

Locally produced hydrogen sulphide detecting water quality test kits increase household level monitoring in rural Tanzania

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ABSTRACT

In developing countries, rural water sources have the highest levels of faecal contamination but are the least monitored. Affordable field-based water quality tests are needed. The presence of faecal indicator bacteria can be determined with hydrogen sulphide (H₂S) detecting tests, that are inexpensive and simple to make locally. In rural Tanzania, a non-governmental organisation (NGO) designed, produced and evaluated a new H₂S water quality test kit. The H₂S test results correlated with log₁₀ *Escherichia coli* densities from conventional water quality tests. The production cost was US\$ 1.10 and the test retailed for US\$ 1.37. In total, 433 tests were sold through local pharmacies and NGOs. Additionally, 165 WaSH education meetings, reaching 3,408 community members, were conducted with the H₂S test demonstrated in over half the meetings. Pre- and post-surveys of 294 meeting participants saw an increased reporting of household level water treatment by 24%. The H₂S test was widely accepted, with 94% of those surveyed willing to buy the test in the future. International and national guidelines for drinking water monitoring need to be amended to include locally produced H₂S water quality tests. This will enable households to monitor their own water sources and make informed choices about water safety and treatment.

Key words | drinking water, education, hydrogen sulphide, monitoring, testing

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INTRODUCTION

Inadequate water, sanitation and hygiene (WaSH) is estimated to cause 842,000 diarrhoeal deaths annually (Prüss-Ustün *et al.* 2014). This represents 58% of all deaths due to diarrhoea and equivalent to 1.5% of the global disease burden (Prüss-Ustün *et al.* 2014). In sub-Saharan Africa (SSA), nearly 68% of the population use unimproved water sources for drinking water (UNICEF & WHO 2015) and the clustered burden of inadequate WaSH is estimated

to contribute to 61% of all diarrhoeal deaths (Prüss-Ustün *et al.* 2014). In SSA, a review of 72 institutions from ten countries, reveals that monitoring is predominately conducted in urban areas by institutions with higher water quality budgets (Peletz *et al.* 2016). Further, improved water sources, as defined by the Joint Monitoring Program (UNICEF & WHO 2015), were monitored up to three times more frequently than unimproved sources (Crocker & Bartram 2014; Kumpel *et al.* 2016). In the SSA study, the most highly monitored water sources are urban piped water systems (64% of samples) by water utilities, which had the lowest levels of contamination (4% of samples)

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(Kumpel *et al.* 2016). Unimproved water sources are more frequently contaminated with faecal indicator bacteria (FIB) at higher risk levels, especially in rural areas and poorer countries (Bain *et al.* 2014).

One of the main barriers to increased testing is the cost of water quality tests and the technical skills and laboratories to conduct the tests. *Escherichia coli* and thermotolerant coliforms (TTC) are the only FIB for contamination in water recommended by the World Health Organization (WHO) Drinking Water Guidelines, 2011. There are a range of laboratory and field-based commercial water quality tests that identify *E. coli* and TTC. Water quality tests range in price from US\$ 0.50 to US\$ 7.50 for reagents, plus there are costs for consumables, specialist equipment and training (Bain *et al.* 2012). The estimated total cost of a water quality test is estimated between US\$ 7.09 and US\$ 7.44 per sample, with labour and transportation costs the largest fractions (Crocker & Bartram 2014). For disadvantaged rural communities, the costs are prohibitive. More affordable and accessible field-based drinking water quality testing is needed for the world's population, who rely on unimproved water sources.

The hydrogen sulphide (H₂S) bacteria detecting test was first developed in India as a simple and inexpensive field water quality test with incubation at ambient temperatures (Manja *et al.* 1982). The H₂S test detects the presence of H₂S changes in colour to black, as a presence/absence test. Utilising molecular microbiology, the specificity of the H₂S tests for bacterial genera associated with faecal contamination is confirmed (McMahan *et al.* 2012). The H₂S tests detect a much larger range of micro-organisms and yet are still comparative to TTC tests. Meta-analysis of 51 H₂S tests (reporting 13,853 samples) compared to TTC, reported an average sensitivity of 87% (CI₉₅ 80–92%) and specificity of 82% (CI₉₅ 72–90%) (Wright *et al.* 2012).

H₂S tests have been successfully used to detect faecal contamination in water, across the world, for over 30 years (Wright *et al.* 2012). The H₂S test is a very effective water quality monitoring tool for low-resource settings (Khush *et al.* 2013), including in the hands of trained community members (Genthe & Jagals 2003). A small number of institutions in SSA are presently using H₂S tests for water quality monitoring (Peletz *et al.* 2016). The tests have been progressively recommended by the Government of India

in the 2006 Guidelines for National Rural Drinking Water Quality Monitoring and Surveillance Programme for community water point for initial monitoring, with positive results required to be confirmed by laboratory-based tests. However, the H₂S test is not presently recommended by the WHO in the 2011 Guidelines for Drinking Water.

An important part of motivating people to improve their water sources is education. People need to understand water contamination and risk; demonstrating water quality testing is one method available to achieve this. Urban Indian households, given access to water quality tests results are 1.5 times more likely to start buying commercially available safe water (Hamoudi *et al.* 2012). Further, there is an 11% increase in uptake in household level water treatment (Jalan & Somanathan 2008). Other studies in rural India reported a positive change in attitude to improve water quality, after the community received water quality test results that 49.8% of samples ($n = 313$) were positive for FIB (Tambe *et al.* 2008). In peri-urban Dar es Salaam, Tanzania, hygiene interventions across 334 households disseminating drinking water quality results and WaSH education, had no measurable differences in WaSH behaviour between groups (Davis *et al.* 2011). This indicates that the WaSH education design is an important factor in success between studies. The Dar es Salaam study also raised questions about the cost-effectiveness of using commercial water quality tests in interventions (Davis *et al.* 2011). Affordable water quality testing combined with appropriate WaSH education is a potential tool to trigger community-driven demand and behaviour change, however further evaluation is needed. Interestingly, the role and effectiveness of H₂S tests for household level water quality testing and WaSH education programmes has not been explored to date.

The main aim of this research was to improve WaSH awareness and behaviour through community use of H₂S water quality tests. This was achieved through the following four objectives: (1) to produce H₂S tests locally in rural Tanzania for the first time, (2) to validate the effectiveness of the H₂S tests used in the hands of the community testing local drinking water sources, (3) to design a marketing and WaSH education programme that included H₂S tests, and (4) to determine if the inclusion of the H₂S tests improved WaSH education outcomes.

METHODS

Test production

The original composition of the H₂S test was selected (Manja *et al.* 1982) and two concentrations of liquid media were trialled: 2.5 mL (Mosley & Sharp 2005) and 5 mL per 100 mL of water sample (Manja *et al.* 1982). Reagents were sourced and priced from suppliers in Dar es Salaam, Tanzania and produced in the Ifakara Health Institute laboratory in Ifakara, Tanzania. The H₂S producing bacteria *Salmonella enterica* was selected as the positive control. *S. enterica* subsp. *enterica* serovar Typhimurium UT30 (Gebreyes & Altier 2002) was sourced from the Department of Veterinary Medicine at Sokoine University of Agriculture, Morogoro. The strain is known to be multi-drug resistant and was isolated from swine (Gebreyes & Altier 2002). *S. enterica* culture was isolated on the semi-selective MacConkey Agar (Oxoid) and grown in nutrient broth at 37 °C for 24 h prior to inoculation. *S. enterica* was spiked into both 5 mL and 100 mL volume H₂S tests at concentrations of 0, 5, 10, 100, 500 and 1,000 bacteria/100 mL. The purpose of the 5 mL bottles was to determine if a semi-quantitative test could be developed, as reported elsewhere (Roser *et al.* 2005). Incubation was at both 37 °C and ambient temperature (22–30 °C) and observations of colour change made at 24, 48, 72 and 96 h. The experiment was repeated to give two groups of data (A and B). The degree of colour change was recorded during the experiment (Figure S1, available with the online version of this paper). The limit of detection and corresponding risk categories were calculated.

Test validation in the laboratory

The effectiveness of the H₂S test was determined against 47 water sources including treated water, protected and unprotected water sources. Water source classification was based on the WHO and UNICEF Joint Monitoring Programme methodology (UNICEF & WHO 2015). The H₂S tests of volumes 5 mL and 100 mL were inoculated with sample water in duplicate and incubated at ambient room temperature (22–30 °C). The tests were read within 1 hour of inoculation to check that there were no sulphide

compounds already present in the water which might give a chemical-induced sulfide formation (Sobsey & Pfaender 2002). For a subset of 20 water sources, the samples were also tested in parallel for *E. coli* and total coliforms. The method used was membrane filtration with m-ColiBlue24[®] (Hach) growth media according to the manufacturer's instructions which comply with the US EPA 10029 method. Briefly, 100 mL of water samples were filtered through 0.45 µm filters then placed on a membrane pad containing 2 mL of media and incubated at 37 °C (a variation from the method which recommends 35 °C) for 24 h.

Test validation in the community

An initial trial was conducted with 16 households recruited from the villages of Idete and Namawala, Kilombero Valley, Tanzania. The households received training on how to use the tests and then conducted the tests themselves on two water sources: the primary drinking water source and an alternative poorer water source. A negative control (bottled water) was also tested. The tests were left with the household to incubate over 24 h in a warm safe place, such as a window sill. At the time of sampling comparative water samples were taken and tested in the laboratory using H₂S test and for *E. coli*/total coliforms (as previously described). The households also answered some questions on their water source, water treatment, demand for water quality testing, ability to use the H₂S test and willingness to use and pay for the H₂S tests.

Development and marketing of H₂S tests

For the commercial test kit, a smaller water volume of 20 mL with a disposable plastic tube was the most suitable. H₂S medium was delivered via infusing an absorbent cotton pad with 1 mL of medium then drying it, as described previously (Mosley & Sharp 2005). An instruction booklet in kiSwahili language was also developed for the test that included a sanitary survey guide to determine the health risk of the tested water.

A comprehensive marketing campaign for the tests was developed that included print materials and radio presentations. The H₂S test kits were distributed through 15 villages in the Kilombero Valley to be sold commercially as an

affordable water quality test. The tests were distributed for sale by MSABI, other non-governmental organisations (NGOs) and 31 local pharmacies. In total, 713 individual H₂S test kits were distributed over a seven-month period in 2015.

Inclusion of H₂S tests in a WaSH education programme

The H₂S test was introduced as an intervention for randomly selected villages as part of a WaSH education programme run by MSABI. The programme was based on participatory community awareness, delivered via participatory community meetings, demonstration visits and house-to-house visits. The H₂S test kit was added to the programme and a local or household level water source was tested. Participants returned the following day to view the results of the water quality test. In total, 94 out of 165 WaSH education meetings were conducted with the addition of the H₂S test kit. Each meeting had approximately 20 participants. Surveys were conducted with approximately 119 community members before they participated in the standard WaSH education meetings and another 175 who participated in the H₂S test kit in addition to the WaSH education meetings. A tablet-based survey tool was used to gather information on demographics, WaSH behaviours (including hand washing with soap), WaSH infrastructure (including toilet type) and any plans to change WaSH practices (Table S1, available with the online version of this paper). The survey was conducted again two months after the WaSH education sessions.

Statistical analysis

All statistical analysis and graphs were produced using the statistical software program Prism[®] (GraphPad Software, La Jolla, CA, USA). *E. coli* cfu/100 mL data were transformed to log₁₀ and tests for correlation were performed using the Spearman's test. WaSH education survey results were compared in 2×2 contingency tables of responses from pre- and post-education intervention. Chi-square tests with one degree of freedom and Yate's correction were used to compare the final proportions of the two WaSH education groups post-intervention. All results were considered statistically significant at the significance level of $p \leq 0.05$.

Ethical approval

Free and informed consent of the participants or their legal representatives was obtained and the study protocol was approved by the appropriate Committee for the Protection of Human Participants, being the Tanzanian National Institute for Medical Research, and by the Ministry of Health, Community Development, Gender, Elderly and Children, Dar es Salaam, Tanzania, NIMR/HQ/R.8a/Vol.IX/2082, 4 December 2015.

RESULTS

Test production

Reagents were sourced from suppliers in Dar es Salaam and order times for imported reagents were less than two months. The reagent cost per H₂S test pair was only US\$ 0.41 per 100 mL test (Table S2, available online). The two glass bottles of volumes of 5 mL and 100 mL, cost per bottle US\$ 0.83 and US\$ 4.50, respectively. For experimentation with the H₂S tests in the laboratory and some community demonstrations, glass reusable bottles proved an affordable and sustainable option.

The larger reported volumes of H₂S media (Manja *et al.* 1982), without impregnation on an absorbent strip, were selected: 5 mL into 100 mL bottle and 250 μ L into 5 mL (Figure 1(a)). The larger volume, 5 mL of media compared to 2.5 mL, produced a more distinct black colour when positive.

Test validation in the laboratory

Efficacy studies in the laboratory determined the limit of detection for spiked *S. enterica* to be 5 bacteria/100 mL for 100 mL bottles and 20 bacteria/100 mL for 5 mL bottles. The optimal incubation time at ambient temperature was 24 h, for distinct colour change (Figure 1 and Figure S1).

From the laboratory *S. enterica* spiking results in three risk categories were developed: low, medium and high (Figure 2 and Table S3). If both tests (100 mL and 5 mL) were negative, the limit of detection values estimate that less than 20 H₂S producing bacteria were present per 100 mL of water sample



Figure 1 | H₂S water quality testing: (a) water sample being added to 100 mL and 5 mL bottles containing H₂S media; (b) after 24 h at ambient temperatures (22–30 °C) positive samples turned black (bottle on the right) while negative samples had no colour change and remained straw coloured (bottle on the left); (c) H₂S demonstration in the field with a community member correctly identifying the positive sample (far right).

(Table S4). This was determined as low risk. When the 100 mL test was positive and the 5 mL test negative then there is an estimated range of greater than 20 bacteria but less than 100

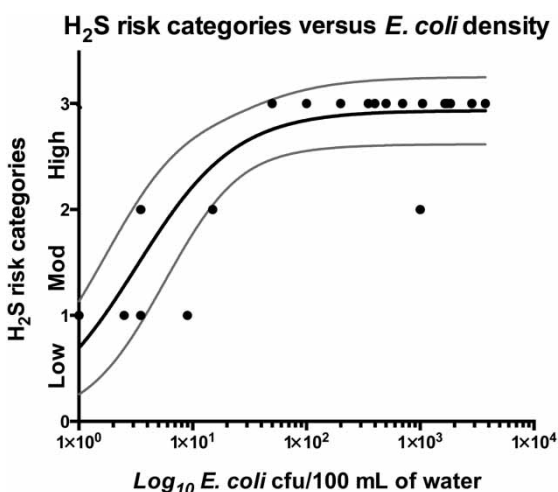


Figure 2 | H₂S score versus log₁₀ *E. coli* density in water samples. Low, medium and high risk scores compared to log₁₀ *E. coli* cfu/100 mL. Data from 20 water sources with non-linear regression (solid line) and 95% confidence intervals (dashed lines).

bacteria/100 mL, thus medium risk category. A high risk category was estimated when both bottles were positive, with an estimated density of greater than 100 bacteria/100 mL. (Tables S3 and S4 are available online.)

Across 47 different water samples the H₂S test results aligned well between the risk categories and if the water source was improved or unimproved (Tables S5 and S6, available online). No H₂S tests changed colour within the first hour, indicating that hydrogen sulphide was not already present in the ground water samples. All except one of the 24 improved water sources were determined to be low risk, with no H₂S producing bacteria detected. The majority of unimproved water sources (17 out of 19), had high risk category results.

H₂S risk categories were correlated to the *E. coli* densities to determine if the categories were adequate in detecting contamination. Test for correlation (Spearman's $\rho = 0.89$) described a significant relationship ($p < 0.0001$) between the H₂S risk categories and log₁₀ *E. coli* densities. Non-linear regression described the relationship with log₁₀ *E. coli* with a hyperbolic function but goodness of fit was low ($R^2 = 0.51$). The low risk category detected *E. coli* densities from 0 to 9 cfu/100 mL, which would be considered low risk by WHO standards. The high risk category also consistently detected concentrations of *E. coli* that would be considered a risk, 50 to 7.2×10^5 cfu/100 mL. However, the moderate risk category was more variable detecting between 3.5 and 1.0×10^5 cfu/100 mL.

Overall, the H₂S test accurately described the risk for the water sources, both with respect to the type of water source (improved and unimproved) and the corresponding *E. coli* densities.

Test validation in the community

In total, 16 households successfully completed the H₂S training and conducted the tests independently. There was an even gender representation. All participants had a positive H₂S sample for at least one of their chosen water sources, as the majority (11 households) primary sources were unimproved, unprotected dug wells. All the bottled water controls were negative, indicating that there was no contamination introduced due to incorrect technique during testing. Community members were easily able to identify the positive black colour change for the H₂S tests (Figure 1(c)) from water

sources that were faecally contaminated, such as shallow open wells. The risk recommendations were translated into kiSwahili and clearly understood and interpreted by community members. All households indicated that the results changed their opinion about their water quality and that they would be willing to purchase the H₂S test in the future.

Development and marketing of H₂S tests

The H₂S test kit was produced for US\$ 1.10 (Table S7, available online). The retail sale price was set at US\$ 1.37 (TZS 3,000) and the wholesale price at US\$ 1.25 (TZS 2,500). This was consistent with the price bracket indicated in the initial community trial.

An eight-page instruction booklet was produced in both English and kiSwahili. The booklet covered the risk of contaminated water, how to use the H₂S test (Figure 3), how to conduct a sanitary survey and how to treat water in the household.

Out of the 713 tests distributed for sale, the majority (300 tests) were sold by other NGOs in Tanzania (Table S8, available online). The sales by local pharmacies were less than had been expected. This was potentially due to the fact that the tests are a new product. This result highlights that more marketing and support to the points of sale was needed.

In total, 31 customers (22 male and nine female) were contacted and surveyed after purchasing and using the test themselves. The majority (22 people) bought the test out of curiosity and the remainder out of concern for their water quality (nine people). Nearly all (30 people) reported that the test results had motivated them to start using household water treatment. Further, all customers surveyed reported that they successfully conducted the test independently and all but one said they would purchase the test again in the future.

Inclusion of H₂S tests in a WaSH education programme

The use of H₂S tests was evaluated through 165 meetings with 3,408 participants (Table S4). In the education meetings that demonstrated the H₂S test, the majority of participants (77%) returned the next day to view the test results (Table S9). The majority of water sources tested were dug-wells (48%). Most of the H₂S test water quality results were in the high to very high range (62%), indicating the overall poor water quality present (Table S10). (Tables S9 and S10 are available online.)

To determine the impact of the H₂S inclusion in the education programme, a follow-up survey was asked of 175 participants in the H₂S education programme and 119 in

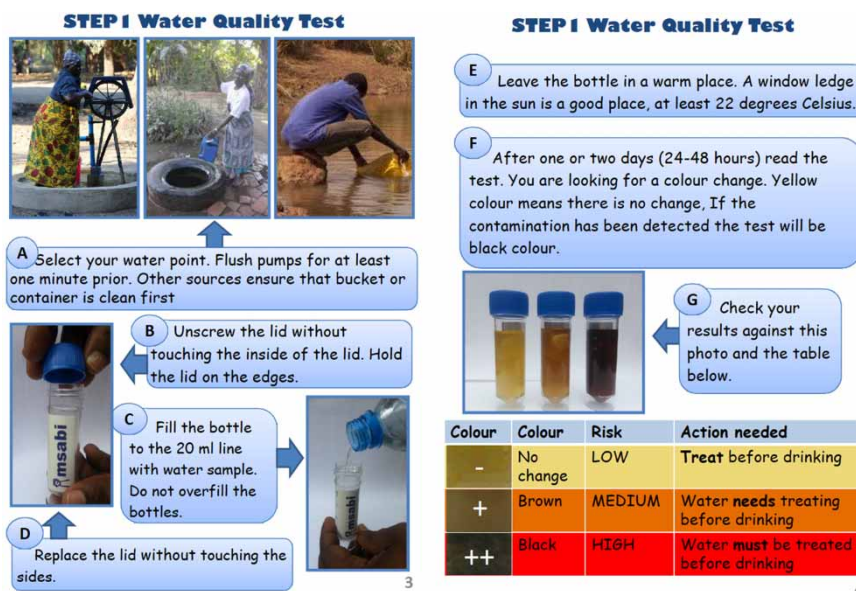


Figure 3 | A two-page excerpt from the instruction booklet for the H₂S test kit detailing how to conduct the water quality test. The final risk level is based on the degree of colour change from yellow to black. The booklet that was included in the H₂S test kit for sale was produced in the local language, kiSwahili.

the standard education programme (Table 1). Overall, the participant responses were very similar between the education groups. The only variation to this was the response to if they had improved their latrine since the education, where improvement was generally increasing cleanliness or adding a cover over the drop hole. For the H₂S group, only 48 of the participants (29%) had improved compared to 41 participants (43%) for the standard education, however this difference was not significant ($p = 0.06$). Both WaSH education programmes increased the number of participants who reported that their water was not safe to drink. For the H₂S group the percentage was comparable (33 people, 20.1%) to the standard group (14 people, 15.4%), with no significant difference ($p = 0.87$). Consequently, there was an increase in the proportion of participants who reported treating their drinking water prior to drinking. The increase was comparable between groups, with the H₂S test group increasing by 24.4% (40 people) and the standard group by 24.5% (23 people). For the remainder of the questions there were minimal differences between the groups. The loss to follow-up of 31 participants (26%) in the standard education group reduced the ability to detect some of the changes between groups.

In the pre-survey, all of the H₂S education group (175 respondents), reported that they would like to have their water tested to gauge its safety. When asked how much they would pay for a water quality test, the majority 58% selected the lower price of US\$ 0.45, with the remainder willing to pay US\$ 1.37 or greater for the test. In the post-education survey, nearly all (94%, 154 respondents) reported that they would buy the H₂S test in the future.

DISCUSSION

Validation in the laboratory and community

The H₂S was successfully produced for the first time in rural Tanzania in a simple laboratory setting using easily sourced imported and local materials. The H₂S tests' reagents costs were only US\$ 0.41 per test, cheaper than commercially available H₂S tests: US\$ 0.60 for PathoScreen™, (Hach, USA) and US\$ 0.80 for Rapid HiColiform™ (HiLab Media, India) (Bain et al. 2012). An additional advantage of making the tests locally was the flexibility to make different volumes and re-use the glass bottles or use disposable plastic

Table 1 | Results from the evaluation survey of the two WaSH education programs (with and without H₂S tests)

Questions	A	WaSH education (+H ₂ S test)					WaSH education (standard)					χ^2 test ^b (p) ^c
		Pre		Post		Δ^a Y/N %	Pre		Post		Δ^a Y/N %	
		n = 175	%	n = 164	%		n = 119	%	n = 88	%		
Q1. Hand washing after toilet use?	Y	166	95	164	100		103	87	87	99		1.0 (0.31)
	N	9	5	0	0		16	13	1	1		
Q2. Hand washing before cooking?	Y	159	90	162	98	1.2	95	80	86	98		0.0 (1.0)
	N	17	10	3	2		24	20	2	2		
Q3. Hand washing with soap?	Y	158	90	164	99	3.6	96	82	85	98		0.34 (0.56)
	N	18	10	1	1		21	18	2	2		
Q4. Water safe to drink?	Y	87	49	42	26		65	55	23	25		0.03 (0.87)
	N	89	51	122	74	20.1	54	45	68	75	15.4	
Q5. Drinking water treatment?	Y	39	22	79	48	24.4	24	20	47	50	24.5	0.02 (0.89)
	N	137	78	85	52		94	80	47	50		
Q6. Improved drinking water source?	Y			19	12				7	8		0.5 (0.47)
	N			144	88				82	92		
Q7. Improved latrine?	Y			48	29				41	43		3.66 (0.06)
	N			117	71				55	57		

The pre-survey was conducted before WaSH education and post-survey was conducted after the WaSH education.

^aThe change between pre- and post-responses, recorded as a percentage increase in Yes or No. If there was no recorded increase in either then no value was entered.

^bThe Chi-squared (χ^2) test (with 1 degree of freedom) compares the post-survey response percentages between both WaSH education groups.

^cThe probability (p) is recorded with significance set at $p \leq 0.05$.

bottles. Restrictions for other organisations to make the tests are the requirement for some basic equipment and knowledge of sterile handling; although successful production of the tests using a simple cooking oven (for sterilisation of strips at 55 °C until dry) has been well described (Mosley & Sharp 2005).

The H₂S effectively detected FIB in a range of improved and unimproved drinking water samples in Kilombero Valley. The comparison tests between *E. coli* and TC tests and locally produced H₂S provide confidence of the risk levels assigned; where a positive H₂S test was determined to be high level risk and correlated with >100 cfu *E. coli*/100 mL of sample (Figure 2). This agrees with studies in SSA, where large numbers of water quality FIB monitoring results were analysed from different tests and the highest risk category was determined to also be >100 FIB/100 mL (Kumpel *et al.* 2016). Based on molecular microbiology research, it has been demonstrated that H₂S producing organisms are a more effective indicator of faecal contamination than *E. coli* (McMahan *et al.* 2012). For that reason, there is little merit in identifying false positives or false negatives between the two different types of tests in this work. Despite this premise, a review of 51 individual H₂S studies only found a small number of studies reported low average (<50%) sensitivity ($n = 1$) and specificity ($n = 4$) (Wright *et al.* 2012). Low sensitivity was associated with smaller H₂S test volumes (<20 mL), shorter incubation times (≤ 24 h) and higher incubation temperatures (>35 °C) (Wright *et al.* 2012). When compared to commercial H₂S tests, laboratory H₂S tests have been reported to produce more false positive but less false negatives (Murcott *et al.* 2015). In the same study, laboratory-made H₂S tests were recommended to detect unsafe water in India (Murcott *et al.* 2015). Similarly, the H₂S test was determined to be a suitable test to indicate faecal contamination of drinking water in rural Tanzania.

Production and marketing of the H₂S tests

MSABI produced the H₂S test kit as a first time offering in East Africa. The test kit was produced for a low cost US\$ 1.10 and sold for US\$ 1.37. This is higher than commercial H₂S tests (PathoScreen™, US\$ 0.80) but lower than the cheapest presence/absence *E. coli* tests (Colilert® 10 mL, US\$ 1.50 plus US\$ 100 in specialist equipment) (Bain

et al. 2012). Further, the H₂S test kit was specifically designed for the local context, and included an instruction and educational WaSH information booklet in the local language (kiSwahili). If production of the local H₂S kit were expanded to a larger scale, the unit cost would reduce further. Research in SSA indicates that for water quality monitoring to be cost-effective, then the cost per person using that water point should be <US\$ 0.05 per person (Peletz *et al.* 2016). The estimated number of users for water sources in the Kilombero Valley is around 20 families (unpublished data), and the average family size in Tanzania is 4.8 (Tanzania National Bureau of Statistics 2015). Therefore, the costs of the MSABI H₂S test per person using the water point equates to US\$ 0.014; well below the recommended cost-effective threshold. Hence, the test is assessed as being at the right price point for extended use in the region.

The user acceptance of the H₂S tests and users' ability to conduct the test independently was confirmed across all the communities in which they were used in the Kilombero Valley. The black colour change of the positive tests was a powerful visual indicator for community members that the water was 'machafu' (kiSwahili for dirty) and required treatment. An additional benefit of the H₂S test was that community members had a sense of ownership; they were able to complete the testing themselves after a short demonstration. Additionally, community members were able to keep the tests in their home and incubate them for 24 h. This gave confidence to the household that the results were genuine and not a result of any trick or addition to the sample overnight. Empowerment is known to be an important motivator in WaSH behaviour change education (Goodman *et al.* 2016).

The majority of users who bought the test said that they would buy it again, as well as those who saw the test demonstrated in the WaSH education programme. The price of the test at US\$ 1.37 was reported as affordable for 42% of education survey respondents. More market testing is needed on the price of the test, as reported willingness to pay would need to be tested further as it does not equate to willingness to accept (Venkatachalam 2004). In this case, people's willingness to actually hand over money for the H₂S test would need to be tested along with any perception changes if it were freely available. Additionally, if there was an understanding that the test would only need to be less

than once per month then people may be willing to pay more for it.

The distribution and sales of H₂S tests relied heavily on the motivation of the distributor. It was found that some pharmacies did not have the knowledge or interest in selling the tests. It is recommended for future distribution that pharmacy selection for distribution should be based on the interested and trial sales numbers. Further, well-planned and wide-reaching education and marketing strategies are needed to increase sales. Further research avenues include working with other WaSH non-government organisations in Tanzania to promote the tests.

Inclusion of H₂S tests in a WaSH education programme

In the WaSH education programmes, the addition of the H₂S test demonstration did not have any significant measurable impact on reported behaviour change. This could be because the water quality message was a central WaSH message conveyed in the education programme and that the addition of the H₂S test did not change or add to that message. Although there was no measurable difference, educators reported that using the test enhanced audience engagement and interest. Hence, the test may not be a key trigger but still a useful addition to aid in the teaching process and for the educator to gain recognition as a technically skilled person. The demonstration of the test was successful in raising awareness and demand for the H₂S test, with 94% of people indicating that they would buy the test in the future.

Overall, both WaSH education programmes resulted in an increase of 24% in the reported use of household level water treatment. Reporting and knowledge of a WaSH practice can be significantly different to actually conducting that practice on a day to day basis (Rabbi & Dey 2013). Hence, further observations of household practices would be needed to determine the actual changes in daily practices.

H₂S tests are presently not recommended by the WHO in the Guidelines for Drinking Water testing (2011) or by any international standard (Bain *et al.* 2014), despite a growing number of organisations using the tests. To increase access to affordable water quality testing in rural and poor areas the H₂S test should be advocated as a water quality test. Following the Government of India's model, after positive H₂S

results further testing with quantifiable FIB tests should be sought. To encourage regular water quality monitoring, distribution of tests should be led by the local government (Crocker & Bartram 2014). This would be consistent with the current Tanzanian Water Sector Development Programme (2005–2025), that gives responsibility of water point management to local community organisations.

CONCLUSIONS

The H₂S test has proven to be an affordable, locally producible water quality test in rural Tanzania. Further, it is an empowering tool in WaSH education programmes. The H₂S test should be advocated for inclusion in international guidelines as a preliminary water quality test at household level and in community WaSH education programmes. Tools such as this are critical so that communities can be informed of their water quality and takes steps to improve household WaSH practices, which will ultimately reduce illness and protect environmental water sources.

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REFERENCES

- Bain, R., Bartram, J., Elliott, M., Matthews, R., McMahan, L., Tung, R., Chuang, P. & Gundry, S. 2012 *A summary catalogue of microbial drinking water tests for low and medium*

- resource settings. *International Journal of Environmental Research and Public Health* **9** (5), 1609–1625.
- Bain, R., Cronk, R., Wright, J., Yang, H., Slaymaker, T. & Bartram, J. 2014 Fecal contamination of drinking-water in low- and middle-income countries: a systematic review and meta-analysis. *PLoS Med.* **11** (5), e1001644.
- Crocker, J. & Bartram, J. 2014 Comparison and cost analysis of drinking water quality monitoring requirements versus practice in seven developing countries. *International Journal of Environmental Research and Public Health* **11** (7), 7333–7346.
- Davis, J., Pickering, A., Rogers, K., Mamuya, S. & Boehm, A. 2011 The effects of informational interventions on household water management, hygiene behaviors, stored drinking water quality, and hand contamination in peri-urban Tanzania. *The American Journal of Tropical Medicine and Hygiene* **84** (2), 184–191.
- Gebreyes, W. A. & Altier, C. 2002 Molecular characterization of multidrug-resistant *Salmonella enterica* subsp. *enterica* Serovar Typhimurium isolates from swine. *Journal of Clinical Microbiology* **40** (8), 2813–2822.
- Genthe, B. & Jagals, P. 2003 *Application of an H₂S Strip as A Field Test Kit for Microbial Water Quality Assessment*. Water Research Commission, Pretoria, South Africa.
- Goodman, M., Elliott, A., Gitari, S., Keiser, P. H. & Raimor-Goodman, L. A. 2016 Improved water and household water purification practices among orphans and vulnerable children in a multi-sectoral empowerment program in Eastern province, Kenya. *Journal of Water and Health* **14** (3), 513–527.
- Hamoudi, A., Jeuland, M., Lombardo, S., Patil, S., Pattanayak, S. K. & Rai, S. 2012 The effect of water quality testing on household behavior: evidence from an experiment in rural India. *The American Journal of Tropical Medicine and Hygiene* **87** (1), 18–22.
- Jalan, J. & Somanathan, E. 2008 The importance of being informed: experimental evidence on demand for environmental quality. *Journal of Development Economics* **87** (1), 14–28.
- Khush, R. S., Arnold, B. F., Srikanth, P., Sudharsanam, S., Ramaswamy, P., Durairaj, N., London, A. G., Ramaprabha, P., Rajkumar, P., Balakrishnan, K. & Colford, J. M. 2013 H₂S as an indicator of water supply vulnerability and health risk in low-resource settings: a prospective cohort study. *The American Journal of Tropical Medicine and Hygiene* **89** (2), 251–259.
- Kumpel, E., Peletz, R., Bonham, M. & Khush, R. 2016 Assessing drinking water quality and water safety management in sub-Saharan Africa using regulated monitoring data. *Environmental Science & Technology* **50** (20), 10869–10876.
- Manja, K. S., Maurya, M. S. & Rao, K. M. 1982 A simple field test for the detection of fecal pollution in drinking water. *Bulletin of the World Health Organization* **60**, 797–801.
- McMahan, L., Grunden, A. M., Devine, A. A. & Sobsey, M. D. 2012 Evaluation of a quantitative H₂S MPN test for fecal microbes analysis of water using biochemical and molecular identification. *Water Research* **46** (6), 1693–1704.
- Mosley, L. & Sharp, D. 2005 *The Hydrogen Sulphide (H₂S) Paper-Strip Test*. South Pacific Applied Geoscience Commission (SOPAC), Suva, Fiji.
- Murcott, S., Keegan, M., Hanson, A., Jain, A., Knutson, J., Liu, S., Tanphanich, J. & Wong, T. K. 2015 Evaluation of microbial water quality tests for humanitarian emergency and development settings. *Procedia Engineering* **107**, 237–246.
- Peletz, R., Kumpel, E., Bonham, M., Rahman, Z. & Khush, R. 2016 To what extent is drinking water tested in sub-Saharan Africa? A comparative analysis of regulated water quality monitoring. *International Journal of Environmental Research and Public Health* **13** (3), 14.
- Prüss-Ustün, A., Bartram, J., Clasen, T., Colford, J. M., Cumming, O., Curtis, V., Bonjour, S., Dangour, A. D., De France, J., Fewtrell, L., Freeman, M. C., Gordon, B., Hunter, P. R., Johnston, R. B., Mathers, C., Mäusezahl, D., Medlicott, K., Neira, M., Stocks, M., Wolf, J. & Cairncross, S. 2014 Burden of disease from inadequate water, sanitation and hygiene in low- and middle-income settings: a retrospective analysis of data from 145 countries. *Tropical Medicine & International Health* **19** (8), 894–905.
- Rabbi, S. E. & Dey, N. C. 2013 Exploring the gap between hand washing knowledge and practices in Bangladesh: a cross-sectional comparative study. *BMC Public Health* **13**, 7.
- Roser, D. J., Ashbolt, N., Ho, G., Mathew, K., Nair, J., Ryken-Rapp, D. & Toze, S. 2005 Hydrogen sulphide production tests and the detection of groundwater faecal contamination by septic seepage. *Water Science & Technology* **51** (10), 291–300.
- Sobsey, M. D. & Pfaender, K. 2002 *Evaluation of the H₂S Method for Detection of Fecal Contamination of Drinking Water*. World Health Organization, Geneva, Switzerland.
- Tambe, P., Daswani, P., Mistry, N., Ghadge, A. & Antia, N. 2008 A community based bacteriological study of quality of drinking water and its feedback to a rural community in Western Maharashtra, India. *Journal of Health, Population and Nutrition* **26** (2), 139–150.
- Tanzania National Bureau of Statistics 2015 *Tanzania in Figures*. Ministry of Finance, Dar es Salaam, Tanzania.
- UNICEF & WHO 2015 *Progress on Sanitation and Drinking Water – 2015 Update and MDG Assessment*. J. M. Program, Geneva, Switzerland.
- Venkatachalam, L. 2004 The contingent valuation method: a review. *Environmental Impact Assessment Review* **24** (1), 89–124.
- Wright, J. A., Yang, H., Walker, K., Pedley, S., Elliott, J. & Gundry, S. W. 2012 The H₂S test versus standard indicator bacteria tests for faecal contamination of water: systematic review and meta-analysis. *Tropical Medicine & International Health* **17** (1), 94–105.

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