Monitoring source and domestic water quality in parallel with sanitary risk identification in Northern Mozambique to prioritise protection interventions

Aidan A. Cronin, Ned Breslin, James Gibson and Steve Pedley

ABSTRACT

Microbiological water quality monitoring in Niassa province, Northern Mozambique, shows groundwater is not, in general, grossly contaminated though contamination levels are strongly linked to season and to risks observable at the wellhead, especially risks dealing with wellhead hygiene and maintenance. Diarrhea incidence, in general, is greatest in the rainy season suggesting poor wellhead protection as a potential mechanism for well contamination. Comparison of source water and stored water in the home shows that significant deterioration in source water quality can occur once transport and storage in the home is undertaken but that this deterioration is also related to the quality of the source water. This study shows that a structured approach to water quality monitoring, with targeted observations and an examination of the relationships between risk and water quality, is important to identify the priority interventions to be undertaken.

Key words | groundwater monitoring, microbiological quality, Mozambique, Niassa, sanitary risk inspection

Aidan A. Cronin (corresponding author)
Steve Pedley
Robens Centre for Public and Environmental Health,
Building AW Floor 2, University of Surrey, Guildford,
Surrey GU2 7XH, UK
Tel.: (0044) 01483 689931
Fax: (0044) 01483 689971
E-mail: *a.a.cronin@surrey.ac.uk*

Ned Breslin
James Gibson
WaterAid,
CP 1726, 1100, Maputo ECP,
Mozambique

INTRODUCTION

The 2004 World Health Report estimates that diarrheal diseases amongst all sexes account for 4.2% of the total DALYs (Disability Adjusted Life Years) (WHO 2004a). If the contribution from other water-related communicable diseases is considered, including some of the parasitic and nematode infections, then this percentage is substantially higher. The Millennium Development Goals (MDG) were developed to tackle world poverty but access to safe water is an essential component of any initiative to raise living standards and income generation ability. Hence, the MDG state are attempting to address the current unacceptable levels of lack of access to safe drinking water by aiming to half the proportion of people without sustainable access to safe drinking water by 2015 (Target 10) and also to achieve a significant improvement in the lives of at least 100 million slum dwellers by 2020 (Target 11).

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The goals promote actions based on the well-founded premises that improvements in water supply (quantity and quality) and sanitation facilities can reduce pathogen transmission and so improve child growth rates and reduce mortality rates (e.g., Blum & Feachem 1983). It is also well accepted that these issues need to be examined in an integrated manner (e.g. Lewis *et al.* 1980; ARGOSS 2001). However, if, for example, faecally-derived pathogens are temporarily stored in a receptacle that will subsequently contaminate drinking water resources drawn from the underlying aquifer, the faecal-oral route of disease transmission has not been broken and the employed form of sanitation and hygiene is failing to fully meet its prime objective of protecting public health. On the other hand, the health risks from the absence of improved excreta disposal are likely to exceed those posed by contamination of groundwater from sanitation (Howard *et al.* in press). Furthermore, the lack of excreta disposal may be a direct cause of contamination of groundwater sources (i.e. improvements in sanitation may also deliver improvements in microbial quality in groundwater; e.g., Howard *et al.* in press). Indeed such contamination results from poor wellhead protection and in some cases this can pose a greater threat to the degradation of water quality than the proximity of latrines, as other studies have already shown (e.g. Gelinas *et al.* 1996).

The percentage of the low-income peri-urban population in developing countries currently using groundwater for drinking water purposes is likely to be 80% or more (Pedley & Howard 1997). There are two possible routes for faecal contamination to pollute groundwater sources in these settings: either via poorly protected wellheads or via another point of entry in the aquifer (such as a latrine or leaking sewer) and the subsequent transport of this contamination through the groundwater into the well (ARGOSS 2001). Both routes have regularly been associated with the contamination of groundwater (e.g. Cronin *et al.* 2004; Howard *et al.* 2003). Discarded faeces or flooded latrine contents can enter poorly finished or unprotected wellheads and this mechanism is referred to below as the wellhead route of contamination. On the other hand, leaking sewers or dug latrines are faecal sources which can degrade groundwater quality from points of entry which can be considerable distances from the well due to the groundwater flow regime and this mechanism is referred to below as the aquifer route of contamination.

Groundwater microbial contamination may be reduced by barriers such as Well Head Protection Areas (WHPA) and well disinfection. However, in developing countries such barriers are rarely rigorously imposed. Furthermore, WHPAs are frequently not properly delineated and so fail to accurately represent microbial die-off to the well or spring (e.g. Taylor *et al.* 2004). Hence, the focus must be solely on breaking the specific pathways between the potential sources of the contamination and the well. Monitoring well water quality is a vital tool in this respect and when contamination is identified, it is critical that the monitoring data enables identification of the source and entry mechanism of the contamination into the well to allow corrective action be taken to prevent further contamination. Simple tools are needed to quickly establish such interconnections and need to be feasible even in the most resource-poor areas. This is the objective of coupling water quality monitoring with sanitary risk inspections and is carried out principally in order to:

(a) identify possible causes of faecal contamination;
(b) identify other potential risks to groundwater quality;
(c) raise awareness among stakeholders as to the impacts of unsanitary conditions or practices on groundwater quality;
(d) identify priority interventions to reduce contamination levels in the well water.

This risk identification approach is being promoted in the latest (3rd edition, Vol. 1) WHO Drinking Water Quality Guidelines (WHO 2004b). These guidelines promote quality assurance, i.e. understanding the risks posed to water quality and verifying protection policies through microbial testing. Such a holistic approach, termed a Water Safety Plan (WSP), differs from previous approaches that controlled water quality solely from end-product testing. The WSP approach recognizes that although monitoring of well water quality is important to ensure water is safe for drinking purposes, it is not sufficient on its own to secure water safety. The risk identification approach has proved useful in other groundwater quality assessments in developing countries in order to identify appropriate remedial action (Howard *et al.* 2003; Cronin *et al.* 2004) and has proved valuable in testing a common presumption that microbiological contamination of groundwater derives from poorly sited or constructed sanitation facilities (Melian *et al.* 1999), i.e. the presumption that the aquifer route of contamination predominates.

Hence, water and sanitation programs need to be examined in an integrated fashion though other issues are also central to water-borne disease prevention. Authors dealing with the prevention of diarrhea also stress the importance of hygiene and the availability of sufficient water (to a greater extent than that of excellent bacteriological water quality), for example VanDerslice & Briscoe (1995) and Jensen *et al.* (2004). This hygiene awareness extends from personal (e.g. bathing, hand washing) to household (e.g. latrine use, drinking water storage) to community level (water source maintenance, stagnant water drainage etc.). The sanitary survey approach promotes improved hygiene awareness in the community by highlighting the risks to water quality posed by poor hygienic practices.

Poor hygiene practices related to water transport and/or storage can lead to good quality source water becoming contaminated at the household level. Cairncross *et al.* (1990) state that protection of the source is effort wasted if deterioration occurs to household water. Hence, the risks of water contamination during transport to and storage in the home requires close attention (Clasen & Bastable 2003). This issue is addressed in the latest WHO guidelines that state 'It is important that people are aware of the risks to health from contamination of water from the point of collection to the moment of consumption and have the means to reduce or eliminate these risks' (WHO 2004b).

The literature is not consistent on this issue of the relationship between source and stored water quality. Moyo *et al.* (2004) found little difference in quality trends of stored water from protected and unprotected sources, despite significant water quality differences at source. However, Moe *et al.* (1991) stress the importance of source water protection by showing that in a study in Cebu, Philippines, little difference was seen in illness rates in children drinking source quality water with up to 100 *E. coli*/100 ml but children drinking source water with >1000 *E.coli*/100 ml had significantly higher rates of diarrheal disease, despite the presence of several diarrhea transmission routes. Jensen *et al.* (2004) did not find an association between the numbers of *E. coli* in the drinking water sources and the incidence of childhood diarrhea. An increase (statistically not significant) was seen in the incidence of childhood diarrhea with increasing numbers of *E. coli* in the household drinking water storage vessels. This study also found that high levels of stored water contamination were evident and water from a source with a low faecal contamination most susceptible to quality deterioration in the home. Quick *et al.* (1999) demonstrated that interventions to improve water quality at household level also have positive health outcomes.

VanDerslice & Briscoe (1995) point out that water contamination at source may represent a greater hazard than contamination in the home as household contamination is predominantly the 'recycling' of pathogens in the domestic environment while source water pathogens are external and new threats. This argument, however, does not consider the evolution of new and/or increased virulence effects of pathogens. Ewald (1991) argues that it is due to the effect of water purification and treatment that diarrhoeal pathogens may evolve to lower levels of pathogens. Hence, the argument of VanDerslice & Briscoe (1995) must be treated with caution as the 'recycling' of pathogens is unacceptable when susceptible members outside the immediate family circle ingest water contaminated by unsafe transport storage practice.

Hence, there are many mechanisms for contaminating water from source to home and minimising the risk of contamination may involve much technical and educational work with the communities. Curtis *et al.* (2000) propose that in order not to overload low-income communities with an excessive number of messages and dilute scarce resources, priority interventions are needed to achieve a maximum decrease in disease transmission. Even just considering water- and food-borne transmission gives rise to a multitude of potential public health messages. An integrated and focused approach to examining these issues and prioritising interventions from source water protection to water storage in the home is essential if water is to be of the maximum health benefit possible. However, it is crucial to gain a strong understanding of the contamination mechanisms in order to correctly identify the priority interventions that are necessary to be undertaken.

This paper investigates variations in water quality between different sources and over different seasons. The important issue of quality deterioration after transport and storage in the home is also examined. Interventions to protect and improve drinking water quality are identified, prioritised and subsequently tackled providing ways to reinforce hygiene awareness work being undertaken at community level. The case study site highlighted is the town of Lichinga and its neighbouring areas in the Niassa province, northern Mozambique.

STUDY AREA

Lichinga (13° 18′S, 35° 15′E) is the provincial capital of Niassa, Mozambique's largest and least developed province

(Figure 1). It is a rapidly expanding town with a population approaching 100,000 people. A piped water system exists but serves only a very small percentage of the population and is generally unreliable, which increases the pressure on households to use groundwater. Niassa is almost entirely underlain by crystalline basement characterised by plateaus formed during several erosion cycles with local inselbergs and mountainous areas. Many parts of the extensive plateaus are underlain by deeply weathered rocks. The basement complex is dominated by gneiss and a gneiss-granite-migmatite complex that forms part of the Mozambique Metamorphic Belt (Ferro & Bouman 1992). This crystalline basement landscape has led to complex local drainage patterns with many local swamps and rivers that are often used for drinking water purposes. The majority of people in urban areas in Niassa draw water from unprotected, unlined traditional wells and/or surface water (WaterAid Mozambique 2004). The shallow hand-dug wells are on average 8m deep (52 wells measured as part of this study) with an average depth to water of 5 m (based on 93 wells tested). Many such unprotected traditional wells have been improved by the installation of a concrete plinth and windlass along with education on how to store the bucket and rope when not in use. The most common handpump used on public lined wells is the AfriDev though many of these are currently in a state of disrepair and thus force many families back to unprotected sources. High failure rates in drilling are common and yields are seldom in excess of 1.5 l/s. Yields can be increased in areas of fracturing and along dykes.

The province receives over 1100 mm of rain per year, mainly during the wet season from November to April. Latrine coverage rates vary from 60 to 90% from a survey of two district towns in Niassa (Maúa and Nipepe) though the vast majority of these are traditional latrines which are not considered adequate provision under the national sanitation policy (WaterAid Mozambique 2004). Rural sanitation coverage is much lower than this. Ecological Sanitation (EOCSAN) toilets are increasing in popularity and aim to reuse some of the nutrients in human waste after storing the waste for a sufficient period to ensure pathogen die-off. There are 2 types of ECOSAN toilet in use in Niassa, the Fossa Alterna and the Arbour Loo. The Fossa Alterna uses two partially-lined permanent shallow pits with 1 moveable latrine slab. The slab is alternatively moved between pits and pits are only emptied when the other pit is also completely full. The Arbour Loo sees a young fruit tree planted on the site of a full latrine pit (Breslin 2001). This option is rarely used at household level but has great potential as a latrine option at family agricultural plots.

METHODS

Data on diarrheal cases (including dysentery and cholera) presented at the health clinics at Lichinga (City and

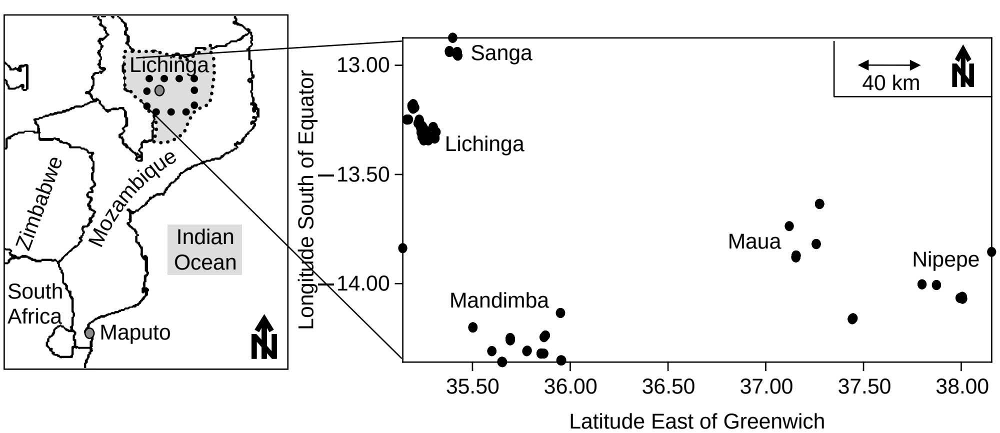


Figure 1 | Inset map: Location of Lichinga in relation to Mozambique and its capital city Maputo; the province of Niassa is shaded grey and the study area is denoted by the dashed box. Main map: Co-ordinates (degrees longitude and latitude) of all wells sampled as part of this study. The main towns of the province of Niassa are also shown.

District) and the other major towns in Niassa (Mandimba, Sanga, Maúa and Nipepe) was collected for the purpose of comparison of season and disease outbreak. Rainfall data was used from the meteorological station near to Lichinga town (13.3° S, 35.2° E, altitude 1365 m) that measures rainfall on a daily basis.

Microbiological analysis for thermotolerant coliform bacteria (TTC) was conducted in the field using a portable Delagua water quality testing kit. TTC are frequently used as a bacterial indicator of faecal contamination (Feachem 1980). All sampling was undertaken in the period April 2002 to August 2004. Sampling was carried out on a quarterly basis of 74 wells (Figure 1) chosen on the criteria of number of well users, well type and location. Added to this were single samples on a range of other wells ($N = 159$). As often as possible, comparison samples were taken from storage vessels in the home to compare this domestic water quality with the source water quality. As a check on the reliability of the TTC indicators, additional samples were collected in sterile containers and brought back to the UK for the analysis of laboratory-based indicators for sulphite reducing clostridia (SRC), another potentially useful indicator in tropical waters. All coliphage samples (30 ml) were also collected for analysis in the UK after preservation with chloroform (1 ml).

The isolation and enumeration of the TTC was carried out using membrane filtration and growth on membrane lauryl sulphate broth (OXOID, UK; HMSO 1994). The plates were incubated for 1 hour (minimum) to 4 hours (maximum) at ambient temperature to aid bacterial resuscitation, before transferring to 44 ± 0.5°C for a total incubation period of 16 to 18 hours. Yellow colonies were counted as being Thermotolerant coliform colonies. All results were noted in a project database. Plates that had too numerous colonies to count (in excess of ~300) were entered as 500 cfu/100 ml as this was above the highest level of contamination directly recorded from colony counts (after Howard *et al.* 2003.). Sulphite-reducing clostridia (SRC) were isolated from 100 ml sample volumes using membrane filtration and selectively enumerated by culture on perfringens agar (HMSO 1994). Enumeration of coliphage was determined by assay of 1 ml of sample using the double agar layer technique (Adams 1959).

Physical parameters were also measured at the wellhead and consisted of pH, turbidity, temperature and electrical conductivity (EC). Turbidity was measured using graduated turbidity tubes with a range of 5 to 2,000 TU. pH was assessed using a graduated comparator cell to which phenol red tablets were added (range 6.8 to 8.4). Temperature and electrical conductivity were measured in the field using a Palintest Micro 500 Conductivity meter (Palintest, UK). This meter measures up to three different ranges (0 to 199.9 μS, 0 to 1999 μS and 0 to 19.99 mS with associated resolutions of 0.1 μS 1 μS and 0.01 mS) and accuracy is quoted at ± 1%. The measurement range for temperature is 0 to 80°C, with 0.5 °C accuracy and 0.1 °C resolution.

During each sampling visit sanitary-risk inspections were carried out as recommended by the WHO (WHO 2004b) and the American Water Works Association (EPA 1999). These inspections comprise of a systematic logging of observable faults that may lead to the degradation of water quality by sewage (Lloyd & Bartram, 1991). Each fault is considered as one point on the sanitary risk inspection score.

RESULTS

Rainfall and diarrhea

Incidence of normal diarrhea, dysentery and cholera reported at health centres in Lichinga (City and District) and the other major towns in Niassa (Mandimba, Sanga, Maúa and Nipepe) are plotted against rainfall in Figure 2a. The data for the other main towns in Niassa (Mandimba, Sanga, Maúa and Nipepe) show a strong positive relationship with rainfall Lichinga (city and district). This is obvious for the January 2002 results when the spike from the combined town grouping corresponds with the peak rainfall month. The Lichinga cases also display a positive relationship with rainfall though there are significant peaks outside of the rainy season also.

These different spikes clearly show the effects of several aetiological agents and/or transmission routes. The two distinct case groupings of wet and dry season monthly case totals, defined here as rainfall above or rainfall below 40 mm/month, are shown in Figure 2b. These results suggest a constant source of pathogens all year around with high incidents of disease (and prevalence) outside the

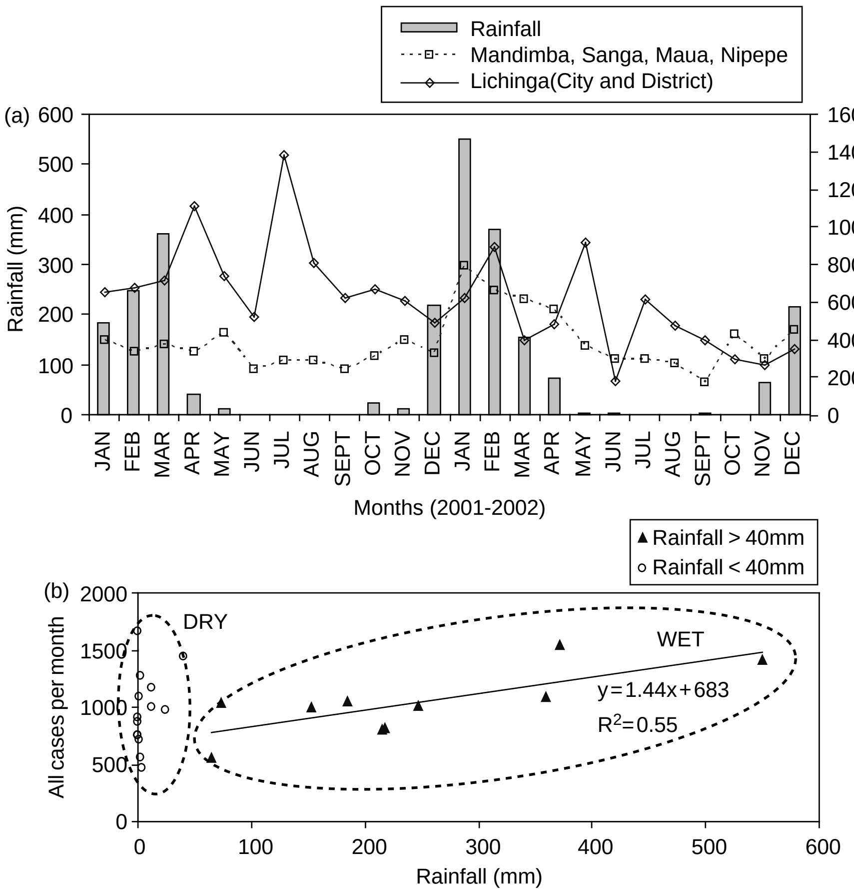


Figure 2 | (a) Monthly rainfall (mm) and total monthly cases of diarrhoea, cholera and dysentery being presented at Lichinga (city and district) and other Niassa health centres (Mandimba, Sanga, MaŪa, and Nipepe) for January 2001 to December 2002 inclusive. (b) Total number of cases presented per month in all Niassa health centres for which data was available graphed against rainfall. Two distinct groupings can be seen – those grouped as the dry season results (rainfall <40 mm/month) and the wet season results (rainfall >40 mm/month). The trend line shown is for wet season results only.

wet season. However, during the wet season there is a correlation with increasing total number of cases and increasing rainfall ($R^2 = 0.55$ for months with rainfall over 40 mm) and this would point more to poor wellhead construction, as opposed to the aquifer route of contamination, as the mechanism for contamination.

However, there are substantial diarrheal incidents also during the dry season, especially in Lichinga. First of all it must be considered that such data cannot be over-interpreted as not all of the population has ready access to these clinics and so there is substantial under-reporting of true disease incidence. In addition, there are other important transmission routes apart from water-borne transmission that are contributing to these reported cases. These result mainly from poor sanitation coupled with poor community, personal and food hygiene. However, limited though the data presented here is, it is the only available data at the study scale and it allows the development of a hypothesis that there are distinct routes of pathogen transmission dominating at different times of the year. Hence, latrine and food-borne transmission, flies, direct contact and so on, may contribute to diarrheal incidents all year round but poor sanitary protection of wells may dominate in the wet season when the level of rainfall may determine the amount of surface contamination flushed into the well and so the incidence of diarrhea in the community.

Water quality monitoring

The results of water quality monitoring from the four main drinking water source types (surface water, traditional wells, improved windlass wells and handpumps), as described above are summarized in Table 1. The surface water sources (consisting of swamps and springs, both of which are unprotected) show gross contamination with both average and median counts in excess of 100 cfu/100 ml. The other sources, all utilising groundwater, have high average counts but low median counts (<10 cfu/100 ml) suggesting that whereas certain sources can exhibit heavy incidents of contamination, the aquifer itself, on the whole, is not grossly contaminated. Traditional wells show the most positive TTC detects and the highest averages of the groundwater sources. Improvement of such traditional wells by the addition of a concrete plinth and windlass has brought this average down considerably and has more than halved the median TTC count (9 to 4 cfu/100 ml) which is a significant improvement for a relatively low cost intervention. Handpumps, generally drawing water from greater depths, are the best protected water source with only 8 out of 73 samples having values in excess of 10 cfu/100 ml. These 8 samples raise the average of all 73 analyses to 13 cfu/100 ml but the median TTC score is 0 cfu/100 ml. These results show that the level of protection put in place is directly proportional to the level of indicator TTC measured along with the level of sanitary risk noted at the wellhead. When considering the % of positive detects for all of the water source types, all but handpumps are classified as poor under the WHO guidelines (WHO 2004b: p. 97). These consider 40% or more positive detects as poor for systems serving populations of fewer than 5000. Handpumps, at 34% positive detects, would be classed between poor and fair (Table 1). Combining the median TTC values with the average sanitary-risk scores (WHO 2004b: p. 98) suggests that the surface water and traditional wells are very high risk and require urgent action. The better-protected windlass and handpumps fall into the classification of 'Intermediate to high risk – higher action priority'. The results from the SRC analyses showed that this long lived indicator due to its spore-forming characteristic) mirrored TTC results well (Figure 3) across a range of different water types.

Rainfall is another important control on TTC levels. There is an order of magnitude differences between wet and dry season TTC levels (both average and median) over the rainy and dry seasons (Table 2). This increase in TTC levels is perceived to be due mainly to poor construction quality of the well headworks and sanitary seals allowing the rain to wash contamination accumulated at the surface down into the well. This resulted in an average increase of 65 cfu/100 ml in the wells sampled in both the dry and wet seasons. Wet and dry season effects on solute values are also visible on electrical conductivity values. Natural levels of electrical conductivity in Niassa are generally less than 500 μS/cm and elevated values generally represent anthropogenic influences in urban areas (Cronin et al., submitted). Average electrical conductivity values increase from 155 to 175 μS/cm from dry to wet season (N = 231 wells and 86 wells respectively). This is somewhat surprising as non-mineralised recharge waters can potentially dilute conductivity values. However, the increases can be explained by the surface-derived debris being washed into the wells at this time and reinforces the effects on water quality of poor wellhead protection, as seen in the TTC results.

The deterioration of water quality as it is stored in the home can negate much good work in protecting the source. This study sampled both source and stored water whenever feasible. These samples (N = 169) provide an opportunity

Table 1 | Average and median Thermotolerant coliform counts (TTC) and % of positive TTC detects with respect to sanitary risk score and well type. N is number of analyses

Water source	N	Average TTC cfu/100 ml	Median TTC cfu/100 ml	% positive TTC detects	Average sanitary risk score
Swamp/Spring	21	238.4	130	91	10.3
Traditional	85	72.1	9	82	9.0
Windlass	128	56.2	4	68	5.0
Afridev handpump	73	13.2	0	34	4.6

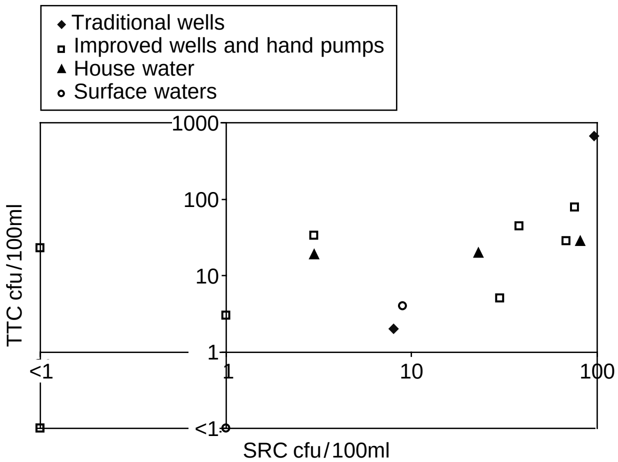


Figure 3 | Comparison of standard faecal coliform indictors (TTC) with sulphite reducing clostridia (SRC) from 16 water points sampled July 2004. All values are in colony forming units/100 ml.

to assess water storage practices in the home. 80% of stored water samples showed a positive detect for TTC and this resulted in average and median values of 78 and 9 TTC/100 ml respectively. Four distinct groups can be seen in this data (Figure 4). Group I (14% of total) show a very good source water quality (<1 TTC) and this standard is maintained in the house. Group II (19% of total) again show an excellent source water quality but this quality is not maintained in the home. Many of these analyses show gross contamination due to poor transport, storage or handling procedures.

The majority of samples (63%) fall into Group III that has positive counts both for source and stored water. This Group III data is expanded upon in the column graph where 3 bands of wellwater quality have been devised. These columns show the % of different bands of stored water quality for each band of wellwater quality. This graph shows that the majority of stored water quality samples fall into the same water quality band as that of the wellwater, i.e. the majority of stored water quality samples (~60%) in the wellwater band of 1 to 10 TTC cfu/100 ml are also in the category of 1 to 10 TTC cfu/100 ml. This emphasises the quality correlation between the two sampling sites. The linear trendline correlation for Group III is $R^2 = 0.5$. Group IV (4% of total) exhibit positive TTC detects in the source water but zero TTC detects in stored water. It is believed some of these stored samples may have been boiled though this is not general practice in Niassa.

An important aim of this monitoring work is to be able to prioritise the risks causing the greatest deterioration in source water quality. These priority risks should become the priority interventions to tackle. Risks were ranked by calculating the difference in the % occurrence of each particular risk between wells exhibiting positive TTC detection and wells exhibiting negative TTC detection (Table 3). Hence, the risk ranked no. 5 'Is the drainage channel cracked, broken or in need of cleaning?' occurs 11.8% more often in the group of wells with positive TTC detects than in those exhibiting no TTCs. Such methods for the examination of relationships between water quality and identified risks are straight-forward and applicable for developing countries without access to statistical computer packages. More developed countries may employ more complicated statistical correlation techniques using odds ratios etc. (Howard *et al.* 2003). By far the strongest positive TTC-risk relationship was shown by the risk dealing with unhygienic storage and use of the bucket (and rope for windlass wells). This relationship (34.2%) was significantly higher then the next risk of cement plinths under 1 m (23.1%).

DISCUSSION

In general, though not exclusively, the highest incidences of diarrhea occur in the rainy season suggesting poor wellhead

Table 2 | Comparison of Thermotolerant Coliforms (TTC) monitoring results and Electrical conductivity (EC) for the wet and dry seasons. N is number of analyses

	N	Average TTC cfu/100 ml	Median TTC cfu/100 ml	N	Average EC μs/cm	Median EC μs/cm
Dry	231	39.1	2	141	155.4	129
Rainy	86	121.2	13	83	174.2	133.8

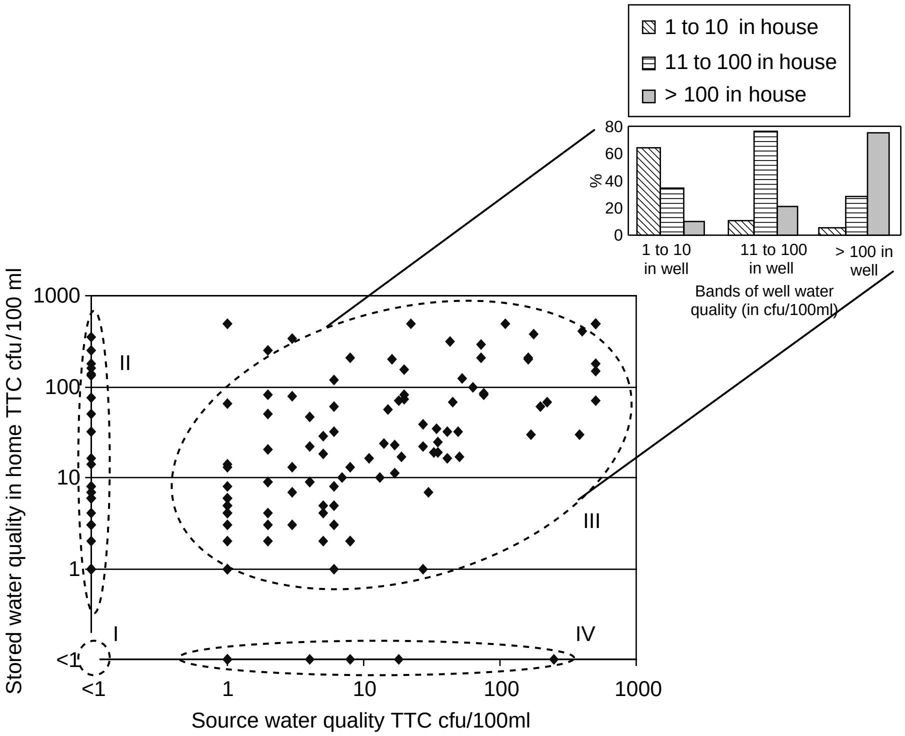


Figure 4 | Source water quality versus stored water quality in the home. All points represent TTC cfu/100 ml. 4 distinct groupings (I to IV) are identified – see text for explanation. Group III points have been divided into three separate bands (wellwater quality <10, 11 to 100 and >100 TTC cfu/100 ml) and then the corresponding columns represent the % of stored water quality falling into the same TTC bands.

protection as a potential mechanism for contamination entering the well. The water quality monitoring results suggest that the aquifer is not grossly contaminated but the level of TTC indicators is correlated with seasonality in rainfall and sanitary risk. Only the top 6 ranked risks exhibit strong positive relationships with water quality (arbitrarily defined here as a % difference in excess of 10%). These risks deal either with poor well maintenance (risks 1 and 5) or poor well construction (risks 2 to 6). Interestingly, latrines were quite low on the ranking (risk 10) than expected, similar to other study findings for instance Howard *et al.* (2003). This is a positive finding as to tackle this risk by replacing traditional latrines with alternative sanitation systems not utilising the ground as a waste receptacle would be almost impossible given the lack of resources and expertise.

All of these observations favour the wellhead rather than aquifer route of contamination and suggest that focused interventions on hygiene practices at the wellhead and proper wellhead protection could yield rapid improvements in water quality, as Table 1 suggests. The similar trends in SRC results (generally increasing with increasing TTC) reinforces this (Figure 2) and suggests that contamination is occurring locally before substantial attenuation (due to physio-chemical adsorption, dispersion and die-off) can occur. Also of importance is that significant deterioration in source water quality can occur once transport and storage in the home is undertaken. However, this deterioration is proportional to the quality of the source water (Figure 4). This correlation serves to highlight the importance of integrating both source water protection and hygiene work to prevent deterioration of water quality once collected from the source. Indeed, Jensen *et al.* (2002) who examined water quality at source and in the home in Pakistan found that domestic contamination is only significant when the water arriving into the home contains less than 100 *E. coli*/100 ml. They argue that if the water source quality has greater than this value, interventions to prevent domestic contamination will have only a minor affect in comparison with public domain interventions. Hence, interventions to protect source water quality, principally those risks at the wellhead, are important on a number of different levels.

Table 3 | Order of priority of risks identified by correlating the TTC counts and risks identified at the wellhead. % Diff = % of wells with positive TTC detects that exhibit that risk - % of wells with negative TTC detects that exhibit that risk

% Diff.	Priority rank	Risk description
34.2	1	Is the bucket and/or rope in a position that it can become contaminated?
23.1	2	Does the cement floor extend less than 1.0 metre from the well?
20.3	3	Is the pump loose where attached to the base, allowing water to enter the casing/For a well without a pump is the cover in an unhygienic position?
16.6	4	Are the well walls poorly sealed below ground level?
11.8	5	Is the drainage channel cracked, broken or in need of cleaning?
11.6	6	Are there cracks in the cement floor which could permit water to enter the well?
3.1	7	Are there any open water sources within 20 m of the borehole?
1.8	8	Is there ponding beyond the cement floor within 3 metres of the well?
0.9	9	Is there any ponding of water on the cement floor?
0.2	10	Are there any latrines within 30 m of the well?
−3.1	11	Is there any scattered waste within 30 m of the well?
−3.1	12	Do animals have access to within 10 m of the well (is there a fence)?

Two approaches to interventions are currently being undertaken in Niassa to address the principal risks outlined here. On the well construction side, training courses in well construction techniques are being organised with the local contractors, who are involved in the construction of wells, receiving training in better construction techniques as well as quality control. The other intervention is to tackle poor well maintenance and storage practices, especially the principal risk of bucket and rope storage. This involves the use of diagrams, drawn by a local artist (Figure 5), that show both incorrect practices that may add to contamination levels, and correct practices of storing the bucket and rope inside the well. To deal with poor storage practices hygiene promotion workers revisited many of the homes showing the greatest discrepancy between source and stored waters in order to ensure proper procedures were put into place to maintain good quality. Follow-up visits showed significant water quality improvements. Also of importance during follow-up or repeat sampling visits is the explanation of previous sampling results to the well users. A methodology was developed to split results into 3 categories: low, medium and high risk. Both TTC and sanitary scores are risk proxies so both sets of results are being fed back to the communities via simple facial expressions (Table 4).

It is hoped that this simplified approach can begin to decrease TTC levels in drinking water in the study area. However, these interventions are seen only as the first step in a process that will see all risks in Table 3 addressed. This intervention strategy, via a step-by-step approach, is to ensure well users do not initially become weighed down by

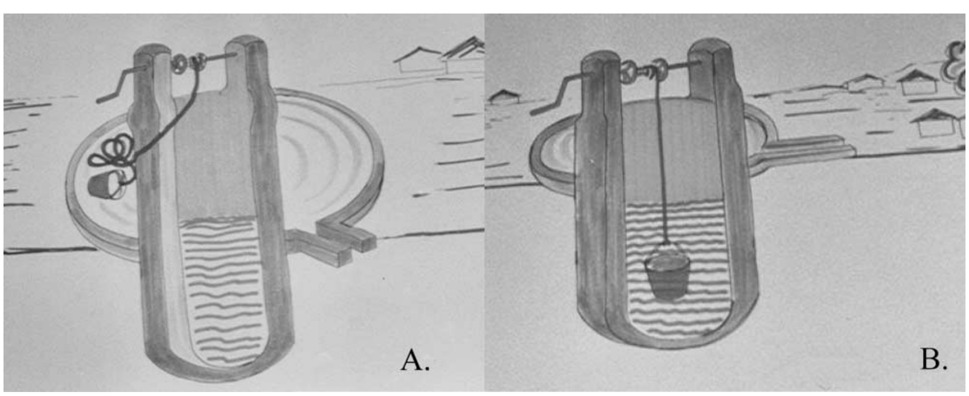
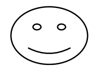
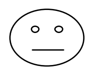
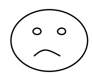


Figure 5 | Diagrams drawn by a local artist to show both incorrect procedures for bucket and rope storage (A) and correct practice (B).

Table 4 | Methodology of feedback of results to the well users

Risk category	Sanitary score	TTC ranges (cfu/100 ml)	Symbol used in community feedback
Low	0–4	0–10	
Medium	5–7	11–50	
High	8–12	>51	

a variety of complicated messages. On-going monitoring is being undertaken to monitor the effectiveness of these interventions and to ensure that the correct risks are being targeted.

The methodology adopted here has shown the importance of adopting a structured approach to water quality monitoring. Such an approach, employing targeted observations, can identify and prioritise risks to water quality degradation. In general, the analysis of TTC is too costly a task to be sustained by low-income communities and needs to be supported by government or NGO funding. However, sanitary risk assessments can be quickly, frequently and easily carried out by local well users at no cost to themselves. Well users could be helped in this respect to monitor their own resources. In settings like Lichinga, where the aquifer is not grossly contaminated, it is possible for well owners to identify contamination risks and improve their own water quality. In other urban settings, where population densities are much higher, this may not always be feasible for example Cronin *et al*. (submitted). Hence, such an approach as outlined here with both TTC and sanitary risk assessments and used in a regional setting, like Niassa, can target the priority interventions. The recommendations in the 3rd edition of the WHO Guidelines for community managed supplies are that sanitary inspections should be used as a routine monitoring tool and then combined with testing of indicator organisms in a surveillance programme to provide verification of water safety (WHO 2004b).

Such approaches are also important for NGOs and donor agencies working in the water supply area for two reasons. Firstly, they can maximize the effectiveness of their resources by quickly determining the priority interventions and, secondly, they are able to demonstrate the effectiveness of the projects they fund. The latter is of increasing importance with the emergence of such initiatives as the Sphere Standards (Sphere 2004) which, as a set of minimum expectations for humanitarian relief programs, is also formalising the need for the donor community to measure, analyse, document and report their findings in the WATSAN sector, among others.

CONCLUSIONS

Monitoring of groundwater in Lichinga, Northern Mozambique, has determined that the underlying aquifer is not grossly contaminated but the level of bacterial faecal indicators (thermotolerant coliforms) is positively related with both rainfall seasonality and sanitary risk. The number of cases of diarrheal disease presenting at health centres are also correlated with seasonality in rainfall though a significant proportion of cases occur in the dry season also and are linked with aquifer contamination pathways and other transmission routes such as food borne transmission. Contamination of the source water is considered to derive from poor wellhead construction or maintenance rather than contamination entering the aquifer directly, e.g. via latrines. A correlation of water quality analysis and risks identified in the vicinity of the wellhead allowed a prioritisation of interventions. Poor hygienic practice with respect to buckets and ropes at the wellhead was seen as the principal risk to water quality at the wellhead and this issue is currently being tackled as a priority intervention by hygiene promotion workers. Significant deterioration in source water quality can also occur once transport and storage in the home is undertaken. However, this deterioration is proportional to the quality of the source water. It is suggested that improved access to and better protection of source water quality can not eliminate but can reduce stored water contamination levels in the study area setting. The approach adopted by this study shows that a structured approach to water quality monitoring, with targeted observations, is important to programs in order to identify the priority interventions to be undertaken.

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