Research Paper

Physical factors limiting access to clean groundwater in Tanzania villages

Zaina Hussein Mseli, Devon Goeller, Mackenzie Scharenberg,
William J. S. Mwegoha, Rebecca Gianotti, David Bongiorno
and Audrey H. Sawyer

ABSTRACT

Low yield, poor water quality, and nonfunctional infrastructure impede physical access to clean groundwater in rural Tanzania. We studied boreholes in 45 villages as part of a rehabilitation program led by the Global Water Institute at The Ohio State University. Villages were chosen because their groundwater supply systems were inoperative or unsustainable. The most common cause was pump failure, which occurred in more than half of the villages. Even if broken pumps were repaired or replaced, low pump capacities and potential yields would limit physical access in many villages. Low potential yield is often mistaken for a broken pump, but easily diagnosed with a pump test. Pump test records were available for only eight villages, highlighting the need for more testing and data accessibility. One-third of the villages had low water quality. In comparison to secondary water sources such as springs, impoundments, and dug wells, boreholes tended to have lower levels of nitrate and fecal coliform, greater total dissolved solids, and similar fluoride levels. In many villages, groundwater is the only viable water resource to support development, but drilling records and hydrogeologic data are sparse. We recommend better digital data archiving with governmental water supply authorities and the assessment of potential well yields and sustainable yields.

Key words | contamination, fractured rocks, groundwater development, nitrate, water supply

Zaina Hussein Mseli
William J. S. Mwegoha
College of Earth Sciences,
University of Dodoma,
Dodoma,
Tanzania

Devon Goeller
Mackenzie Scharenberg
Audrey H. Sawyer (corresponding author)
School of Earth Sciences,
The Ohio State University,
Columbus, Ohio,
USA
E-mail: *sawyer.143@osu.edu*

Rebecca Gianotti
Global Water Institute,
The Ohio State University,
Columbus, Ohio,
USA

David Bongiorno
WorldServe International,
Springfield, Missouri,
USA

INTRODUCTION

Hundreds of millions of people across sub-Saharan Africa suffer due to inadequate access to clean water (WHO & UNICEF 2017). Three decades ago, the United Nations set a Millennium Development Goal to halve the proportion of the population without sustainable access to safe drinking water and sanitation, but the goal was not met in Tanzania – the proportion of the population that gained access to safe water was only 29% (UNICEF & WHO 2015). Nonfunctional water distribution points frequently limit access to clean and safe water. The average functionality rate of public distribution points is only 60% (United Republic of Tanzania 2015).

Although groundwater supplies two-thirds of all rural water points in Tanzania (United Republic of Tanzania 2015), Tanzania's aquifers are generally of low to moderate productivity (MacDonald *et al.* 2012). More than half of the

doi: 10.2166/washdev.2019.198

recorded boreholes in the country have a yield of less than 900 L/h (Kongola 2004). Groundwater quality also varies widely. In some areas, concentrations of nitrate exceed 100 mg/L, the WHO maximum recommended level for drinking water (Nkotagu 1996; Elisante & Muzuka 2015). The natural contaminant fluoride is also prevalent in regions such as Arusha and Singida (Bardecki 1974; Ali *et al.* 2016), likely due to the dissolution of minerals in igneous rocks such as volcanic ash (Nanyaro *et al.* 1984; Ghiglieri *et al.* 2012). Despite these challenges, groundwater is a critical water resource in rural areas because much of the interior of the country is semi-arid with low annual rainfall (Supplementary Materials, available with the online version of this paper), and groundwater supplies are more resilient to drought than surface water. Additionally, wells are cheaper to install and require less centralized management than piped schemes that source surface waters. Centralized drinking water provision in Tanzania is largely limited to urban utilities.

Studies are needed to understand the multiple complex physical factors that limit clean groundwater access in rural areas. These physical factors include infrastructure failure, low yields, and poor groundwater quality, which all influence the potential for sustainable groundwater resource development. While socioeconomic and political factors also influence water access, our objective was to study the physical factors by surveying 45 villages in rural Tanzania that were reported as having poor access to clean groundwater. The survey was conducted collaboratively by the Global Water Institute at The Ohio State University, the University of Dodoma, Majitech Engineering and the Ministry of Water and Irrigation in Tanzania, as part of the Sustainable Village Water Systems Program to improve access to clean water in rural communities. The 45 villages were selected from a list supplied by the Ministry of Water and Irrigation of 110 rural villages with inoperative boreholes, based on a range of hydrologic and geographic factors, including annual rainfall, proximity to water sources, and topography. Due to cost constraints, it was also desirable to select villages near paved roads that could be accessed within a day's drive. We show that most villages had multiple confounding physical factors that hindered access to clean groundwater, but the most common and immediate limitation was inoperative infrastructure, specifically broken pumps.

MATERIALS AND METHODS

Survey approach

The 45 villages are distributed across seven regions and have populations ranging from 1,000 to 7,000 people. Information on climate and hydrogeology is provided in the online Supplementary Materials. In each village, information on water accessibility was obtained through field observation and the assessment of infrastructure by technicians. The assessment form, which was adapted from the WHO guidance on sanitary surveys and the National Groundwater Association's recommendations on water point inspections, included observations of water body sources and characteristics, water usage, site-specific attributes, potential pollution sources (especially those related to human or animal wastes), and an intervention appraisal. Driller's reports and other available water data were acquired, where possible, from district water engineers and village executive officers in person. Data were also sought from the Ministry of Water and Irrigation offices, including aquifer type, thickness, static water level, information on well yield or specific capacity, and water quality.

Hydrogeological analysis

Completion reports and pump test results were only available for boreholes in eight villages. For those villages, we used pump test data to estimate the specific capacity and potential well yield. Potential well yield is important because it reflects the maximum pumping rate a well can sustain without experiencing excessive drawdown. At greater pumping rates, the well quickly goes dry, and the water level must recover before pumping can resume. Without an assessment of potential well yield, pumps cannot be effectively sized for wells. Specific capacity (SC) was calculated as follows:

$$\mathrm{SC} = Q/s \tag{1}$$

where Q is the pumping rate and s is the drawdown. In some cases, a step test was conducted, and we approximated Q as a weighted average of the pumping rates during each period.

Potential well yield (Y_{pot}) was calculated as follows:

$$Y_{\text{pot}} = \text{SC}\, s_a \tag{2}$$

where s_a is the available drawdown, which was assumed to be 3 m less than the difference between completion depth and static water level.

Where driller's reports were not available, the district water engineer supplied information such as completion depth and reported yield. The reported yield was typically inferred from the time required to fill a storage tank and is not equivalent to potential well yield based on aquifer pump tests (Equation (2)). The district water engineer also reported static water level for about half the villages.

Samples were collected for water quality from the borehole or the nearest access point. In addition to boreholes, many villages had secondary water sources, including springs, charco dams (hand-made earthen dams that store overland flow during the rainy season), and dug wells (shallow wells dug by hand to the water table). In three cases, a river was also accessed as a secondary source. Samples were collected from these secondary sources (mostly consisting of surface water and shallow groundwater from dug wells) to compare against borehole water. More information on water quality testing is available in the Supplementary Materials, including the type of secondary source for each village.

RESULTS

Infrastructure assessment

More than half of the villages (26 out of 45) had an inoperative pump, which prevented groundwater withdrawals altogether (Figure 1). Typical pump problems included broken parts and frequent need for repairs. Of the nine villages with a hand pump, all required replacement due to current or frequent breakdown. The low capacity of hand pumps also hindered access to water. Four villages had relatively new boreholes that were never fitted with a pump. Thirteen villages had submersible pumps that were broken or needed regular repairs (many of these were old Mono pumps). Two of the villages with Mono pumps had old engines that frequently broke. The exact reasons for breakdown and failure to repair were not explored, but common reasons include corruption of funds, the inefficiency of water user committees, and lack of spare parts or technical expertise to make repairs (Rural Water Supply Network 2014).

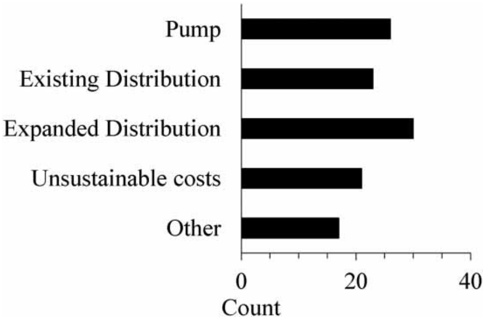

Figure 1 | Infrastructure needs. 'Pump' indicates villages where the pump was not working or broken frequently. 'Unsustainable costs' indicates that diesel costs or electricity tariffs imposed practical limits to pump operation. 'Existing distribution' indicates a need for repairs to the existing infrastructure (leaky pipelines and storage tanks, adjustments to improve delivery head), but does not assume that the existing infrastructure is sufficient to serve all community members. 'Expanded distribution' reflects a need to increase the capacity and distribution of the water system (additional boreholes, pipeline, or distribution points) in order to sufficiently serve all community members. 'Other' indicates miscellaneous requests such as private extensions to homes or new infrastructure to meet non-domestic needs such as cattle troughs.

Other infrastructure problems also limited access or contributed to unsustainability (Figure 1). In fact, 85% of villages had more than one infrastructure problem. Twenty-one villages experienced unsustainable costs associated with powering the pump. Of these, eight had electricity-powered pumps and 13 had diesel-powered pumps. Both electricity tariffs and the cost of diesel fuel are set by the national regulator, but corruption within community-managed schemes could influence the cost for consumers. Twenty-three villages had existing distribution networks that required repairs or additional storage tanks or lacked a distribution system altogether. Thirty villages needed pipeline extensions and new distribution points to improve access.

Yield assessment

Yields were reported for 32 boreholes and ranged from 0.21 to 8 L/s (Supplementary Materials, available with the online version of this paper). The reported yield met the basic domestic water needs of the village population in only 15 villages

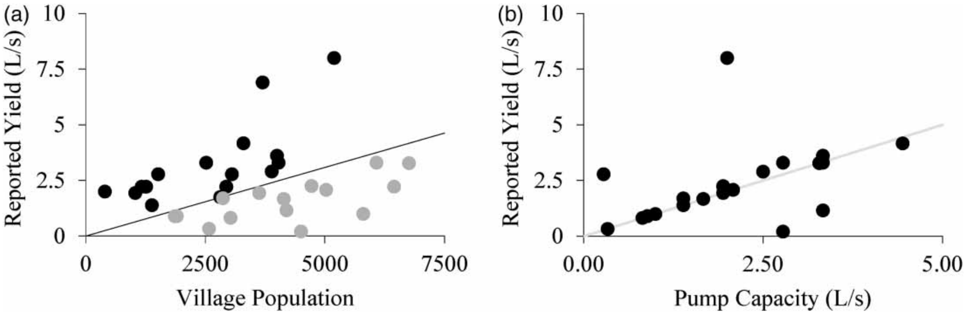

Figure 2 | (a) In half of the villages (shown in gray), the reported yield failed to meet basic domestic water needs for the population (black line). (b) The reported yield generally matched the pump capacity (gray line).

(Figure 2(a)). This calculation assumes a requirement of 20 L/person over a 9-h daytime usage period. The boreholes with inadequate yield were randomly distributed across the regions of Kagera, Kilimanjaro, Mara, Singida, and Tabora. The reported yield tends to reflect the capacity of the existing pump (Figure 2(b)), rather than the potential yield of the borehole, which is measured with a pump test.

In three of the 17 villages with low reported yields, well test records were available to calculate potential yields (Supplementary Materials). In two villages (Mwalala and Bulumbela, Tabora Region), the wells had potential yields that would meet domestic needs if the existing pumps were replaced with more powerful ones. In other words, the pump constrains the yield. In the other village (Mahene, Tabora Region), the potential yield could not meet domestic needs. In other words, the aquifer constrains the yield. If a second well were drilled with the same potential yield, the combined production from both wells could meet the domestic needs of the village.

In the absence of pump test records, we compared the pump capacity with the reported yield, which was typically based on the time to fill a storage tank (Figure 2(b)). For most villages, the reported yield and pump capacity were nearly the same, suggesting that the well was capable of yielding water at the rate it was being pumped (Figure 2(b)). In two villages, the pump capacity was significantly less than the reported yield – in other words, the pump is undersized. Although both villages' pumps meet the domestic needs of the current populations, the wells could yield more water for other needs with a more powerful pump. In Mubaba (Kagera Region), a hand pump with a capacity of only 0.28 L/s was installed in a well where the district water engineer reported the yield of 2.78 L/s, and the pump test results suggested a potential yield of 3.89 L/s (Equation (2)). In Shighatini (Kilimanjaro Region), no pump test results were available, but the capacity of the existing pump was only one-fourth of the reported yield. This village had an operating pump and power source and an expressed interest in extending the pipeline distribution system and starting a bottling plant.

In two villages (Rungwa and Unyankhanya, Singida Region), the reported yield was significantly less than the pump capacity – in other words, the pump is oversized and causes excessive drawdown (Figure 2(b)). Neither village's yield meets the current population's domestic needs. In Rungwa, their 60 m^3 storage tank sometimes requires a week to fill. The well also suffers from siltation and runs dry 3 months of the year, though it flowed year-round when it was first installed. A likely explanation is that the static water level falls below the depth of the well during those dry periods due to declines in rainfall and recharge. For both villages, a pump test would be useful for evaluating the potential yield and sizing the borehole with a pump that would produce a more constant and reliable (but low) flow. Oversized pumps that rapidly drain the well lead to wear and tear on the pump and create unpredictable fluctuations in water supply.

In the eight villages with pump test results, specific capacity ranges from 2.2 to 55.9 m^2/d (Supplementary Materials). The median value is 11.1 m^2/d. Six of these wells penetrate fractured granite. Specific capacity is generally greater in deeper wells (Supplementary Materials), but the correlation is weak ($r^2 = 0.1946$). One interpretation is that deeper wells are more likely, but not guaranteed, to intercept more conductive fractures. The four wells with above-average specific capacity are all 150 m or deeper. Three of these wells may have been drilled deeper because the static water levels were deep (greater than 60 m).

Water quality assessment

Of the 35 boreholes that were tested, 15 did not meet the World Health Organization guidelines for drinking water (Supplementary Materials). Specifically, nine out of 35 boreholes had elevated fluoride (>1.5 mg/L), six out of 30 had elevated nitrate (>50 mg/L), and three out of 19 contained fecal coliform (Figure 3). While the World Health Organization does not have a guideline for total dissolved solids (TDS), water becomes increasingly unpalatable above 1,000 mg/L (Bruvold & Ongerth 1969). Three of the 35 tested boreholes had TDS concentrations above 1,000 mg/L, one of which also contained elevated fluoride (Figure 3).

TDS in 35 tested boreholes had a median value of 308 mg/L and ranged from 31 to 2,387 mg/L (Figure 3(a)). The three boreholes that had TDS concentrations above 1,000 mg/L were located in different regions (Mara, Tabora, and Singida), but all had completion depths greater than 90 m (Supplementary Materials). One was the only well observed to have a substantial specific capacity (more than 50 m^2/d). Secondary water sources had comparatively lower TDS concentrations than boreholes, with a median of 100 mg/L and a range of <1–1,500 mg/L (Figure 3(a)).

Fluoride in 35 tested boreholes had a median value of 0.8 mg/L and ranged from 0.1 to more than 3.0 mg/L (the maximum concentration measurable with a field photometer) (Figure 3(b)). Eleven boreholes had fluoride concentrations above the World Health Organization guideline of 1.5 mg/L, mostly in the regions of Singida and Kilimanjaro. It is unclear whether the two samples that exceeded the range of the field photometer would have violated the Tanzania drinking water standard of 4.0 mg/L. Fluoride in all borehole samples did not show a strong correlation with available parameters such as completion depth, pH, alkalinity, or TDS.

Fluoride distributions in secondary water sources were similar to boreholes (Figure 3(b)), with a median of 0.8 mg/L and a range of 0.1–3.0 mg/L (the maximum concentration measurable with a field photometer). Of the nine secondary water samples that exceeded the World Health Organization guideline for fluoride, eight were from various dug wells, springs, impoundments, and rivers in the Singida Region.

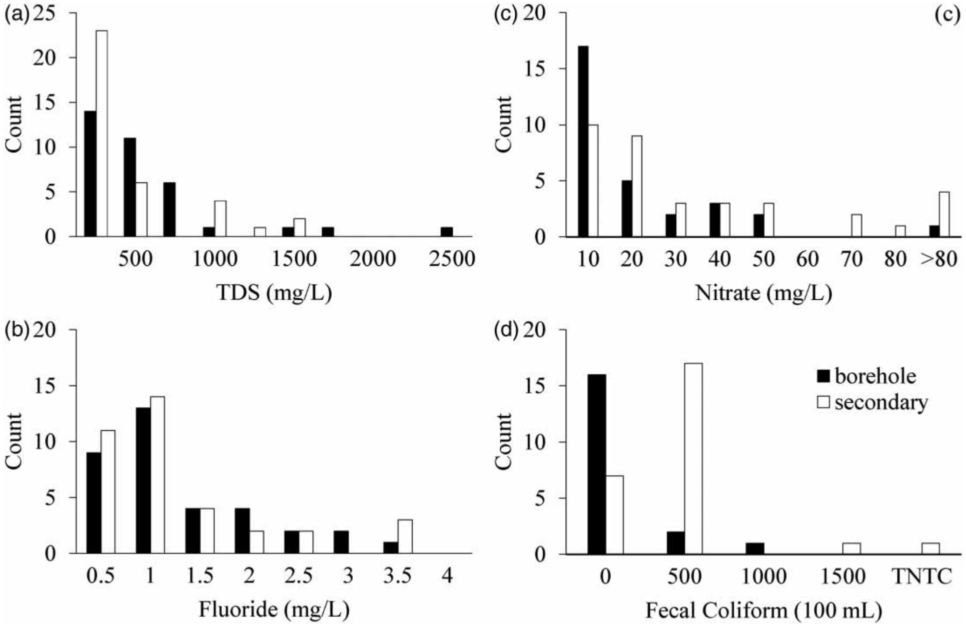

Figure 3 | Histograms of TDS (a), fluoride (b), nitrate (c), and fecal coliform (d) in village boreholes and secondary water sources.

Nitrate in 30 tested boreholes had a median value of 6.93 mg/L and ranged from 0.1 to 328 mg/L (Figure 3(c)). Three boreholes had nitrate concentrations above the World Health Organization guideline of 50 mg/L, all in the Singida Region. Like most villages, the three with high nitrate concentrations have pit latrines, a potential source. Two villages also use water for livestock, which could introduce nitrate if livestock are watered near wellheads. Borehole nitrate concentrations showed no obvious correlation with depth, likely due to the complex nature of contaminant flow in fractured rock. Secondary water sources had comparatively greater nitrate concentrations than boreholes, with a median of 19.3 mg/L and a range of 0–832 mg/L (Figure 3(c)). Some of the highest concentrations were found in rivers and impoundments in the Singida Region.

Fecal coliform was present in three of 19 tested boreholes (median of 0 and range from 0 to 550 in a 100 mL sample) (Figure 3(d)). All three boreholes were located in the Mara Region and had acceptable concentrations of other tested contaminants, but nitrate was only tested in one of them. The boreholes with fecal coliform were shallower than 100 m, but no other relationship was evident between fecal coliform and depth. One of the sampled boreholes lacked a concrete pad, which increases vulnerability to contamination. The other two samples were not representative, as they were collected from stagnant boreholes that had not been pumped for several months. Total coliform was present in eight of the 19 boreholes tested, but the World Health Organization cautions that total coliform bacteria are not acceptable indicators of water quality, especially in tropical regions where many nonpathogenic bacteria can be present. Secondary water sources contained fecal coliform in greater frequency than boreholes (Figure 3(d)). Out of 26 samples, 19 contained fecal coliform. The median was 16 with a range of 0–1,999 in a 100 mL sample. Many of the samples containing fecal coliform came from dug wells or reservoirs (including small impoundments behind earthen dams).

DISCUSSION

The physical factors that limit access to clean and safe groundwater in rural Tanzania are multifaceted and widespread. One-third of all villages had low yields that could not meet domestic water requirements for the population, one-third had poor water quality, and more than half had inoperable pumps (Figure 4). Although the villages in this study were selected because of known infrastructure problems, the prevalence of broken pumps has been observed previously in Tanzania and other rural developing countries (Nkongo 2009; van den Broek & Brown 2015). Other infrastructure challenges that hindered access included leaky pipelines, a lack of distribution points, and high costs of powering the pump (Figure 1).

A third of all villages faced more than one physical challenge (Figure 4). Four villages had sufficient water quality, but had low yield and an inoperative pump. These villages need reliable and affordable pumps and power but may also need additional boreholes to increase supply in low-yielding aquifers. Seven villages had poor water quality and an inoperative pump. This implies that even if the pumps are repaired or replaced, the produced water will require treatment to improve quality. Two villages experienced the triad of the inoperative pump, low reported yield, and poor water quality. These villages need a reliable pump and power source to bring the existing well online, but they may also require additional boreholes to increase yield and water treatment to improve quality.

Some of the low reported yields were due to pump constraints, while others were due to the aquifer and well

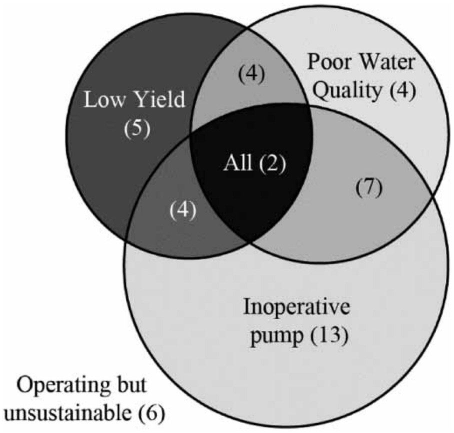

Figure 4 | Venn diagram of factors that hinder access to clean groundwater in the 45 villages. The six villages with an operating pump and reasonable yield and water quality still suffer from unsustainable infrastructure challenges such as leaky pipes, inadequate storage and distribution, and high fuel or electricity costs.

constraints (Figure 2(b)). Aquifer productivity is known to be low across most of Tanzania due to the low permeability of old cratonic rocks (MacDonald *et al.* 2012). Seven out of eight boreholes with pump test records had specific capacities less than 20 m^2/d (about 1 gal/min/ft), in line with low-yielding wells from other nations with fractured bedrock aquifers (Bakundukize *et al.* 2016).

A large number of villages in this study lack pump test data to determine aquifer properties and select an appropriate pump. Although it is government policy to conduct pump tests in all new wells and submit results to the Ministry of Water for record, the enforcement of this policy is challenging. Multiple villages that lack pump test records have oversized pumps that frequently cycle on and off to fill a storage tank. Where pump test records exist, it is unclear whether the data were considered in selecting the pump. One borehole that could have accepted a submersible pump was instead fitted with a low capacity hand pump, perhaps due to power or financial considerations. A clear need exists for more pump testing, data accessibility, and hydrogeologic training to improve pump selection.

Groundwater quality poses another large physical constraint on access to clean water. Although the quality of water from boreholes was generally better than secondary sources, it remains far from ideal (Figure 3), similar to other studies in rural Tanzania (Elisante & Muzuka 2016). Elevated nitrate was common in groundwater, especially in the Singida Region, where concentrations were frequently in the range of 30–50 mg/L and in one case above 300 mg/L. Similar concentrations (on the order of hundreds of mg/L) have been observed by Elisante & Muzuka (2015) in the areas of Dar Es Salaam and Dodoma. High nitrate and coliform in groundwater can be caused by the lack of wellhead protection (Elisante & Muzuka 2016). Some boreholes in this study lacked concrete pads or fencing to exclude livestock. In some cases, simple wellhead protection strategies can improve nitrate and coliform in groundwater (WHO 2006). However, nitrate and coliform also enter aquifers through natural recharge through fractures (Malard *et al.* 1994; Reddy *et al.* 2009). As populations grow, rural areas develop, and the intensity of anthropogenic activities increases, it is likely that nitrate and pathogen contamination will increase, especially in fractured bedrock aquifers (Elisante & Muzuka 2015). Nevertheless, groundwater remains more protected from these anthropogenic contaminants than surface water because processes such as denitrification and filtration reduce nitrate and pathogen concentrations in aquifers (Figure 3(c) and 3(d)).

Groundwater from boreholes is also prone to fluoride, a geogenic contaminant, but perhaps no more so than water from secondary sources (Figure 3(b)). Fluoride has been reported to be a major groundwater quality problem in the rift valley of Tanzania and Kenya (Nanyaro *et al.* 1984; Olaka *et al.* 2016), where it is associated with volcanic rocks and crystalline basement. Bardecki (1974) reported average groundwater fluoride concentrations of 5.85 and 1.91 mg/L in Singida and Kilimanjaro, respectively (both above the World Health Organization guideline). In this study, all 11 villages with high fluoride concentration are within areas of known fluoride contamination. We observed similar fluoride concentrations in boreholes and secondary sources (including rivers and springs), in agreement with Nanyaro *et al.* (1984). This implies that installing more boreholes to replace secondary sources may not increase fluoride exposure and may decrease nitrate and coliform exposure. We caution that our fluoride results are based on a small number of observations under challenging field conditions, and the collection and handling of samples did not consistently adhere to standard protocols. In particular, we did not quantify concentrations above 3 mg/L using the field photometer, and laboratory measurements were anomalously low (Supplementary Materials, available with the online version of this paper).

RECOMMENDATIONS

We advocate for greater hydrogeologic testing as part of rural groundwater development. Pump testing is rarely reported and must become a priority to improve understanding of yield and selection of the appropriate pump. Both the pump test and water quality records must also be made available and accessible. Without pump tests and access to trained experts who can interpret the data, it is difficult for communities to identify the reasons why their pump cycles off or their storage tank requires days to fill. For example, one village in this study has a solar-powered pump and expressed interest in a new power source because the pump rarely works at the end of the day. The cause is likely low well yield rather than an inadequate power supply. Low potential yield can be wrongly diagnosed as a pump or power problem. In the absence of pump test data, deeper wells are likely to be better candidates for submersible pumps for multiple reasons. First, hand pumps can become difficult to operate when the required lift is large. Second, our limited data suggest that deeper wells (>150 m) may be more likely to have higher specific capacities in fractured bedrock aquifers.

We also recommend installing more boreholes in areas with low aquifer productivity but good groundwater quality, particularly in areas where nitrate and fluoride concentrations tend to be low but aquifer transmissivity is also low. Adding more wells with smaller pumps distributes pressure on the aquifer and reduces the drawdown, facilitating a steady, reliable flow at each well. In this study, Tabora had relatively good groundwater quality (low concentrations of nitrate and fluoride). In regions such as Singida and Kilimanjaro with higher fluoride concentrations, it is important to evaluate health benefits and risks of groundwater development. However, fluoride is often high in dug wells and surface water as well, so installing new boreholes is likely to improve access to water that is lower in nutrients and pathogens and perhaps similar in fluoride levels.

Despite the physical challenges of infrastructure maintenance, low yield, and marginal water quality, groundwater development will continue to be an important ingredient for water security in rural Tanzania. Groundwater is less susceptible to anthropogenic contaminants like pathogens and nutrients that plague surface water during the rainy season, as long as boreholes are properly constructed and protected with concrete aprons. Groundwater can have higher total dissolved solids, but this is fortunately one of the easiest and most affordable water quality parameters to test and monitor. Groundwater is also accessible year-round and is less influenced by climate than surface impoundments and rainwater harvesting systems. To support groundwater development, improved understanding of potential well yields and sustainable yields is needed. An evaluation of sustainable yield requires analysis of diverse factors such as natural recharge rates, connections to surface water bodies such as rivers and springs, and connections to other aquifers (Theis 1940; Zhou 2009). We advocate for further assessment of sustainable yield as part of the decision-making process for groundwater development in Tanzania.

ACKNOWLEDGEMENTS

We thank the staff of Majitech Engineering for their assistance with data collection and assimilation. We also thank the Ministry of Water and Irrigation in Tanzania, village leaders, and District Water Engineers for their support. Logistical support was provided by the University of Dodoma. Funds were provided by the Global Water Institute. We also thank Cathy Ryan and three anonymous reviewers for suggestions that improved this manuscript.

REFERENCES

Ali, S., Thakur, S. K., Sarkar, A. & Shekhar, S. 2016 Worldwide contamination of water by fluoride. *Environmental Chemistry Letters* **14**, 291–315. doi:10.1007/s10311-016-0563-5.

Bakundukize, C., Mtoni, Y., Martens, K., Van Camp, M. & Walraevens, K. 2016 Poor understanding of the hydrogeological structure is a main cause of hand-dug wells failure in developing countries: a case study of a Precambrian basement aquifer in Bugesera region (Burundi). *Journal of African Earth Sciences* **121**, 180–199. doi:10.1016/j.jafrearsci.2016.05.025.

Bardecki, C. J. 1974 Fluoride probability in Tanzanian waters. *Maji Review Ministry of Water Development and Power* **1**, 55–61.

Bruvold, W. H. & Ongerth, H. J. 1969 Taste quality of mineralized water. *Journal of American Water Works Association* **61**, 170.

Elisante, E. & Muzuka, A. N. N. 2015 Occurrence of nitrate in Tanzanian groundwater aquifers: a review. *Applied Water Science*. doi:10.1007/s13201-015-0269-z.

Elisante, E. & Muzuka, A. N. N. 2016 Sources and seasonal variation of coliform bacteria abundance in groundwater around the slopes of Mount Meru, Arusha, Tanzania. *Environmental Monitoring and Assessment* **188** (7), 395. doi:10.1007/s10661-016-5384-2.

Ghiglieri, G., Pittalis, D., Cerri, G. & Oggiano, G. 2012 Hydrogeology and hydrogeochemistry of an alkaline volcanic area: the NE Mt. Meru slope (East African Rift-Northern Tanzania). *Hydrological Earth System Science* **16**, 529–541. doi:10.5194/hess-16-529-2012.

Kongola, L. R. E. 2004 Status of groundwater resource in Tanzania. In: *A Paper Presented in the Annual General*

Conference of the Tanzania Geological Society (GST), Mwanza.

MacDonald, A. M., Bonsor, H. C., Ó Dochartaigh, B. É. & Taylor, R. G. 2012 Quantitative maps of groundwater resources in Africa. *Environmental Research Letters* **7** (2), 024009. doi:10.1088/1748-9326/7/2/024009.

Malard, F., Reygrobellet, J. L. & Soulie, M. 1994 Transport and retention of fecal bacteria at sewage-polluted fractured rock sites. *Journal of Environmental Quality* **23** (6), 1352–1363. doi:10.2134/jeq1994.00472425002300060032x.

Nanyaro, J. T., Aswathanarayana, U., Mungure, J. S. & Lahermo, P. W. 1984 A geochemical model for abnormal fluoride concentration in waters in part of northern Tanzania. *Journal of African Earth Sciences* **2**, 129–140.

Nkongo, D. 2009 *Management and Regulation for Sustainable Water Supply Schemes in Rural Communities*. WaterAid Tanzania.

Nkotagu, H. 1996 The groundwater geochemistry in a semi-arid, fractured crystalline basement area of Dodoma, Tanzania. *Journal of African Earth Sciences* **23**, 593–605.

Olaka, L. A., Wilke, F. D. H., Olago, D. O., Odada, E. O., Mulch, A. & Musolff, A. 2016 Groundwater fluoride enrichment in an active rift setting: central Kenya rift case study. *Science of the Total Environment* **545–546**, 641–653. doi:10.1016/j.scitotenv.2015.11.161.

Reddy, D. V., Nagabhushanam, P. & Peters, E. 2009 Village environs as source of nitrate contamination in groundwater: a case study in basaltic geo-environment in central India. *Environmental Monitoring and Assessment* **174**, 481–492. doi:10.1007/s10661-010-1472-x.

Rural Water Supply Network 2014 *Water Point Mapping: Indicators, Pump Functionality, Accuracy of GPS, Using and Sharing Data, Synthesis of Discussion and Activities May and June 2014*. Available from: http://www.rural-water-supply.net/_resources/documents/default/1-588-2-1406117553.pdf.

Theis, C. V. 1940 The source of water derived from wells: essential factors controlling the response of an aquifer to development. *Civil Engineering* **10**, 277–280.

UNICEF & WHO 2015 *Progress on Sanitation and Drinking Water: 2015 Update and MDG Assessment*. UNICEF, Geneva, p. 90.

United Republic of Tanzania 2015 *Water Points Location in Rural Water Supply*. Directorate of Rural Water Supply, Ministry of Water and Irrigation. Available from: http://opendata.go.tz/dataset/water-points-in-rural-water-supply (accessed 10 January 2018).

van den Broek, M. & Brown, J. 2015 Blueprint for breakdown? Community based management of rural groundwater in Uganda. *Geoforum* **67**, 51–63. doi:10.1016/j.geoforum.2015.10.009.

WHO (World Health Organization) 2006 *Protecting Groundwater for Health: Managing the Quality of Drinking Water Source*. IWA, London.

WHO (World Health Organization) & UNICEF (United Nations Children's Fund) 2017 *Progress on Drinking Water, Sanitation and Hygiene: 2017 Update and SDG Baselines*. UNICEF and WHO, Geneva.

Zhou, Y. 2009 A critical review of groundwater budget myth, safe yield and sustainability. *Journal of Hydrology* **370**, 207–213. doi:10.1016/j.jhydrol.2009.03.009.

First received 20 December 2018; accepted in revised form 23 April 2019. Available online 20 May 2019