Coliform bacteria and salt content as drinking water challenges at sand dams in Kenya

Doug Graber Neufeld, Bernard Muendo, Joseph Muli and James Kanyari

ABSTRACT

Sand dams can be an effective community-scale solution to increasing water supplies in some arid and semi-arid regions, but there are few studies that have investigated water quality at sand dams. This study investigated the levels of coliform bacteria and salt content as parameters of potential concern. Most water taken from sand dam sources had fecal coliforms present. Median fecal coliforms were in the range of 150–800 cfu/100 ml for unprotected sources (scoop holes, surface water or hand dug wells), levels which are considered high or very high health risk. Pump wells had less contamination, with fecal coliforms detected in one-third of samples in the dry season. Despite this contamination, user surveys indicated that 74% of communities generally view water as clean for drinking, and 72% reported that no or few people in their community treat their water. Salt content in the dry season was in the poor or unacceptable range (above 900 ppm as total dissolved solids) in 33% of water samples. Results suggest that fecal coliforms and salt content represent two types of challenges to water quality at sand dams: fecal coliforms are a health hazard, whereas high salt content potentially reduces the amount of usable water that is available.

Key words | coliform bacteria, sand dam, sanitation, WASH, water harvesting

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INTRODUCTION

For residents of arid and semi-arid lands, residents must not only find water in sufficient quantity, but find water that is free from contamination for drinking, livestock and crop watering, and other household uses. In the semi-arid Ukambani region of southeastern Kenya, sand dams have been successfully promoted as community-level solutions to providing sufficient water (Lasage *et al.* 2008; Teel 2019). Sand dams are conceptually simple, and over the long term are one of the most cost-effective strategies of water harvesting if utilized as planned (Lasage & Verburg 2015). Concrete dam structures are built on bedrock or other impermeable materials in ephemeral waterways that are common in the region. During the wet season, sediments (ideally sand) accumulate behind the dam structure (see Figure 1(b)), which holds water in the pore space and prevents its evaporation. Sand dams, thus, can hold a substantial volume of water, which communities commonly harvest in the dry season by digging scoop holes into the sand, into which water percolates and then is collected. Although there are no exact records, estimates that several thousand sand dams have been built in the region over the past century attest to their importance in the region for water provision.

The provision of clean drinking water is a major health concern worldwide and, thus, is named as one of the United Nations Sustainable Development Goals. Sand dams have been promoted as providing water which is relatively clean, on the basis that the water in the dam filters through the sand (Hussey 2007; Kimani *et al.* 2015). Although the theory behind this assumption is clear, as analogous sand filters are clearly effective at removing pathogens (Lea 2008), very little work has been done to test the assumption that water extracted from sand dams is clean. The widespread presence of livestock manure on sand dams (often close to scoop wells), and the open nature of the water source, raise concerns that these assumptions of sand dams may be incorrect.

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Figure 1 | Examples from categories of water sources at sand dams used for this study: (a) scoop hole, (b) surface water below the eroded dam, (c) hand dug well, (d) pump well adjacent to sand dam, (e) household water container and (f) rain barrel (blue) for roof water collection. Please refer to the online version of this paper to see this figure in color: http://doi.org/10.2166/wh.2020.192.

This study investigated the water quality of sources that are used by communities at the sand dam, focusing on coliform bacteria and salt content as two parameters of potential concern. To our knowledge, there is only one published study on microbiological contamination in water from sand dams, finding that newly accessed water from deep in the dam is clean, but that water from sources routinely used by community members is not (Quinn *et al.* 2018). Conductivity was also measured, as the reported high salt content of water in the region (Kitheka 2016; Sila 2019) can make the water less desirable to drink and more difficult to use for cooking staples such as beans. We compared these measures of water quality to community perceptions of water quality and self-reported water treatment behaviors.

METHODS

Study site

This study sampled sand dam communities in the Ukambani region of Kenya (Makueni, Machakos and Kitui Counties), a semi-arid region located to the southeast of Nairobi. Although most streams in Ukambani are ephemeral, there are two rainy seasons when heavy storms can rapidly (but briefly) cause waterways to flow strongly, replenishing the water in sand dams. Sampling during the dry season occurred from August to October 2016 by visiting 97 sand dams, 89 of which were randomly selected dams from the records of two local NGOs: Utooni Development Organization (UDO) and Sahelian Solutions Foundation (SASOL). The 89 randomly selected sites were chosen by a random number generator from a comprehensive list of 953 dams which had been constructed since 1990 (records were not available for dams constructed earlier). The remaining eight sand dams visited were constructed during the colonial era, and were selected based on knowledge of their location, and the organization's historical connection with the adjacent communities. In total, 42 dams had water which could be sampled during the dry season. Wet season sampling occurred in November 2016 and April 2017, and visits were made to 37 sand dam sites. Because of time limitations, wet season samples were not randomly chosen: some were selected as sites that had been visited in the dry season, and others chosen as new sampling sites based on ease of access.

Water samples at sand dams were taken from scoop holes (dug by community residents), surface water (e.g. pools or flowing water), hand dug wells (usually open) and pump wells (Figure 1(a)–1(d)). These sources were either on the dam itself, adjacent (e.g. pump wells at the edge of dams which access the aquifer), or in the immediate area below the dam structure (which tends to collect leaked water, or water from the aquifer, and is therefore a common location to find water). Samples at nearby household locations were collected from storage vessels in the house (Figure 1(e)), or from water collected in rain barrels during the wet season (Figure 1(f)). At all sand dam locations, regardless of whether water was present, we conducted group interviews with users to assess perceptions of water quality and use.

Coliform bacteria

Water samples were tested for fecal and general coliform bacteria, standard indicators of microbiological contamination (Tallon *et al.* 2005). Water samples from all sources were plated directly onto Easygel cards (Micrology Laboratories LLC, Goshen, IN, USA) in the field. Easygel cards are based on the same Coliscan method as the Easygel petri dish method, one of the common low-cost standard methods used worldwide (Chuang *et al.* 2011). Cards were stored at −4 °C until taken to the area of Kenya being studied, where they were held at room temperature in a storage container to prevent temperature fluctuations and light exposure. Cards were held in sealed plastic bags in the dark at all times. Cards were then transported to the field for sampling, with care taken not to leave them in a hot vehicle.

We tested 0.5 ml for all water samples except control (bottled water) where 1 ml was used. New sterile plastic pipets were used for each sample. For scoop holes, water was taken from several centimeters beneath the surface directly from the scoop hole. For pump wells, we ran the water for approximately 3 min before taking a sample directly from the water flowing from the nozzle. Cards plated with the water samples were then stored in a cooler to minimize temperature fluctuations during incubation; incubation temperature varied from 25 to 35 °C, depending on the weather at the time. Plates were monitored up to 48 h to monitor growth, and colony-forming units (cfu) were counted and photos taken for all cards once standard colony size was reached. General and fecal coliforms are identified based on colony color.

All samples were performed in duplicate; the average RPD (relative percent difference) between duplicate cards was 44% for fecal coliforms. Negative controls were either purchased bottled water or solar disinfection (SODIS) treated water. Of 25 negative controls tested, two controls had 1 general coliform colony each and the remaining 22 controls had no bacteria.

We used the following commonly used risk categories for fecal coliforms (Gruber *et al.* 2014):

0 cfu/100 ml – safe
1–10 cfu/100 ml – low risk
11–100 cfu/100 ml – intermediate risk
101–1,000 cfu/100 ml – high risk
>1,000 cfu/100 ml – very high risk

Since the water was taken as 0.5 ml samples, the effective limit of detection for two cards was taken as 100 cfu/100 ml. Cards lacking fecal coliforms did not, therefore, imply that water was within the WHO limit of no fecal coliforms per 100 ml. Although this did not allow for fine distinctions at low bacterial levels (e.g. at low or intermediate risk levels), this methodology did allow us to screen for sources of high concern.

Salt content

The presence of undesirable levels of salts in water was assessed by measuring conductivity with a Hanna Pocketester field instrument. The instrument was calibrated at the start of the day to an 84 μS standard solution. Two consecutive measurements were made from each sample, and the average used as the final value. Since total dissolved solids (TDS) in ppm is the more common reporting parameter, we converted conductivity to TDS using a standard conversion factor (0.65).

We used the following WHO categories to rate drinking water based on TDS concentrations (Fawell *et al.* 2003):

<600 ppm – good
600–900 ppm – fair
900–1,200 ppm – poor
>1,200 ppm – unacceptable

Statistics

Bacteria and conductivity data were normally distributed when log-transformed (Kolmogorov–Smirnov Test of Normality), consistent with how microbiological measurements are normally calculated as geometric means. Statistical analyses (ANOVA with Tukey's HSD *post hoc* test, *t*-test), therefore, were performed on log-transformed data.

Perceptions of water quality and use

Community surveys which included questions on perceptions of water quality and use were implemented in the local language, Kikamba, by native Kikamba speakers. Questions were largely open-ended, rather than defining specific categories. Answers were recorded in English, and interviews normally lasted approximately 30 min, which included questions related to water quality and use, in addition to questions related to sand dam functionality (for a separate study).

Given the communal nature of sand dam usage and general social structure of the region, we chose community groups rather than individuals as the interview 'units'. Responses, therefore, represent the collective answers of the interview group. Interviewees were requested to answer based on what they know of perceptions and behaviors of the community as a whole, not just their own perceptions and behaviors. The median group size of interview sessions was 3, with group size varying between a single individual and larger groups of around 10 individuals. Individuals in the groups were those that used the dam and/or were part of the groups that made and managed the dam. A lead spokesperson from the group led responses during the interview process, with input from other community members. The lead interviewee was female in 47% of interviews conducted, and the median age of the lead interviewee was 51.

RESULTS

Drinking water sources

The community survey confirmed that sand dams are a major source of drinking water for communities. More than half of communities that had sand dams relied on water from the sand dam for drinking during the dry season (Figure 2). Most communities collected water from rooftops during the wet season but still relied on water from the waterway with the sand dam.

Coliform bacteria

The median levels of fecal coliforms in surface water, scoop holes and open wells were in the high to very high risk range (>100 cfu/100 ml) in both the dry and wet seasons (Figure 3). Water from pump wells had significantly fewer fecal coliforms than surface water, scoop holes and hand dug wells in both the dry and wet seasons ($p < 0.01$; two-way ANOVA with Tukey's HSD *post hoc* test). These patterns were identical for general coliforms (Figure 4). There was no statistically significant difference between the dry and wet seasons for either fecal or general coliforms ($p > 0.05$). Water from roof rainwater collection during the wet season was less contaminated with fecal coliforms (Figure 3), with only 3 of 14 samples showing fecal coliforms. General coliforms were high in the roof rainwater (Figure 4), apparently bacterial contamination occurred, but was selective for non-fecal coliforms.

At 12 households in the dry season, we asked residents for samples from their household water storage container that they use for drinking. Median fecal and general coliform concentrations were 200 and 2,800 cfu/100 ml, respectively. Thus, stored household water generally reflects the contamination of the sources.

We investigated several design and use characteristics which could affect the degree of contamination of water in scoop holes. Livestock exclusion fencing could keep contamination away from the water source, such fencing was recorded for 22% of the scoop holes visited. There was no significant difference in either fecal coliforms or general coliforms ($p > 0.05$, *t*-test) between fenced and unfenced scoop holes. We investigated whether the depth of the scoop hole was correlated with contamination, with the presumption that deeper sources might have water more extensively filtered. Scoop holes were classified as 'shallow' (<0.5 m depth; $n = 27$), 'medium' (0.5–2 m; $n = 17$) or 'deep' (>2 m; $n = 10$). Although fecal coliforms did not significantly correlate with depth (ANOVA, $p > 0.05$), general coliforms were significantly (ANOVA with Tukey's *post hoc* test; $p < 0.01$) lower in shallow wells compared to medium or deep wells. Finally, clearing water

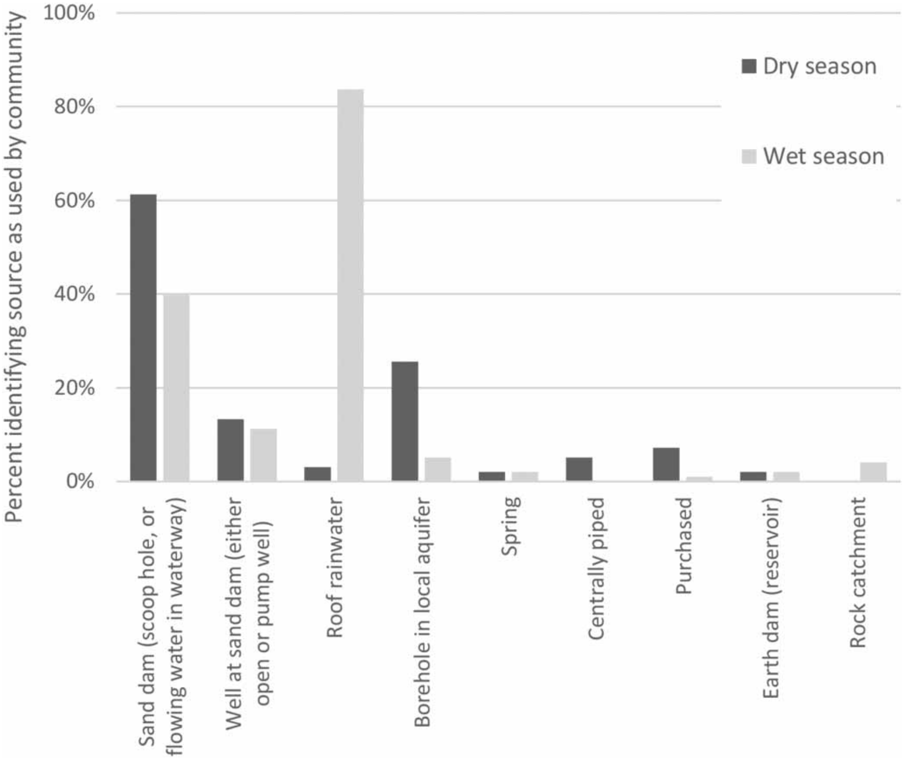

Figure 2 | Drinking water sources during the dry and wet seasons. Interviewees could give multiple answers when multiple sources are used by a community.

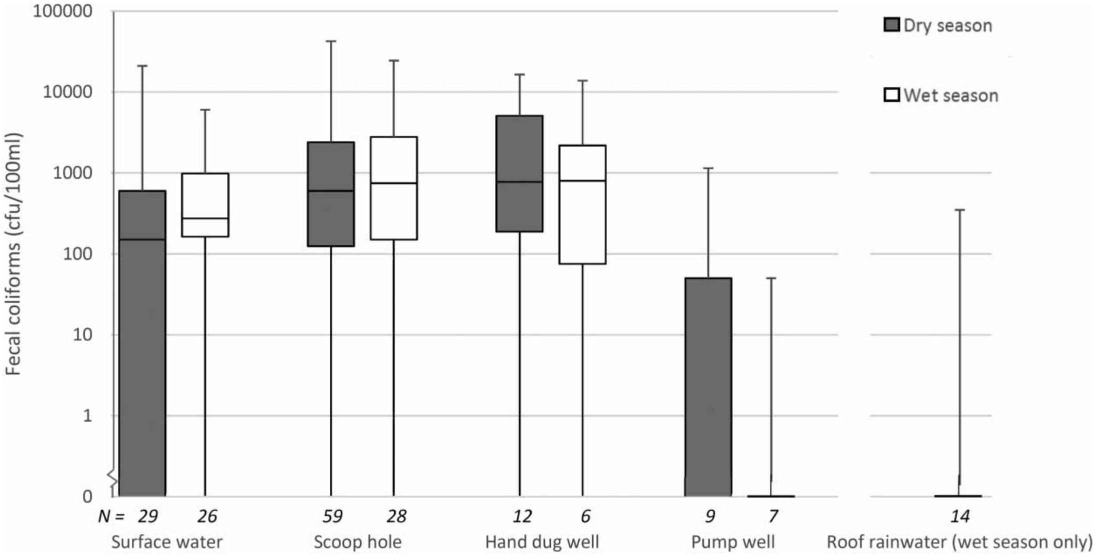

Figure 3 | Fecal coliforms by the type of water sources and season, plotted on a log scale. Box and whisker plot shows median (middle horizontal bar) and first and third quartiles (the lower and upper ends of box). Lines outside box are highest and lowest observations.

from scoop holes and then letting water seep back into the scoop holes is a common practice for residents. We tested bacteria in 12 scoop holes before and after performing this clearing process. Clearing scoop holes did not significantly (paired *t*-test; $p > 0.05$) reduce levels of either fecal or general coliforms (Figure 5). Thus, the contamination of scoop holes occurred regardless of the design characteristics (fencing or depth) or method of use (clearing water before use).

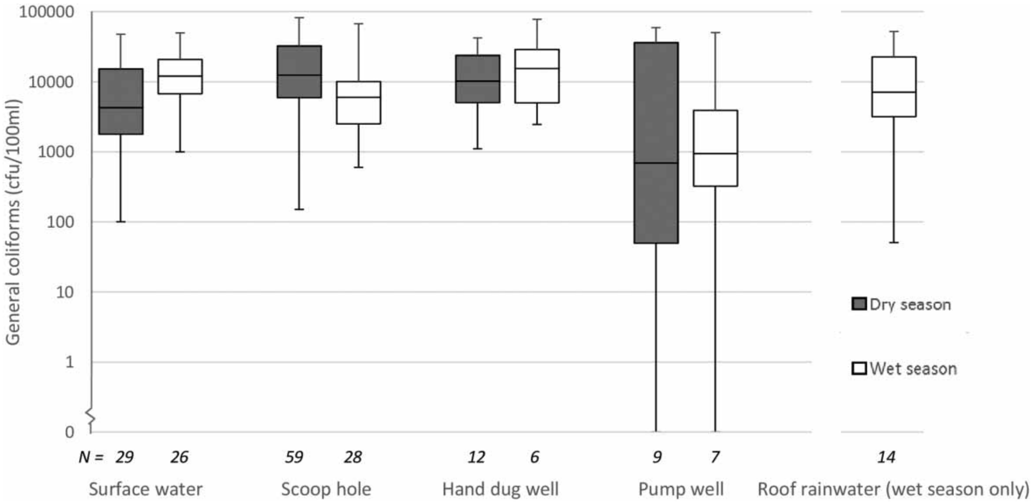

Figure 4 | General coliforms by the type of water sources and season, plotted on a log scale. Box and whisker plot shows median (middle horizontal bar) and first and third quartiles (the lower and upper ends of box). Lines outside box are highest and lowest observations.

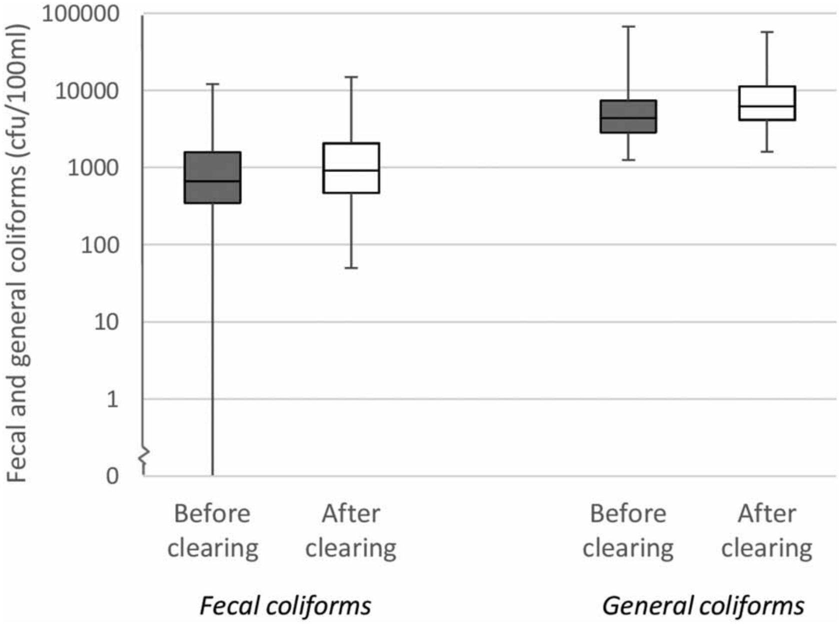

Figure 5 | Fecal and general coliform, plotted on a log scale, before clearing water from 12 scoop holes, and after water has seeped back in.

Salt content

Salt content, calculated as TDS, was frequently in the fair, poor or unacceptable categories in the dry season (Figure 6) but dropped significantly during the wet season ($p < 0.01$; two-way ANOVA with Tukey's HSD *post hoc*). There was no significant difference in TDS between scoop holes, hand dug wells and surface water in a given season ($p > 0.05$), but pumps wells had significantly higher TDS than other sources in both the dry and wet seasons ($p < 0.01$). Rainwater collected from rooftops (wet season) had a very low salt content, with a median TDS of 15 ppm.

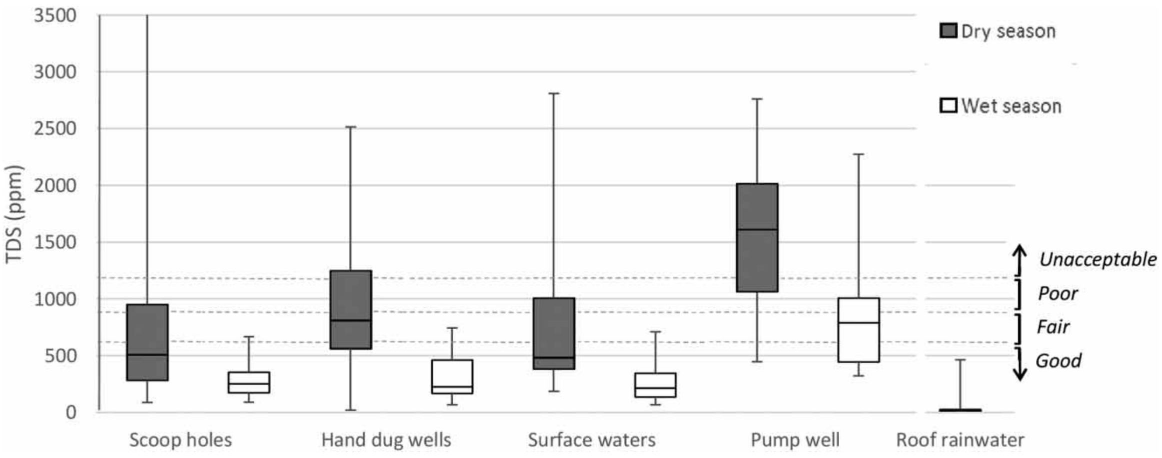

Figure 6 | Seasonal salt content of water sources reported as TDS.

Survey of attitudes and practices

When asked what sand dam users think of water quality, about three-quarters of interviewees indicated that users of the dam generally believed water was clean to drink (Figure 7(a)). For those who believed it was clean to drink, the most common reasons given were that the water looked clear (50%), the sand filtered it (22%), or that they did not observe the water causing illness (18%). For those who believed it was not clean to drink, answers were most commonly that the source was not covered (30%), the water was not clear (17%) or the water was not treated (17%). Most interviewees (nearly three-quarters) reported that no or few sand dam users treat their water (Figure 7(b)), consistent with the majority perception that water is clean to drink. However, 49% of groups who thought water was clean to drink reported that water was still treated at times. When water is treated, the most common methods reported were the commercial chlorine product WaterGuard (76%) and boiling (55%).

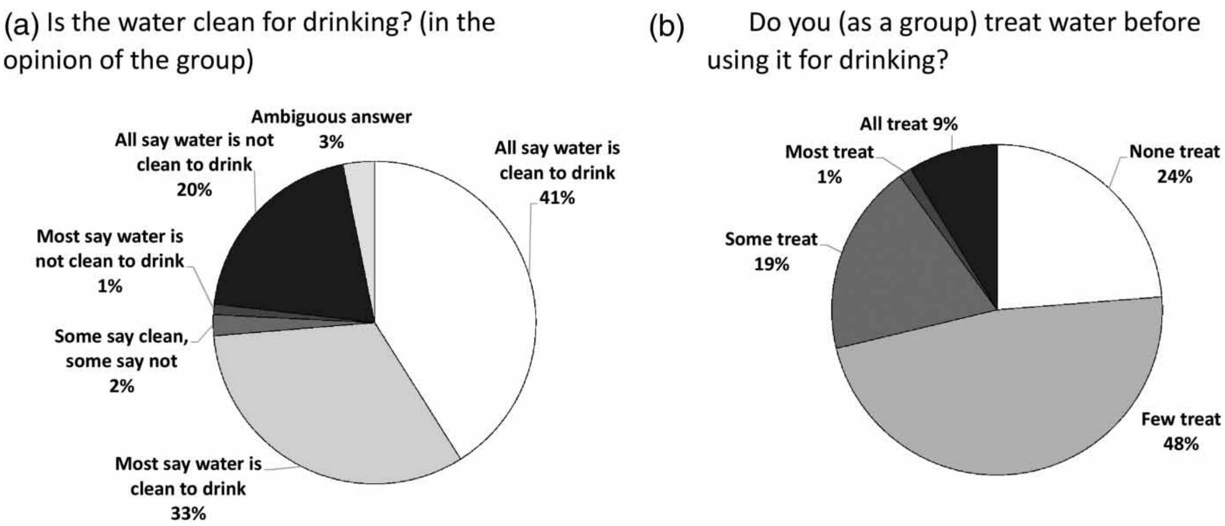

Figure 7 | Perceptions of water cleanliness (a) and frequency of treatment (b) from all water sources at sand dams. Interviewees reported on their understanding of perceptions from that community of sand dam users.

DISCUSSION

Sand dams were a critical source of water for communities in this study (Figure 1), confirming the importance of sand dams in providing drinking water in this semi-arid region. Locally, appropriate means of adaptation such as sand dams will become increasingly important under scenarios of climate change (Aerts *et al.* 2007; Lasage *et al.* 2008), which is already affecting this area in decreased rainfall (Aerts *et al.* 2007). Given the linkage between water quality (especially microbiological quality) and health measures (Hodge *et al.* 2016), it is important to establish whether this reliance on sand dams for drinking water presents a potential health hazard to these communities.

Contrary to assumptions that the water that residents are using from sand dams is clean (e.g. Borst & De Haas 2006; Hussey 2007), this study identifies a high prevalence of fecal coliform bacteria in most water sources, confirming the recent report of high levels of bacteria in established scoop holes of sand dams in the same area of Kenya (Quinn *et al.* 2018). Although contamination in waterways of the region is known (Sila 2019), the study by Quinn *et al.* (2018) is the only published investigation into microbiological levels that focuses on water from sand dams. That study found a median value of 159 TTC/100 ml from established scoop holes, on the same order found in our study (600 fecal coliforms/100 ml median for the dry season). WHO standards for drinking water are zero fecal coliforms per 100 ml (WHO 2017), a standard met by only 17% (dry season) and 11% (wet season) of our scoop hole samples. This is likely an overestimate, as our test relied on a small sample volume, so we could not detect levels below 100 cfu/100 ml. The majority of samples where fecal coliforms were detected were therefore in the high or very high risk categories (Gruber *et al.* 2014). Total coliform levels are typically not regulated, but high numbers such as those seen in samples from sand dams are also considered indicative of the higher risk of pathogens in the water.

The pattern of contamination did not change with the season for both general and fecal coliforms. Changes in contamination of water sources would be determined by the balance between a variety of factors such as the input of uncontaminated water (e.g. flushing during the wet season), the input of new contamination (e.g. from manure which is mobilized) and the proliferation of existing bacteria. However, our results suggest that on average the sum of these factors apparently does not greatly change with the season. In practical terms, communities should be aware that contamination exists regardless of the season.

The absence of any previously published assessment of bacteria in sand dams likely derives from the general assumption that water filtering through sand dams is analogous to the well-known filtering effects of sand in general (e.g. in biosand filter technologies; Pooi & Ng 2018). Undoubtedly, some filtering does occur, as indicated by the general absence of thermotolerant bacteria in fresh, deep holes dug by Quinn *et al.* (2018). Likewise, in our study pump wells, which take water from deeper via sealed pipes, were significantly less contaminated than the other sources (although one-quarter still contained fecal coliforms). This is consistent with other studies comparing water sources, where pump wells are found to be cleaner than open wells or surface water (e.g. Parker *et al.* 2010; Quinn *et al.* 2018). Frequent bailing of water has been proposed as a means of improving water quality (Sutton 2002). However, our trials did not show bailing lowered contamination levels, and the established scoop holes containing thermotolerant bacteria in the study of Quinn *et al.* (2018) were all bailed before sampling. Neither this usage practice nor design features of fencing holes or accessing deeper scoop holes had any significant mitigating effect on contamination. The study was not designed to confirm whether sand filtering provides clean water when freshly dug holes are used, but our evidence does point toward limited net effects of any sand filtering on water quality at collection points that are currently actually used at sand dams.

Although we did not investigate the specific source of bacterial contamination, observations point toward livestock as the most likely source. Livestock is usually allowed on to the sand dam in order to access the water source. In both this study and the study of Quinn *et al.* (2018), manure was readily visible on the surface of most sand dams, and fencing was usually absent or inadequate to keep livestock away. Movement of contamination from feces on the dam surface is consistent with the known susceptibility of shallow groundwater to contamination through the lateral movement of pathogens (Howard *et al.* 2003). The effectiveness of sand filtration for water purification is dependent on a variety of factors such as percolation rates and saturation levels (Pooi & Ng 2018), and it is not clear whether particular conditions at sand dams are optimal for handling the quantity of contamination introduced by the manure.

High salt content is a known water quality issue in the region, sometimes limiting the utility of sand dams as a source of drinking water. The high salt content represents a different type of challenge to users from bacterial contamination. Although less of a direct health risk, it does make water unpalatable and essentially, therefore, decreases water availability (WHO 2017). We confirmed that TDS as a measure of salt content was relatively high at many sites. This is a particular issue during the dry season, as was previously reported by Kitheka (2016) and Sila (2019). This was particularly true for pump wells, which were classified as poor or unacceptable in over half of the samples, and suggests that the advantage of reduced microbial contamination of water in pump wells can be offset by a greater likelihood of high salt content.

Roof-collected rainwater represented the major water source during the wet season and had notably higher water quality as measured by both fecal coliforms and conductivity. Fecal coliforms were virtually absent, although there were high numbers of general coliforms. The source of general coliforms is not clear, although roof contamination (such as the likely presence of bird droppings) could easily have washed off into the collection barrel. Alternatively (or in addition), there could have been contamination established in the collection vessel which continues to grow despite the input of clean rainwater. This is consistent with studies such as that of Parker who likewise found much lower thermotolerant bacteria in rainwater compared to other sources (Parker *et al.* 2010). Salinity was extremely low (usually <50 ppm TDS), at around 10% of the median dry season values found at sand dams themselves. These results are unsurprising, given that there is limited potential contact of the collected rainwater either with fecal material or salts and highlights the higher quality of water from roof collection, at least with respect to these two parameters.

Although there is a health risk from bacterial contamination at sand dams, our community survey indicated that most users do not treat their drinking water. This is consistent with the finding of Woodring (2014) who found 2 out of 16 self-help groups at sand dams believe that contamination was an issue of concern. Results of our survey suggest that this is partly due to misperceptions about when water is clean or contaminated. Most commonly, users thought water was safe since it appeared clear, as has been found in other drinking water studies (e.g. Onyango-Ouma & Gerba 2011). This assumption is reinforced by assumptions that movement of water through the sand sufficiently cleans water.

There are indications that users have a more nuanced understanding of water quality than suggested by the general lack of concern about water cleanliness. Communities practice some interventions meant to keep water clean, such as the practice of clearing water out of the scoop hole prior to collecting water (Sutton 2002), or fencing off holes from livestock (Cruickshank 2010), although our results indicated that these practices did not actually have a significant impact on fecal coliform levels. Our results indicate that half of those communities that thought water was safe to drink still treated water occasionally. Some users felt it was safe for them to drink, but thought it was too risky for their children. These observations suggest that users are aware of some degree of risk but are needing an easy source of water, and perhaps believe the water is ‘clean enough’. This is analogous to the nuanced view found by Onyango-Ouma & Gerba (2011) who found some evidence that people felt they had no choice when in the field except to drink the water. From a health risk perspective, the challenge is how to reduce this health risk within the context of limited options for water sources. These results indicate that communities would be open to steps which would increase water quality.

CONCLUSIONS

While sand dams clearly provide a critical source of drinking water for communities, particularly during the dry season, results from this study point to several challenges related to water quality. Most notably, this study found significant levels of fecal coliforms in community water sources that are currently used at sand dams. The prevalent belief that the water from existing sand dam scoop holes is clean enough to drink is not supported by these results. There were some differences in contamination levels, such as pump wells and roof-collected rainwater that were significantly less contaminated. However, even in pump wells and roof-collected rainwater, fecal coliforms were present in more than a quarter of samples. Our results are consistent with the recent finding of Quinn *et al.* (2018), which is the only other published study of microbiological water quality at sand dams. This study also confirms the known issue with high salt content in this area, an issue which can limit the effective availability of the water from sand dams. Based on conventional standards (such as those of WHO), treating water from sand dam sources would accrue health benefits, and the evidence points toward a greater need to include water sanitation components in sand dam projects.

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