INVESTIGATION OF WATER QUALITY AND AVAILABILITY IN RURAL TANZANIAN VILLAGES

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By

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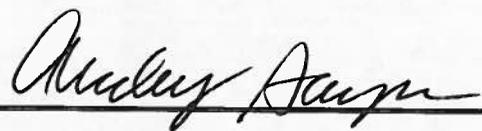
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TABLE OF CONTENTS

ABSTRACT

Many rural African villages rely on groundwater to meet domestic water needs, and solar-powered pumps are often sought to replace traditional hand pumps in village boreholes. As part of a collaborative project at The Ohio State University, a team of students is planning to design and install a solar-powered pump in an existing borehole within the rural village of Marwa, Tanzania. Herein, I report on a hydrogeologic assessment of boreholes within the surrounding regions of Kilimanjaro and Manyara to determine potential groundwater quality concerns and well yields. Based on an analysis of 67 water samples, boreholes commonly have low nitrate and coliform but occasionally have high total dissolved solids (TDS) and fluoride, relative to both drinking water standards and secondary water sources (dams, dug wells, and springs). I recommend testing the borehole in Marwa for TDS and fluoride during an upcoming data collection trip in May 2017. Based on an analysis of pump tests in ten boreholes across the region, typical aquifer transmissivities are moderate to low. I use this information to design a pump test for the borehole in Marwa, to be conducted during the data collection trip. If aquifer transmissivity is 5.098 m^2/day, I anticipate a potential well yield on the order of ~4,200 L/hr. A solar powered pump would be suitable for this yield and could provide enough water for the village of Lesirway with a population of 500-1,000 people. The well could meet domestic needs, with a possibility of having some water supplied for irrigation and livestock watering.

LIST OF FIGURES

INTRODUCTION

Hundreds of millions of people across sub-Saharan Africa lack adequate access to clean water (Water and Sanitation, 2016). Africa is home to 15% of the world's population, but only contains 9% of the world's freshwater resources (African Water Atlas, 2010). Africa is the second driest continent in the world after Australia and the second most populous after Asia. In 2008, the annual average water availability per capita was 4,008 m^3/yr compared to the world average of 6,498 m^3/yr. In short, Africa's current water supply cannot meet the demand (African Water Atlas, 2010).

Africans rely heavily on groundwater to meet their domestic water needs. Only 45% of the world uses groundwater as the primary supply for domestic water, but 75% of Africa's population depends on groundwater for domestic use (UNICEF, 2016). In rural villages, boreholes and hand-dug wells play an important role in increasing water accessibility, particularly in arid and semi-arid regions where surface water supplies are prone to drought and climate change. When strategically placed and maintained, boreholes offer a clean source of drinking water and are reliable during the dry season. However, proper borehole placement is challenging in remote areas that lack good geologic data (UNICEF, 2016). Locations of faults and fractures in relation to drilled boreholes greatly affect their efficiency, which can be variable over short distances.

There is projected to be significant economic and agricultural growth in Africa (Villholth, 2013). With growth and development comes an increase in demand and competition for groundwater resources. Many risks accompany increased withdrawal rates such as depletion, pollution, and saltwater intrusion in coastal areas. Some of these problems can be avoided by proper positioning, installation, and maintenance of boreholes (UNICEF, 2016). Another consideration in developing groundwater resources is the difficulty of maintaining wells and pumps. Borehole functionality typically drops between 70-85% within the first two years of the borehole's operation. (UNICEF, 2016) (Figure 1). In a recent study assessing 45 non-functioning rural water access points throughout Tanzania, approximately half reported a broken pump as an infrastructure problem inhibiting water access (Scharenberg et al., 2016). The high cost of powering the pump was another contributing factor at 58% of 45 points. Hand pumps are cost effective and mechanically simple to repair but cannot produce water at very high rates. Solar powered pumps are an attractive option to increase yield if the geology is amenable, and they do not require fuel or electrical power. Solar pumps were requested by 47% of rural Tanzanian villages in a recent survey (Scharenberg et al., 2016).
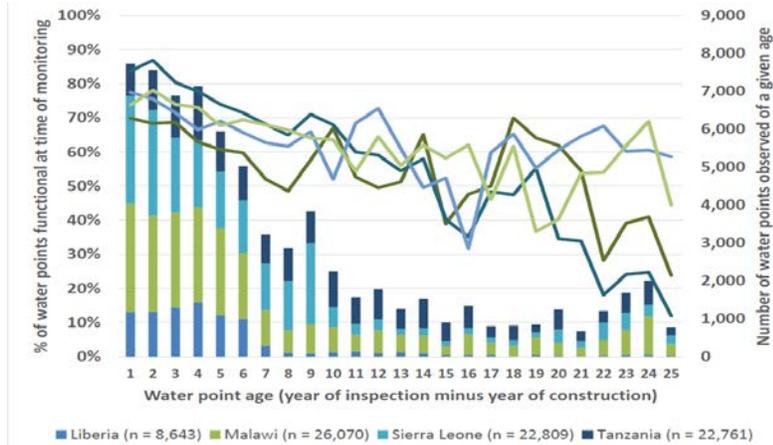
Figure 1 Functionality rapidly declines with borehole age in three African countries (UNICEF, 2016). Contributing factors for decline include vandalism, accidental damage by users, or initial flawed design or construction.

This study is part of a larger collaboration with the Department of Civil, Environmental, and Geodetic Engineering at The Ohio State University that will secure a reliable groundwater source for the village of Marwa in the region of Kilimanjaro, Tanzania. The primary drinking water supply for much of the village is the Pangani River. A portion of the village relies on a single borehole equipped with an operable hand pump. A team of engineering students is currently designing a system that will pump groundwater from the borehole to a storage reservoir using a solar powered submersible pump. The solar pump will increase groundwater supplies without the need for fuel or electric power. However, the potential yield of the borehole is unknown. It is also uncertain whether water quality may deteriorate with increased production. A nearby borehole in the same village is no longer in use because it began to produce brackish water after roughly two years of pumping (Tony Duke, personal communication, 2017).

In May, I will travel with civil engineering students to Marwa to conduct aquifer pump tests and sample groundwater in order to quantify the potential well yield and gather baseline water quality data. Here, I analyze existing pump test and groundwater quality data in the surrounding regions of Kilimanjaro and Manyara in order to plan the tests I will conduct in country. My analysis suggests that the well yield will likely be sufficient to support the installation of a solar-powered pump, but a pump test will be essential because well yields vary widely in fractured rock aquifers in the region. I recommend groundwater testing for total dissolved solids (TDS) and fluoride in particular.

BACKGROUND

Tanzania Climate

The climate of Tanzania is tropical along the coast and temperate in the highlands (Figure 2). In the village of Marwa at 643 m elevation, mean annual precipitation is 800–1000 mm (Figure 2). Some areas of the country have a bimodal rainfall distribution, including the village of Marwa, while others are monsoonal with a unimodal distribution (Kashaigili, 2010). Along the coast, in

the northeastern highlands, and in the Lake Victoria Basin, short rains occur from October to December, and long rains dominate from March to June (Kashaigili, 2010). Across the rest of the country, the rainfall distribution is unimodal or monsoonal, and groundwater recharge only occurs during the wet season (Taylor et al., 2013). Climate records from Makutapora suggest that significant recharge does not occur unless monthly rainfall exceeds 200 mm or seasonal rainfall exceeds 670 mm. According to figure 2, annual rainfall likely results in recharge. The threshold effect may be due to the high rates of evapotranspiration that counterbalance precipitation even during the monsoon season. Evapotranspiration rates in the tropics during monsoon season are estimated to be 160 mm/month (Taylor et al., 2013). Rainfall is expected to grow more intense and less predictable with climate change (Taylor et al., 2013; MacDonald et al., 2011). Temperature, evapotranspiration, recharge, and runoff are expected to increase, resulting in uncertain groundwater storage conditions (MacDonald et al., 2011).
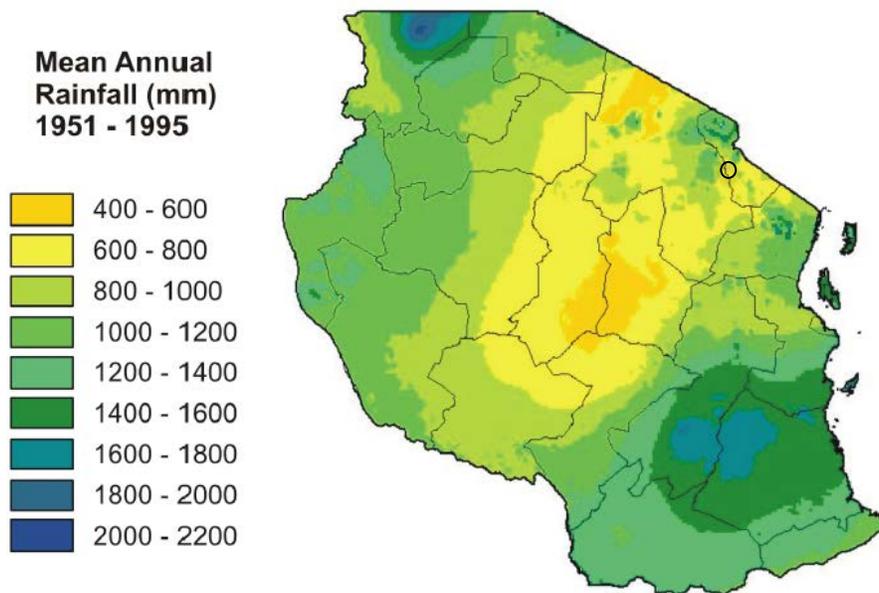
Figure 2. Mean Annual Rainfall in Tanzania from 1951-1995 (MacDonald and Tyler-Whittle, 2002). Village of Marwa is indicated with a black circle.

Hydrogeology

The East African Rift System runs through Tanzania and has shaped much of its geology and aquifer characteristics. Tanzania's interior consists mainly of fractured Precambrian crystalline rocks (metamorphics and granite) that form a central plateau (British Geological Survey, 2000). Intrusive and volcanic igneous rocks dominate the northern and southern highlands, including the regions of Kilimanjaro and Manyara that surround Marwa. Sedimentary basins dominate in southern Tanzania (Odada and Olago, 2002). Accordingly, the aquifers of Tanzania can be

3

characterized into three main types: 1) Plutonic-Metamorphic/Gneiss rocks, 2) Volcano-Plutonic/granite, and 3) Old, Paleogene, Neogene and Quaternary sediments (Figure 3).
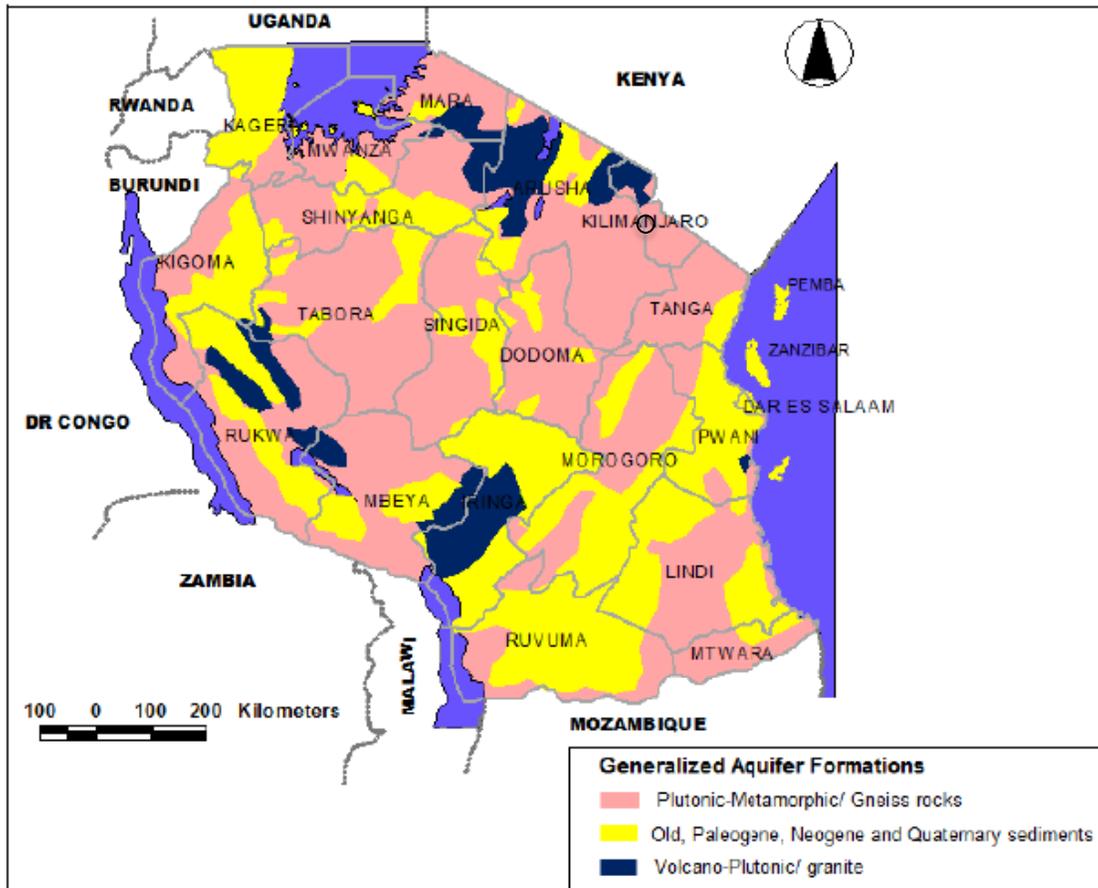
Figure 3 Map of primary aquifer types from Kashaigili (2010). The village of Marwa is shown with a black circle.

The Plutonic-Metamorphic/Gneiss rock aquifers are fractured granites and gneisses. The Volcano-Plutonic/granite aquifers are consolidated volcanic and fractured granitic rocks. The Old, Paleogene, Neogene and Quaternary sediments range from unconsolidated to semi-consolidated gravels, sands, silts, and muds (Kashaigili, 2010). Where shallow aquifers are composed of unconsolidated sands and gravels, their high porosity and permeability allow for high well yields and recharge rates. Where shallow aquifers are composed of volcanic and metamorphic rocks, fractures are essential for facilitating high well yields and recharge rates. Fractures allow direct rainwater infiltration and preferential flow. Some permeable volcanics may also act as recharge zones (JICA, 2008). Aquifer productivity across most of the region and broader country is low to moderate, especially in regions with metamorphic rocks (Figure 4).

The Kilimanjaro and Manyara regions' aquifers are dominantly Plutonic-metamorphic/ Gneiss rocks, with the northwest portion of Kilimanjaro being composed of volcano-plutonic granites. The village of Marwa lies within the Manyara region about 2.3 km to the west of the Kilimanjaro-Manyara border. The mapped aquifer type is metamorphic gneiss. The village lies near the mapped boundary between a zone of low/medium productivity (0.5–1.0 L/s) and a zone of high productivity (5.0–20.0 L/s) (Figure 4).
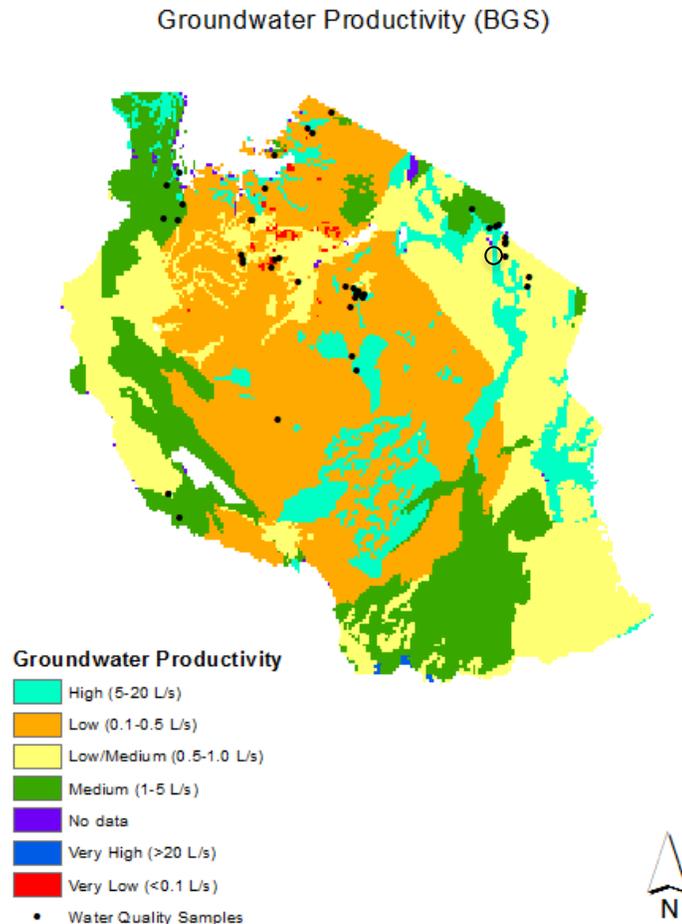
Figure 4 Aquifer productivity in Tanzania (British Geological Survey, 2011). Marwa is shown with a large black circle.

Groundwater Quality

Total dissolved solids (TDS) are a known problem in many aquifers in rural Africa (Edmunds, 2012). TDS in drinking water can be derived from natural sources (rock-water interaction) or from anthropogenic sources like industrial wastewater, urban run-off, or agricultural contaminants. In addition to creating an undesirable taste and odor to drinking water, some

dissolved solids can cause health implications including cancer and heart disease (Saana et al., 2016). Even at low concentrations, TDS can be corrosive to metal water infrastructure components (Saana et al., 2016). In irrigation water, excessive salts can also accumulate in soils and eventually hinder plant growth. The Tanzania standard for TDS in drinking water is 2000 mg/l. The WHO has the following rating system for TDS in drinking water: <300 mg/l excellent, 300–600 mg/l good, 600–900 mg/l fair, 900–1,200 mg/l poor, >1,200 mg/l unacceptable (WHO, 1996). In general, TDS values below 1,000 mg/L are considered fresh, and values between 1,000 mg/L and 5,000 mg/L are considered brackish (Water Quality Association).

Groundwater in the Kilimanjaro region of Tanzania has historically contained elevated levels of fluoride, likely due to the dissolution of igneous rocks like granite and volcanic tuff (Elisante and Muzuka, 2015; JICA, 2008). High fluoride concentrations are often correlated with high sodium and alkalinity where weathering of sodium-rich igneous rocks occurs (MacDonald and Tyler-Whittle, 2002). Geothermal water can also contribute high fluoride, sodium, and alkalinity (MacDonald and Tyler-Whittle, 2002). Finally, evaporation of shallow groundwater can concentrate fluoride and other salts in groundwater. Fluoride in drinking water can cause health implications such as aching joints associated with skeletal fluorosis and mottling of teeth, caused by hypomineralization of teeth enamel. The Tanzania standard is 4.0 mg/L, and the WHO standard for fluoride in drinking water is 1.5 mg/L.

Nitrate in groundwater has been an issue in various drainage basins throughout the country, although the Pangani basin has not been identified as one of the more problematic areas (Elisante & Muzuka, 2015). Sources of high nitrate concentration are often poor sanitation in urban centers or agricultural fertilizers that are transported in runoff. In rural communities, livestock and nearby latrines could be a source. Unsafe levels of nitrate can lead to infant death. The WHO standard for nitrate in drinking water is 30 mg/L.

Coliform is a blanket category for many different types of bacteria in the environment. Most coliform bacteria do not cause illness but rather act as "indicator" organisms for the presence of disease-causing (pathogenic) bacteria. Their presence suggests the likelihood of a pathway between a source of pathogens and the water source. Since coliform bacteria live in water longer than typical pathogens, the lack of coliform indicates drinkable water (Swistock et al., n.d.). Pathogens in drinking water can come from leaching of manure, storm runoff, and livestock. They are more common in surface water than groundwater sources, as aquifer materials strain many pathogens. However, pathogens can be problematic in fractured rock aquifers. The WHO standard for coliform is 0 CFU/100 mL.

SITE DESCRIPTION

The village of Marwa is inhabited by the Masai people and has a population of 4,000–7,000, who are mostly livestock keepers. Exact populations are unknown because the Masai do not participate in the national census in resistance to the government. The village is 28 miles long and 7 miles wide and is divided into 4 sub villages (from north to south): Lesirway (500–1,000 people), Njakitai (1,000–2,000), Marwa (2,000–3,000), and Patelli (500–1,000) (Figure 5). There are two main sources of water for the 196 mi^2 village: the Pangani river and the Lesirway borehole. The Pangani river runs parallel with the length of the village and is a 9 km walk from

the most densely populated areas. The sub villages of Njakitai, Marwa, and Patelli all rely on the river for drinking water. The Lesirway borehole offers reliable, relatively clean water to the sub village of Lesirway and attracts people from other sub villages who have means of travel (motorcycle, etc.). The Njakitai borehole was installed by a church group from the United States around 2002 and produced fresh drinking water for approximately two years but has since become brackish. The people of the village have attempted to use this water for cleaning clothes or floors, but the very high salinity leaves salt residue and can damage clothing.
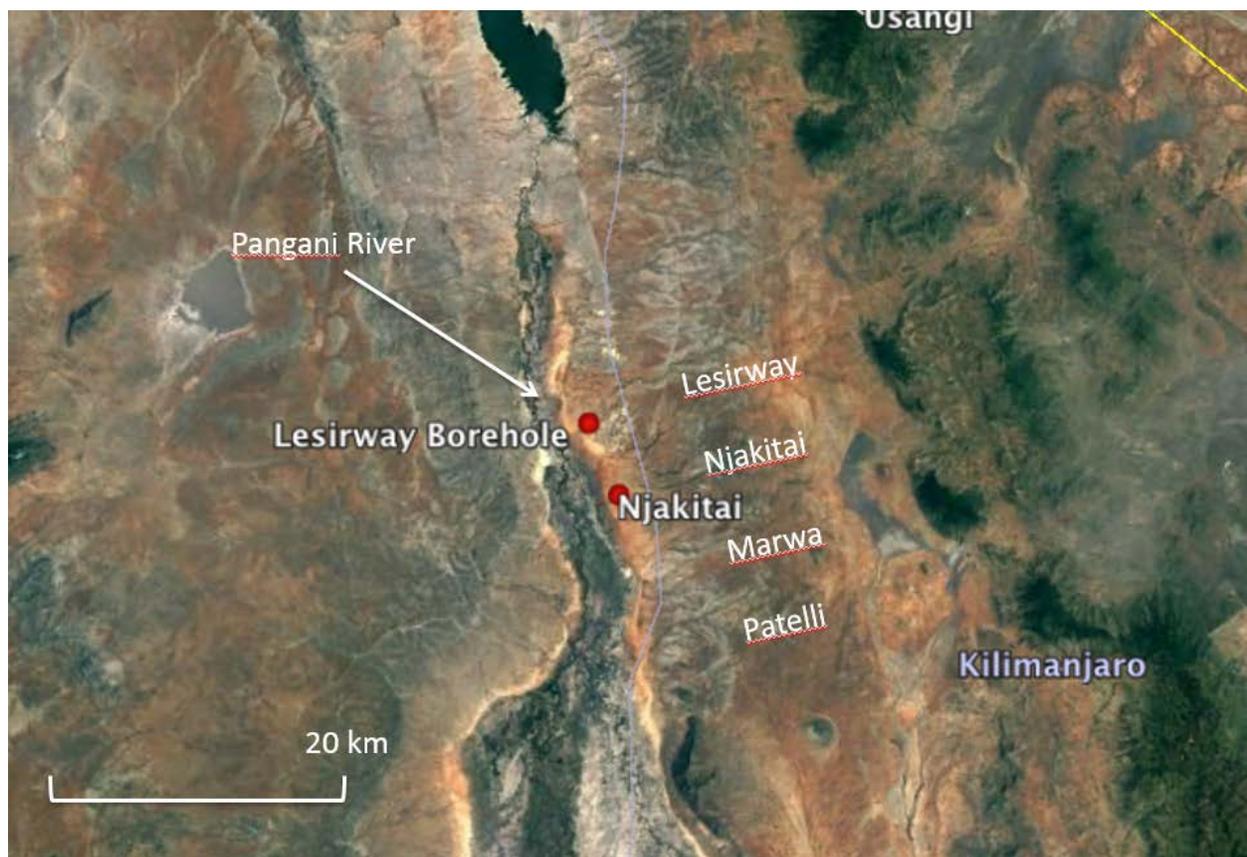
Figure 5 Map showing the Njakitai and Lesirway borehole, and the Pangani River to the East running North to South.

The village does not treat water from either the Pangani river or the Lesirway borehole. At most, river water is allowed to settle to reduce turbidity before use. The lack of river water treatment could contribute to the cholera issue in the village (Michael Hagenberger, personal communication, 2017). Groundwater is likely more protected from pathogens but contains elevated levels of fluoride. In 2009, a groundwater sample from the borehole in Lesirway contained fluoride at 3.47 mg/L. This value is below the Tanzania standard of 4.0 mg/L but is almost 2 mg/L over the World Health Organization standard of 1.5 mg/L. The borehole lacks a completion report and any formal aquifer pump test. The only available document is a sketch of the borehole, showing a completion depth of 58 meters, a casing radius of 5 inches, and a screened interval from 45m to 54m. No static water level is shown (see Appendix I).

Survey of national water quality data

Water quality data were collected by Majitech analyzed from rural villages across the country to assess typical groundwater quality from boreholes. It is important to note that boreholes sampled for water quality generally do not correspond with boreholes analyzed for potential yield and aquifer properties. In order to place borehole water quality data in the context of alternate water sources, I also analyzed available data from rivers, springs, and dug wells (secondary water sources). A total of 38 borehole samples and 29 secondary water source samples were collected by Majitech Engineering, Ltd (Majitech) between December 2015 and April 2016. Samples were collected as part of a survey of 45 non-functional rural water access points (Scharenberg et al., 2016). The survey examined socioeconomic, hydrogeologic, and infrastructure factors that inhibited water access. Technicians sampled water directly from boreholes where possible, but more often, the borehole was inaccessible. In those cases, samples were collected from the attached storage tank or a distribution point. Technicians took water samples to National Water Laboratories in Arusha, Mwanza, Musoma, Rukwa, Singida, and Shinyanga for further testing. These samples were unlikely filtered, chilled, or frozen before transport. The national labs tested for a variety of contaminants, but I focused on TDS, fluoride, nitrate, and coliform.

Groundwater quality likely varies strongly across the country of Tanzania. Ideally, this analysis would be restricted to samples from the Kilimanjaro and Manyara regions. However, only 10 borehole samples and 1 secondary water sample were available from the Kilimanjaro region. No samples were collected in Manyara. I therefore analyzed data from all available regions, which include Kegara, Kilimanjaro, Mara, Mwanza, Rukwa, Singida, and Tabora.

Regional well test analysis

In order to plan a pump test for the Lesirway borehole in May, I analyzed available pump test data from 10 boreholes in the regions of Kilimanjaro and Manyara (5 from each region). All data were provided by Majitech Engineering, Ltd (Majitech). In general, the well tests were performed by pumping at a steady rate, or in some cases a stepped rate with two or more pumping stages, for several hours and measuring drawdown in the pumping well. Pumping rates varied from 2,000 to 100,000 L/hr. In all of the wells, recovery data were also available. No observation wells were available for these tests. Therefore, aquifer storage parameters cannot be determined.

I first analyzed the drawdown data for specific capacity, SC:

$$SC = Q/ \Delta h, \qquad\qquad\qquad \text{(Equation 1)}$$

where Q is the pumping rate and Δh is the total drawdown at the end of the pumping period. Some of the pump tests had multiple pumping periods with different rates. In these cases, only the first pumping period was used to avoid the effects of superposition on drawdown.

Specific capacity was then used with available drawdown (ADD) to estimate a potential borehole yield (Y) according to:

$$Y = SC * ADD. \hspace{3cm} \text{(Equation 2)}$$

Available drawdown was estimated from the driller's log as the borehole depth minus the static water level and an additional 3 meters, since the pump cannot rest on the bottom of the well.

Aquifer transmissivity (T) was also estimated from SC according to an empirical relationship developed for alluvial aquifers (Razack and Huntley, 1991):

$$T= 0.36 * SC^{0.67} \text{ for alluvial aquifers} \hspace{2cm} \text{(Equation 3)}$$

and an empirical relationship developed for fracture bedrock aquifers (Huntley et al., 1992):

$$T= 0.29*SC^{1.18}. \hspace{3cm} \text{(Equation 4)}$$

Given a known aquifer thickness (b), hydraulic conductivity (K) can also be estimated as T/b. Estimation of b is subjective, given the limited data on aquifer hydrogeology. To estimate b, I utilized information from the driller's logs. I first examined the geologic description and water strikes to assess whether the aquifer was likely confined or unconfined. If the first water strike was significantly below the static water level and if clays or other relatively impermeable units were reported at shallow depths, I assumed the aquifer was confined. For confined aquifers, I interpreted b as the distance from the first water strike to the bottom of the well. For unconfined aquifers, I interpreted b as the distance from the static water level to the bottom of the well. This interpretation assumes that the driller had adequate understanding of the geology and stopped drilling below the most productive intervals (essentially, the base of the aquifer).

I also estimated T and K from pump test results using two separate approaches. In the first approach, I fit the late-time drawdown behavior during the pumping period using the Cooper-Jacob straight line method in Aqtesolve. This approach involves fitting the slope of the data on a plot of drawdown versus log(t), where t is time since the start of the test. In the second approach, I fit the late-time residual drawdown behavior during the recovery period using the Theis solution in Aqtesolve. This approach involves fitting a type curve with a plot of residual drawdown versus log(t/t´), where t´ is the time since the start of the recovery period. No observation wells were present for the tests, so storativity was not analyzed in either approach.

Finally, I used the range of T and K values to estimate a range of expected aquifer properties, specific capacities, and well yields for the Lesirway borehole. I also used the geometric mean of the K values to compute drawdown for a design test for the Lesirway borehole, in preparation for the test I will conduct in May. The forward solution for drawdown and recovery was computed using the Theis solution for flow to a fully-penetrating well in an infinite, homogeneous, confined aquifer.

RESULTS

Water Quality

TDS is generally low in both secondary water sources and boreholes, but a greater proportion of boreholes have elevated TDS values. There were 39 of 66 samples found to be within the World Health Organization's "excellent" range (Figure 6). Of those 39, 17 were boreholes and 22 were secondary sources. Within the Kilimanjaro region, not one of the 10 borehole samples was found

to be poor or unacceptable, but only 7 samples were excellent. The highest measured TDS from a borehole within the Kilimanjaro region was 737 mg/L in Shighatini. The highest measured TDS from a borehole within all 7 regions was 2,387 mg/L, double the WHO "unacceptable" range of 1,200 mg/L. This borehole was located in Kamugendi (Mara region).
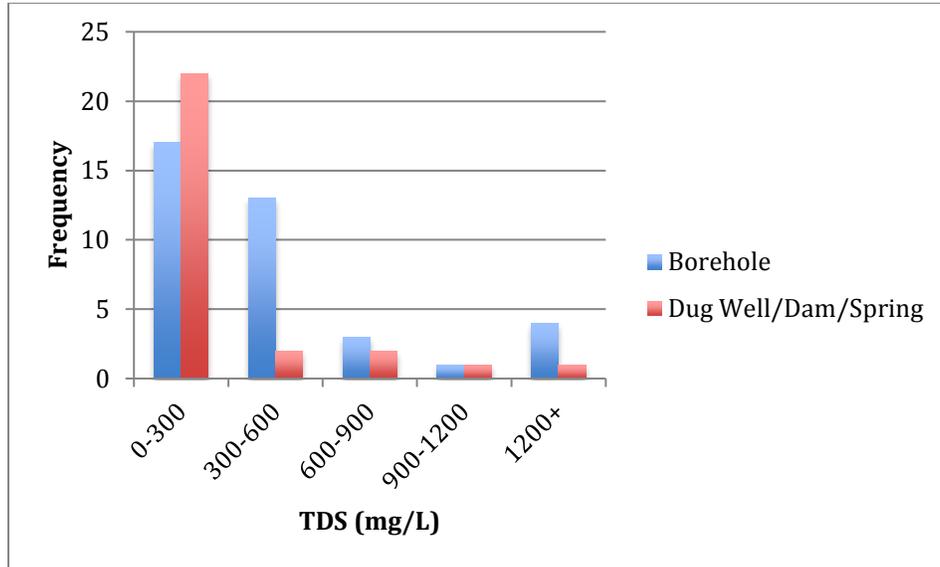
Figure 6 Histogram showing the comparison of TDS values in boreholes and other water sources.

Fluoride is generally low in both borehole and secondary water samples. However, the three samples that exceed the WHO limit for fluoride of 1.5 mg/L are from boreholes. None of these three samples exceed the Tanzania standard of 4.0 mg/L. Unfortunately, 2 of the 3 samples are located in the Kilimanjaro region.
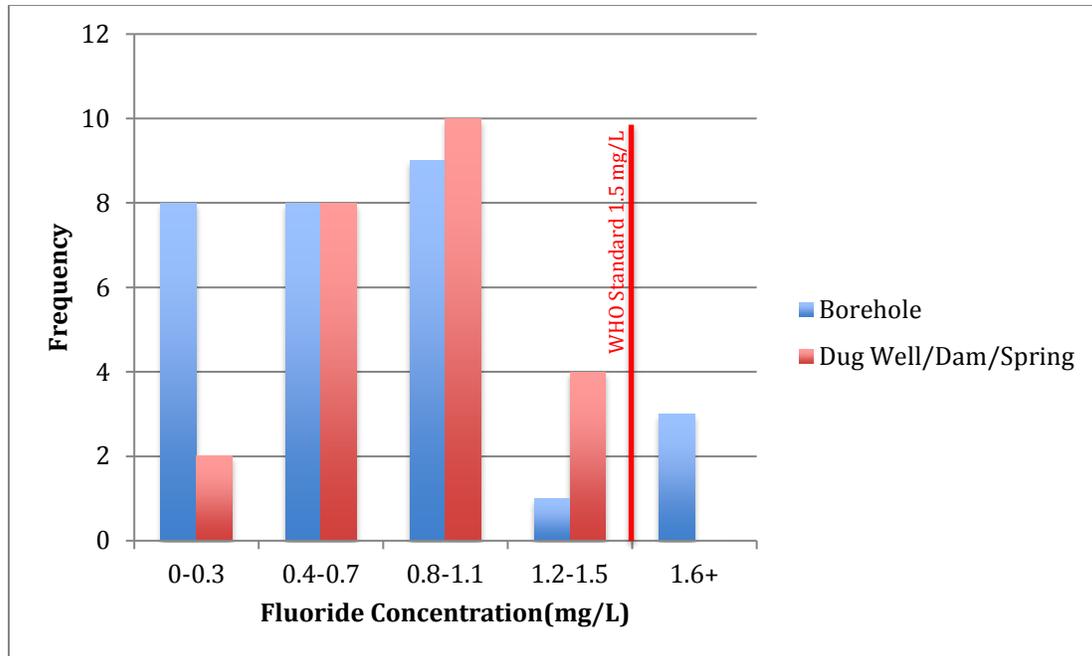
Figure 7 Histogram showing fluoride concentrations in boreholes and other water sources.

Nitrate is most commonly an issue in secondary water sources rather than in boreholes because of the nutrient's association with agricultural runoff and wastewater. Of the 30 borehole samples, 27 have nitrate levels below the WHO limit of 30 mg/L (Figure 9). The 3 high concentrations may be due to improper well placement or design. For example, high nitrate in a borehole in the village of Kitaramanka (Mara region) is likely due to a lack of well head protection (Figure 8). Nitrate concentrations exceed the limit in a larger fraction of secondary water samples (8 of 25 samples). There were some extremely high values of nitrate from secondary sources in the Singida region. A sample from a charco dam in Sagara Barabani had a concentration of 419.52 mg/L. Another sample from a charco dam in the same region measured 837 mg/L, 28 times the WHO limit. These dams are stagnant pools of water and allow for polluted surface runoff to enter easily. None of the samples from the Kilimanjaro region exceeded the WHO limit.

Figure 8 Kitaramanka borehole with a nitrate measurement of 221 mg/L (Scharenberg et al., 2016).
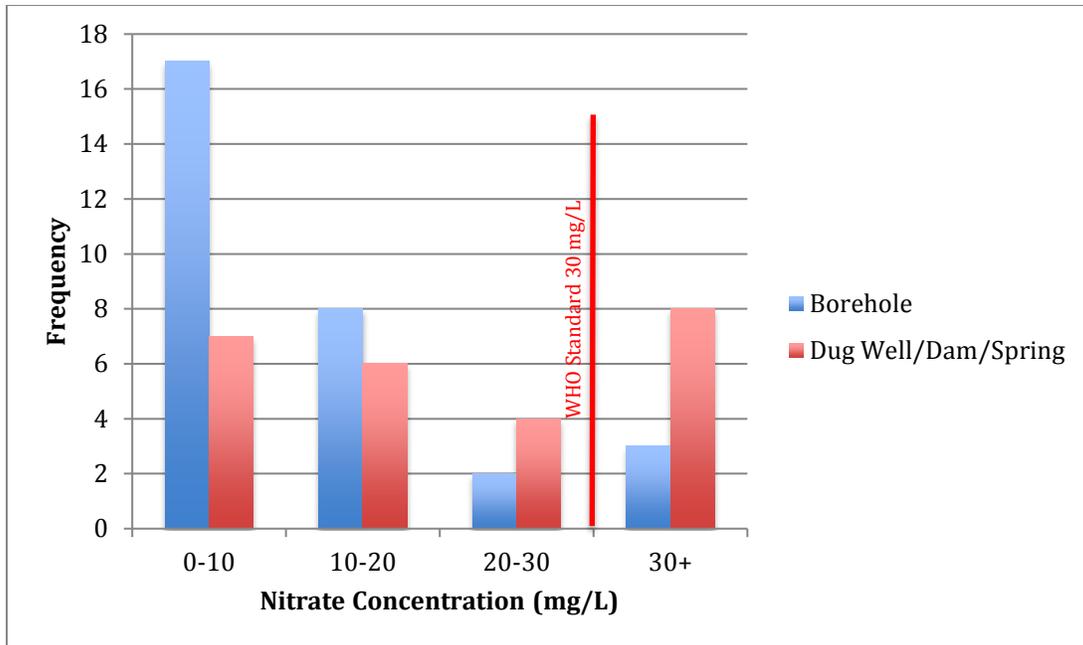
Figure 9 Histogram of nitrate concentrations in boreholes and other water sources.

Secondary sources generally have higher values of coliform than do the boreholes (Figure 10). Of 19 secondary water samples, only 2 lacked coliform. A surprising number of boreholes (11 out of 21) do have some measurable amount of coliform. Unfortunately, coliform was not measured on any water samples from Kilimanjaro because these samples were tested in the Arusha lab, which apparently does not perform coliform testing.
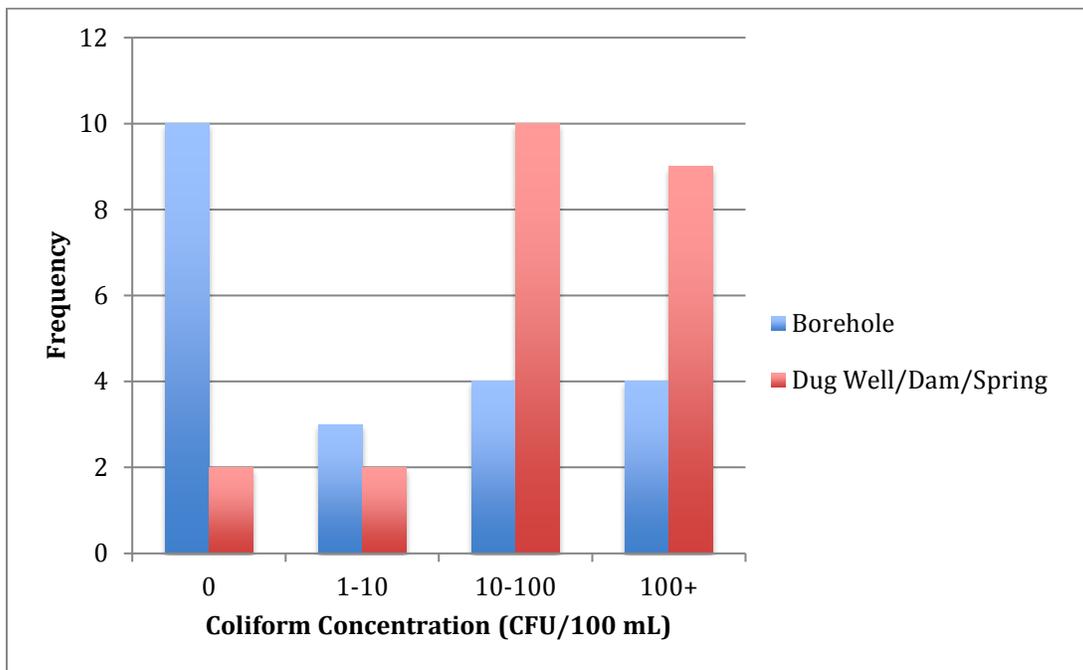
Figure 10 Histogram of coliform values in boreholes and other water sources. Seven samples were considered "too numerous to count" and are indicated here as having more than 100 CFU/100mL. WHO considers any amount of coliform to be unacceptable.

Aquifer Type and Potential Well Yield

Kilimanjara and Manyara boreholes penetrated both alluvial and fractured bedrock aquifers. Seven of the ten boreholes were in fractured rock (Figure 11). Alluvial aquifers were characterized by fine to course sand with gravel. Fractured bedrock aquifers were commonly metamorphics or weathered/fractured igneous rocks. I interpreted 7 of the 10 to be confined, and the other 3 were interpreted as unconfined.
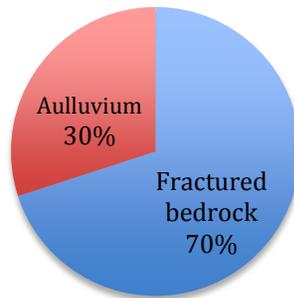
Figure 11 Aquifer type for the 10 boreholes, determined by the geology present in the driller's logs.

Borehole depths ranged from 31 meters to 193 meters. Overall, completion depths were not significantly different in alluvial and fractured bedrock aquifers (Figure 12). The boreholes often had multiple lengths of short screen intervals that appeared to be positioned randomly and occasionally inconveniently in clays, suggesting that borehole design was often sub-optimal for the hydrogeology at each site.

Figure 12 Completion depths for 10 boreholes in Kilimanjaro and Manyara. Alluvial aquifers are shown in blue, and fractured bedrock aquifers are shown in orange.
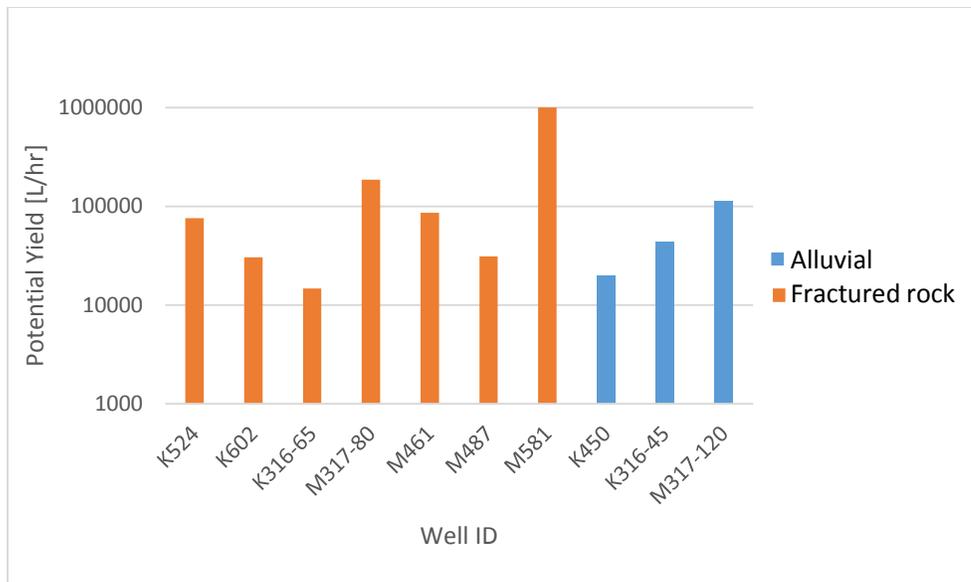
Figure 13 Potential yield of 10 wells.

Specific capacities ranged from 0.00407 m^2/min to 0.436 m^2/min and averaged 0.0167 m^2/min in alluvial aquifers and 0.0843 m^2/min in fractured bedrock aquifers. Potential yield ranged from 14,000 L/hr to 1,000,000 L/hr (Figure 13). Assuming a daily domestic per capita requirement of 20 L/d that is produced over a typical 9 hour day, 0.617 L/s (or 2220 L/h) is needed to sustain 1000 people. The lowest yielding well would therefore meet the domestic needs of a population of 6,200 people, while the highest yielding well would meet the domestic needs of a population of 450,000 people. It is important to note that potential yield is not the same as (and often less than) the sustainable yield. Sustainable yield considers additional factors such as the effects of drawdown on recharge, nearby surface water bodies, and leakage from other aquifer units of variable water quality.

Both the highest and lowest yields were in fractured rock. The high yield at M581 is subject to uncertainty. The reported pumping rate in this well was higher than any other (100,000 L/h), and measured drawdown was on the order of centimeters. It is possible that the borehole penetrates one or more extremely productive fractures, or an error in data reporting may have occurred. Within the alluvial aquifers, deeper wells tended to have higher yields (compare Figures 12 and 13). Well K450 has the shallowest drilled depth and the lowest yield, and well M317-120 has the deepest depth and the highest yield. The potential yields were not significantly different between alluvial and fractured rock (Figure 13).

Estimated Transmissivities and Hydraulic Conductivities

Transmissivities from drawdown and recovery analysis ranged over orders of magnitude from 0.124 m^2/day to 3,500 m^2/day (Figure 14). Well K450, located in an unconfined alluvial aquifer, had the highest transmissivity estimates. Transmissivity estimates from recovery data generally were within an order of magnitude but slightly greater than transmissivity estimates from drawdown data (Figure 14). This is to be expected, since the recovery period is generally less prone to borehole inefficiency associated with frictional energy loss or formation damage, both of which decrease apparent transmissivity.
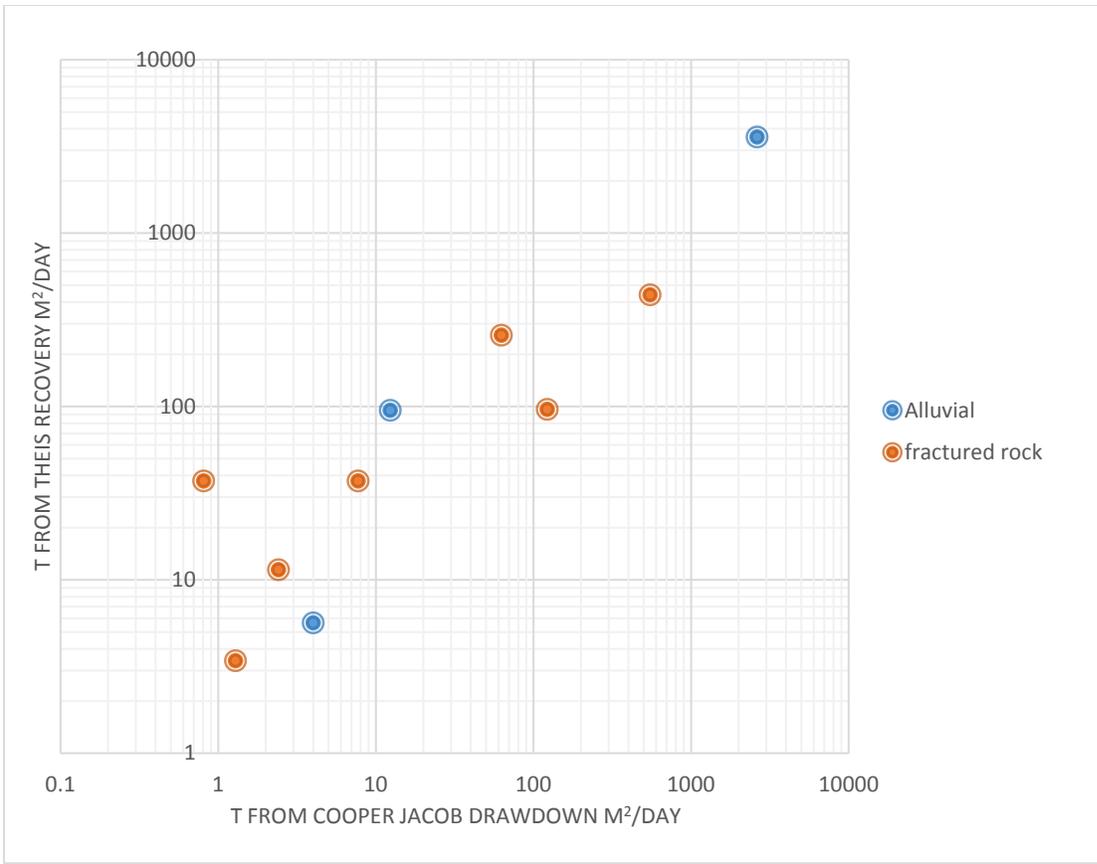
Figure 14 Cross plot of transmissivites from the Cooper-Jacob and Theis recovery methods.

Empirical estimates of transmissivity were more variable and ranged from 0.969 m^2/day to 240.5 m^2/day (Equations 3 and 4, Figure 15). These estimates also tended to be higher for the alluvial aquifers than the fractured rock aquifers.
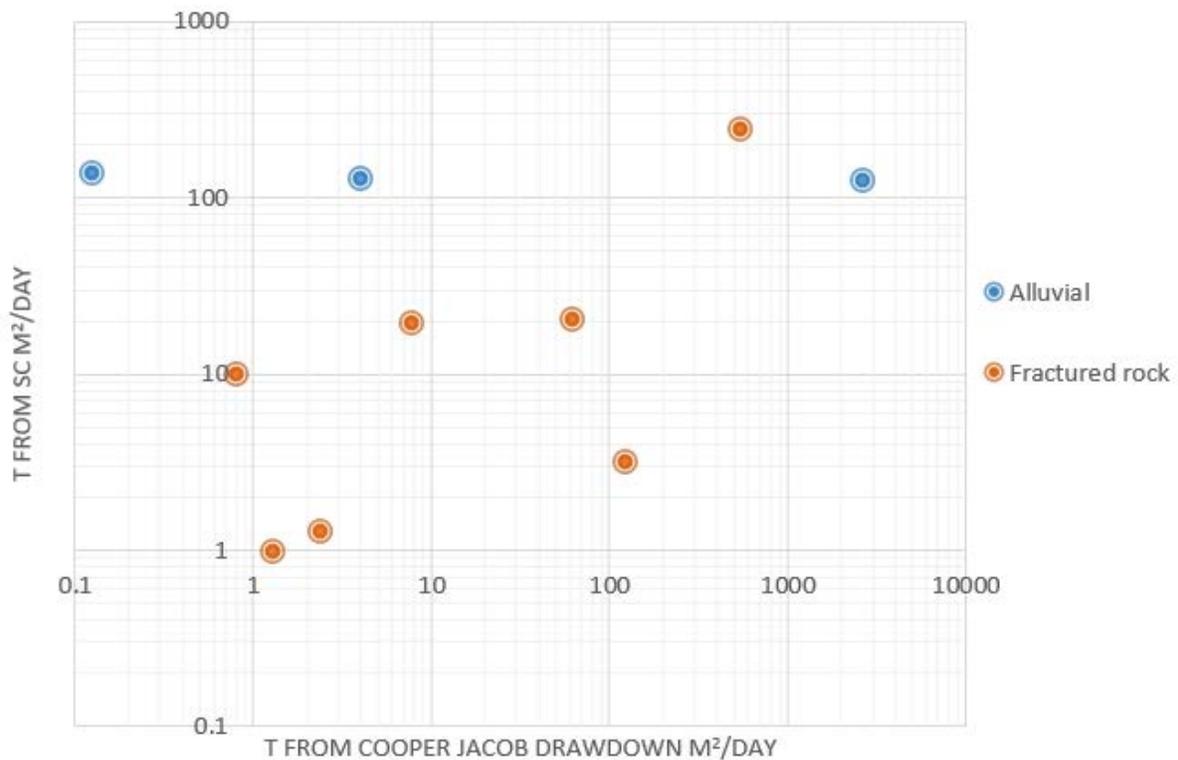
Figure 15 Cross plot of estimated transmissivities from specific capacity and Cooper-Jacob drawdown.

Calculated hydraulic conductivites were generally low. Using transmissivities from the empirical estimation (Equations 3 and 4), hydraulic conductivities ranged from 2.21×10^{-7} m/s to 7.73×10^{-5} m/s. For the alluvial aquifers, all values were around 1×10^{-5} m/s, typical of clean sand and silty sand (Freeze and Cherry, 1979). For fractured bedrock aquifers, K values were mostly between 1×10^{-7} m/s and 1×10^{-6} m/s, typical of fractured igneous and metamorphic rocks (Freeze and Cherry, 1979). Using transmissivities from drawdown and recovery analysis, hydraulic conductivities were more variable, ranging from 2.02×10^{-7} m/s to 1.73×10^{-3} m/s in the wells that penetrated fractured bedrock (Freeze and Cherry, 1979). The highest of these permeabilities was unusually high for fractured igneous and metamorphic rocks. Overall, hydraulic conductivities were relatively low and representative of marginal aquifer materials (see appendix II).

16

DISCUSSION

Recommended Water Quality Testing

In May 2017, testing for fluoride will be a priority. If the measured concentration is significantly higher than the recorded concentration from 2009 (3.47 mg/L), the installation of a solar powered pump on this borehole might need to be reconsidered. Given the anecdotal increase in TDS in the Njakti borehole over two years of pumping, testing for TDS will also be a priority.

If water quality is marginal or trending downward in the Lesirway borehole, the installation of a solar powered pump should be reconsidered. The population of Marwa is expected to grow after project completion, which would be problematic if the water quality is poor. Furthermore, mechanical failure is a common problem in rural villages, especially on submersible pumps (UNICEF, 2016). Repair of a solar-powered submersible pump is much more difficult than of a hand pump, and replacement parts are often unavailable in rural areas. It might be better to retain the existing hand pump and install a solar pump in a new borehole to guard against common pitfalls for borehole decline (Figure 1).

Plans are also underway to install a water treatment system for Pangani River water. Testing for coliform in the Pangani River would be of interest in May, since the majority of Marwa villagers currently rely on river water. No water quality samples have been taken from the river to date.

If possible, water samples should be collected in duplicate and run at the regional labs and The Ohio State University. The methodology and equipment for testing water samples at some of the regional labs is currently uncertain and should be considered.

Recommended Pump Test Design

Based on pump test data from regional boreholes, I recommended a constant-rate drawdown test with a maximal pumping period. The goal is to pump the well long enough to ensure that drawdown approaches a late-time response (linear trend on a semi-linear drawdown-time plot). The pump period will probably be limited to daylight hours so that recovery occurs overnight and withdrawals by villagers can resume the next morning. I therefore suggest an 8-hour pumping period with a rate of 3,000 L/hr. Assuming a hydraulic conductivity of 2.31×10^{-6} m/s (the geometric mean of the seven boreholes in fractured rock aquifers), and a storativity of 5×10^{-4}, I expect a total of 16.24 m of drawdown at the end of the pumping period (Figure 16). Recovery is expected to occur over approximately 12 hours. This calculation assumes the aquifer thickness is 25.7m, or the difference between the average depth to static water level in regional boreholes and the completion depth in the Lesirway borehole. A formal borehole completion report for the Lesirway borehole is not available, so an accurate saturated thickness using a provided static water level could not be determined.

Based on the design test, the specific capacity of the Lesirway borehole would be estimated as 3.08×10^{-3} m^2/min. If the available drawdown is 22.7 m, the potential yield would be 4,193 L/hr. This yield would meet the domestic needs of just under 1,900 people, which is more than the current population of Lesirway.
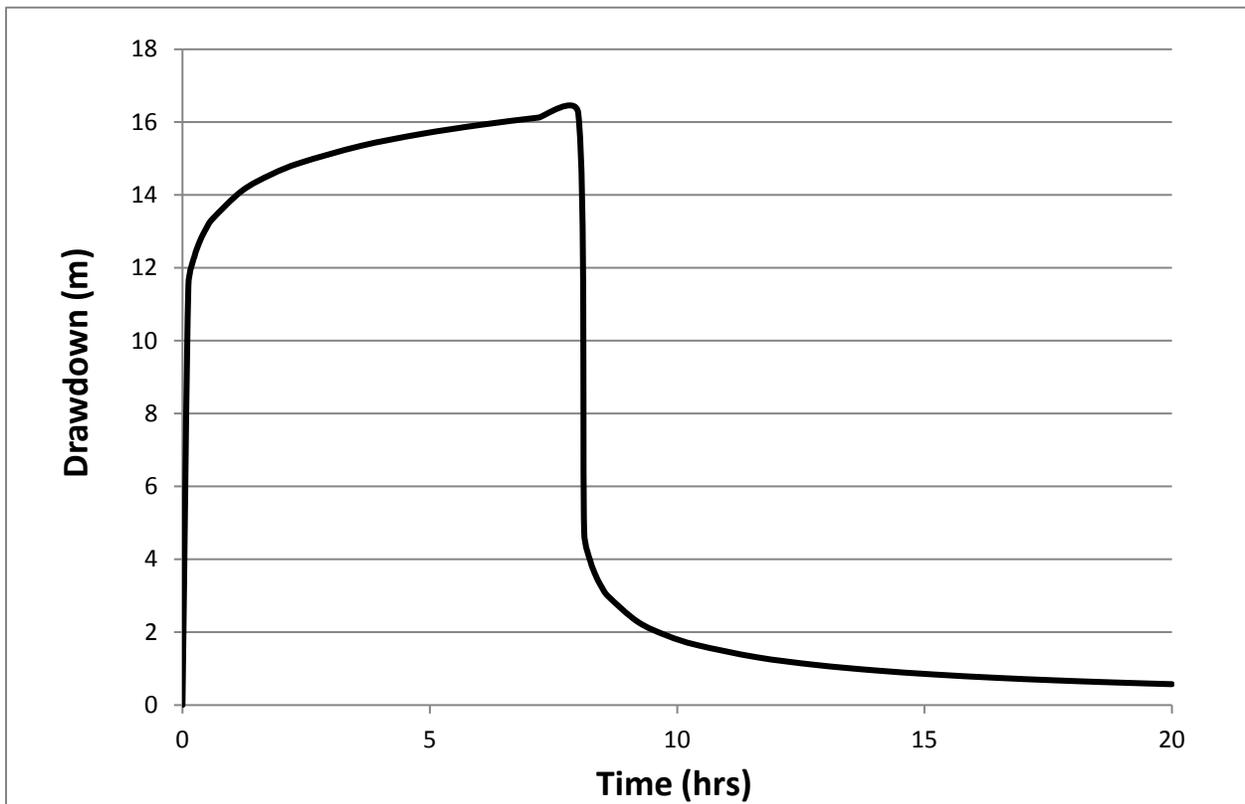
Figure 16 Estimated drawdown of the Lesirway borehole using a pumping rate of 3,000 L/hr for 8 hours with a 12 hour recovery period after.

Assuming a worst-case hydraulic conductivity of 2.12×10^{-7} m/s (the lowest estimate from the seven boreholes in fractured rock aquifers) and a storativity of 5×10^{-4}, the projected drawdown would rapidly increase, and the test would need to be cut short to avoid burning up the submersible pump (Figure 17). If that were to occur, I would resume a new pump test at a significantly slower pumping rate.
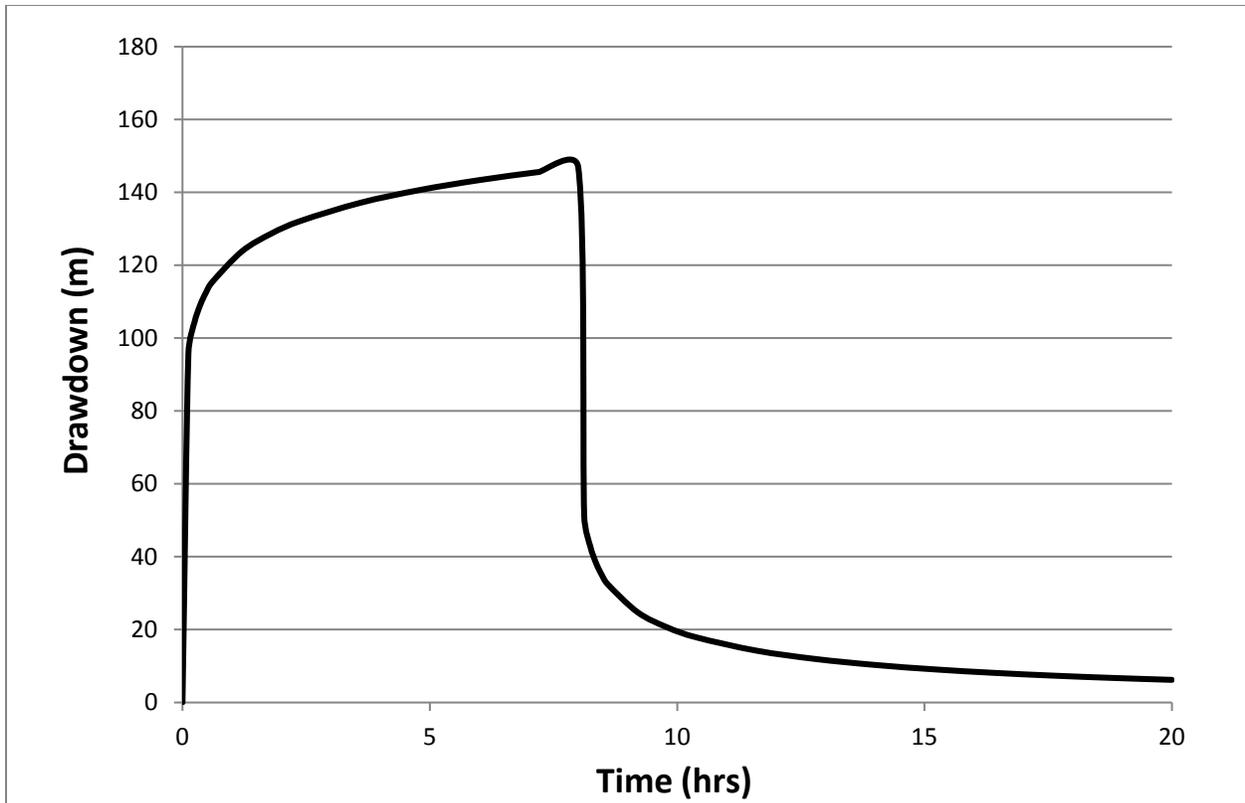
Figure 17 Estimated drawdown for a worst-case hydraulic conductivity of 2.12×10^{-7} m/s. The predicted drawdown is much greater than the available drawdown, so the test would need to be stopped in order to protect the submersible pump.

Data Quality and Borehole Design in Regional Wells

Borehole completion reports and pump test data contained some anomalies. GPS coordinates were often inaccurate or not provided. Often, one or more dry wells was reported for every successful well, emphasizing the need for more geological information in the area. Furthermore, screened intervals were sometimes placed in clays and other impermeable units. In pump test reports, borehole yield was reported as the pumping rate for the test. In other words, observed drawdown and available drawdown were not factored in. A clear opportunity exists to improve the collection of drilling data and the design of future wells through continued workforce training. UNICEF identified workforce training as one of the most important needs to increase the lifespan and performance of drinking water wells in developing regions.

Conclusions

Well design and lithology influence both groundwater access and quality in rural villages. In this investigation of rural village boreholes in Kilimanjaro and Manyara, aquifer transmissivities are generally lower in fractured rock aquifers and higher in alluvial aquifers. Potential yield appears not to depend significantly on aquifer material but is related to the completion depth. Deeper wells are likely to have higher yields. I recommend an 8-hour pump test to determine the potential well yield in the Lesirway borehole.

Water quality is altered by both natural and anthropogenic sources. Higher fluoride and TDS measurements tended to occur in boreholes. The primary source of these contaminants is likely natural rock-water interactions. Unsafe levels of nitrate and coliform were more common in secondary water sources like dug wells, dams, and springs. The sources of nitrate and coliform may be related to livestock watering or sanitation practices. I recommend testing of all water sources (two boreholes in Marwa and the Pangani River) for fluoride, TDS, nitrate, and coliform during field work.

While the installation of a solar powered pump on the Lesirway borehole could provide water at a much higher rate than its current India Mark II hand pump, if a failure such as pump burnout occurs, water would become inaccessible. Well functionality is compromised by improper borehole installation and pump failure. Better knowledge of the geology is needed to site and design wells for long-term performance. The Njakitai borehole is an example of an abandoned borehole that should be studied to avoid similar abandonment in future boreholes. Two years after its installation, the well started to produce brackish water that was unsuitable for its desired uses. Now, the chain attached to the hand pump has broken and there is no plan to repair the pump with the current state of the water. The Lesirway borehole should be monitored for TDS to ensure that it is not on the same salinization trajectory. The wells should also be sounded, and pump tests should be conducted in both wells to evaluate whether they are likely in similar aquifer materials.

RECOMMENDATIONS FOR FUTURE WORK

Opportunities to investigate groundwater quality in the Kilimanjaro area are numerous. Studies on weathering susceptibility in the regional volcanics would provide a better framework to predict and avoid high concentrations of fluoride and TDS in groundwater. Furthermore, the cause of the salinization trends in the Njakitai borehole remains in question. A field investigation that includes measurements of soil salinity and groundwater samples from other wells would aid in the placement of future wells and reduce the likelihood of well abandonment.

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APPENDIX I

Lesirway borehole sketch
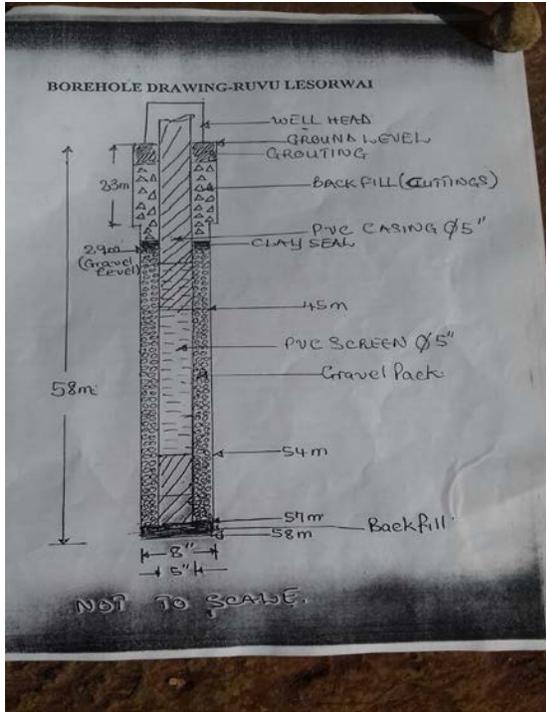
APPENDIX II

Hydraulic conductivity chart (Freeze and Cherry, 1979)
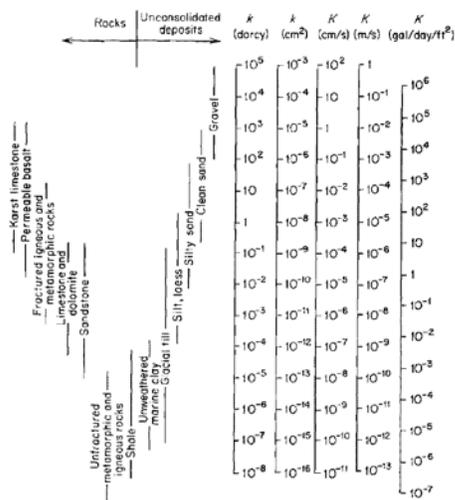
APPENDIX III

Aquifer properties computed via Aqtesolv

Kilimanjaro

Well ID	Saturated Aquifer Thickness [m]	Transmissivity (Cooper Jacob) [m²/day]	Transmissivity (Theis Recovery) [m²/day]	Hydraulic Conductivity (Cooper-Jacob) [m/s]	Hydraulic Conductivity (Theis Recovery) [m/s]	Aquifer material
524	46.5	0.812432	37.1376	2.02×10^{-7}	9.24×10^{-6}	fractured rock
602	103	2.42	11.44	2.72×10^{-7}	1.24×10^{-6}	fractured rock
316-65	53	1.29	3.41	2.82×10^{-7}	7.45×10^{-7}	Fractured rock
450	24	2635	3585.6	1.3×10^{-3}	1.73×10^{-3}	alluvial

Manyara

Well ID	Saturated Aquifer Thickness [m]	Transmissivity (Cooper Jacob) [m²/day]	Transmissivity (Theis Recovery) [m²/day]	Hydraulic Conductivity (Cooper-Jacob) [m/s]	Hydraulic Conductivity (Theis Recovery) [m/s]	Aquifer material
317-120	96	4.02	5.64	4.85×10^{-7}	6.8×10^{-7}	alluvial
487	31	122.92	96.19	4.6×10^{-5}	3.59×10^{-5}	fractured rock
317-80	71	62.9	257.18	1.02×10^{-5}	4.2×10^{-5}	Fractured rock
461	30	7.74	37.11	2.9×10^{-6}	1.43×10^{-5}	fractured rock
581	36	551.81	440.5	1.77×10^{-4}	1.42×10^{-4}	fractured rock

Aquifer properties from empirical estimation

Fractured Rock

Region	Well #	Flow rate [L/hour]	Drawdown at end of pumping period [m]	Specific Capacity [m²/day]	Potential Yield [L/hr]	Transmissivity [m²/day]	Hydraulic conductivity [m/s]
Kilimanjaro	524	5040	2.89	41.85	75961.6	9.847	2.45E-06
Kilimanjaro	602	12000	39.3	7.33	30534.35	1.26	2.65E-06
Kilimanjaro	316	2000	8.1	5.87	14666.67	0.9691	2.12E-07
Manyara	317	12000	3.73	77.2	186595.17	20.28	3.84E-06
Manyara	461	45000	14.66	73.67	85948.16	19.19	7.40E-06
Manyara	487	16200	24.42	15.92	31179.36	3.148	1.18E-06
Manyara	581	100000	3.83	627.9	1098798.96	240.52	7.73E-05

Alluvium

Region	Well #	Flow rate [L/hour]	Drawdown at end of pumping period [m]	Specific Capacity [m²/day]	Potential Yield [L/hr]	Transmissivity [m²/day]	Hydraulic conductivity [m/s]
Kilimanjaro	450	30000	32	22.5	19687.5	123.39	5.95E-05
Kilimanjaro	316	6000	5.47	26.33	43327.24	137.09	5.29E-05
Manyara	317	38000	38.74	23.53	113724.3	127.15	1.53E-05