An assessment of microbiological water quality of six water source categories in north-east Uganda

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ABSTRACT

Target 7C of the Millennium Development Goals is to "halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation". However, the corresponding indicator measures the "proportion of population using an improved drinking water source". This raises the question of whether "safe" and "improved" can be used interchangeably. This paper tests this hypothesis by comparing microbiological water quality in 346 different water sources across the District of Amuria in Uganda to each other and to defined standards, including the WHO drinking water standard of zero TTC per 100 ml, and the Ugandan national standard of 50 TTC per 100 ml. The water sources were grouped into six different categories: boreholes, protected springs, covered hand dug wells, open hand dug wells, open water and roofwater harvesting. The paper concludes that the ranking from the highest to the lowest microbiological quality water was: boreholes, protected springs and roofwater harvesting, open and covered hand dug wells, open water. It also concludes that sanitary surveys cannot be used to predict water quality precisely; however they are an essential component of the monitoring of safe water supplies.

Key words | faecal contamination, groundwater, microbiology, roofwater harvesting, sanitary survey, water quality

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INTRODUCTION

Target 7C of the Millennium Development Goals is to "halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation". However, the indicator for monitoring the proportion of people with sustainable access to safe water is indicator 7.8 which measures the "proportion of population using an improved drinking water source" (UN 2008). This paper explores the extent to which a range of improved and unimproved sources are indeed safe.

The WHO and UNICEF Joint Monitoring Programme (JMP) (2008) defines "improved" water sources as piped water, public taps, standpipes, tubewells, boreholes, protected dug wells, protected springs and rainwater collection. However, there are a number of unclear questions such as "can protected hand dug wells provide the same microbiological quality water as boreholes which are generally deeper", and "does roofwater harvesting provide a good alternative where groundwater is not available?"

Previous studies have examined correlations between microbiological water quality and aspects of up to three differing source types (this study compares six different source types). Lloyd & Helmer (1991) reviewed the factors thought to influence the potential for faecal contamination of groundwater sources and found that they fall into two basic categories: (i) the location of the source, with poor locations being close to where surface water can enter the aquifer (e.g. a sink hole), or there is a high concentration of microbes (e.g. a concentration of livestock), and (ii) poor

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construction of groundwater installations, which can fail to block contamination pathways.

The extent to which improving traditional wells and springs increases water quality is debatable, with only some authors claiming that contamination is reduced (e.g. Howard *et al.* 2001, 2003; Sutton 2002). Other authors claim there is no difference at all (e.g. Godfrey *et al.* 2006). For large diameter wells, the main problem is that despite often being covered at the top with a handpump installed, there may be no well lining or sanitary seal, offering pathways for contamination (Lloyd & Bartram 1991; Lloyd & Helmer 1991; Gelinas *et al.* 1996). However, it should be noted that such requisite improvements in source management are often synchronous with improvements in infrastructure (Sutton 2002).

Some authors have measured microbiological water quality for two or three different types of ground water sources and compared results between them, but have not compared ground water to roofwater harvesting (for example Lavoie & Viens 1983; Lloyd & Bartram 1991; Lloyd & Helmer 1991; Sutton 1994; Magrath 2006).

The extent to which improved water sources continue to provide protection from contamination in the long term will have a bearing on water safety. Sanitary surveys provide a set of questions that can be used to assess the quality of construction and maintenance of a water supply (Lloyd & Helmer 1991). Each "yes" answer corresponds to an aspect of poor construction or maintenance. Some authors (for example, Howard *et al.* 2003; Godfrey *et al.* 2006) have used statistical methods to link specific questions in sanitary surveys to water quality, although they each concentrated on only one source type (protected springs and covered hand dug wells, respectively).

This paper aims to assess the safety of improved water sources in terms of microbiological water quality by comparing the water quality of six different source types, four of which are improved according to the JMP (2008) definition (boreholes, protected springs, roofwater harvesting and covered hand dug wells) and two of which are unimproved (open hand dug wells and open water). As poor construction or maintenance of the source improvements can also lead to unsafe water, the paper also investigates whether sanitary surveys are a useful measure of improvement.

METHODS

Field area

The study location was primarily Amuria District in NE Uganda, although some sites were visited in the neighbouring districts of Katakwi and Soroti. The study area is flat with wide, shallow valleys that consist predominantly of swampland. Land use is either arable or pastoral with the majority of the population involved in subsistence agriculture. The area is underlain by a crystalline bedrock with a deep overlying weathered layer ranging from 10 to 25 m in thickness (DWD 2003). Safe water coverage is estimated as 55% by the District Water Office (personal communication 2008).

Water quality indicators

Thermotolerant coliforms (TTC) are widely used as faecal indicator organisms. Although some TTC are capable of survival in decaying plant material and soils, studies in shallow groundwater in Uganda found that 99% of the TTC detected were in fact *E. coli* (Howard *et al.* 2003). TTC were therefore the preferred faecal indicator organism in this study as they can be measured easily in the field using a DelAgua kit (University of Surrey 2004), and no further confirmatory tests were practical in the absence of a fully equipped microbiology laboratory.

WHO (2006) guidelines for safe water state that TTC should not be present in a 100 ml sample; however, they acknowledge that this target may not be realistic in low-income countries and encourage medium-term targets to be set, so, for example in Uganda, the Ministry of Water and Environment (2006) has adopted a maximum level of 50 TTC/100 ml for untreated water. This is higher than other developing countries; for example Swaziland has a level of 10/100 ml (Busari 1999) and South Africa has 0/100 ml (Department of Water Affairs and Forestry 1996).

Turbidity was selected as an additional indicator of water quality because it is quick and cheap to measure. Its use as a proxy for TTC measurements is examined in this paper.

Description of different water sources

The following descriptions outline the source classifications in Amuria District.

Boreholes

These are small diameter (less than 300 mm), machine drilled wells and typically 30–90 m deep. These sources are all cased, screened and equipped with a sanitary seal and drainage aprons. The majority use the India Mark II hand pump.

Protected springs

These are natural springs that are protected with some or all of the following: concrete spring boxes, head walls, drainage channels, fences and cut-off ditches. They are generally located along the borders of the swamps.

Roofwater harvesting

This includes both formal (i.e. with guttering, downpipe, covered storage and tap) and informal (i.e. open container under roof or gutter) systems for the collection of rainwater. All samples were from metal roofs, but these included houses, latrines, schools and other institutions. Collection vessels are plastic, concrete or metal. These sources tend to be located along or close to main roads and in clusters at commercial centres where buildings tend to be larger and a greater proportion have metal roofs.

Covered hand dug wells

These are hand dug wells (4–5 m deep, 1.5 m in diameter) capped with an apron and a Nira pump. Beneath the apron the well is lined with brick masonry and back filled, although the back fill is not necessarily impermeable. These features offer more protection than open hand dug wells. The wells are typically 100–150 m from swampland.

Open hand dug wells

These are hand dug wells of circular or rectangular section, typically at least 2 m deep (maximum 30 m deep). They are unlined, uncapped and without pumps. Only a small proportion (seven out of 24 sampled in this survey) have aprons. They are typically built within household compounds. Some wells have part of the shaft sealed with brickwork, and some have a headwall.

Open water

These sources are open to the environment and include rivers, lakes, swamps, unprotected springs and shallow (less than 2 m) scoop holes and pits. Sometimes they are fenced.

Data collection

Data collection was undertaken between May and July 2008, visiting as many villages as possible in the time available (346 in total–Table 1).

In each village, the LC1 (Local Councillor 1) provided directions to water sources. Thus most water sources in each village were sampled, although some were overlooked, either due to the lack of knowledge by the LC1, or communication issues. In particular, it is possible that some unimproved or household sources were missed. At each location, three types of data were collected.

Firstly, turbidity was measured in-situ using a turbidity tube (University of Surrey 2004).

Secondly, a sample was collected in a pre-sterilised 60 ml HDPE bottle for testing later for TTC. The collection method was the same as used to extract water by users:

- For pumped sources, water was taken directly from the pump head.
- For open hand dug wells samples were taken by pouring water into the bottle from the bucket used to extract water.
- For roofwater harvesting systems, samples were taken from the tap if available or otherwise from the pouring jug usually used.
- For protected springs, samples were taken from the same tap or open pipe as the users.
- For open sources, samples were taken by submersion, wading to the relevant position if necessary, or if it was a very shallow scoop hole then the same mug as the user was used to scoop the water If the source was flowing at all then the opening of the bottle would clearly be positioned upstream.

Taps and containers utilised by the water users were not flamed or disinfected in any way, so the sample would be an

Table 1 | Details of the sources visited. Boreholes, protected springs, roofwater harvesting and covered hand dug wells are defined as improved by the WHO and UNICEF Joint Monitoring Programme (2008), open hand dug wells and open water are thus unimproved

Source category	Number of sources visited	Percentage with TTC = 0	Percentage with TTC ≤ 50	Median TTC count	Median turbidity (NTU)
Boreholes	71	69	89	0	5
Protected springs	49	14	61	18	5
Roofwater harvesting	49	33	63	12	5
Covered hand dug wells	70	17	26	235	10
Open hand dug wells	24	0	4	1,070	17
Open water	83	6	6	1,200	75

accurate reflection of the water drunk by the user. The samples were not analysed on site, but returned to the field laboratory for analysis. They were transported in cool, dark conditions and processed within six hours. The field laboratory was located in a house in the middle of the study area. Electricity was supplied by generator, water was from a nearby borehole or roofwater storage tank and heat (for sterilising equipment by boiling) was provided by a charcoal stove.

The chosen method for measuring TTC in the field laboratory was to use the Oxfam DelAgua kit. The measurement procedure is described by the University of Surrey (2004). The DelAgua kits use the membrane filtration method (Environment Agency 2009).

The incubation unit was calibrated for temperature control (44 ± 0.5°C) at the start of the research in line with ISO 9308 (ISO 1998). Sterilisation of non-disposable items in between uses was done by boiling as methanol was unavailable in the field.

If there was uncertainty as to the likely level of TTC in the water sample, two different volumes were filtered and incubated (e.g. 50 ml and 10 ml, or 10 ml and 1 ml). If two valid counts resulted (i.e. both Petri dishes were readable, and neither exceeded 100 counts (the number at which counting inaccuracies are likely to be introduced)), the count from the larger volume sample was used. If two equal volumes were taken the mean was used.

Thirdly, a sanitary survey was performed. The questions used were taken from Lloyd & Helmer (1991), the most widely used set (e.g. Sutton 2002; Howard *et al.* 2003; Godfrey *et al.* 2006; Magrath 2006). No recognised set of survey questions for open water sources exists.

Statistical analysis techniques

The indicator data (TTC and turbidity) collected in this study are not normally distributed, (for example, it is expected for certain source types that there will be a large number of zero values and the distribution will have a long tail). Hence parametric tests (e.g. Student's *t*-test) cannot be used to compare samples, so non-parametric tests have to be used, which work with ranks rather than absolute numbers. The tests used were the Kolmogorov–Smirnov two sample test, the Kruskal–Wallis test and Spearman's rank correlation coefficient, performed using Matlab's statistics toolbox.

RESULTS AND ANALYSIS

Comparison between sources

The percentage of sources with TTC count of zero per 100 ml (the WHO (2006) limit) and less than 50 per 100 ml (the limit set by the Ugandan Ministry of Water and Environment (2006)) and the median values for TTC and turbidity are shown in Table 1. The distribution of the TTC count and turbidity are shown in Figures 1 and 2 respectively. Figure 1 shows that whilst 89% of boreholes met Ugandan national standards, only about 60% of protected springs and roofwater harvesting sources met these standards and only 26% of covered hand dug wells met the standards, despite all four sources being defined as safe according to the WHO and UNICEF Joint Monitoring Programme (2008). Table 1 shows a similar trend in the sources meeting WHO standards, with boreholes again having the highest percentage that meet the standard.

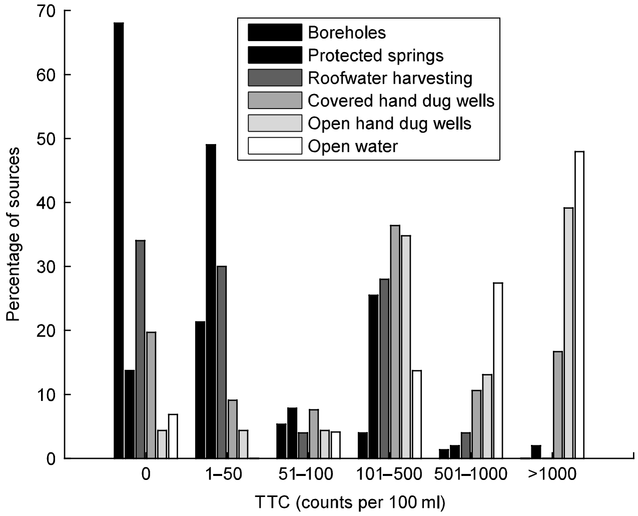

Figure 1 | Histogram to show distribution of TTC measurements with different source types.

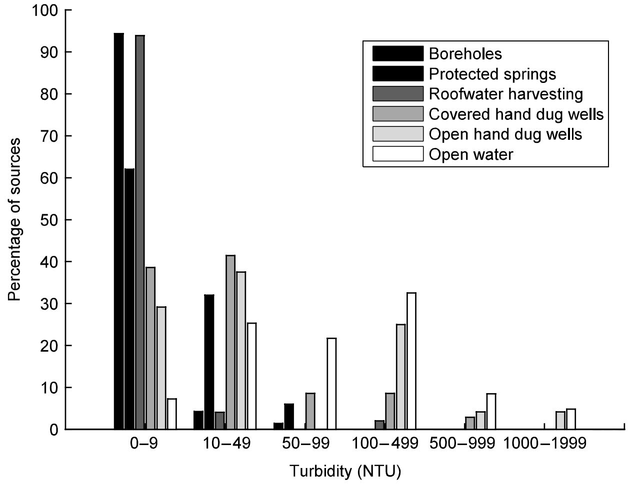

Figure 2 | Histogram to show distribution of turbidity measurements with different source types.

The Kruskal-Wallis test was used to compare the different water source types according to the two different indicators measured: TTC and turbidity. The results are shown in Figures 3 and 4 for TTC and turbidity respectively - both indicators gave similar results. Whilst it is possible to rank the sources by median TTC count per 100 ml (shown in brackets below) where there is overlap in the bars between two source types (in Figure 3 or 4) it is incorrect to conclude that one of the source types is significantly better or worse than the other. However:

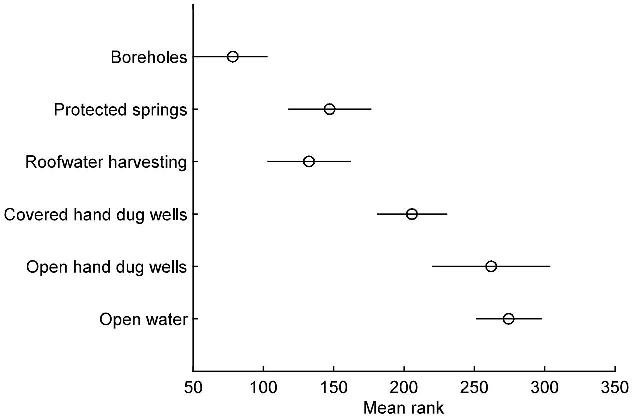

Figure 3 | Kruskal–Wallis comparison of the different water source types according to TTC.

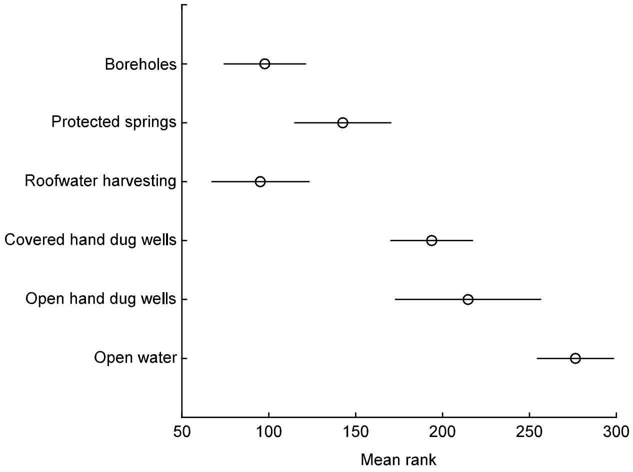

Figure 4 | Kruskal–Wallis comparison of the different water source types according to turbidity.

- Boreholes (0) are significantly better than protected springs (18), covered hand dug wells (235), open hand dug wells (1,070) and open water (1,200).
- Both protected springs (18) and rain water harvesting (12) are better than covered hand dug wells (235), open hand dug wells (1,070) and open water (1,200).
- Covered hand dug wells (235) are better than open water (1,200).

The only difference for the turbidity indicator was that boreholes were not significantly better than protected springs.

Comparison between sanitary survey questions

The Kolmogorov–Smirnov test was used to find out if any one sanitary survey question is always associated with poor water quality. For each question, TTC and turbidity values were divided into two sets according to whether the question was answered "yes" or "no". These sets or sub-samples were then tested against each other to see whether they were from the same distribution. This was initially performed on a source-by-source basis. For TTC, the only two questions to which a "yes" answer gave significantly poorer water quality were:

- in open hand dug wells i. "Are there cracks in the concrete apron, or is the apron absent?";
- in protected springs h. "Is the outlet dirty?".

Using turbidity as an indicator gave no significant questions to which a "yes" answer gave significantly poorer water quality.

Some questions had no "yes" answers, so the test could not be applied. This included (for boreholes, open hand dug wells, protected springs and covered hand dug wells) questions (a) "Is there a latrine within 10 m of the well" and (b) "Is the nearest latrine uphill of the well".

One of the problems with this analysis was that for many of the questions, there were very few "yes" answers, meaning that sample sizes were small. This makes it impossible to achieve a statistically significant result. For all the groundwater sources (boreholes, open hand dug wells, protected springs and covered hand dug wells) some of the questions were similar, so it was possible to group the data and reanalyse them. For both TTC and turbidity the significant questions were:

- "Is the apron less than 1 m radius around the top of the well?"
- "Are there cracks in the concrete apron?"

For TTC an additional significant question was:

- "Is there an adequate fence around the well?"

For turbidity an additional significant question is:

- "Is the drainage channel cracked, broken or need cleaning?"

Another way to find out if any one sanitary survey question is always associated with poor water quality is to use the Kruskal–Wallis test. A sample for each question was defined which contained the TTC values for each source that gave a "yes" answer. These samples were then compared using the Kruskal–Wallis test. For all five sources, no question was significantly associated with higher or lower quality water.

Comparison between indicators

Thus far, TTC and turbidity have been considered as separate indicators of water quality, and have produced similar, but not identical, results. They are plotted against each other in Figure 5. The graph shows that when turbidity is high, TTC is also high, but when TTC is high there is a wide range of turbidity (i.e. no sources plot in the high turbidity, low TTC quadrant). This suggests that if turbidity were to be used as the sole water quality indicator, sources may appear to be safe when in reality they have a high TTC count. To test how well they compare to each other, Spearman's rank correlation coefficient was calculated for all sources combined ($\rho = 0.63$, $p = 3.6 \times 10^{-40}$). The results suggest that whilst there was significant correlation between TTC and turbidity, 37% of the variation in turbidity cannot be explained by variation in TTC. Overall, this suggests that turbidity is not an acceptable indicator of water quality.

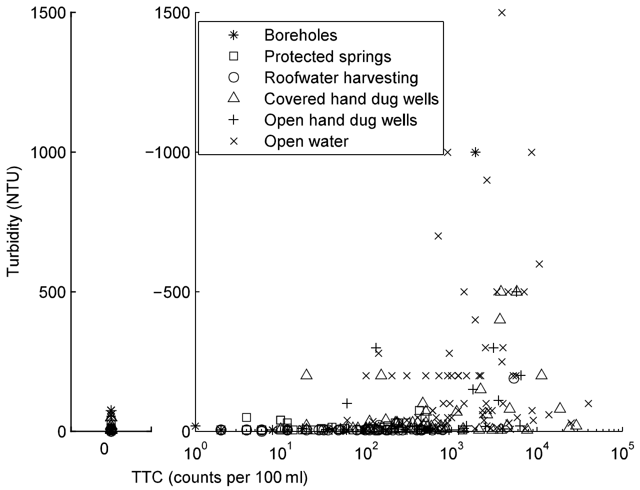

Figure 5 | Plot of TTC against turbidity. Note the log scale for TTC on the right-hand graph.

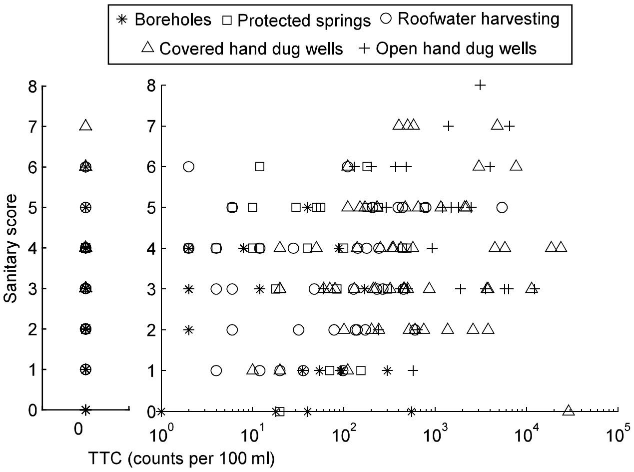

Figure 6 | Plot of TTC against sanitary score (note the log scale for TTC on the right-hand graph).

Correlation between TTC and sanitary score

TTC and sanitary score are plotted against each another in Figure 6. To test how well they compare to each other, Spearman's rank correlation coefficient was calculated for all sources combined ($\rho = 0.29$, $p = 1.1 \times 10^{-3}$). The results suggest that whilst there was significant correlation between TTC and sanitary score, this correlation was weak and 71% of the variation in TTC cannot be explained by variation in sanitary score. Overall this suggests that sanitary surveys cannot predict water quality precisely.

DISCUSSION

Source comparison

This study agrees with other studies (for example by Lavoie & Viens 1983; Lloyd & Bartram 1991; Lloyd & Helmer 1991; Sutton 1994; Magrath 2006) which state that boreholes have the highest microbiological quality water, followed by open hand dug wells and protected springs which are of similar quality, with open water having the lowest quality. No previous studies have compared roofwater harvesting to other source types, but in this study it is rated as better than covered hand dug wells, open hand dug wells and open water. In general, this ranking of sources was expected because as water sources are increasingly separated from the human environment, contamination pathways are reduced (in number and potential impact), and hence microbiological water quality increases. Only boreholes, protected springs and roofwater harvesting had median TTC counts below the levels set by the Ugandan Ministry of Water and Environment (2006). Only boreholes had a median TTC count that met WHO (2006) guidelines (zero TTC count per 100 ml), with 69% of boreholes meeting this value. Of the sources defined as improved by the WHO and UNICEF Joint Monitoring Programme (2008) only 35% met WHO microbiological water quality standards, and 56% met Ugandan national standards. This means that even if Millennium Development Goal 7C is met, there will still be a significant proportion of people without access to safe water.

However, it was noted during the data collection that some people use the dirtiest sources only for washing and agriculture, and choose to travel further to collect safe drinking water, so the proportion of unsafe sources may not accurately reflect the proportion of people without access to safe water. Conversely, post collection contamination in the household often compromises water quality (for example Trevett *et al.* 2004; Wright *et al.* 2004), so this may increase the proportion of people drinking unsafe water. Roofwater harvesting is advantageous in this regard as the storage is nearer to the home than most groundwater supplies and in tanks so the opportunities for contamination during transport or storage are reduced.

It is worth noting that whilst no open hand dug wells (classified as unimproved) met WHO (2006) guidelines, 6% of open water sources did. Sutton (2002) also found that open scoop holes could be comparable to fully protected wells if the aquifer is not contaminated as they have low storage (typically not more than 0.2 m depth of water in scoop holes) and thus frequent regeneration through bailing (Sutton 2002). However, this study area was Zambia, which has an exceptionally low population density (15.5 people/km^2 compared to 120 people/km^2 in Uganda (UN 2004)) and thus less likelihood of aquifer contamination through human activity.

For households currently accessing the lowest quality water in unimproved sources, a change to accessing the best quality water possible, i.e. boreholes, may be unrealistic for financial and technological reasons. Instead it may be more appropriate to take intermediary steps, upgrading to a source with better water quality, but not the best water quality, for example to a protected spring, rather than a borehole.

Sanitary surveys

This study also assessed how the maintenance and construction of the improvements to water sources affected microbiological water quality. Total sanitary survey scores did not correlate well with water quality, which means that poor sanitary scores do not necessarily indicate sources need improvement. This is contrary to the findings of Lloyd & Helmer (1991), Sutton (1994), Howard *et al.* (2003) and Magrath (2006). The reason for this could be that this study was conducted during the dry season, and measurements were only made at one point in time. Previous studies (for example Howard *et al.* 2003; Godfrey *et al.* 2006) found that water quality is typically compromised following rainfall events. Reade (2001) points out that it is often rainwater that transports coliforms into the water source, so lower levels of microbiological contamination would be expected during the dry season.

This study also asks the question “If this sanitary survey question is answered positively, is the water likely to be of poor quality?”. The fact that open hand dug wells are the only groundwater source where cracks in the concrete apron, or the absence of a concrete apron were associated with low water quality could highlight the importance of sanitary completion below the apron which is absent in most of these wells. Whilst this assessment is somewhat weak as it is only based on 24 samples, it is similar to the findings of Lloyd & Bartram (1991), Lloyd & Helmer (1991) and Gelinas *et al.* (1996). In addition, these wells typically only have a thin unsaturated zone which does not remediate infiltrating water effectively. When these wells are upgraded, the installation of a sanitary seal in the well should be considered of primary importance. The only other water source category where a significant question was highlighted by the water quality indicators was dirty spouts in protected springs. For example some outlets had been removed or a bottle had been inserted into them to form a spout. Magrath (2006) and Duah (2006) cited that proximity to latrines compromised microbiological water quality. However, this hypothesis could not be tested here as none of the groundwater sources were near latrines; typically latrines in villages in Amuria District are not located near water sources.

When considering all groundwater sources together, it is notable that both high TTC and high turbidity correlated with failures in the apron. This was also found by Sutton (2002), Howard *et al.* (2003) and Godfrey *et al.* (2006). High turbidity values also correlated with failures in the drainage channel. This could suggest that a key pathway for contamination is directly downwards from the area immediately surrounding the well head or spring box. The importance of maintaining the apron and drainage channel should be highlighted to those responsible for source maintenance. High TTC correlated with the absence of a fence (which allows animals near the well, whose excreta could be a source of contamination if there is a pathway for contamination such as a faulty apron). Howard *et al.* (2003) and Magrath (2006) also found an inadequate fence to be a key contributor to microbiological water contamination.

Of course, it is incorrect to consider aspects of construction and maintenance independently. As Reade (2001) points out, many aspects would not cause contamination individually. For example water pooling on the apron will only cause contamination if there are cracks in it. However, whilst certain combinations of sanitary survey aspects could cause contamination, it is possible to envisage factors contributing to a high sanitary score whilst not actually causing contamination; for example, a borehole with a faulty apron, drainage channel and fence but a thick unsaturated zone which attenuated any bacterial contamination.

Sanitary surveys seem to logically set out the risks, but this logic is not backed up by the data. Total sanitary scores do not seem to correlate with dry season water quality. However, sanitary surveys are a vital part of a water safety plan ethos.

The ranking of different water sources should remain the same during the rainy season, although whilst the sources with the best water quality will remain good, the more contaminated sources will have increasingly poor water quality, as rainwater provides a transport mechanism from faeces to the drinking water source.

CONCLUSIONS

This study presents a new dataset testing microbiological water quality against water source type. It was found that the source types ranked as follows, in descending order of water quality from the highest to the lowest:

- boreholes
- protected springs and roofwater harvesting
- open and covered hand dug wells
- open water

For the purpose of this study, two definitions of "safe" water were used: either the WHO drinking water standard of zero coliforms per 100 ml or the Ugandan national standard of 50 coliforms per 100 ml. Whilst this study does suggest that "improved" water sources are "safer" than unimproved sources, not all "improved" sources are "safe", using either definition. The MDG target 7C indicator measures the proportion of the population using an "improved" source, however there may be significantly fewer people using a "safe" source. Boreholes were the safest source, 89% providing water of a microbiological quality that met Ugandan national guidelines, significantly better than any other source type. Protected springs and roofwater harvesting met these guidelines 61 and 63% of the time, respectively, with covered hand dug wells meeting them just 26% of the time.

Improved sources must be well maintained if they are to offer protection to a water supply in the long term. Sanitary surveys can be useful to highlight key aspects of a source's improvement, but these may not always be relevant. They cannot be used to predict water quality precisely, however they are widely considered to be an essential component of the monitoring of safe water supplies.

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REFERENCES

Busari, O. 1999 *Rural Water Quality Guidelines and Rationale Case Study From Swaziland*. Development Bank of Southern Africa.

Department of Water Affairs and Forestry 1996 *South African Water Quality guidelines*. Vol. 1, Domestic Use, 2nd edition.

Duah, A. A. 2006 Groundwater contamination in Ghana. In *Groundwater Pollution in Africa* (ed. Y. Xu & B. Usher), pp. 57–64. Taylor and Francis, London.

DWD 2003 *Summary report for Soroti monitoring well.* Water Resources Management Department, DWD, Kampala.

Environment Agency 2009 The Microbiology of Drinking Water – Part 4 – Methods for the isolation and enumeration of coliform bacteria and *Escherichia coli* (including *E. coli* O157:H7). *Methods for the Examination of Waters and Associated Materials*. Environment Agency, Standing Committee of Analysts, London.

Gelinas, Y., Randall, H., Robidoux, L. & Schmit, J. 1996 Well water survey in two districts of Conakry (Republic of Guinea), and comparison with the piped city water. *Water Res.* **30**(9), 2017–2026.

Godfrey, S., Timo, F. & Smith, M. 2006 Microbiological risk assessment and management of shallow groundwater sources in Lichinga, Mozambique. *Water Environ. J.* **20**, 194–202.

Howard, G., Mutabazi, R. & Nalubega, M. 2001 Rehabilitation of protected springs in Kampala, Uganda. In *Water, Sanitation and Hygiene: Challenges of the Millennium* (ed. J. Pickford). *Proceedings of the 26th WEDC Conference*, Dhaka, Bangladesh, pp. 20–23. WEDC, Loughborough University, UK.

Howard, G., Pedley, S., Barrett, M., Nalubega, M. & Johal, K. 2003 Risk factors contributing to microbiological contamination of shallow groundwater in Kampala, Uganda. *Water Res.* **37**, 3421–3429.

ISO 1998 *Water Quality–detection and Enumeration of Coliform Organisms, Thermotolerant Coliform Organisms and Presumptive Escherichia coli. Pt.1, Membrane filtration method*. International Organization for Standardization, Geneva.

Lavoie, M. C. & Viens, P. 1983 Water quality control in rural Ivory Coast. *Trans. R. Soc. Trop. Med. Hyg.* **77**(1), 119–120.

Lloyd, B. J. & Bartram, J. K. 1991 Surveillance solutions to microbiological problems in water quality control in developing countries. *Water Sci. Technol.* **24**(2), 61–75.

Lloyd, B. & Helmer, R. 1991 *Surveillance of Drinking Water Quality in Rural Areas*. Longman Scientific & Technical on behalf of the World Health Organisation and the United Nations Environment Programme, Harlow.

Magrath, J. 2006 *Towards Sustainable Water Supply Solutions in Rural Sierra Leone*. Oxfam Research Report.

Ministry of Water and Environment 2006 *Water and Sanitation Sector Performance Report 2006*. Government of Uganda, Kampala (unpublished report).

Reade, A. 2001 *Interpretation of water quality surveillance data for maintenance purposes in the Highlands of Guatemala*. MSc Thesis, Cranfield University.

Sutton, S. E. 1994 Microbial quality of groundwater supplies in rural Zambia. In *Groundwater Quality* (ed. H. Nash & G. J. H. McCall), pp. 139–144. Chapman and Hall, London.

Sutton, S. 2002 *Community led improvements or rural drinking water supplies*, Knowledge and Research Project (KAR) R7128, SWL Consultants, DFID.

Trevett, A., Carter, R. C. & Tyrrel, S. F. 2004 Water quality deterioration: a study of household drinking water quality in rural Honduras. *Int. J. Environ. Health Res.* **14**(4), 273–283.

United Nations 2004 *World Prospects Report*. United Nations, New York.

United Nations 2008 *The Millennium Development Goals Report 2008*. United Nations, New York.

University of Surrey 2004 *OXFAM-DELAGUA, Portable Water Testing Kit (version 4.1)*. University of Surrey, Guildford, UK.

WHO 2006 *Guidelines for Drinking-water Quality*, 3rd edition, incorporating first addendum edition, World Health Organisation, Geneva.

World Health Organization and United Nations Children's Fund Joint Monitoring Programme for Water Supply and Sanitation (JMP) 2008 *Progress on Drinking Water and Sanitation: Special Focus on Sanitation*. UNICEF, New York and WHO, Geneva.

Wright, J., Gundry, S. & Conroy, R. 2004 Household drinking water in developing countries: a systematic review of microbiological contamination between source and point-of-use. *Trop. Med. Int. Health* **9**(1), 106–117.

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APPENDIX: SANITARY SURVEY QUESTIONS (LLOYD & HELMER 1991)

Boreholes:

a. Is there a latrine within 10 m of the hand pump?
b. Is the nearest latrine on higher ground than the hand pump? (animal excreta, rubbish, surface water …)
c. Is there any other source of pollution within 10 m of the hand pump?
d. Is there ponding or stagnant water within 2 m of the cement floor of the hand pump?
e. Is the drainage channel faulty? Is it broken? Permitting pounding?
f. Is there inadequate fencing around the installation which allow animals in?
g. Is the cement floor less than 1 m radius all round the hand pump?
h. Is there ponding on the cement floor around the hand pump?
i. Are there any cracks on the cement floor around the hand pump?
j. Is the hand pump loose at the point of attachment to the base (allowing water in)?

Protected springs:

a. Is there a latrine within 10 m of the spring?
b. Is the nearest latrine uphill?
c. Is there any other source of pollution within 10 m of the spring?
d. Is the runoff drain not in place? Is it not functional?
e. Is there inadequate fencing around the installation which allow animals in?
f. Is there inadequate drainage at the collection point?
g. Is there a potential contamination between the spring and the collection area?
h. Is the outlet dirty?

Roofwater harvesting:

a. Is there visible contamination on roof?
b. Are the guttering channels which collect water dirty?
c. Is there any deficiency in the filter box at the tank inlet?
d. Is there any other point of entry to the tank which is not properly covered?
e. Is there any defect in the walls or top of the tank which could let in water?
f. Is the tap leaking or otherwise defective?
g. Is the cement floor under the tap defective or dirty?
h. Is the water collection area inadequately drained?
i. Is there any source of pollution around the tank or water collection area?

Covered hand dug wells:

a. Is there a latrine within 10 m of the well?
b. Is the nearest latrine uphill of the well?
c. Is there any other source of pollution within 10 m of well?
d. Is there pooling of stagnant water within 2 m of the well?
e. Is the drainage channel cracked, broken or need cleaning?
f. Is the fence missing or faulty?
g. Is the apron less than 1 m radium around the top of the well?
h. Is there pooling on the cement floor?
i. Are there cracks in the concrete apron?
j. Is the hand-pump loose at point of attachment to the well head?

Open hand dug wells:

a. Is there a latrine within 10 m of the well?
b. Is the nearest latrine uphill of the well?
c. Is there any other source of pollution within 10 m of well?
d. Is there pooling of stagnant water within 2 m of the well?
e. Is the drainage channel cracked, broken or need cleaning?
f. Is there an inadequate wall around the well?
g. Is the apron less than 1 m radium around the top of the well?
h. Are the walls inadequately sealed any point 3 m below ground?
i. Are there cracks in the concrete apron, or is the apron absent?
j. Are the rope and bucket unsanitary?