0.59 (95% CI 0.39–0.91, $P = 0.018$) if only households with access to an 'improved' source were used for comparison. Also, although we did collect data on dysentery (diarrhoeal disease with blood present in stool), no cases were reported during this study.

Table 4 Summary of diarrhoeal disease surveillance data

	Domestic service	No domestic service, 'improved' and 'unimproved'	'Improved' sources only
Total number of people	1156	373	303
Total person-weeks of recall	4250	1356	1147
Cases diarrhoeal disease, all	103	51	42
Unadjusted longitudinal prevalence of diarrhoea	0.025	0.037	0.037

Discussion

Results of our study suggest that on-plot piped water access results in benefits to connected households over other available sources, even those that meet the definition of 'improved' under the WHO/UNICEF JMP. Households connected to piped water supply systems benefited from better water quality and greater water quantity. Connected households also were at lower risk of diarrhoeal disease over the study period unconnected households, even those with access to 'improved' sources and sources very near to the household (within a self-reported 20-min total collection time).

Systems are facing challenges, however. Maximum tariffs mandated by the government may constrain operators to charge less than the true cost of providing safe water to communities. No free or total chlorine residuals were detected in piped water samples from systems in this study (detection limit: 0.01 mg/l) in more than 1200 samples. In an analysis of the impact of chlorination as practised in these systems on water quality as delivered, we did not detect a measurable difference in microbial counts between households in systems that received pretreatment chlorination and those that did not (Table 3). One hundred percent of connected respondents indicated that intermittent service – a risk factor for system contamination – occurred regularly, an average of 1.8 times per month during the 4-month surveillance period.
A final disinfection step in treatment is recommended to

ensure that a disinfectant residual is maintained throughout the distribution system. With no disinfectant residual and intermittent service, system contamination and the delivery of unsafe water are likely. An inspection of the treatment systems and interviews with operators suggested that chlorine dosing is inconsistent and generally for pre-treatment only, at the sedimentation step of the treatment train, rather than immediately before pumping to the distribution network. Although operators know that post-treatment chlorination can reduce risk of recontamination in the system, this practice is avoided to limit chlorine taste in the water, which is perceived as objectionable by users. Water system managers, thus, have a disincentive to consistently disinfect drinking water as it may lead to reduced sales. Water managers have reported customer complaints about the chlorine taste in water. Indeed, we observed that systems employing pre-treatment chlorination delivered less water to users per month: 3400 (95% CI 3100–3800) litres per household per month (chlorinated) *vs* 4100 (95% CI 3800–4400) litres per household per month (unchlorinated), although we have not adjusted these estimates for other potential factors that may explain this difference.

At the time of this study, government regulation of small water supply systems in Vietnam required one sample for microbiological testing every 6 months, and no systematic enforcement was in place for many systems. In systems where microbiological quality monitoring is infrequent, maximum tariffs limit investment in other forms of water treatment/disinfection, and user distaste for disinfectant is widespread, alternative approaches to ensuring the safety of drinking water may be required. Among them is expanded coverage of household water treatment and safe storage (HWTS) as a secondary step to protect consumers, provided that HWTS is practised consistently and correctly (Brown & Clasen 2012; Enger *et al.* 2012). In this study, boiling as currently practised in these communities does not seem to be a good option: we found detectable levels of *E. coli* and total coliform in stored boiled water, potentially as a result of unsafe storage and handling practices (Table 3). Although boiling was practised in the majority of households, our observations suggested that this was usually in small amounts for making tea and not the source for the majority of the households' drinking water. We did, however, observe that boiling as practised resulted in a 0.71 $\log_{10}$ reduction of *E. coli* (95% CI 0.63–0.78) among households connected to a piped water supply and a slightly higher reduction among other households (1.1 $\log_{10}$, 95% CI 1.0–1.3; Table 3). Our data were consistent with the 90.1% estimate of boiling prevalence and 97% reduction of thermotolerant coliform (TTC) in a 12-week study of 50 households in Vietnam by Clasen *et al.* (2008).

Maintaining drinking water quality in small supply systems in resource-limited settings is a challenge. Although systems in this study did provide improved water quality over other available sources, including 'improved' sources – and the longitudinal prevalence of diarrhoeal disease was a low 2.8% across all households in the study – microbial counts in water samples were elevated beyond what would be considered safe according to historical water quality standards from wealthier countries [defined variously as <1 cfu TC/100 ml (USA), <1 cfu *E. coli*/100 ml (WHO historical standard)]. We recommend a water safety plan (WSP) approach to identifying and controlling risks to these and like systems (WHO 2009, 2011; Gunnarsdottir *et al.* 2012). WSPs can be useful in helping to determine cost-effective quality control strategies for small systems.

This study had a number of known limitations. First and most importantly, the possibility of unmeasured confounding limits our confidence in the health impact data, so these estimates should be interpreted with caution and in light of the non-random allocation of the exposure groups. Although less diarrhoea was observed in the group with on-plot water connections, we also know that, on average, people with domestic water access may be wealthier and therefore may be more educated, healthy and health conscious than others, all factors which may be associated with a lower risk of diarrhoeal disease. We observed no differences in education or self-reported wealth, but indicators of wealth were different between the two groups. Specifically, households without on-plot service were more female, there were more single-parent households, and there was a greater likelihood that these households did not own their dwellings. Although we can and did adjust for these factors in our analysis (and observed no differences between estimates of effect), other, unknown and unmeasured factors may have confounded or modified the reported association between water access and health. This study, then, should be considered suggestive of health impact only and not the same strength of evidence as would result from a randomized, controlled trial.

Second, the limited sample size prevented a more sophisticated analysis of health data. This study may have benefitted from particular attention to age stratum-specific estimates of diarrhoeal disease, including for children under 5 years of age who are most susceptible to serious outcomes related to faecal-oral diseases. The lower-than-expected prevalence of diarrhoeal disease resulted in a study that was underpowered to detect differences between subgroups of the total study population.

Third, a number of measured variables were collected using subjective self-report from participants in the study. This includes the main health outcome variable of diarrhoeal disease (7-day recall) as well as system performance data, control households' cost of water and user perceptions. We were not able to include triangulating health data (e.g. clinic or anthropometric data) or water system-level data from operators or non-piped water cost data. Collection times and distances to water sources were collected from users themselves, who may or may not have been able to provide reliable estimates.

Fourth, the length of the study was too short to observe seasonal changes that may have influenced water system operation, maintenance and performance as well as water quality and health measures. Each of these variables may be influenced by seasonal changes that impact water sources, water use and handling practices, sanitation and hygiene behaviour and diarrhoeal disease prevalence.

Despite these limitations, our study has provided evidence that on-plot access to a piped water connection can afford households significant and measurable benefits over other water sources, even those that meet the JMP definition of 'improved', and in spite of the fact that quality and continuity of the piped supply were less than ideal. Specifically, findings from this study support the following conclusions that: (i), households connected to a piped water supply had consistently improved drinking water quality over those relying on other sources, including 'improved' sources, as indicated by microbial counts and (ii), individuals in households connected to a piped water supply had an approximate mean 40% lower risk of diarrhoea than those in households without one. Connected households also had access to greater quantities of water.

Apart from possible gains in water quality, increased water quantity and health, there are several important additional potential benefits of on-plot water supply over other, even 'improved' sources. A number of studies have provided evidence that on-plot water can convey advantages in terms of time and convenience (Cairncross & Cliff 1987; Churchill *et al.* 1987; Sorenson *et al.* 2011) and economic and social well-being (White *et al.* 1972; Tomkins *et al.* 1978; Aiga & Umenai 2002; Tumwine *et al.* 2002; Devoto *et al.* 2011), and that benefits may greatly outweigh costs (Hutton *et al.* 2007). Willingness to pay for household piped water connections is often high, enabling projects to be sustainable in many, although not all, contexts. Taken together, these benefits underscore the importance of keeping the focus in the water sector on household connections to functional and safe piped water supplies as the end goal. The Joint monitoring programme has estimated that only 54% of households globally had on-plot water (WHO/UNICEF 2012) access in 2010. Despite recent pronouncements that goal 7c of the millennium development goals has been met (Clasen 2012), much work remains to be done to ensure that the benefits of sustainable safe water are enjoyed by all.

Acknowledgements

This study was funded by USAID-RDMA as part of the WaterSHED Global Development Alliance. Laboratory assistance was provided by Vu Thuy Tien and Hoang Tuong Vi. Interview data were collected by To Thi My Thanh, Ngo Thi Hong, Tran Huu Loc and Nguyen Van Nhan. The authors gratefully acknowledge the contributions of the East Meets West Foundation. We also thank Prof. Sandy Cairncross for comments on a draft version of this manuscript. We especially thank study participants who welcomed us into their communities and homes.

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