Research Paper

Analysis of water security and source preferences in rural Tanzania

Tula M. Ngasala, Susan J. Masten, Mantha S. Phanikumar and Emiliana J. Mwita

ABSTRACT

The public health and well-being of people in many rural communities in developing countries suffer due to poor water resources management and undesirable agricultural practices. This study was conducted in a pastoral community in northern Tanzania. The objective was to identify the most reliable water source in terms of quality and access from three main water sources: surface water, shallow wells, and deep wells. The Water Quality Index (*WQI*) was used to assess the overall water quality and was determined to be 1,876, 875 and 157, respectively, for surface water, shallow wells, and deep wells (<50 – excellent, >300 – poor). A Water Poverty Index (*WPI*) tool was used to quantify five factors that limit access to water: (1) seasonal availability, (2) distance to water sources, (3) cost of purchasing water, (4) preference, and (5) water quality. *WPI* scores indicated that surface water has the highest score followed by shallow wells; deep wells had the lowest score. In conclusion, in terms of access and quantity, deep wells and shallow wells were the least reliable, and surface water although highly contaminated, is the most reliable. Improving water quality and access of existing water resources is critical to improving the well-being of rural populations.

Key words | rural communities, shallow wells, surface water, Tanzania, Water Poverty Index, Water Quality Index

Tula M. Ngasala
Susan J. Masten (corresponding author)
Mantha S. Phanikumar
Department of Civil and Environmental Engineering,
Michigan State University,
East Lansing, MI 48823,
USA
E-mail: *masten@egr.msu.edu*

Emiliana J. Mwita
Department of Geography and Economics,
Dar es Salaam University College of Education,
Box 2329, Dar es Salaam,
Tanzania

INTRODUCTION

The availability of potable water is recognized as key to achieving the UN Millennium Development Goals (Murphy & Fukuda-Parr 2004; UNICEF 2004) (MDGs), and the United Nations post-2015 dialogue (United Nations 2013) goes one step further by building on the MDGs to identify Sustainable Development Goals (SDGs). Goal 6 of the SDGs focuses on ensuring the availability of water and the sustainable management of water and sanitation. Two sub-goals/targets focus on access to safe and affordable drinking water by all by 2030 (target 6.1) and improving water quality (target 6.3). However, during the development of the post-2015 goals, it was noted that challenges to achieving these goals are still significant, especially in rural, remote, or otherwise marginalized areas (United Nations 2015). The major challenges facing rural communities in many developing countries include water scarcity and poor water quality. In rural areas, people are affected greatly by water scarcity mainly due to unpredictable rainfall patterns, prolonged dry seasons, and limited options to access water. When the availability of water becomes limited, people are forced to use contaminated water from unprotected water sources, which results in increased outbreaks of waterborne diseases. Lack of adequate water supply systems, sanitation

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and drainage results in both insect-borne and waterborne diseases (Satterthwaite 2003). Many preventable waterborne diseases, such as cholera and severe diarrhea, are common and result in high mortality rates, especially in children under five years of age (Pickering *et al.* 2011). The main sources of contamination of both surface and groundwater sources in rural areas are poor animal waste management, improper farming practices, and unhygienic sanitation practices including open defecation (Centers for Disease Control and Prevention 2016).

This study focused on a pastoral community environment. More than 90% of the residents in this community are pastoralists with an average of 300–500 livestock per household. The study area is located in a semi-arid environment with limited rainfall and prolonged dry seasons. Since livestock in pastoral communities are highly valued, they are given priority over humans, especially when it comes to water and pasture. Animals and humans share the same water sources because of the high demand for and lack of access to water, particularly in dry seasons. As livestock are allowed to wade in the water sources to drink, the quality of water becomes compromised from urination, defecation, and contaminants carried on their bodies. Although water scarcity is also a problem in arable areas of Tanzania, it does not occur to the same extent as it does in semi-arid and agro-pastoral areas such as our study area. Additionally, in most arable locations in Tanzania, crops are often rain-fed. In such areas, animal agriculture is uncommon, so water is rarely affected by livestock.

Access to existing water sources depends on five main factors: (1) seasonal availability, (2) distance to water sources, (3) cost of purchasing water, (4) preference of water source type, and (5) water quality. Access to each water source is usually dependent on at least two or three of the aforementioned factors. For example, if the distance to water source limits a family from collecting water from the water source that is free of charge, they will go to a closer water source which charges a fee. Similarly, a family that cannot afford to pay for water will have no choice but choose a distant water source that has poor quality. In many cases, the issue is not lack of water but the aforementioned factors that limit families from choosing the best water source. In order to properly manage water sources at the community level, it is important to consider all five factors in order to determine the security of a water source and assess improvement and management changes that will result in a source that meets the needs of the communities. In this study, we assessed the quality of available water sources by using the Water Quality Index (*WQI*) and then used the Water Poverty Index (*WPI*) to assess the security of potential water sources by applying the five factors mentioned that limit people to access water sources. The goal is to understand how people use these factors to make decisions regarding what water source to use, regardless of the quality of that water source.

The objective is to identify the most reliable water source in terms of quality and access. We hypothesize that in rural communities where agriculture (crop and livestock production) is the predominant source of employment and groundwater sources tend to be ephemeral, surface water, although highly contaminated, is the most secure water source.

METHODS

The study was conducted in a pastoral community (Maasai) located in the Monduli district within the Arusha region in northern Tanzania. The main activities in the village are farming and livestock keeping and they have limited access to clean water and sanitation facilities. There are three types of water sources used by the residents. Surface water is obtained from three water storage ponds that are rain-fed, identified herein as Pond 1, 2, and 3. There are three shallow wells that are located at the river bed: (1) SW N, (2) SW NE, and (3) SW E. These are hand-dug wells that are available during the rainy season when the river is dry. The hand-dug wells tend to be ~3–5 ft deep. After the wells are dug, the women wait for water to seep into the well before collecting it. Finally, there are three deep wells that are more than 70 meters deep, located within the study area: (1) DW S, (2) DW N, and (3) DW NE. The study area and description of water sources are shown in Figure S1 and Table S1 in the Supplementary materials (available with the online version of this paper).

Field investigations, home visits to 107 households, and open-ended surveys from the water committee at the village were conducted during the dry season (June–August 2016) to obtain information about the location of water source(s) used, water rates, water usage, and demographics. Guidance from the Department of Statistics and Probability at Michigan State University helped frame the survey design. The survey received exempt status from the Tanzania Commission of Science and Technology (#2016-294-ER-2015-210) and the Institutional Review Board at Michigan State University (IRB x14-680e/16-107). To assess the water quality of the water sources, 19 water samples were collected: seven samples from surface waters, six samples from shallow wells, and six samples from deep wells. Water sampling and storage techniques followed World Health Organization (WHO) standards. Chemical and microbiological analyses were performed for all water samples collected by following Standard Methods (US EPA 2015). Parameters tested were turbidity, pH, ammonia, nitrate, nitrite, and bacteria. Details of the laboratory testing methods and results can be found in Table S2 in the Supplementary materials (available online).

Water Quality Index

The Water Quality Index (*WQI*) was used to calculate the general water quality of each water source. The application of *WQI* was first proposed by Horton in 1965 (Horton 1965) and it was based on the professional opinion of a panel of 142 water quality experts (Dinius 1987). In this paper, *WQI* was calculated using data from water samples that were collected from all three water sources. The assigned weight of each parameter ranged from 1 (least significant) to 4 (most significant) based on the opinions of the experts (Alobaidy *et al.* 2010). WHO water quality standard was used for each parameter. The relative weight of each parameter was calculated using Equation (1), where RW is the relative weight, AW is the assigned weight of each parameter and n is the number of parameters. The quality rating scale (Q_i) for all the parameters was calculated using Equation (2), where C_i is the value of the water quality value obtained from the laboratory test conducted, and S_i is the recommended maximum contaminant level according to WHO standards. Sub-indices (SI_i) were calculated using Equation (3) for each contaminant, then Equation (4) was used to calculate the *WQI* for each sample (Ramakrishnaiah *et al.* 2009). For details of the laboratory methods and relative weight of the water quality parameters, see Tables S2 and S3 in the Supplementary materials (available online).

$$RW = \frac{AW_i}{\sum_{i=1}^{n} AW_i} \tag{1}$$

$$Q_i = \frac{C_i}{S_i} \times 100 \tag{2}$$

$$SI_i = RW \times Q_i \tag{3}$$

$$WQI = \sum_{i=1}^{n} SI_i \tag{4}$$

The overall water quality based on the computed *WQI* is classified into five categories; <50: excellent, 50–100: good, 100–200: poor, 200–300: very poor, >300: unsuitable (Mophin-Kani & Murugesan 2011).

Water Poverty Index

The Water Poverty Index (*WPI*) is a metric that is useful for effective water resources management (Sullivan 2002). The *WPI* can help identify the important socioeconomic factors and link them to household water availability (Lawrence *et al.* 2002). In this study, the *WPI* was employed to assess the poverty level of three main types of water sources commonly used in the study area by taking into account five key factors: (1) Seasonal availability (S) which is expressed as months in a year that water source is available, (2) Distance (D) which is expressed as average return-trip walking distance (in kilometers) to a water source, (3) Water rates (R) which are expressed as the price of a 20 L bucket of water (in Tanzanian shillings) for a water source, (4) Preference (P) which is the general preference of the community members on the type of water source to use, (5) Water quality (Q) which is the quality of water from each source calculated using Water Quality Index (Lawrence *et al.* 2003; Jemmali & Sullivan 2014). Table S4 in the Supplementary materials (available online) provides a detailed description of the five indicators used, and the associated *WPI* component.

The general expression for *WPI* is shown in Equation (5):

$$WPI = \frac{\sum_{i=1}^{n} W_i X_i}{\sum_{i=1}^{n} W_i} \quad (5)$$

where X_i refers to a component of the *WPI* structure for a particular location, N is the total number of *WPI* components and W_i is the weight applied to that component. Five water poverty indicators were analyzed in the following subsections.

Seasonal availability (*S*)

The availability of water significantly affects access to water. In the village, surface water sources and shallow wells are affected by seasonal availability. During the dry season, surface water sources often become completely dry. If water is present in the ponds, the concentration of contaminants tends to increase due to high evaporation rates, especially during summer. Seasonal availability of each water source was obtained from household survey responses and by field investigations. Seasonal availability (*S*) was calculated by taking the number of months a water source provides water in a year and dividing it by 12 months (one year), as shown in Equation (6):

$$S = \frac{Months\ water\ source\ holds\ water}{12} \times 100 \quad (6)$$

Distance (*D*)

The average distance walked to a water source was obtained from every household member that was interviewed by using GPS coordinates and the distance tool in ArcGIS version 10.3. Recorded distances were grouped based on the type of water source. The distance (*D*) indicator was calculated as shown in Equation (7) where d_i is the distance traveled to the particular source and d_{max} is the maximum distance traveled from any home to a source.

$$D = \left(\frac{d_{max} - d_i}{d_{max}} \times 100\right) \quad (7)$$

Water rates (*R*)

The price of water from each source was determined from survey responses. The cost component was calculated based on the cost of each water source per 20 L bucket. The water rate (*R*) indicator for each water source was calculated by subtracting the fee charged for a water source (F_i) from the maximum fee charged of all water sources (F_{max}) then multiplied by 100 as shown in Equation (8):

$$R = \left(\frac{F_{max} - F_i}{F_{max}} \times 100\right) \quad (8)$$

Preference (*P*)

Each head of household surveyed was asked what type of water source they prefer to use regularly. Some household members selected more than one water source, which increased the sample size because each selection was counted as one response. Responses were sorted based on the water source type selected. The preference (*P*) indicator was calculated by using maximum–minimum equation based on the number of people who preferred a certain water source, as shown in Equation (9) where N_i is the number of households that selected a particular water source, N_{min} and N_{max} are the least and greatest number of households that selected that particular water source, respectively.

$$P = \left(\frac{N_i - N_{min}}{N_{max} - N_{min}} \times 100\right) \quad (9)$$

Water quality (*Q*)

Water quality values from the Water Quality Index section discussed earlier were used to calculate the water quality indicator. To calculate water quality (*Q*), maximum–minimum equation was used separately for each water source, as shown in Equation (10) where q_i is the *WQI* of the water source, q_{min} is the least *WQI*, and q_{max} is the greatest *WQI* for all sources tested:

$$Q = \left(\frac{q_i - q_{min}}{q_{max} - q_{min}} \times 100\right) \quad (10)$$

Finally, from all five indicators discussed above, the *WPI* was calculated by combining factors for each water source using Equation (11):

$$WPI = \frac{W_S S + W_D D + W_R R + W_P P + W_Q Q}{W_S + W_D + W_R + W_P + W_Q} \quad (11)$$

where W_i is the weight applied to each of five water access-limiting factors: seasonal availability (*S*), distance (*D*), water rates (*R*), preference, (*P*) and water quality (*Q*), and the product is the weighted average of each factor. Each indicator was given equal weight because they all have an impact on the well-being of the community (Komnenic *et al.* 2009). *WPI* values are between 0 (worst situation) and 100 (best situation). Past applications of the *WPI* approach indicated that assessments at large scales (e.g., national scale) do not necessarily reflect the realities at smaller scales such as villages (Sullivan *et al.* 2006). Novel aspects of the *WPI* approach as modified and used in the present work include the use of a participant-driven indicator (*P*) to quantify the general preference of a household for one water source over another (as opposed to assigning equal or other arbitrary weights for different sources) and the use of the Water Quality Index that combines the results of several water quality parameters to provide an assessment of the overall state of water quality of a given source (as opposed to using a single water quality parameter as was done in earlier studies). This approach of combining the *WQI* with *WPI* is expected to be useful where the focus is not just on access to 'improved' water supply as stated in the MDGs, but on water quality and sustainable management of water supplies (target 6.1 of the SDGs).

RESULTS AND DISCUSSION

Water quality

Water quality results showed that surface water sources are highly contaminated, while shallow wells are less contaminated and deep wells offer the highest quality water. All water samples exceeded WHO maximum contaminant levels for the five parameters tested (ammonia, nitrate, nitrite, turbidity, and bacteria counts) except for pH. When this study was conducted, some of the ponds had started to dry up, therefore the turbidity of water samples collected from those ponds was very high. As shown in Figure 1(b), ammonia concentrations were much greater for surface water compared to shallow wells and deep wells. On the other hand, nitrate levels were higher in shallow and deep wells while the concentrations of ammonia and nitrite were low (see Figure 1(a) and 1(f)). As shown in Figure 1(d), the bacteria counts for deep wells were relatively low compared to surface water and shallow wells; however, the numbers were still very high compared to the recommended maximum water quality level. The *WQI* of each sample was calculated and used to determine the average value for samples that were collected from the same source. The average *WQI* values for surface water sources, shallow wells, and deep wells were 1,876, 875, and 157, respectively (see Table S5 in the Supplementary materials for a description of the category, available online).

Water access

Table S6 in the Supplementary materials summarizes the survey responses and field investigation. Values from Table S6 were used to calculate sub-*WPI* shown in Table S7. (Tables S6 and S7 are available online.)

The seasonal availability (*S*) of all three water sources varied tremendously and the community shares them with livestock and wild animals. For surface waters, pond 1 was found to store water all year round, but ponds 2 and 3 were found to be very seasonal, with water available for ten months and nine months, respectively. All three shallow wells were found to be seasonal with water storage of five months or less while deep wells were found to be available all year round. Pearson *et al.* (2016) compared seasonal shifts in primary water sources in several pastoral communities in Uganda and found that, from wet to dry season, households often switch from a water source with lower risk of contamination to a water source with a higher risk.

The distance to water sources poses a challenge for many community members since most obtain water on-foot. When water is not accessible due to high cost, residents have no choice but to walk long distances to free water sources. On average, surface water sources were found to be the most distant (*D*) compared to shallow and deep wells. Pond 1 is located furthest from the village compared

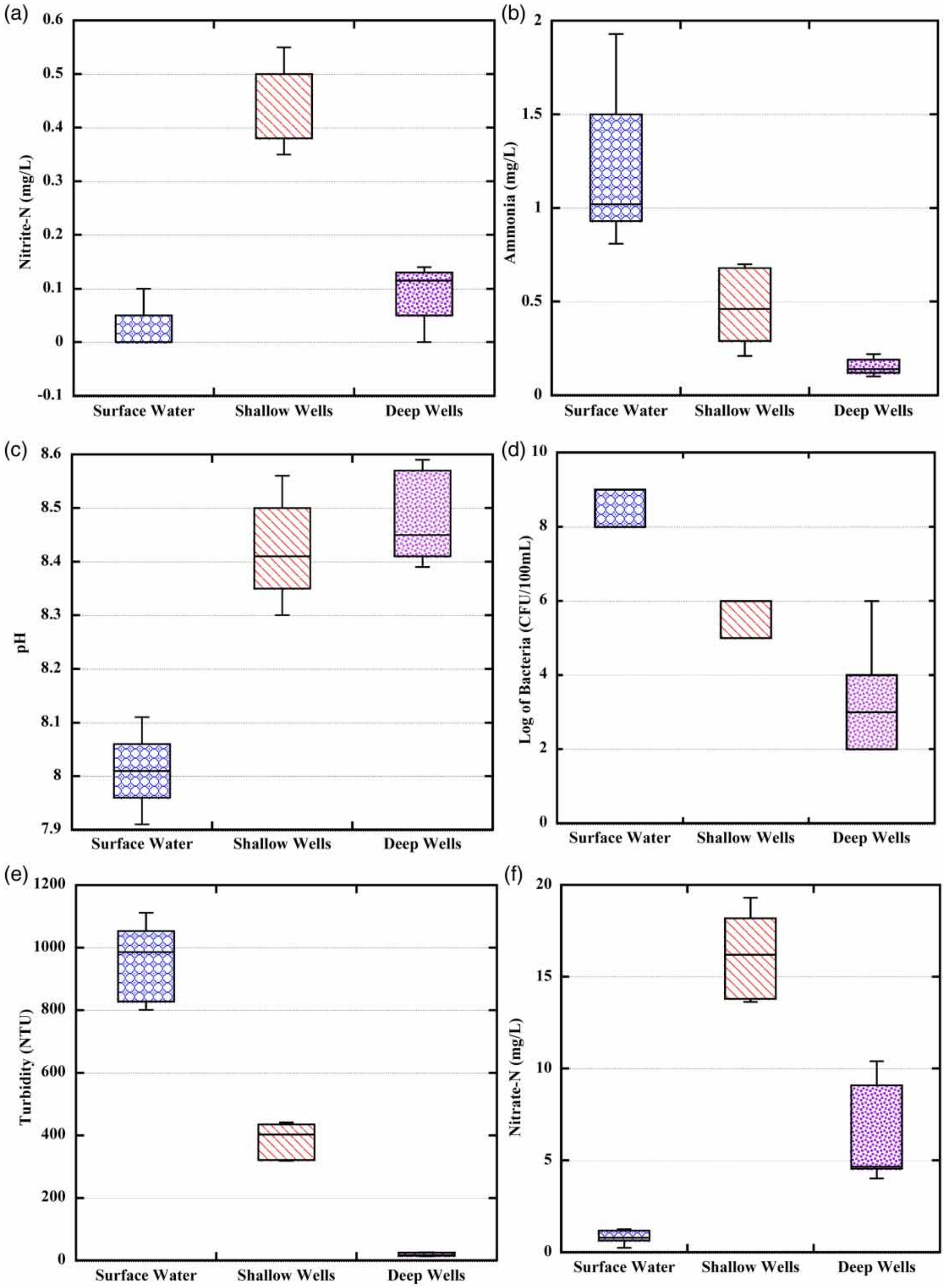

Figure 1 | Concentration distributions of six water quality parameters in surface water, shallow wells, and deep wells.

to the other two ponds with an average distance of nearly 7 km one-way. Some villagers can transport water using donkeys, whereas other villagers carry buckets of water on their heads. Shallow wells were slightly closer to homes with an average distance of 4 km. Deep wells were the closest to many homes. Although some of the deep wells are located close to many homes, the inability of some villagers to pay water fees forces them to travel long distances to surface water sources. Unlike, in urban areas, where the distance to a water source is rarely an issue, the waiting times commonly limit access. For example, in one of the inner cities in Sri Lanka, water taps are available within

50 m of most houses, but there are only two taps to serve the community of 460 people (Sullivan *et al.* 2003). In rural areas, houses are more scattered and water sources are usually much more distant to households compared to urban areas. As previously mentioned, women in this community often have to travel upwards of 14 km per day to access water.

The inability of a community member to pay for water can affect the choice of the type of water source to use. Survey responses indicated that water from ponds and shallow wells is free of charge while community members must purchase water from deep wells. Only 18% of the household surveyed were reported to have access to water from the borehole. The average price for a 20-L bucket from a deep well is Tanzanian shillings (Tshs) 75/- (median per capita household monthly income is Tshs 7,793) (Social-economics of Tanzania 2016). Assuming that the average household uses 50 L/person·day, ~30% of the household income would be spent on purchasing water. As such, community members who can purchase well water are those with high income, i.e., those residents who own a large number of livestock. Twenty-six percent of the household surveyed considered themselves to be of 'high income' and 85% of them reported to have access to water from the deep wells.

The preference (*P*) of community members for a particular type of water source was assessed. Our survey revealed that 81% of the community members preferred free water sources (31% for shallow wells and 50% for surface water), whereas deep wells were preferred by only 19%. This is crucial because sometimes people prefer using a certain water source over others for their own personal reasons. Results showed that the most preferred water source was surface water followed by shallow wells. One of the reasons for this preference includes the fact that people, especially women, might prefer using distant water sources to meet and socialize. Sometimes, women find it easier to do some of the household activities such as laundry near the pond than at home.

Water quality (*Q*) results from *WQI* showed that deep wells are the highest quality, followed by shallow wells, and surface water had the poorest quality. The level of all parameters tested was very high in all water sources, especially in surface waters. Since fertilizers are not used in this village, the source of the inorganic nitrogen (nitrate, nitrite, and ammonia) is most likely from human and animal waste. The presence of nitrate might indicate the presence of other contaminants that originate from human waste, animal waste, and agricultural activities. High nitrate levels in water can cause blue baby syndrome for infants less than six months (Oregon Health Authority 2016). Poor animal waste management and sharing water sources with animals can result in higher levels of nitrate, nitrite, and ammonia in drinking water (Oregon Health Authority 2016). Turbidity levels were the highest in surface water, followed by shallow wells. For deep wells, turbidity levels were within the acceptable range (below the WHO limit of 10 NTU). The decrease in water level along with the high evaporation rates, as well as the erosion of pond banks, result in high turbidity levels. Aerobic bacteria testing results showed extremely high numbers of colony forming units in all water samples, which also indicates the possible presence of pathogens in water. The low number of bacteria counts in deep wells indicates that groundwater is subjected to less bacterial contamination as compared to shallow wells and surface water.

Water Poverty Index scores

All five factors affect the access to water sources differently. Sub-*WPI* score values are the normalized values before calculating *WPI* (details are in Table S7 in the Supplementary materials). The higher the score, the less negative impact the indicator has on that water source type. The *WPI* values shown in Figure 2 are the summation of all sub-*WPI* for each water access limiting factor from each water source. Figures S2–S4 in the Supplementary materials (available online) show the *WPI* for each individual water source (three ponds, three shallow wells, and three deep wells). Noting that a high value is optimal, Figure 3 indicates that the most reliable and secure water source is surface water followed by shallow wells and deep wells.

By using sub-*WPI* values from Table S7 in the Supplementary materials, we analyzed the degree of association among the ten possible pairs of the five components by using Kendall's correlation coefficient (τ_b) (Cho *et al.* 2010). The values of Kendall's correlation coefficient (τ_b) are reported in Table S8 in the Supplementary materials

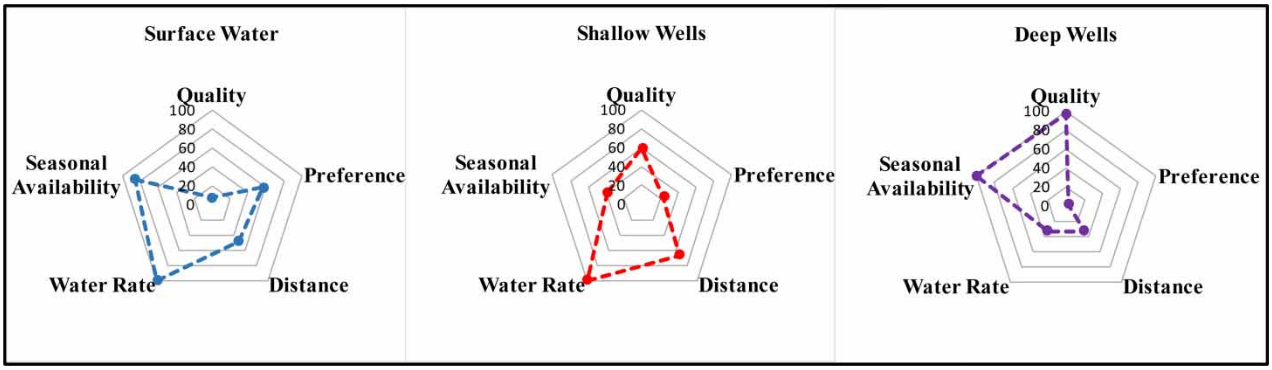

Figure 2 | Water poverty mapping of five water access limiting factors for three water sources.

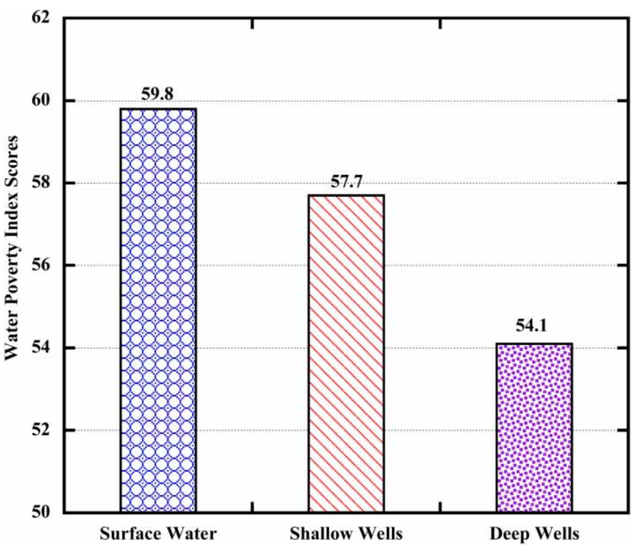

Figure 3 | Water Poverty Index scores for all three water sources.

(available online). Four conclusions can be drawn from these data. First, water rates and quality show the highest significant negative correlation (−0.745), which means that water sources with good quality are more expensive and those with poor quality are affordable. Second, the significant negative correlations (−0.623) of water rates and seasonal availability indicate that water sources that are available all year-round cost more compared to ephemeral water sources. Third, the water rates and preference shows a significant positive correlation (0.596) which means that in general, people prefer water sources that are free or cost less. Distance and quality, as well as distance and preferences, exhibit the lowest bivariate correlations (0.056) which means that there is not a significant relationship between the quality of water sources, preferences and the distance people walk to go to these water sources to collect water.

CONCLUSION

The main objective of this study was to assess the reliability of all water sources used by the community in terms of quality and access by understanding the indicators that force people to make decisions of what type of water source to use. We sought to assess the most secure water source by using the *WPI* and *WQI* to identify the general quality of water sources. Observed water source preference from survey responses showed that community members focus on one or two indicators that are within their capability to select the water source to use. *WPI* results from this study assessed all five indicators that limit access to these water sources. *WQI* classification showed the level of contamination in a comprehensive manner, allowing for a representation of water quality based on scientific criteria. The quality varies depending on the type of water source, human practices, and management of existing water sources. Surface water sources were found to be poorly managed, as animals are allowed to venture into the ponds, contaminating water with feces and urine, and causing erosion. Lack of knowledge of best management practices contributes to the poor quality of water sources.

Results from *WPI* showed that surface water is more secure followed by shallow wells. Deep wells had the lowest score. It was clear that shallow wells are not very reliable since all of them were very seasonal, distant, and the quality was also poor. Although the seasonal availability is good for deep wells, and the quality is the best, many community members cannot afford to purchase this water. Using *WPI* variables, the link can be made between water availability, water access, and household water stress for effective water resources management. The *WPI* values are useful to develop estimates at different levels to assist water managers, NGOs, and the government in project prioritization. Water quality information is one of the important factors in the data structure, ensuring that the relevance of the *WPI* is sustained over time. Changing human practices and behaviors, especially at the local level, can contribute to the achievement of a more sustainable way of life. Community participation during data collection is the best way towards a sustainable solution because local people will be empowered, through better understanding of their water needs.

This study serves as an example of how community leaders can assess the water quality and security within their villages. The water quality tests employed are inexpensive, readily available, and easy to use. The approach of using water poverty and water quality indices provides leaders with a tool to quantify both water quality and security, which can be used to inform management decisions. These tools can also be used by government officials to develop regulations and policies to protect and/or rehabilitate water sources or to prioritize proposed projects. This work demonstrates that the *WPI* and *WQI* tools can be applied to rural communities that have water scarcity challenges.

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