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A quantity-quality tradeoff: Water quality and poverty assessment of drinking water sources in Southern Tanzania

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Abstract

Despite being key to people's survival, accessing potable water remains a challenge in many rural African areas and exposes communities to waterborne diseases. In this paper, a study was conducted to establish the most secure water source in the study area in terms of quality and access. The quality of five drinking water sources in rural southern Tanzania was assessed using the water quality index (WQI). Water stress was ascertained using the water poverty index (WPI). Out of 88 households in the community, a socioeconomic survey of 26 households was conducted to quantify water accessibility against four selected WPI components (distance to water sources, preference, seasonal availability, and quality). The results indicated that all water sources were of poor quality, with surface water and shallow wells yielding WQI of 222.5 and 112 respectively (> 50 excellent, < 300 unsuitable). The WPI scores however indicated that shallow wells were more secure at 45.7 compared to surface water at 33.8 (0-poorest levels, 100-best levels). The study concludes that shallow wells were the most secure water sources in the study area in terms of quality and accessibility. We recommend adequate treatment of water before use and urgent provision of the community with safe, reliable, and easy access to water.

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Introduction

The United Nation's Sustainable Development Goal (UN SDG) 6 (the 'water goal') aims to ensure accessibility as well as the sustainable management of water for all (Leal Filho, 2018). The first goal of Tanzania's Vision 2025 also aims to achieve for its citizens, a high-quality livelihood, and central to this is to realize 'Universal' access to safe water for the people (Tandari, 2004). Lack of sustainable access to safe drinking water has forced many rural communities to turn to surface water as an alternative source because it is easy to get (Madilonga *et al.,* 2021). However, undeveloped sources of water have a higher chance of being polluted than developed sources of water such as piped water, public taps, and boreholes (Shields *et al.,* 2015; Kumpel and Nelson, 2016).

The use of contaminated drinking water constitutes a serious health risk that can result in outbreaks of waterborne diseases like dysentery, cholera, and typhoid (Saria and Thomas, 2012). For instance, the World Health Organization (WHO, 2002) report showed that around 2.2 million people, mostly children, die annually from diseases caused by lack of safe drinking water, inadequate sanitation, and poor hygiene. Water scarcity significantly affects the female populations who fetch water in developing countries (Sorenson *et al.,* 2011). In some rural areas, girls can spend approximately six hours collecting water (Pereira *et al.,* 2009). The time that women and children sacrifice to fetch water could be used to generate income, take care of their families, or learn in schools. This has been confirmed in the study by Demie *et al.* (2016) which showed a correlation between education and water scarcity. Walking long distances to fetch this scarce resource also negatively affects the education, health, and safety of children (Cherutich *et al.,* 2015).

Numerous endeavors are being made by various organizations like the WHO, United Nations Children's Fund (UNICEF), and the United Nations (UN) to reduce the extent of this challenge and increase water availability. The United Republic of Tanzania (URT) (2002) in its National Water Policy 2002 estimated that only about half of the rural population were served by a reliable water supply service. It also noted that more than 30% of the available rural water schemes were malfunctioning, mostly because of poor operational and maintenance arrangements. To counter this, the Tanzanian government with funding from various development partners, implemented the National Rural Water Supply and Sanitation Plan (NRWSSP) for the period 2006-2025. The NRWSSP aimed to increase the percentage of rural population with access to safe water to 65% by 2010 and at least to 74% by mid-2015. It also targets that by 2025, the rural population with sustained access to water will have increased to 90%.

The study area in Milola ward, in Lindi district, southern Tanzania is one of the rural populations that is severely affected by issues of water scarcity. The residents often depend on locally available water sources (shallow wells and surface waters which are mostly contaminated). The study area has five available water sources whose quality has never been assessed. This study used the water quality index (WQI) to analyze the sources' quality and a water poverty index (WPI) tool to assess water stress based on factors that influence the community in their choices of water sources. The objective was to establish the most dependable sources of water within the area and indicators of water access together with their connections to different sources of access. According to Lawrence *et al.* (2002), the main components that contribute and were used to assess water stress in an area include *access, use, environment*, and *quality*. These components were further broken down into variables, i.e., access in the distance covered to a water source; use preference for the community; seasonality in terms of availability and quality. These variables are commonly inter-linked (Ngasala *et al.,* 2018). For example, a family might prefer a seasonal rain-fed source that is closer despite a further source of better quality. The use of this holistic approach can help to understand the complex nature of water issues and their correlation with poverty (Sullivan and Meigh, 2003). The results of this study will be useful in informing resource allocation to water-related projects in rural areas and help in water distribution targets for both the Millennium Development Goals (MDGs) and the Tanzania Development Vision 2025.

Materials and methods

Study Area

The study was carried out in Ngwenya, Milola Ward in Lindi District in the south-eastern corner of Tanzania (Fig. 1).

Its geographical coordinates are 9° 59' 0" South, 39° 24' 0" East. The area has two rainy seasons, from November-December and March-May, with an average annual precipitation of 800-1000 mm. Farming is the dominant economic activity in the area although large tracts of forest cover are present. The community population is approximately 300 people and does not have an identified water source and depends on unimproved water sources as described in Table 1.

Data Collection

The study area has a relatively small population due to the existing water challenges which causes residents to migrate to other areas that have improved water sources. The current population in the study area is approximately 400 and 88 households in total. A household survey was carried out in 26 households with a baseline questionnaire to evaluate the water sources in the population and satisfaction with the quality and quantity. The questionnaire discussed the type of drinking water source, reasons for choosing a particular water source, time spent for water collection, household water treatment methods, perceived quality, and occurrence of waterborne diseases. The respondents voluntarily gave informed consent to participate in the survey. Surveys were also done with the local water committee and dispensary. Three water samples were collected from three seasonal surface waters (Pond 1, 2 and 3) during the rainy seasons and two shallow wells (SW 1 and 2) for quality analysis, giving a total of 15 samples. From the 26 surveyed households, 33 drinking water samples were collected for bacterial analysis since some households stored water from more than one source. The water samples were tested for physicochemical and microbial analysis in previously sterilized polyethylene plastic bottles. Bacterial analysis was performed within 6 hours of sample collection. In-situ measurements were done for temperature, pH, electrical conductivity (EC), and dissolved oxygen (DO) using a multi-parameter kit. For further laboratory analysis, samples were preserved by adding concentrated nitric acid to lower the pH (<2). After preservation, the samples were kept in cooler boxes and transported to the laboratory where they were stored at 4°C. The coordinates of the sampling points were taken using handheld GPS. Table 2 shows the methods used in analyzing the water samples.

Data Analysis

Water Quality Index

The quality of existing water sources was analyzed using the WQI by comparing the physicochemical and biological water parameters against the respective standards by WHO (Karunanidhi *et al.,* 2021). The WQI integrates different quality parameters into a mathematical equation that rates the quality of a water source, thereby determining the suitability of drinking water (Ochuko *et al.,* 2014). The method assumes that the weight for different water quality parameters was inversely proportional to the approved standards for the correlating parameters (Mishra and Patel, 2001). WQI follows three steps: i) select the water parameters to be evaluated, ii) determine individual parameters' quality functions, and iii) aggregate the parameters through a mathematical function (Tyagi *et al.,* 2013).

Parameters were allocated a weight (w_i) between 1 and 5, taking into account their significance in drinking water quality (Vasanthavigar *et al.,* 2010). The most and least important parameters were given weights of 5 and 1 respectively. According to WHO, the most important consideration should go to parameters that affect health the most like microbiological parameters, which are mostly identified at significant concentrations in drinking water. We divided each parameter's unit weight by the total sum of all unit weights to get the relative weight (W_i) as shown in Equation 1.

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where W_i-relative weight; n-total number of parameters (for this study, n = 8) and w_i-unit weight for each parameter

Units and dimensions of water quality parameters were converted to the common scale. The concentration of each parameter was divided by its respective WHO standard and the result was multiplied by 100 to obtain the rating scale (Q_i) as shown in Equation 2.

$$Q_i = \left(\frac{C_i - I_i}{S_i - I_i}\right) \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where Q_i-rating scale; C_i-concentration for i^{th} parameter inmg/L at a given sampling location; I_i-ideal value of i^{th} parameter in pure water (i.e., pH = 7, and zero for all other parameters) and S_i-WHO standard for i^{th} parameter inmg/L

Each parameter's relative weight (W_i) was multiplied with its rating scale (Q_i) to determine the water quality sub-index value (SI_i) as shown in Equation 3.

$$SI_i = W_i \times Q_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where: SI_i is the sub-index value for i^{th} parameter.

The additive aggregation was applied to obtain the WQI as the sum of sub-indices of all selected parameters as shown in Equation 4.

$$WQI = \sum_{i=1}^{n} SI_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

The computed WQI values are classified into five categories (Table 3):

Water Poverty Index

A WPI tool was used to report on the most reliable water source based on the components decided upon in the present study. It integrates data from multiple components that directly and indirectly contribute to water stress such as water access and quantity, water quality and variability; environmental aspects; water uses (domestic), and the ability for water management into a single number (Sullivan *et al.,* 2003). The selected components are assigned equal weights to avoid subjectivity and bias while also making the resulting indices more comparable and transparent (Pandey *et al.,* 2012), and each component affects the overall community welfare (Komnenic *et al.,* 2009). The components measured in the present study are in Table 4. The general formula that was used to calculate WPI is shown in Equation 5.

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

Where: X_i -WPI component for a particular site; W_i -component weight and n-total number of WPI components (n=4 for the present study).

The description, calculation, and normalization of the 4 WPI components are analyzed in the following subsections. In the normalization step, the minimum–maximum method was used to get indicators into a standard comparable scale from 0 to 100 (Jemmali and Matoussi, 2013).

Seasonal availability (S)

This component concerned the physical availability of water sources throughout the year. Lack of improved water sources in Ngwenya means the community gets its water from unimproved sources like shallow wells and surface waters. The existing surface water sources in the community are rainfed and during the dry season, they often dry up completely. From the study surveys, each source's seasonal availability was determined and calculated using Equation 6 where the number of months a source is available annually was divided by 12 months.

$$\mathrm{S} = \frac{\text{Months in a year water is available in a source}}{12} \times 100 \ldots\ldots\ldots\ldots\ldots (6)$$

Distance (D)

The component assessed the distance in kilometers to & from a water source by a household as obtained from the household surveys and GPS coordinates. This is presented in Equation 7 where d_i is the distance to a source and d_{max} is the maximum distance traveled from any household to a source.

$$D = \frac{d_{max}-d_i}{d_{max}} \times 100 \ldots\ldots\ldots\ldots\ldots \text{(7)}$$

Preference (P)

This component assessed the preference of households to a particular water source due to different reasons. This was calculated as shown in Equation 8 according to the number of households that preferred a particular water source, where N_i is the number of households that selected a source, N_{min} is the least number of households that selected that water source, and N_{max}.

$$P = \frac{N_i-N_{min}}{N_{max}-N_{min}} \times 100 \ldots\ldots\ldots\ldots\ldots \text{(8)}$$

Water quality (Q)

This component concerned the quality of the water source from the previously obtained WQI scores. The maximum–minimum equation (Equation 9) was used separately for each water source, where q_i is the WQI of the water source, q_{min} and q_{max} is the least and greatest WQI respectively, for all tested water sources.

$$Q = \frac{q_i-q_{min}}{q_{max}-q_{min}} \times 100 \ldots\ldots\ldots\ldots\ldots \text{(9)}$$

The WPI was then determined by aggregating each water source's components using Equation 10 (Lawrence *et al.,* 2002).

$$WPI = \frac{W_S S+W_D D+W_P P+W_Q Q}{W_S+W_D+W_P+W_Q} \ldots\ldots\ldots \text{(10)}$$

Where Wi represents the weight of each of the four components: seasonal availability (S), water quality (Q), distance (D), and preference (P). The result is the weighted average of each component and WPI value ratings are between 0 (poorest levels) and 100 (best levels).

Results and discussion

Water Quality Parameters and Index Scores

WQI was used to evaluate the water sources' overall quality. The collected water samples were tested for physicochemical and microbial parameters and results are represented in Fig. 2.

The findings are reported on the physicochemical and microbial characteristics of the study area water sources. The p^H levels for all water sources fall within the recommended WHO and Tanzania Bureau of Standards (TBS) guidelines. Water p^H is an important parameter that influences bicarbonate and carbonate levels as well as the formation of various metal ion complexes. The electrical conductivity values ranged from 117.2 to 199.5μS/cm (Table 6) and fell within the accepted recommendation of <1400 and 2000μS/cm by WHO & TBS respectively. High conductivity is an indicator of saline conditions that are commonly associated with eye irritation in humans. The turbidity levels ranged between 5 and 7 NTU whereby WHO recommends levels <5 NTU. However, these levels were within TBS guidelines of 5-25 NTU.

The fluoride levels all fell below both WHO (1.5mg/L) & TBS (4mg/L) recommended levels with ranges between 0.25-0.55mg/L. Excessive levels of fluoride (> 0.5mg/L) in drinking water can cause dental caries. Skeletal fluorosis and dental diseases are also associated with >1.5mg/L of fluoride (Ayele *et al.,* 2019). The nitrate levels were low (2.2-4.5mg/L) and complying with levels set by both WHO & TBS of 50 and 75mg/L respectively. These low levels are likely due to minimal fertilizer usage in agricultural fields by the residents.

Iron concentration was between 0.24 and 0.84mg/L against the 0.3mg/L WHO recommended value. These levels were still within the TBS recommended level of 1mg/L. Iron changes the appearance and taste of water and high levels can cause hypertension, congestion of blood vessels, and increased respiration rates (Islam *et al.,* 2018). Total hardness of the drinking water sources ranged from 0 to 54.3mg/L which was below WHO recommendations of 500mg/L.

Bacterial counts in the water sources ranged from 70 to 980 cfu/100m/L. The WHO recommends zero presence of bacteria in drinking water and water that is contaminated with bacteria is considered unfit for human consumption as it can pose serious health risks and outbreaks of water-borne diseases like dysentery, cholera, and typhoid (Saria and Thomas, 2012). The pollution of the water sources in the study areas was likely due to bathing, laundry, defecation around the sources. From the water samples collected from the households, even higher levels of bacteria ranging from 10 to 2000 cfu/100m/L were established. These levels exceeded the recommended value of 0 cfu/100m/L by far, meaning the water was not fit for consumption. The potential sources of contamination were observed to be from poor storage and handling practices, especially in households with small children (Ngasala *et al.,* 2019).

The various water quality parameters were used to calculate the WQI and WHO standards applied for drinking water quality (Table 7). The WQI scores ranged between 28 and 605.2 (Fig. 3). The average WQI for surface water (Pond 1-3) was 222.5 compared to 112 for the shallow wells (SW 1 & 2). As per the WQI classification represented in Table 1, these values indicate that the general water quality water in Ngwenya was generally poor but the shallow wells had better quality than surface water. While most parameters fell within the WHO & TBS standards, bacteria numbers which are critical in water quality measurements due to human health risks were way above the recommended guidelines.

The common waterborne diseases from the local dispensary are diarrhea, UTI and schistosomiasis. The data was for children under 5 years old & above 5 years old and for adults aged above 60 years from 2018 to 2020 (Fig. 4). Diarrhea is the second leading cause of death in children under five years old. Each year diarrhea kills around 525,000 children under five (WHO, 2017). Diarrhea can easily be treated and easily prevented through drinking-water treatment and adequate sanitation and hygiene.

Water Poverty Parameters and Index Scores

The WPI is a comprehensive tool that exhaustively analyzes water stress at both individual and society levels (Sullivan *et al.,* 2003) and can be used to recognize and assess poverty with regard to water resource availability. The index focuses on measuring the actual availability of water in comparison to the population's ability to access it by integrating data from multiple components like water access and quantity, water quality and variability; environmental aspects; water uses, and water management into a single number (Sullivan *et al.,* 2003). A summary of the survey responses concerning the WPI components used in the present study is presented in Table 8.

Although a population may be 'water-poor' if water is available but they cannot afford it, people can be 'water-poor' when they do not have access to water to adequately cater for their basic needs due to unavailability (Lawrence *et al.,* 2002). This may be due to long distances to access the water or limited quantity for various reasons. In 2015, United Nations Educational, Scientific and Cultural Organization's (UNESCO) World Water Assessment Programme, estimated that women in water-poor areas walk an average of 6 km in one day for water (Connor, 2015). In the present study, the distance walked to fetch water was the average return trip distance in km. SW 2 was the furthest location from the community. SW 1 which was available year-round was also quite far (7.5km). Pond 2 was the closest but also the most seasonal with availability at only 4 months of the year. Ponds 1 and 3 were located at average distances of 8.5 and 9.2km respectively.

Seasonal rainfall variations and water accessibility may influence households to change their water sources (Majuru *et al.,* 2012; Dos Santos *et al.,* 2017). In the present study, only one water source (SW 1) was available all year round. While the community accessed water in SW 2 for 9 months in a year, the surface waters in ponds 1, 2, and 3were accessible for 7, 9, and 4 months respectively. This is because these sources are rain-fed and dry up over time. Once the surface sources dried up, the community accessed water from SW 1 which while far, remained available all year round. However, being shallow, SW 1 presented limited water and the community members had to dig around it to allow water to seep above so that they could access it.

Preference is the number of households that prefer one water source regardless of the available sources. In the present study, SW 1 and Pond 3 were the most and least preferred water sources respectively. Varied reasons influence the choice of water source, mainly the quality and quantity of water and the distance covered to access the water. Water quality was derived from the WQI results from the 8 parameters that were analyzed in the present study. Pond 3 had the least WQI of 28 while Pond 2 had the highest (605.2) thus was most unsuitable for human consumption. Pond 2 had the least score for WPI at 16.6 while SW 1 had the highest WPI (66.6) (Fig. 5).

The average WPI scores for the surface waters and the shallow wells were 33.8 and 45.7 respectively. The WPI ratings were between 0 (poorest levels) and 100 (best levels). The shallow wells were, therefore, the most secure water sources in the study area compared to surface waters. The WPI was calculated by aggregating the WPI components into sub-indices. The calculation of the sub-index's values for each water source and WPI components are presented in Table 9 while Fig. 6 shows the summary of total sub-indices for each WPI component from the grouped water sources.

Pearson's Correlation Coefficients

Pearson's correlation coefficient (r) analysis determines the relationship between two variables, and their degree of association (Seo *et al.,* 2019). A positive correlation coefficient indicates that an increase in the first variable would correspond to an increase in the second variable, implying a direct relationship between the variables. A negative correlation indicates an inverse relationship whereby if one variable increases, the second variable decreases.

Turbidity showed strong negative correlations with EC at -0.86 (Table 5). Nitrate had strong positive correlations with pH levels at 0.93. Bacteria indicated positive correlations with pH and nitrate at 0.64 and 0.71 respectively. Total hardness was strongly positively correlated with EC at 0.81, while strongly negatively correlated with turbidity at -0.76. Bacteria strongly positively correlated with pH and nitrate at 0.64 and 0.71 respectively and had strong negative correlation with EC at -0.74.

In the present study, seasonal availability of the water sources was strongly and positively correlated with preference (r = 0.83) (Table 10). This indicates that people preferred water sources that were available for longer periods in the year. The distance from water sources also showed strong positive correlations with water quality (r = 0.82), indicating that sources with better water quality were further and people had to travel for long distances to access good quality water. Preference and water quality had the least correlation (r = 0.07), meaning that there was no significant relationship between people's preference and water quality, or that the people could use any water source regardless of the quality.

Conclusion

The present study aimed to establish the quality and access of water sources in Ngwenya community. Using the WQI, baseline data on the quality of the available water sources was assessed. The results showed that the water quality in the sources was poor despite most parameters complying with the regulatory standards set by WHO and TBS. The shallow wells presented better overall quality compared to the surface water sources. High levels of bacteria were found in all water sources probably due to mismanagement of resources and the presence of activities such as bathing and laundry in the surface water sources. Water samples from the households recorded higher bacterial numbers due to poor storage. Using the WPI to assess water stress, the surface water sources were found to be less reliable due to seasonality and poor quality compared to the shallow wells. The locals had to walk long distances to access poor quality water. The use of WPI has been used in other 'water poor' rural areas worldwide to provide lasting solutions and can thus be applied in the present study area to influence and inform decisions to help alleviate the water situation. The combined use of WQI and WPI can effectively provide stakeholders with the basis for making important decisions regarding water management. The present findings also necessitate educating the community on best water management practices like treatment and storage. The study was limited by the COVID-19 pandemic which disrupted travel plans to the study area and allowed for data collection only in the rainy season. Further research is recommended to show the linkage between poor storage of drinking water and high levels of waterborne diseases in the community, especially among households with small children.

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Conflict of interest

The authors declare no conflict of interest in the publication of this paper.

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