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Microbiological risk assessment and management of shallow groundwater sources in Lichinga, Mozambique

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Abstract

The principal water target of the Millennium Development Goals (MDG) is to ensure environmental sustainability by halving the proportion of people without access to safe water by 2015. Although great strides have been made in meeting this challenge since the year 2000, the safety of many of these water supplies remains unknown. Acknowledging the weaknesses of current water quality and hydrogeological means of assuring microbial safety, this paper has the objective of developing improved methods for the assessment and management of microbiological water safety based on a 'risk' paradigm. This paper provides evidence for the risk assessment of both conventional aquifer pathways and localised (short circuiting) pathways to 25 wells of three well technology types in Mozambique between 2002 and 2005.* Findings from the research outline improve methods of risk assessment and management by demonstrating that (1) the predominant source of contamination was from animal faeces rather than from latrines/septic tanks, (2) short circuiting is a significant risk to shallow groundwater in developing countries, (3) the use of alternative indicator organisms (e.g. enterococci) may improve risk understanding and (4) the World Health Organisation Water Safety Plans are recommended as an appropriate method of risk management.

Introduction

Because of rising populations in developing countries, many surface water resources are becoming highly vulnerable to anthropogenic chemical and microbial pollution. Consequently, many low-income communities have become increasingly reliant on shallow groundwater resources defined in this research as the water bearing materials that are strongly influenced by physical and chemical processes on the ground surface (Melian *et al.* 1999). These shallow groundwater sources are often exploited using low-cost technology facilities such as wells or tubewells, where the water quality is monitored based on 'end-product testing' of selected microbiological and chemical parameters and controlled through the establishment of groundwater catchment protection zones (Watt & Wood 1979; Collins 2000).

Fundamental weaknesses in both the 'end-product testing' and groundwater catchment approach have been highlighted in the third edition of the World Health Organisation (WHO) Guidelines for Drinking Water Quality and the British Geological Survey (BGS) study of Associated Risks to Groundwater from On-Site Sanitation (ARGOSS) (ARGOSS 2002; WHO 2004). Limitations highlighted by WHO include analysis based on a restricted range of indicator organisms and overreliance on a non-representative sample volume (Payment *et al.* 2003; WHO 2004). Similar limitations in conventional approaches to groundwater catchment protection zones for developing countries have also been highlighted recently. Studies by the BGS on the ARGOSS suggest a high risk of short circuiting of the wellhead protection zone through *localised pathways* such as poorly sealed annuluses of boreholes or cracks in surface aprons (associated with construction faults and inadequate maintenance of wells) (Gelinas *et al.* 1996; ARGOSS 2002).

To counteract these weaknesses, the WHO propose a fundamental shift away from end-product testing towards alternative risk-based approaches termed *Water Safety Plans (WSPs)*, where risk is defined as a combination of the probability or frequency of a particular event occurring with the consequences of its occurrence (Dixon *et al.*

2001; Godfrey & Howard 2005; Godfrey & Smith 2005; Godfrey *et al.* 2005). This is supported by the ARGOSS study, which concludes that effective groundwater risk assessment and management must include two main pathways of contamination:

(a) *aquifer pathway*: migration of pathogens from the base of a pit latrine to the water table and then into intake of a well or a screen;

(b) *localised pathway*: developed through poor design, construction and/or operation and maintenance of the water supply.

In light of this debate, the objective of this paper is to develop improved methods for the assessment and management of microbiological water safety based on a 'risk' paradigm. The conceptual basis of risk is defined in this context by the source pathway receptor model, where the source is defined as the hazard event/environment (e.g. septic tank), the pathway as the vulnerability of the media (e.g. soil type) and the receptor as the receiving water infrastructure (e.g. hand-dug well).

Materials and methods

This study was undertaken in Niassa province in northern Mozambique through joint research between the UK Water, Engineering and Development Centre (WEDC), the Mozambique Estação Agraria de Lichinga (Agricultural Research Centre) and the UK charity WaterAid. The precise study area selected was the town of Lichinga (population 110 000), the capital of Niassa province, located at 13°18′S, 35°15′E. Three sample communities (Nomba, Lulimile and Ceramica) were selected from within Lichinga based on practical/logistical criteria to achieve a statistically valid sample size (i.e. number of statistically valid water points). To calculate n water points for a population of size N within these communities, the Student's t-test was selected (Helsel & Hirsch 1992; Dziegielewski *et al.* 1996). For a statistically valid sample of the total 362 water points in Lichinga, 20 water points would be required (plus five control 'traditional wells' at 25% of the sample size). Categorical (nonchanging) and parametric (continuous) data were collected at each of the 25 well sites over a 12-month period from November 2003 to October 2004. Historical data were made available to the researcher from August 2002 to October 2003. The methods selected for each variable are outlined in Table 1.

Results and data analysis

Data analysis was conducted for the source, pathway, receptor and water quality data in three stages:

- data description (based on geographical and technological data),
- data mining (statistical extraction of data) and
- data analysis [statistical analysis using logistic regression and chi-square (χ^2) significance weightings (P-values)].

Table 1 Methods of analysis

Variable	Method	Frequency
SOURCE		
Hazard/vulnerability analysis	Sanitary survey	Monthly
Distance from latrines	Field survey	Monthly
Depth of latrine	Field survey	Annual
Land use	Field survey	Annual
PATHWAY		
Rainfall/precipitation	DipFlex manual rain gauge	Daily
Depth to water/water level	HORON dip test	Monthly
Aquifer media	Ciba-Geigy agrochemicals guide to soil identification	Annual
	GEO-VISION borehole camera	Annual
	Field survey	Annual
	Particle size distribution (BS1377-2)	Annual
Hydrogeological survey	Field survey	Annual
	Visual soil classification	Annual
	Subsoil thickness	Annual
	Geological observations	Annual
RECEPTOR		
Surface hardness	MASTRAD Schimdt Hammer (BS1881-201)	Annual
Water lifting	Structured survey	Annual
Headwork survey	Borehole camera	Annual
	Structured survey	Annual
Well design/lining	Borehole camera	Annual
	Structured survey	Annual
WATER QUALITY		
Turbidity	Turbidity tube	Monthly
pH	Handheld comparator	Monthly
Presumptive thermotolerant coliforms	UK methods for examination of water and associated materials	Monthly
Presumptive enterococci	UK methods for examination of water and associated materials	Monthly

Note: Source is defined as the hazard event/environment (e.g. latrine). Pathway is defined as the vulnerability of the media (e.g. soil type). Receptor is defined as the receiving water infrastructure (e.g. hand-dug well).

Data description

Hazard variables

Results from 325 sanitary inspections indicated high usage of latrines by adults and low usage by children, resulting in the high presence of children/babies and livestock faeces in the wellhead catchment.

Pathway variables

A total of 1047 and 1042 mm of rainfall were collected in the two rain gauges during the 12-month study. The highest rainfall was noted during the months of monomodal rains (November–April) (see Godfrey *et al.* 2005). Additionally, water table depths were collected monthly in each well over the 12-month period. During the rainy season, increased recharge resulted in shallow water levels to 5.1 mbgl (metres below ground level) at both locations. During the dryer period, the water level dropped to below 7.5 mbgl. Lowest recorded levels were noted as 8.62 mbgl in October.

Rainfall- and water-level data were linked to hydrogeological data, which indicated that Lichinga is underlain by metamorphic rock with overlying alluvial drift. Because of limited available data on the hydrogeology of the area, subsoil field investigations were undertaken using the Ciba-Geigy classification method and soil particle size distribution (PSD) analysis (see Fig. 1). The Ciba-Geigy method relies on visual examination and physical behaviour of the soil when handled without using analytical equipment. The Ciba-Geigy survey revealed very high silt and clay content in samples from all three sites (CIBAGEIGY 1986). In comparison, PSD results indicated a very high fine sand/silt content with a limited percentage of coarse materials. The K permeability value for each of the samples suggested a moderate to low permeability range at 10^{-4}–10^{-8} m/s (BS1377-2 1990).

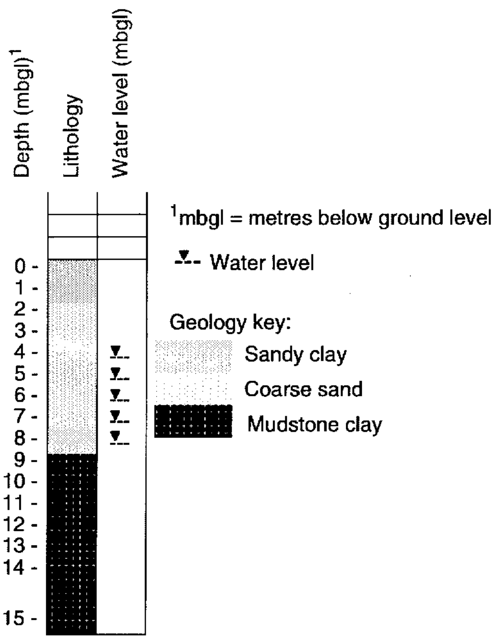


Fig. 1. Subsurface geology.

Receptor variables

Conventionally, hydrogeologists assess risk to groundwater based on pollutant source loading and vulnerability of aquifer pathways. This research also assesses the influence of the receptor in minimising risk through localised pathways (e.g. short circuiting through the wellhead protection zone). The wellhead is defined as the underground and overground construction of the abstraction facility as well as the immediate area surrounding the abstraction point (Howard *et al.* 2003a).

The headworks of the wellhead were assessed using 510 Schmidt Hammer surface hardness tests at four specific points on the apron of each well and a qualitative headworks inventory. For the Schmidt Hammer tests, optimum levels of $R=30$ were used as the lowest levels as recommended by the manufacturer for concrete products (Mastrad 2004) Using $R=30$, it can be concluded that only the precast reinforced concrete capping beam produced results ≥ 30 and that the quality of concrete used in all the headworks was poor. Visual inventories revealed high levels of visible aggregate (suggesting poor mixing of concrete by hand) and surface cracking and dry jointing. Examination of these cracks and dry joints revealed high levels of risks of direct ingress of surface contaminants through the unlined annuluses of wells to the well reservoir.

Water quality

Microbiological results

As outlined in Fig. 2, low levels of compliance to the WHO guideline values for thermotolerant coliforms (TTC) were noted in both traditional wells and improved wells during the rainy season (November–March). This improved during the drier months of March to July and then deteriorated again in the leadup to the rains in August to September. It should be noted that increased demand on the wells during the later part of the year, combined with minimal yield, may have resulted in increased levels of contamination. Minimal difference, however, was noted between traditional and upgraded wells. Levels of enterococci (EF) were noted as being consistently greater in all well technologies. Higher counts of EF were recorded in wells at greater depth. This is explained by the robustness of the organism and its ability to survive, but not multiply under environmental conditions at depth (Mara 2003).

Data mining

In order to then refine the data, a process of data mining was undertaken. Data mining is described as the

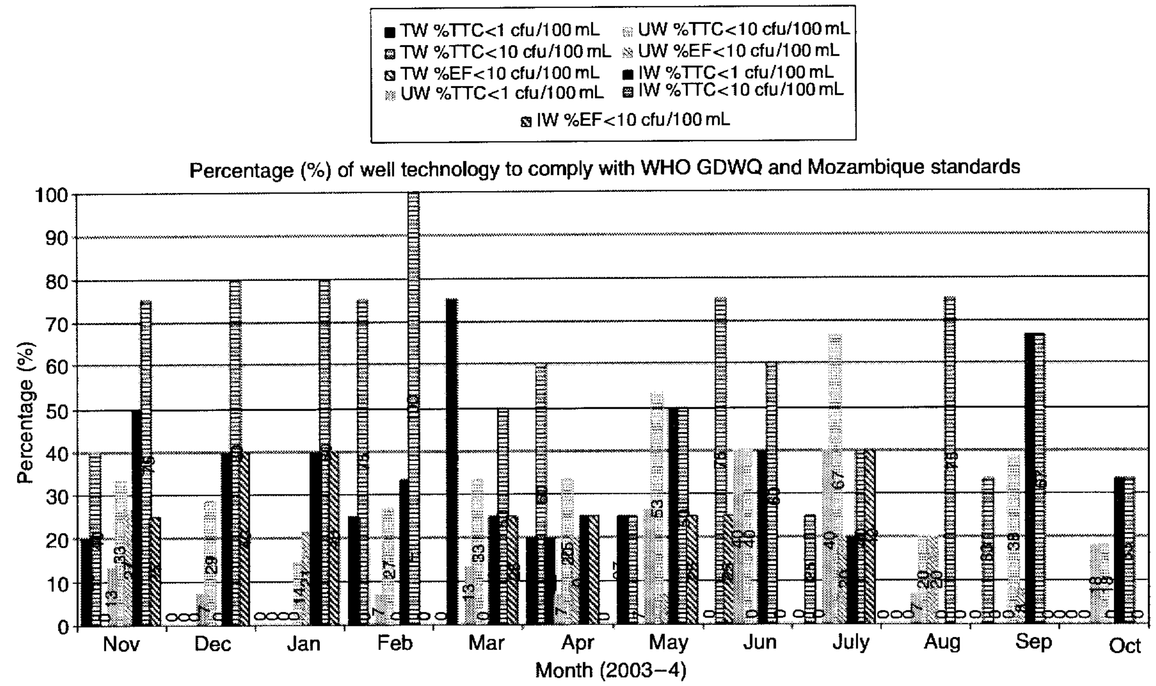


Fig. 2. Percentage compliance to World Health Organisation GDWQ third edition 2004. TW, traditional wells; UW, upgraded wells; IW, improved wells; EF, enterococci; TTC, thermotolerant coliforms.

exploration and analysis, by automatic or semiautomatic means, of large quantities of data in order to discover meaningful patterns and rules (Helberg 2002). For this research, data mining of the source variable level of contaminant loading from the field data was undertaken using an adaptation of the pollutant origin source hazard (POSH) method of load characterisation – see Fig. 3 (Foster *et al.* 2002). The POSH method characterises the potential sources of subsurface contaminant load on the basis of two characteristics:

1. association of the likelihood of the presence of a groundwater-polluting substance with the type of anthropogenic activity and
2. estimation of associated hydraulic load (surcharge) on the basis of water-use activities (Foster *et al.* 2002).

The POSH method provides three levels of 'potential to generate a subsurface contaminant load', namely, Reduced, Moderate and Elevated. As noted in Table 2, by combining the variables affecting subsurface contaminant load potential, it was observed that a Moderate to Reduced level of hazard is present in the study site.

Data mining of subsoil vulnerability was analysed using an adaptation of the methods developed by the University of Dublin and the Geological Survey of Ireland, termed the *adapted hydrogeological settings method.* The method considers four categories of vulnerablity – extreme, high, moderate and low (Robins 1998; Swartz *et al.* 2003). As noted in Table 3, these categories are calculated by combining subsoil field descriptions, grain size data, subsoil thickness (determined from waterlevel data) and qualitative estimates of soil permeability. The permeability is used to define the specific hydraulic conductivity (Swartz *et al.* 2003).

From the hydrogeological settings method, it was observed that 0% of the wells were within the Extreme vulnerability category. Fifty per cent of the wells were within the High vulnerability category and 50% of the wells were within the Moderate. Because of lack of available data, three wells had no vulnerability category. Because of time and financial constraints, additional factors such as ambient temperature of soil microbes relative to physiologic temperature and specific porosity have not been researched. The literature, however, suggests that any one indicator of vulnerability should not be used in isolation and that a more holistic approach such as the adapted hydrogeological settings method is of greater use (Stejmar 1998). A moderate to high level of vulnerability was found in the selected well sites, with no wells categorised as having either extreme or low vulnerability.

Data analysis

Statistical analysis was undertaken using *logistic regression.* This technique was selected because of its successful use

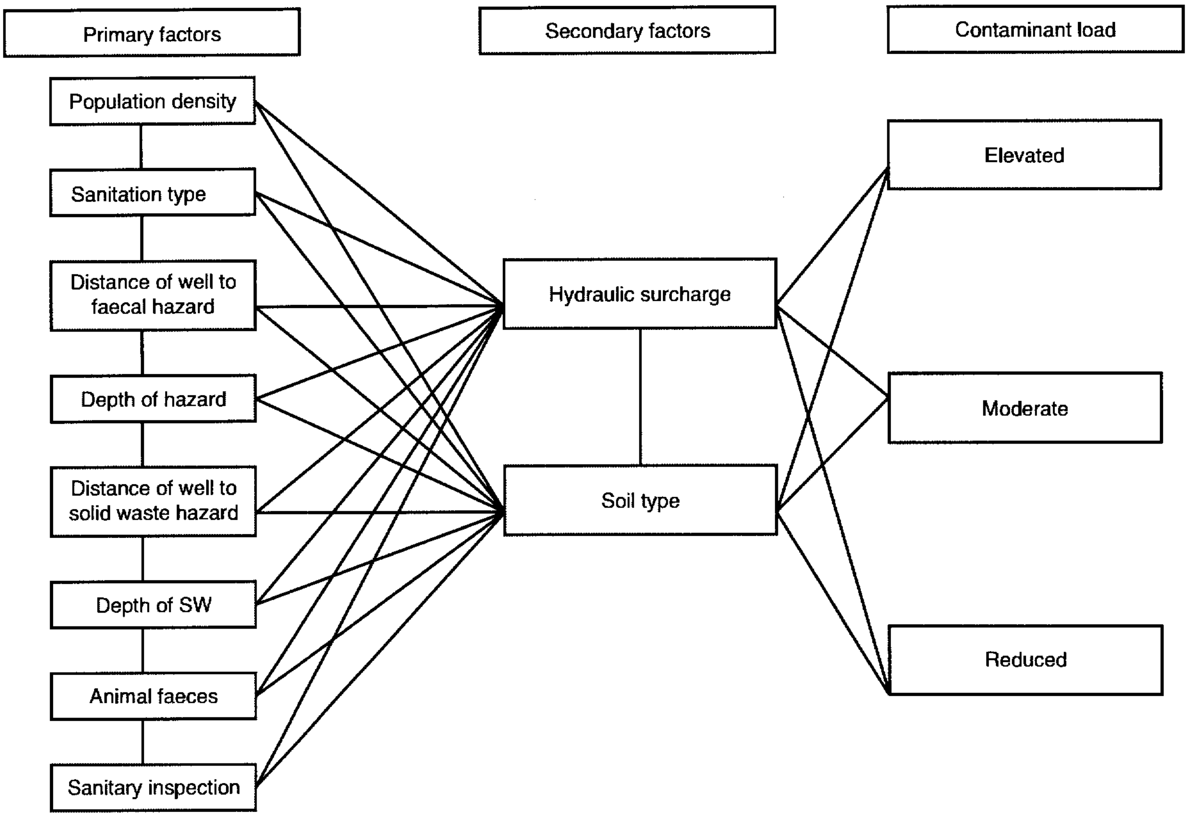


Fig. 3. Pollutant origin source hazard data mining.

Table 2 Source variable – subsurface contaminant load potential

Category	Wells
Elevated	6, 17
Moderate	2, 3, 4, 5, 7, 8, 10, 12, 13, 14, 18, 19
Reduced	1, 9, 11, 15, 16, 20, 22

in other studies (Howard *et al.* 2003b; Tesoreiro *et al.* 2003). Because of the large number of covariates, four analyses were performed using logistic regression. This paper will focus on one of the analyses, namely

- monthly analysis of source, pathway, receptor and significance of specific sanitary inspection results to microbial noncompliance.

Data were dummy coded as 0 or 1 in SPSS 11 based on compliance or noncompliance with the selected critical limits below for each well technology:

- TTC > 10 cfu/100 mL=high risk, < 10 cfu/100 mL= low risk;
- EF > 10 cfu/100 mL=high risk, < 10 cfu/100 mL=low risk.

Outlined below are the results for significance weightings of individual sanitary inspection results and specific source, pathway and receptor variables for the noncompliance of EF and TTC in three well types:

- traditional wells,
- improved wells and
- upgraded wells.

For each, the categories along the x-axis (SI2–SI10 inclusive) refer to specific individual questions on the sanitary inspection form used. Each sanitary inspection (SI) number presented is a statistically generated number based on the mean of 12 months data. The y-axis presents the statistical weighting represented as a P-value at 95% confidence or 0.05.

Traditional wells (Fig. 4)

Results summary: traditional wells

Statistical significance ≤ 0.05,

Statistical significance > 0.05.

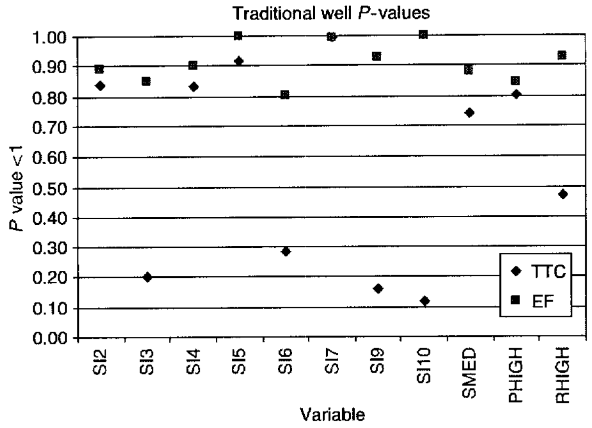
Two risk variables were identified to be significant in traditional wells:

- rope on floor and
- bucket on floor.

Table 3 Vulnerability indices using the adapted hydrogeological settings method

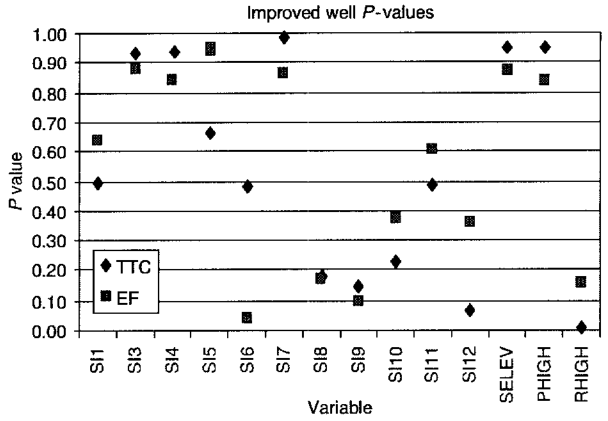
		Subsoil thickness (m)		Grain size distribution (BS1377)						Permeability (m/s)	Permeability (adapted from Swartz *et al.* 2003)	
Well no.	Location	Recorded as shallowest depth	Sample depth (m)	Gravel	Sand	Fines	Clay	Ciba-Geigy description	BS1377/ description	High (e.g. gravel, sand)	Medium (e.g. sand, sandy silt)	Vulnerability category
1	Nomba	5.0	0.5, 2, 5[5]	2	24	28	46	Silty loam[6]	Sandy silt MHS, clay	10^{-4}–10^{-6}	Medium	High
2	Nomba	5.0[4]	0.5, 2	2	24	28	46	Sandy clay	MHS, clay	10^{-4}–10^{-6}	Medium	H-moderate
3	Nomba	5.0[4]	0.5	2	24	28	46	Silty loam	MHS	10^{-4}–10^{-6}	Medium	H-moderate
4	Nomba	5.7	0.5	2	24	28	46	Sandy silty loam	MHS	10^{-4}–10^{-6}	Medium	H-moderate
5	Nomba	5.1	0.5	2	24	28	46	Silty clay loam	MHS	10^{-4}–10^{-6}	Medium	H-moderate
6	Lulimile	9.1	0.5	1	31	21	47	Sandy clay loam	Sandy clay CLS	10^{-4}–10^{-6}	Medium	H-moderate
7	Lulimile	7.8	0.5, 1, 2	1	31	21	47	Sandy clay	Sandy clay CLS, clay	10^{-4}–10^{-6}	Medium	H-moderate
8	Lulimile	5.8	0.5	1	31	21	47	Silty clay loam	Sandy clay CLS	10^{-4}–10^{-6}	Medium	H-moderate
9	Lulimile	8.7	0.5	1	31	21	47	Sand	Sandy clay CLS	10^{-4}–10^{-6}	Medium	H-moderate
10	Ceramica	4.4	0.5	1	33	25	41	Loamy sand	Sandy silt MLS	10^{-3}–10^{-5}	Medium	High
11	Ceramica	5.7	0.5	1	33	25	41	Silt loam	Sandy silt MLS	10^{-3}–10^{-5}	Medium	H-moderate
12	Ceramica	5.0	0.5	1	33	25	41	Sandy clay	Sandy silt MLS	10^{-3}–10^{-5}	Medium	High
13	Ceramica	5.0	0.5, 1, 2, 4	1	33	25	41	Sand	Sandy silt MLS, clay	10^{-3}–10^{-5}	Medium	High
14	Ceramica	5.9	0.5	1	33	25	41	Sandy clay	Sandy silt MLS	10^{-3}–10^{-5}	Medium	H-moderate
15	Ceramica	5.3	0.5	1	33	25	41	Silty clay	Sandy silt MLS	10^{-3}–10^{-5}	Medium	H-moderate
16	Ceramica	5.5	0.5	1	33	25	41	Sandy clay	Sandy silt MLS	10^{-3}–10^{-5}	Medium	H-moderate
17	Ceramica	5.5[4]	0.5	1	33	25	41	Sand clay	Sandy silt MLS	10^{-3}–10^{-5}	Medium	H-moderate
18	Ceramica	4.4	0.5	1	33	25	41	Sandy clay loam	Sandy silt MLS	10^{-3}–10^{-5}	Medium	High
19	Ceramica	4.5	0.5	1	33	25	41	Silty loam	Sandy silt MLS	10^{-3}–10^{-5}	Medium	High
20	Ceramica	4.8	0.5	1	33	25	41	Silty loam	Sandy silt MLS	10^{-3}–10^{-5}	Medium	High
21	Ceramica	4.9	0.5	1	33	25	41	Silty loam	Sandy silt MLS	10^{-3}–10^{-5}	Medium	High
22	Ceramica	4.9	0.5	1	33	25	41	Sandy clay loam	Sandy silt MLS	10^{-3}–10^{-5}	Medium	High
23	Ceramica	5.1	0.5	1	33	25	41	Silty clay	Sandy silt MLS	10^{-3}–10^{-5}	Medium	H-moderate
24	Ceramica	4.9	0.5	1	33	25	41	Silt loam	Sandy silt MLS	10^{-3}–10^{-5}	Medium	High
25	Ceramica	4.7	0.5	1	33	25	41	Loamy sand	Sandy silt MLS	10^{-3}–10^{-5}	Medium	High

MHS, elastic silt with sand; CLS, lean clay with sand; MLS, silt with sand.



SI no.	Hazard	Result		Risk
		TTC	EF	
2	Existence of animals excreta close to well	0.84	0.88	Low
5	Solid waste dumps within 30 m of the well site	0.91	1	Low
7	Insanitary head works within 3 m of the well	0.99	0.99	Low
10	Insanitary use of rope and bucket	0.11	1	High/Low

Fig. 4. Traditional well sanitary inspection results. EF, enterococci; TTC, thermotolerant coliforms.



SI no.	Hazard	Result		Risk
		TTC	EF	
4	Discarded open wells or refuse pits	0.94	0.83	Low
6	Stagnant water on apron	0.98	0.05	Low/High
7	Cracks in apron	0.98	0.85	Low
8	Deficient drainage	0.18	0.18	High
9	Headwork's diameter <2 m	0.10	0.13	High
10	Insanitary condition of pumphead (pump and base)	0.212	0.371	High
	Receptor category	0.01	0.15	High

Fig. 5. Improved well sanitary inspection records. EF, enterococci; TTC, thermotolerant coliforms.

Improved wells (Fig. 5)

In comparison, in caisson-lined improved wells, evidence of high risk relates to the receptor (receiving water infrastructure).

Results summary: improved wells

The receptor was identified as being the principal route of contamination. Three specific risk factors were identified:

1. presence of stagnant water on and around the wellhead,
2. loose base of the handpump and
3. cracks at the base of the handpump.

The high level of significance of the receptor is explained by evident faults in the headworks, which may result in greater risk of localised pathways of contamination.

Upgraded wells (Fig. 6)

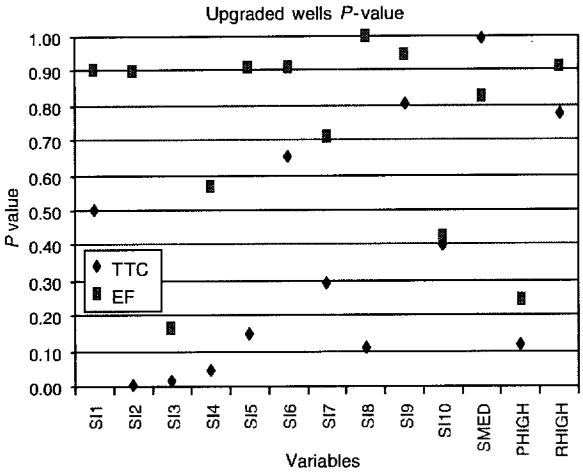
Results summary: upgraded wells

Three risks were identified as being of significance for upgraded wells:

- solid waste <30 m,
- animal excreta <30 m and
- deficient headworks (no well cover).

Discussion

Analysis of specific pathways to contamination supports the view that localised pathways are significant in northern Mozambique. This supports earlier studies by BGS and Robens (ARGOSS 2002). In traditional wells, localised pathways or direct ingress of contamination were a significant variable in the presence of EF contamination.



SI no.	Hazard	Result		Risk
		TTC	EF	
1	Latrine <30 m	0.50	0.90	Low
2	Animal excreta <30 m	0.00	0.89	High/Low
5	Solid waste <30 m	0.15	0.91	High/Low
8	Deficient headworks	0.11	1	High/Low
9	No well cover	0.81	0.97	Low
	Pathway category	0.11	0.28	High/Low

Fig. 6. Upgraded well sanitary inspection records. EF, enterococci; TTC, thermotolerant coliforms.

In improved and upgraded wells, localised pathways were significant for both TTC and EF. To manage the risk through localised pathways, the study recommends the application of WSPs as outlined in the third edition of the WHO GDWQ (Godfrey *et al.* 2005). To achieve this, hazards are identified from the risk assessment and are then ranked according to the severity of their risk based on recommendations outlined in Davison *et al.* (2004) and WHO (2004). A control measure (defined as steps in drinking-water supply that directly affect drinking water quality) is assigned to each hazard event, and then a method of monitoring these measures is considered with an emphasis on simple, frequently repeatable methods (e.g. sanitary inspection or turbidity monitoring). These control measures are then verified using microbial indicator organisms.

Furthermore, the findings in Mozambique indicate that, statistically, EF would be a more appropriate indicator for all three well types studied than TTC. In agreement with studies by Massa *et al.* (2001), this study notes that evidence from analysis of polluted groundwater waters suggests that EF may be 'a more reliable indicator of faecal pollution than faecal coliforms in raw water' (Massa *et al.* 2001). EF displayed a higher survival and was less susceptible to die-off, dilution or filtration (Bitton *et al.* 1983; Melian *et al.* 1999; Maeler & Merkle 2000; Massa *et al.* 2001). Their greater survival at depth in this study suggests that EF may be a more appropriate means of verifying the compliance of the system to the control measure.

Conclusions

The objective of this paper was to develop improved methods for the assessment and management of microbiological water safety based on a 'risk' paradigm. To achieve this objective, this paper concludes that the following points are critical for the effective assessment and management of groundwater microbiological risk.

(1) Localised pathways are significant pathways in the risk of contamination of shallow groundwater in northern Mozambique. Contamination through *aquifer* pathways from latrines/septic tanks was not as insignificant as contamination from animal faeces.

(2) The use of alternative indicator organisms (e.g. EF) may improve risk understanding associated with short circuiting. The findings indicated that although TTCs are more prominent in traditional and upgraded wells, EFs are a more detectable organism at depth in improved wells.

(3) The study recommends the WHO WSPs as an appropriate method of risk management.

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