Research Paper

Spatial arrangement of well and latrine and their influence on water quality in clayey soil – a study in low-income peri-urban neighborhoods in Lichinga, Mozambique

Beni Jequicene Mussengue Chaúque, Carlos Miguel Chicumbe, Virgílio Carménia Cossa and Marilise Brittes Rott

ABSTRACT

In this study, the influence of the spatial arrangement of shallow wells and pit latrines on water quality was evaluated in clayey soil during dry and rainy seasons, using 123 randomly selected wells. The distance between well and the nearest latrine was measured and the location of the well in the yard was characterized. The colony forming units (CFU/100 mL) of fecal coliforms were quantified, and pH, electrical conductivity (CE) and turbidity were measured. 100% of the wells were located less than 25 m from the latrine, 74.8% were located in the middle of the yard. In the dry season, 42.4% of the samples presented up to 12 CFU/100 mL, and in the rainy season, 84.4% presented up to 139 CFU/100 mL. 56.9% had pH values between 6.5 and 8.5, and 63.4% presented EC values between 50 and 571 μS/cm. In the dry season, 40.7% of the samples had values below 5 NTU, and 59.3% up to 50 NTU. In the rainy season, 86.6% had values between 6 and 300 NTU. Pearson's correlation between all variables was weak. The wells are susceptible to high fecal contamination, although the clayey soil seems to mitigate the expected high levels of microbial contamination.

Key words | distance from the latrine, fecal coliforms, fecal contamination, latrines, shallow domestic wells, well location

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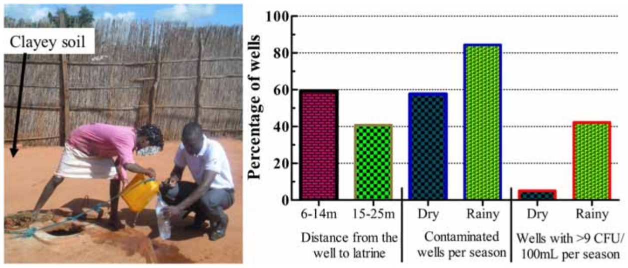
HIGHLIGHTS

- 100% of the wells are less than 25 meters from the nearest latrine.
- In 57.6% of the dry season samples, bacterial CFU/100 mL were not detected.
- In the rainy season, 84.4% of the samples were positive for bacterial CFU/100 mL.
- The clay soil seems to mitigate the expected high levels of bacterial contamination.

doi: 10.2166/washdev.2021.137

GRAPHICAL ABSTRACT



INTRODUCTION

Diarrheal diseases stand out among water-borne diseases and cause about 829,000 deaths annually worldwide (WHO 2019b), although they are a challenge in developed countries, they are more prevalent in developing countries (Pandey *et al.* 2014; WHO 2019a). This situation is related to the ingestion of pathogens in the water, since about 25% of people worldwide and more than 50% in Africa do not have access to water free from microbial contamination (Bain *et al.* 2014; Nowicki *et al.* 2019; WHO 2019a; Ferrer *et al.* 2020). A large percentage of people without access to contaminant-free water are in developing countries, in sub-Saharan Africa (Martínez-Santos *et al.* 2017) whereby the majority of deaths from water-borne diseases are reported. In these countries, a large part of the population consumes water from wells, which in most cases, has a high density of microorganisms that indicate fecal contamination (Lewis *et al.* 1982; Graham & Polizzotto 2013). Fecal contamination of well water has been strongly associated with poor basic sanitation, the presence of latrines and the geomorphological characteristics of the soil (Nichols *et al.* 1983; Knappett *et al.* 2011; Pujari *et al.* 2012; Graham & Polizzotto 2013).

Mozambique is one of the countries with a high prevalence of water-borne diseases and this situation is, partly, associated with the fact that access for drinking water and basic sanitation are still challenging. In Mozambique, about 16.7% of families have access to safely managed drinking water services, and about 38.9% of the population has adequate sanitation (MOPHRH 2018; INE 2019). About 66.6% of the entire population lives in rural areas, and about 43.1% of the rural population has access to a limited drinking water service (MOPHRH 2018; INE 2019). About 39.1% of the Mozambican population consumes water from improvised sources, about 66% of the population uses pit latrines, and about 24.4% still defecates outdoors (INE 2019).

Although the use of latrines is needed because it reduces the occurrence of poor sanitation-associated diseases (Montgomery *et al.* 2010; Capone *et al.* 2020), these have been largely implicated in contamination of groundwater explored through wells (Lewis *et al.* 1982; Verheyen *et al.* 2009; Graham & Polizzotto 2013; Ferrante *et al.* 2018; Ndoziya *et al.* 2019).

The contamination of water in the wells by microorganisms and chemical substances from the latrines is caused by several factors, including, the proximity of the latrines to the well. Lateral distances below 50 m were associated with the presence of adenovirus and rotavirus in well water (Verheyen *et al.* 2009), and lateral distances up to 25 m increase the risk of contamination by bacteria and chemicals (Caldwell 1937; Caldwell & Parr 1937; Dzwairo *et al.* 2006; Graham & Polizzotto 2013). Similarly, soils with high particle size, rocky, sandy, or swampy soils, and the rapid reload of aquifers during heavy rains increase contamination of well water through fecal origin contaminants (Caldwell 1938; Howard *et al.* 2003; Pujari *et al.* 2012). Wells located in low relief areas have been reported to have a higher burden of fecal contamination and were more strongly implicated in cases of diarrhea than those located in high relief areas (Uprety *et al.* 2020). The literature suggests that microorganisms of greater longevity and/or smaller sizes are more likely to reach the well while they are still viable and/or travel a greater lateral distance from the latrine to the well (Taylor *et al.* 2004; Verheyen *et al.* 2009; Graham & Polizzotto 2013).

The access of microorganisms of fecal origin to the wells can occur in several ways, for example: (1) they can be leached from the soil surface, accessing the well through its upper opening; (2) pass through the soil pores, moving from the soil surface or the latrine wall to the well water; (3) water contamination in the well can, also, directly occur through water from contaminated aquifers (Martínez-Santos *et al.* 2017). It has been shown that wells dug in low-permeability soils, such as clay soils, are less prone to contamination because the lower porosity associated with their absorption properties limits the movement of microorganisms (Pujari *et al.* 2012; Martínez-Santos *et al.* 2017; Unuabonah *et al.* 2018). However, in the field situation, the potential for removing microorganisms by clayey soils must be considered in synergy with the implementation of safe lateral distances, always admitting the possibility of geological heterogeneity of the soil (Schijven & Hassanizadeh 2000).

Nevertheless, it is plausible to say that the level of contamination of the soil surface influences the rate of contamination of the wells by different microorganisms, including those of fecal origin. Thus, it is safe to say, that the higher the microbial load on the soil surface next to the well and fewer barriers that prevent these microorganisms from accessing the well water, the higher is the frequency of contamination and the microbial load in the well water. This thought is corroborated by the longitudinal study of Chambers *et al.* (2009), who showed that the surface of sidewalks and puddles near roads had a high relative density of fecal coliforms. These authors demonstrated that, in each footprint, about 10% of the bacteria on the soles of shoes used for walking were moved to previously sterilized floor surfaces. The impact of shoe soles as vectors of microorganisms for floors in hospital, industries, community, and domestic environments has been revised (Rashid *et al.* 2016). The soles of shoes have been implicated as being vectors of several microorganisms, including *Escherichia coli*, fecal coliforms (Chambers *et al.* 2009), *Listeria monocytogenes* (Schoder *et al.* 2015), *Salmonella* spp. (Haddock & Nocon 1994), *Staphylococcus aureus* and *Enterococcus faecalis* (Paduszyńska *et al.* 2014). Evidence in the literature suggests that the floor surfaces that people frequently use are highly contaminated by microorganisms and are potential sources of pathogenic inoculum (Chambers *et al.* 2009; Rashid *et al.* 2016). The influence of the proximity of these surfaces on the water quality of wells has not yet been elucidated and the associated risk needs to be quantified, so that feasible barriers can be used to avoid possible contamination of wells.

This study aimed to evaluate the spatial arrangement of well and latrine and their influence on water quality in clayey soil, in low-income peri-urban neighborhoods (Lucheringo and Estação) in Lichinga city. Lichinga city was chosen because it is located in an area with clay soils (MAE 2014). These low-income suburban neighborhoods were selected because the wells and latrines in these areas are dug by hand, most of them without interior lining, and are the main source of water and for treatment of human feces.

A significant association between family income and the proportion of positive samples for total coliforms for well water in rural areas was found (Smith *et al.* 2014). These authors' findings suggest that low-income families tend to build wells that are more susceptible to fecal contamination than higher-income families. This is particularly true because low-income families in suburban neighborhoods generally live in smaller yards that do not allow safe spacing between the well and the latrines, which are hand-dug, shallow, and without an interior lining, increasing the possibility of water and feces to directly come in contact with the soil (Martínez-Santos *et al.* 2017).

Considering all of this, the wells in the Lucheringo and Estação neighborhoods were suitable for the purpose of this study, as the characteristics of the wells and latrines in these neighborhoods allow us to hypothesize the worse possible scenario of well water contamination by latrines. This clearly allows understanding the influences of the lateral distancing and the location of the wells in the yard for the water quality of shallow wells on clay soil.

METHODS

Study area

The study was carried out in the district of Lichinga, at Administrative Post number 2, Chiuaula, specifically in the Lucheringo and Estação neighborhoods. Lichinga district includes suburban neighborhoods and the city of Lichinga, which is the capital of the province of Niassa, located in northern Mozambique. Lichinga district is a plateau region, above 1,000 m altitude, and has a territorial extension of 5,422 km^2, with a population of 114,024 inhabitants, where 51.4% are women (INE 2012; MAE 2014) (Figure 1). The average annual temperature is between 18 and 24 °C, but on most days of the year it is between 18 °C and 22 °C (MAE 2014). The soils are, predominantly, red clay (Rhodic Ferralsols or Ferralitic), although they may still appear associated with orange, yellowish, and gray ferralitic soils (MAE 2014).

In the entire district, only 1% of the families have access to safely managed drinking water sources inside or outside their yards. About 64% use water from wells and, of that percentage, 75% use unimproved water sources, and about 29.7% use surface water from ponds or rivers (INE 2012).

Water sampling

The study was longitudinal and covered 123 shallow domestic wells. All the selected wells for the study were dug by hand and are cylindrical, not exceeding a depth of 20 m and without an internal lining. Stratified probabilistic sampling was used to split the two neighborhoods into four plots, according to the number of houses (Figure 1). Within each plot, the wells were randomly selected, observing an interval of 25 houses organized in a straight line to separate the sampling points.

The water was not analyzed directly in the well. Samples of 500 mL of water were collected in PET bottles of mineral

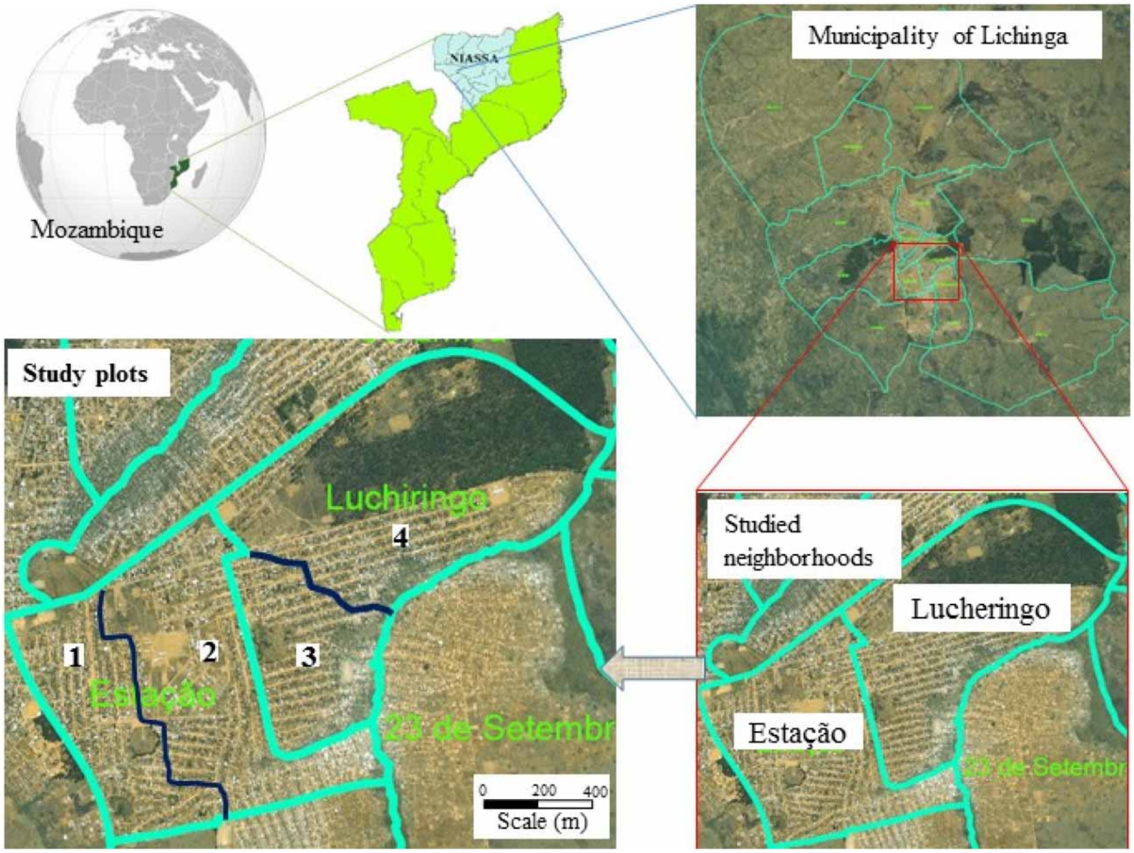


Figure 1 | The geographic location of the studied neighborhoods.

water. In each pack of 24 new, sealed PET bottles containing mineral water, four bottles were randomly selected, sampled, and subjected to analysis for the presence of fecal coliforms to assess the sterility of the bottles. In all the sampled bottles of water, the presence of fecal coliforms was not detected. The outer surface of the sealed PET bottles containing mineral water was washed with chlorinated water by the addition of sodium hypochlorite (8 mg/L). The standardization of water with 8 mg/L of available free chlorine prepared from sodium hypochlorite (NaOCl – 12%, JT Baker) was performed using the N, N-diethyl-p-phenylenediamine (DPD) method (APHA 2005). Shortly before the collection of each sample, the bottle was emptied and acclimated, filling it with water from the well and pouring it out three times, then the sample was collected (Figure 2). The samples were collected in duplicate and preserved on ice until the analysis. Sixty samples were collected in the dry season (May and July) and 63 in the rainy season (December and January). The samples were processed within 4 hours after collection.

Field data collection

Before collecting each water sample, the lateral distance between the well and the nearest latrine was measured with a tape measure. The distances between the well and each latrine belonging to the entire adjacent lot of latrines were considered, and the shortest distance was included in the data.

The location of the well in the yard was visually determined. The well located in the central part, or in any other part of the yard close to where people usually walk, was considered to be in the middle of the yard and was coded with the number 1; the opposite was considered to be at the edge of the yard and was coded with number 0.

Analysis of water samples

The microbiological analyses aimed to determine the number of colony forming units (CFU) of fecal coliforms, using method 10029, from the company Hach, as previously described in the literature (Adhikari *et al.* 2020), with modifications. Briefly, 100 mL of undiluted sample was filtered and the membrane was transferred to a plate containing an absorbent pad that was previously soaked in 2 mL of tryptose lauryl sulfate broth (LSB). Fecal coliforms CFU were checked after 24 hours of incubation at 44 °C. Mineral water samples were used for the negative control. All the colonies were counted, and the results below the detection limit were considered 0 to find out the average. The turbidity was measured using a digital turbidity meter (HANNA brand HI 98703 Turbidimeter), based on the manufacturer's guidelines. The pH and electrical conductivity (EC) were measured using a HANNA-edge digital multifunctional meter, based on the manufacturer's guidelines.

Data analysis

An arithmetic average was calculated between the CFU values of the duplicates of each sample. The normality of data was verified by the Shapiro–Wilk test at 5% level of probability. The data were submitted to descriptive statistics (minimum, maximum, average, and standard deviation). The

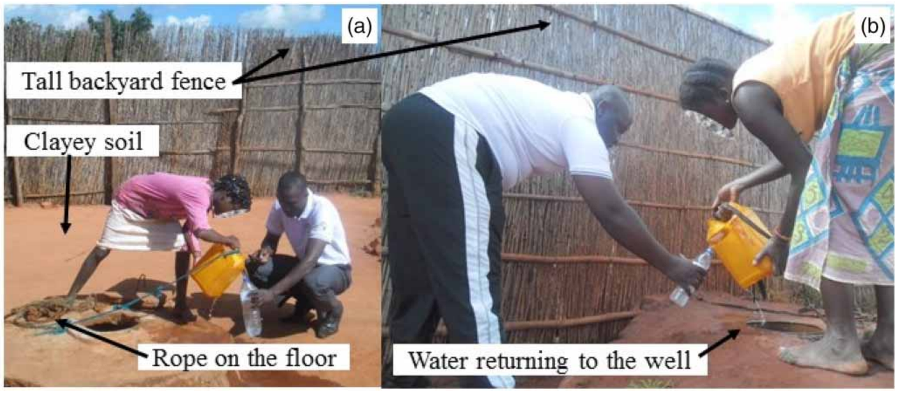


Figure 2 | Collection of samples from wells located in the center (a) and on the edge (b) of the yard.

two-tailed paired t-test was used to determine the differences between the data from dry and rainy seasons. As well, Pearson's correlation was determined among the variables studied. Significant differences were considered once $p < 0.05$. The analyses were done based on BioEstat 5.0 and GraphPad prims 8.02 software.

RESULTS AND DISCUSSION

The results of the 123 shallow domestic wells randomly selected revealed that 58.5% of the wells were located at a lateral distance less than 15 m from the nearest latrines (Figure 3(a)). Most of the domestic wells (74.8%) are located near the areas people usually walk, even when they are not fetching water.

The results (Figure 3(a) and Table 1) show that the wells are not far enough from the latrines, therefore, they are in the fecal contamination risk zone (Ngasala *et al.* 2019). Nevertheless, 41.5% of the wells are more than 15 m away, which is the minimum lateral distance recommended by health authorities in Mozambique (MISAU 1995); the influence of latrines in wells located at 25 m has been reported (Dzwairo *et al.* 2006). The ideal distance reported by the literature ranges from 30 to 50 m (Parker & Carlier 2009; Graham & Polizzotto 2013; Martínez-Santos *et al.* 2017). The standardized distances in the sub-Saharan African countries' guidelines are based on the assumption that wells must be far enough away whereby the movement of microorganisms of fecal origin can take, at least, 25 days until reaching the nearest well (Parker & Carlier 2009). This traveling time is considered long enough to reduce the loads of indicators of fecal contamination to undetectable levels (ARGOSS 2001; Martínez-Santos *et al.* 2017). It is important to note that these standardized fixed distances are not effective in all situations. Geological, hydrological, and human factors, as well as the resistance and longevity of pathogens, can contribute to the continuity of the risk, even when this distance is considered (Hernandez-Cortazar *et al.* 2017; Mena-Rio & Quirós-Veja 2018; Ferrer *et al.* 2020; Houéménou *et al.* 2020).

In general, it was noticed that a considerable number of the wells were built as distant from the latrine in the same yard as possible, but in most cases, it was noticed that they were close to the latrines in the neighboring yards. It is necessary to mention that the distances considered safe by the literature are impossible to be applied in the contexts of peri-urban settlements, as the yards are not large enough to allow the ideal distance between the well and the latrine. This means that the spatial coexistence between wells and latrines in peri-urban contexts will always be a problem; therefore, the adoption of water treatment methods at the point-of-use is extremely necessary.

Table 1 | Characterization of the data of the studied variables

				CFU/100 mL		Turbidity	
	Distance	**pH**	**EC**	**Dry**	**Rainy**	**Dry**	**Rainy**
Samples	123	123	123	60	63	60	63
Avg.	14	7	106	2	14	10	106
StDev.	4	1	109	3	24	10	98
Max.	25	9	571	12	139	50	300
Mín.	6	5	8	0	0	1	3

The results of fecal coliforms are expressed as CFU/100 mL, electrical conductivity (EC) as μS/cm and turbidity (turbidity) as NTU.

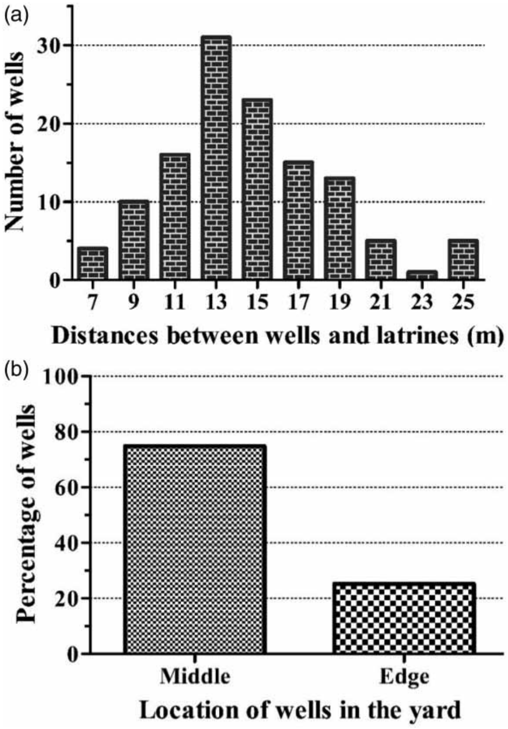


Figure 3 | Lateral distance between the well and the nearest latrine (a) and the location of the shallow well in the yard (b).

Our results (Figure 3(b)) also show that most of the wells were dug in the middle of the yard, meaning that their opening (mouth) is close to the place where people usually walk. This fact is particularly worrying, because the more centralized the well, the greater the chance of it being near the latrine in the same yard. In this study, the size of the yards was not measured and this is a limitation. Although the yards selected were not large enough considering the recommended distance by the literature, most yards measure, approximately, 25 m × 20 m. The other risk associated with this location is that the surface of an area that frequently people pass has a greater chance of being contaminated by microorganisms carried by the soles of shoes (Haddock & Nocon 1994; Chambers *et al.* 2009; Rashid *et al.* 2016). This allows the microorganisms carried from the latrines through the soles of the shoes to reach the edges of the well opening, and then the water in the well (Figure 2). This situation is frequent in the rainy season (Figure 3(b)) when the soil surface is moist for a long period of time and without UV radiation and the sun's heat in abundance, allowing the microorganisms to remain viable for longer, increasing the chance of reaching the water while they are still alive (Castro-Alférez *et al.* 2016, 2017). One of the ways in which microorganisms can be moved from the surface of the floor or the concrete slab around the opening of the well to the water is through the rope attached to the container to fetch water from the well (Figure 2). During the fetching of well water, the rope comes into contact with the surface of the soil several times, where the feet are supported, and then comes back into contact with the water in the well, carrying microorganisms. It is important to highlight that the microbiological risk associated with the location of the well in the yard in a peri-urban context is not based on the high accessibility of the well, but on the lack or insufficiency of barriers that effectively eliminate this risk. In this regard, communities need to be encouraged to build wells in sunny areas and away from the patio walkways. Around the well should be delimited by a fence, and the top of the well should be covered with a waterproof cover and sufficiently wide and oblique. It is necessary to encourage communities, especially in peri-urban contexts, to not consider water from domestic shallow wells as good for immediate consumption, water should be treated before its consumption, as previously recommended (Sobsey & World Health Organization 2002).

The numbers of CFU/100 mL of fecal coliforms found in the dry season and in the rainy season significantly differed from each other ($p < 0.05$). In 57.6% of water samples collected in the dry season, no fecal coliform CFU was detected, 35.6% of the samples had less than 9 CFU/100 mL and 6.8% had up to 12 CFU/100 mL (Figure 4(a)). In the rainy season, fecal coliforms CFU were not detected in 15.6% of the samples, 40.6% of the samples had less than 9 CFU/100 mL, and 42.1% had up to 138 CFU/100 mL (Figure 4(b)).

The wells are at risk (Figure 4(a)) as they are located within the area of the influence of the latrines (Dzwairo *et al.* 2006; Hernandez-Cortazar *et al.* 2017) and most of them are located in the middle of the yard. During the dry season, in most (57.6%) of the water samples, fecal coliforms were not detected and the positive samples showed a low level of contamination. These results were unexpected considering the fact that wells and latrines are shallow, dug by hand, and not lined, allowing water as well as feces to come into contact with the surrounding soil (Lutterodt *et al.* 2018; Capone *et al.* 2020). These data diverge with the data from other works carried out under similar conditions (Martínez-Santos *et al.* 2017). These data can be explained first by the fact that the soil of the Lichinga district is predominantly clayey, with high water filtration capacity and low permeability and porosity (MAE 2014). This increases the amount of time required for the travel of microorganisms, and reduces the flow of water from the latrine to the well (Martínez-Santos *et al.* 2017; Ngasala *et al.* 2019; Ferrer *et al.* 2020) or the retention of microorganisms between soil particles, due to the adsorption properties of the clay (Unuabonah *et al.* 2018). It has been shown that low permeability and longer groundwater residence times are associated with little or no presence of *E. coli* (Leber *et al.* 2011; Van Geen *et al.* 2011). Second, in the dry season, the surface of the soil remains dehydrated for a long period of time and exposed to sun long enough to allow microorganisms to be inactivated by the synergistic effect of heat and UVA and UVB radiation (Castro-Alférez *et al.* 2016, 2017).

Unlike the dry season, in the rainy season, the percentage of contaminated wells and the number of CFU counted per 100 mL were significantly high (Figure 3(b) and Table 1).

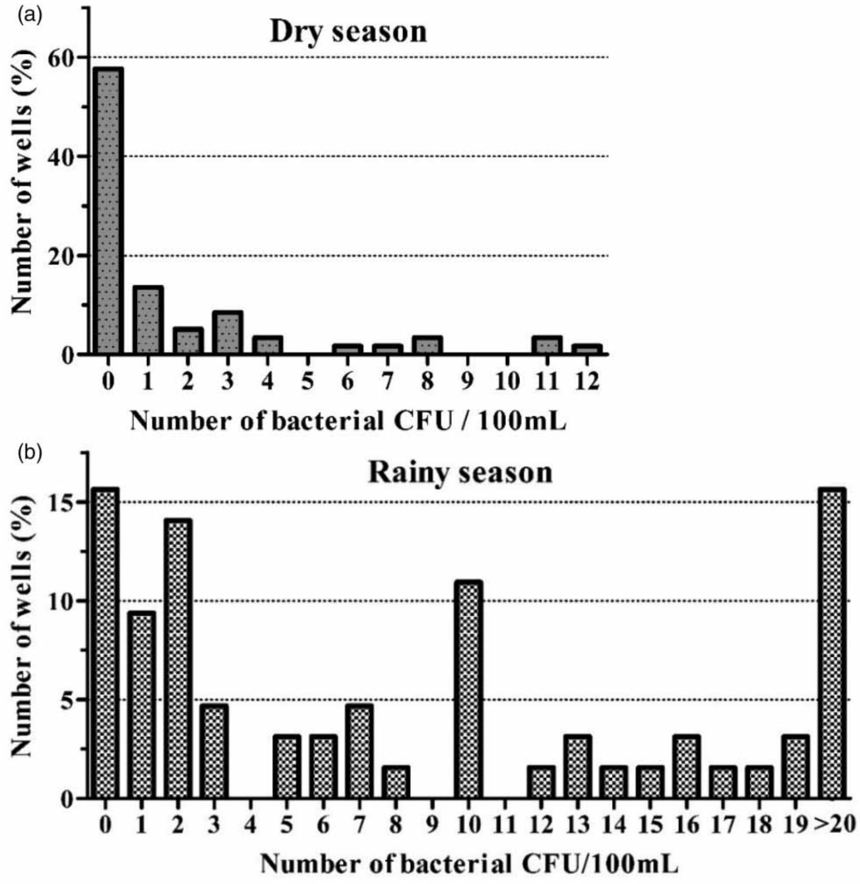


Figure 4 | Number of coliforms in shallow well water in the dry season (a) and in the rainy season (b).

These data are in line with the results of several teams of researchers who reported high levels of microbial contamination during periods of heavy rain (Van Geen *et al.* 2011; Kayembe *et al.* 2018; Ferrer *et al.* 2020). The authors noticed that, in the rainy season, contamination was significantly more intense in areas with sandy or heterogeneous soils, as well as in areas located in low relief areas, especially when the wells are not over 30 m away from the latrines (Ngasala *et al.* 2019; Ferrer *et al.* 2020; Uprety *et al.* 2020). In addition, the fact that the wells and latrines are dug by hand and without internal lining, and the rapid reload of shallow aquifers during the rainy season, as well as the absence of a concrete slab wide enough over the wells, allows intense fecal contamination (Lutterodt *et al.* 2018; Capone *et al.* 2020; Ferrer *et al.* 2020).

It is interesting to note that although the number of CFU/100 mL in the water of many wells was high, especially in the rainy season, the density of coliforms was unexpectedly low, since the wells are highly susceptible to fecal contamination. This seems to result from the mitigation of the contamination by the clayey soil. This assumption is reinforced by the results in Table 2, which show a weak Pearson correlation between the variables studied.

We believe that the location of the wells in the yard close to where people often pass, as well as the manual lifting of water from the well using a rope that often comes into contact with the soil, are factors that also contribute to contamination of the water. Likewise, because the soil is not very permeable to water infiltration, on days of intense rain, water can flood in the backyards and latrines (which are shallower than wells), spreading fecal contaminants over the surface. Associating this factor with the factors previously mentioned (proximity to latrines, location of wells in the yard, moisture on the soil surface for longer, manual

Table 2 | Pearson's correlation between the data of the variables studied in the dry season above diagonal and rainy season under diagonal

	Distance	CFU	Location	Turbidity	pH	EC
Distance		0.0189	– 0.0848	– 0.1135	0.1107	0.0741
CFU	0.0500		0.0220	0.1697	– 0.0609	– 0.0606
Location	– 0.1431	– 0.0009		– 0.1346	0.1489	0.0298
Turbidity	– 0.1393	0.0709	0.0069		0.0944	– 0.2598
pH	0.0633	0.3575	– 0.1471	0.0514		– 0.2747
EC	0.0208	– 0.0368	0.1169	– 0.0132	– 0.2754	

water fetching) increases the frequency and dose of contamination of well water. Although the residents are cautious at building wells on the side of the yard with greater relief, or to coat the well opening with a concrete slab or to accumulate soil around the well opening (Figure 2), there is still the possibility of surface water entering the well on high precipitation days.

The water pH values of shallow wells measured in the dry and rainy season did not significantly differ ($p < 0.05$), that is why an arithmetic average was calculated and presented on a single graph. In 56.9% of the samples, pH values varied between 6.5 and 8.5 and 41.5% of the samples had pH values below 6.6 (Figure 5).

The EC values measured in the dry and rainy season did not show statistically significant differences ($p < 0.05$), and an arithmetic average was calculated and plotted on the same graph. In 36.6% of the samples, EC values below 50 μS/cm were obtained (Figure 6).

In general, it can be said that the parameters pH (Figure 5) and electrical conductivity (EC) (Figure 6) are within the recommended limits for drinking water (BR 2004; MS & SVS 2006). The fact that the values measured in the dry season and in the rainy season showed that pH and EC variables do not significantly differ ($p < 0.05$), suggests that the chemical composition of the water was slightly impacted by the hydrological stations. However, these data are not sufficient to suggest that the water in the wells is not being contaminated by fecal sludge. Future studies will need to measure these parameters in well water and in the fecal sludge, to see if they are substantially different. A considerable difference may be associated with low contamination, depending on the distance between the latrine and the well, the season and the amount of water and fecal sludge in the latrines.

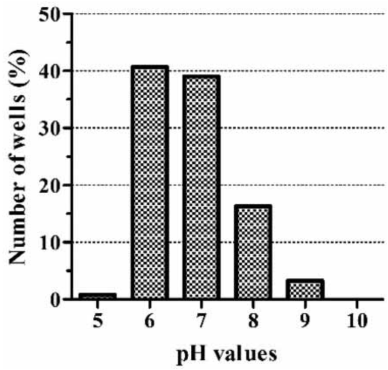


Figure 5 | pH values of water from shallow wells measured in both seasons (dry and rainy).

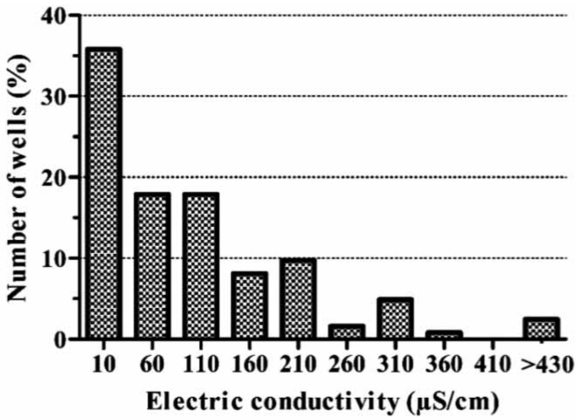


Figure 6 | Electrical conductivity values of shallow well water measured in dry and rainy seasons.

The values of water turbidity measured in the dry season and in the rainy season significantly differed ($p < 0.05$). In the dry season, 54.2% of the wells showed turbidity values up to 5 NTU, 27.1% between 6 and 10 NTU and 23.7% between 11 and 50 NTU (Figure 7(a)). In the rainy season,

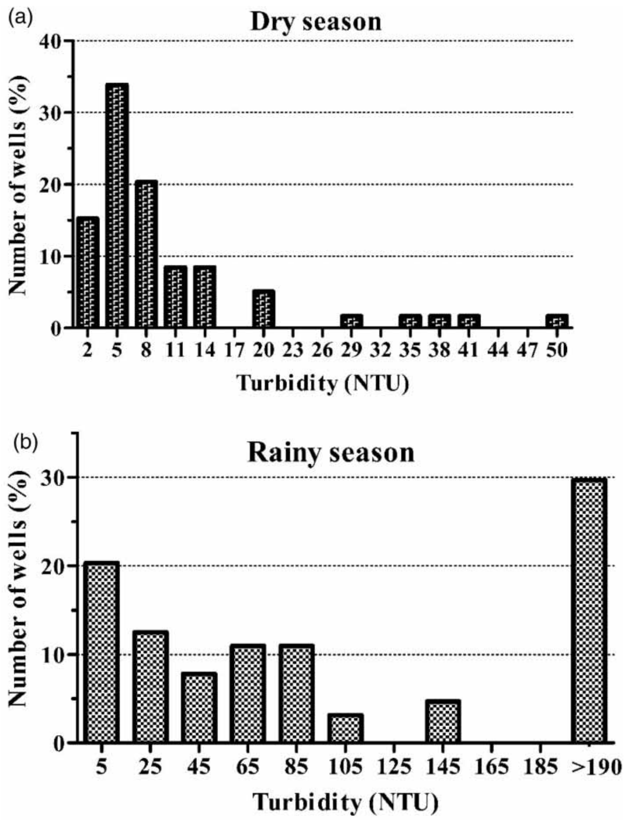


Figure 7 | Water turbidity of shallow wells in the dry season (a) and rainy season (b).

12.5% of the wells showed turbidity values up to 5 NTU, 7.8% between 6 and 10 NTU and 79.7% between 15 and 300 NTU (Figure 7(b)).

The water turbidity values showed a wide temporal variation, being moderate in the dry season (Figure 7(a)) and extremely high in the rainy season (Figure 7(b)). The low level of water turbidity is partly explained by the fact that Mozambique has just two seasons, rainy and dry. Therefore, the dry season is very long and, consequently, a long time passes without the aquifer recharging quickly, which reduces the possibility of severe water turbidity (Howard *et al.* 2003). It is important to highlight that the slight but significant water turbidity in the dry season is essentially because the wells have no internal coating. In addition, the soil particles have a very small particle size and are light enough to be detached from the well walls by water movement during water fetching. The rapid reload of shallow aquifers during the dry season and the clayey soil are the main factors for the high turbidity of water in the wells during the rainy season (Howard *et al.* 2003; Van Geen *et al.* 2011; Kayembe *et al.* 2018), mainly at the beginning of the intense rainy season.

Our data partially converge with the report by the health authorities of high rates of gastrointestinal diseases and chronic malnutrition, mainly in children, the peak of which is in the rainy season. The highest percentage of deaths from diarrheal diseases is recorded in rural or peri-urban areas (INE 2009), whereby, in most cases, shallow wells are the only 'improved' available sources when compared to surface waters (INE 2019). Gastrointestinal diseases transmitted through water are one of the factors that perpetuate the cycle of poverty, as most of the time they result in diarrhea that, in turn, results in dehydration, malnutrition, and low intellectual development (WHO 2019c). This affects children's learning ability and the development of school skills, which in the future will result in disadvantageous situations in different life opportunities.

Recommendations

Our results suggested that the construction of wells and latrines is done on an ad hoc basis in the neighborhoods in which this study was conducted, and this finding can be extrapolated to other peri-urban neighborhoods in the Lichinga district, to the province of Niassa and to the whole country. This reality reflects the situation of unplanned rural and peri-urban settlements in most countries in sub-Saharan Africa (Martínez-Santos *et al.* 2017).

It is necessary to implement different strategies to reduce the risk of contamination of the wells; for example, wells should be built in sunny areas, distant from the backyard's walkways and surrounded or protected with a fence. The interior of the wells should be lined and the upper part covered with a large concrete slab and oblique enough to prevent surface water to be in contact with the well water. People should be advised to not let the rope used to lift water from the well be in contact with the floor. Water from domestic shallow wells, especially in suburban areas, should not be considered good for immediate consumption; therefore, the implementation of water treatment at the point-of-use should precede water consumption. Water treatment should be carried out in reservoirs, not in wells, because water treatment inside the well is not efficient (Martínez-Santos *et al.* 2017). The interior of latrines should be lined with an impermeable material to prevent feces from coming into direct contact with the soil, and to prevent fecal sludge from overflowing on days of intense rain. It is ideal to build small systems to extract and treat water from deep wells and then distribute it through pipes, or have protected areas for the construction of systems to extract and supply groundwater.

Although the construction of drinking water treatment and distribution systems on an industrial scale is considered expensive, it is important to consider the implications of the water and sanitation problem in people's quality of life and for the economy in the medium and long term. Investment in large-scale water supply systems serve to resolve many of the health and sanitation problems, and it can have a positive impact on nutrition and education, and improve the quality of other social services that affect the well-being of the population. It is important and necessary that health education campaigns are carried out as well as inspection on the observance of safety rules when building wells and latrines.

CONCLUSIONS

This study aimed to evaluate the influence of the spatial arrangement of wells and latrines on water quality in clayey soil. The distance between the well and the latrine was measured, the location of the well in the yard was characterized, and the microbiological and physical-chemical quality of the water was analyzed during the dry and rainy season. This study confirmed the impact of latrines on fecal water contamination in shallow wells, in the context of low-income peri-urban neighborhoods, and it was found that the wells are highly vulnerable to microbial contamination of fecal origin. However, although microbial contamination is high, especially in the rainy season, the level of contamination was below the expectations, and this seems to result from the mitigation of the contamination by the clayey soil.

ACKNOWLEDGEMENTS

The authors would like to thank the Rovuma University, Niassa Branch, Mozambique, for the financial support to conduct this research and for the residents of Lucheringo and Estação neighborhoods for their collaboration.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 10 June 2020; accepted in revised form 4 September 2020. Available online 5 January 2021