1 How do people's perceptions of water quality influence the life
2 cycle environmental impacts of drinking water in Uganda?

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11 **Abstract**

12 Over the last two decades, more than 2 billion people have gained access to improved
13 drinking water sources. The choices for water sources and treatment methods at the
14 household level are influenced by people's perceptions of water quality. To ensure long-
15 term sustainability, it is important to evaluate the environmental impacts of water
16 provisions considering people's perceptions. In this study, the life cycle assessment
17 (LCA) method and qualitative data collected from household interviews are used to
18 determine the environmental impacts associated with water sources and household
19 treatment methods. Results showed discrepancies between perceived and measured water
20 qualities. In the case of tap water (i.e. low perceived water quality but high measured
21 water quality), charcoal was used for boiling water at the household level that resulted in
22 a high environmental impact due to a chronic over-treatment of water. In contrast,
23 rainwater (i.e. high perceived water quality but low measured water quality) received

under-treatment that resulted in a low environmental impact but potential health problems. This study highlights the need for an alignment in the perceptions of water quality with the actual, measured quality in order (1) to prevent public health outbreaks due to under-treatment, (2) to reduce the consumption of environmental resources as a result of over-treatment, and (3) to conserve household expenditures being used to purchase charcoal for boiling water.

Keywords: life cycle assessment, perception, drinking water treatment, environmental impact

1.0 Introduction

Over the last two decades more than 2 billion people have gained access to improved drinking water sources (WHO & UNICEF, 2013). While this progress has been applauded, the increasing population continues to drive the need to provide safe drinking water for all. It is important to consider the environmental impacts associated with water supply systems to assure that this basic necessity is being delivered in an environmentally responsible way (Bonton et al., 2012). Consequently, many studies have investigated the environmental impacts of water supply systems using the life cycle assessment (LCA) method (Sombekke et al., 1997; Mohapatra et al., 2002; Homaki, 2003; Lundie, 2004; Raluy et al., 2005; Stokes and Horvath, 2006; Friedrich et al., 2007; Barrios et al., 2008; Vince, 2008; Friedrich et al., 2009; Lyons et al., 2009; Venkatesh and Brattebo, 2012; Godskesen et al., 2013). LCA is an assessment framework used to determine the

environmental burden of products, services, or processes across their life cycle stages (ISO 14040, 2006).

The LCA method has been employed in previous water supply studies for two purposes.

The first type of application is to compare alternative supply options based upon their environmental performance (Lundie, 2004; Raluy et al., 2005; Tangsubkul et al., 2005;

Friedrich et al., 2009; Lyons et al., 2009; Bonton et al., 2012; Godskesen et al., 2013;

Jiang, 2013). For instance, Lyons et al. (2009) compared the environmental impact of

water reclamation, importation, and desalination in Scottsdale, Arizona to determine a

sustainable option to solve water scarcity issues. The second purpose for using the LCA

method is to improve the environmental performance of a system by pinpointing hot

spots that significantly contribute to the overall impact (Tangsubkul et al., 2005;

Friedrich et al., 2007; Lemos et al., 2013). Lemos et al.'s (2013) study found that, in an

urban water system, the electricity consumption for extracting and treating drinking water

caused the greatest impact to the environment. As a result, efficiency improvements in

the distribution network and alternative non-fossil based fuel sources were suggested to

reduce the impact (Lemos et al., 2013). Furthermore, a South African study concluded

similar results for the electricity consumed for pumping water during the collection,

treatment, distribution, and reuse phases. As a result, the study recommended that

electricity consumption should be used as a basic environmental performance indicator to

quickly compare the various pumping steps to determine the best area for improvement

(Friedrich et al., 2007).

A majority of the previous studies have focused on the evaluation of centralized systems

in industrialized, urban areas (Friedrich et al., 2007; Godskesen et al., 2013; Lemos et al.,

2013), whereas only a few studies, primarily in developing regions, have evaluated the impacts of decentralized water supply or treatment schemes (Homaki, 2003; Held et al., 2013; Baird, 2013). In Vietnam, Homaki et al. (2003) assessed the impacts of a community's low quality water provision from a centralized public treatment plant that was being further treated at the household level. The study investigated three energy alternatives (coal briquettes, liquefied petroleum gas (LPG), and electricity) for household level treatment and found that boiling with a tank of LPG resulted in the least environmental impact associated with the decentralized treatment. However, the scope of the study was limited in terms of the water sources considered, environmental impact categories included, and preferences of the community for drinking water sources or treatment options. Another study (Held et al., 2013) investigated community and household level drinking water treatment and source protection in rural Mali based on their embodied energies. The study found that the human energy exerted for water collection and transport outweighed the fossil-based energy for water treatment. This highlights the difference between decentralized community or household level water treatment in developing countries and centralized drinking water treatment in developed countries. Previous studies have found that water provisions in developing countries have some unique characteristics, such as the diversity of source options (Mu et al., 1990; Howard et al., 2002) and the water source preferences based upon perceptions of water quality or cultural norms (Mu et al., 1990; Doria, 2010; Baird, 2013). For example, Mu et al.'s study revealed that certain water supply features like the time it takes to get to a source and its price had a significant impact on household choices whereas household income did not (Mu et al., 1990). Furthermore, the treatment approaches applied at the

household level also depend on multiple factors such as cost, convenience and water quality (Prouty, 2013). People's perception of water quality has a significant impact on household level treatment choices (Rainey & Harding, 2005) that result in different environmental impacts (Homaki et al., 2003; Prouty, 2013). However, there is no study incorporating people's perception into the evaluation of environmental impacts associated with water provisions and household treatment.

Filling this knowledge gap, the purpose of this work is to reveal the effects of people's perceptions of water quality on household treatment methods and to determine the associated environmental impacts. Integrating a social perspective into a technical life cycle analysis reveals the environmental effects of household behaviours that are particularly important for water provision in developing countries since household treatment is a common practice (Homaki et al., 2003; Held et al., 2013; Prouty, 2013).

2.0 Study Site

This study was conducted in two rural, neighboring villages—Nalugala and Kitale, Uganda. These villages were chosen because the collaboration has been established with the community organization Bega Kwa Bega (BKB) that implements water and sanitation projects in the area. These villages are in Wakiso District, Katabi Sub-county which is located in the central portion of Uganda as seen in Figure 1. The study site is situated along the highway corridor from Entebbe to Kampala. Entebbe is the major travel hub for the country as it houses the only international airport; Kampala is the central business district where the majority of foreign embassies, government buildings, and corporate offices are located. The area is characterized by significant urbanization along this

highway corridor, immediately followed by lush vegetation, rolling hills, family farms, and red clay roads or footpaths.

The population in Kitabi Sub-county is approximately 80,000, with a population density of 1,001-1,500 people/km² (Ministry of Water and Environment, 2010). Nalugala and Kitala are the two northernmost villages out of the four that comprise this Sub-county.

The access to different types of water sources within the area is listed in Table 1. The area's drinking water coverage is 78%; the vast majority of these sources are reported to function properly (Ministry of Water and Environment, 2010). The term "coverage," according to the 2005 Uganda National Water Development Report, is defined as the percentage of the population with access to an improved water source within a 1.5 km walking distance (Ministry of Water and Environment, 2005). Table 2 lists the community water sources considered in this study with some design characteristics and performance information.

Figure 1

Table 1

Table 2

3.0 Methods

3.1 Comparative life cycle assessment

The LCA conducted in this study follows the ISO 14040 standards (ISO, 2006) including the following steps—(1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. The LCA was performed using the SimaPro software (Goedkoop et al., 2008).

3.1.1 Goal and scope

The goal of the LCA is to determine the environmental impacts associated with different water supply options involving different household water sources and treatment methods.

The system boundary includes the water source, water collection (if applicable), and the household treatment.

The functional unit is 3.57 liters (L) of potable water meeting the quality defined by the Ugandan National Bureau of Standards' (UNBS) drinking water guidelines (UBOS, 2010). The specific volume was determined by taking a daily average of the drinking water consumed by households in Kitala and Nalugala as reported during the survey (Prouty, 2013). Lastly, the size of the household is assumed to be consistent with the national average of ~5 people (UBOS, 2010), a value that is also consistent with the survey data (Prouty, 2013).

3.1.2 Inventory Analysis

The foreground data are collected and listed in Table 3 based upon each of the stages within the system boundary (source, collection, and treatment). The data was obtained through observation, experience, a review of relevant literature, and community surveys (Prouty, 2013). Background data (materials, processes, transport), however, was obtained from the SimaPro database.

Table 3

3.1.3 Impact Assessment

The impact assessment method used to quantify the effect on the environment was Eco-Indicator 99 (H) Version 2.07 (Amersfoort, Netherlands). The “H” refers to the hierarchical perspective associated with equal end-point weighting for damages to human health and ecosystem quality, and half as much weight for impacts to natural resources (Goedkoop & Spriensma, 2001; Brent & Hietkamp, 2003; Goedkoop et al., 2008). This

methodology is chosen because its weighting scheme is consistent with the purpose of this research (to connect community behavior to impacts on their health and local ecosystem), it has been applied in previous studies of similar geographic and socio-economic means (Homaki et al., 2003; Mahgoub et al., 2010), and it encompasses all of the impact categories that correspond to the life cycle inventory (Goedkoop et al., 2008). The impact categories include fossil fuels, minerals, land use, acidification, eutrophication, ecotoxicity, ozone layer, radiation, climate change, respiratory inorganics, respiratory organics, and carcinogens. The impacts are represented by the unit of Eco-Indicator Points (Pt). One millipoint (mPt) represents a thousandth of the yearly environmental load of an average European citizen; this scale provides a baseline for comparison (Goedkoop & Spriensma, 2001).

3.1.4 Interpretation

The LCA results are interpreted and compared for two scenarios—environmental impacts associated with household water treatment based on measured and perceived water qualities—to investigate the influence of household behaviours on the environmental impacts of water provision. The most significant impact categories and stages for household drinking water provisions will be identified to promote responsible stewardship of environmental resources.

3.2 Household surveys

The survey was designed to obtain information about the water sources and household treatment options in Nalugala and Kitala. The sample size for the household survey was calculated using a confidence level of 95% and a confidence interval of ± 7 based on Equation 1

$$186 \quad \text{Sample Size} = \frac{Z^2 p (1-p)}{c^2} = \frac{1.96^2 0.5 (1-0.5)}{0.07^2} = 196 \quad (1)$$

187 where the Z value represents the confidence level (e.g. 1.96 for 95% confidence level), p
 188 is the sampling distribution (0.5 is used to reflect a conservative, normal distribution),
 189 and c is the confidence interval (e.g., 0.07= ±7). The total sample size was calculated to
 190 be 196 households, although 200 were actually sampled. Considering these statistical
 191 factors—confidence interval and confidence level—there is a 95% confidence level that a
 192 measured value in the research reflects a representative response for the northern portion
 193 of this sub-county’s population.

194 Prior to implementation of the survey, Institutional Review Board (IRB) clearance
 195 (Pro00007256, University of South Florida) and certification through the Collaborative
 196 Institutional Training Initiative (CITI) was obtained (3530214, University of South
 197 Florida). Households were selected to participate based upon convenience. If a
 198 household was vacant, unable, or unwilling to participate, the researcher skipped it and
 199 moved to the next available home. The researcher and a trained field translator conducted
 200 surveys in both English and Luganda (the local language characteristic to central
 201 Uganda). The survey began with a brief introduction about the partnership between the
 202 researcher and the community-based organization BKB. It was followed by an
 203 explanation of no risks, benefits, or penalties to a participating respondent or an
 204 individual who chose to discontinue the survey prior to completion. Next, the researcher
 205 and translator were required to obtain verbal, informed consent from the participant (a
 206 household member 18 years of age or older). Furthermore, as the questionnaire was
 207 administered, the translator clarified any inquiries that arose from the respondent after
 208 they were first discussed with the researcher. This process was followed to prevent any

unintentional leading of the respondent into specific answers. Each day, after all the surveys were completed, the researcher and translator discussed field notes and made necessary clarifications. Following this, the researcher recorded the anonymous survey answers in Microsoft Excel spreadsheets to maintain the accuracy of the day's field data and observations.

The first portion of the survey is related to household water sources. These questions were aimed at understanding household preferences, decision-making, and important factors that were considered when households collected water from various sources (Prouty, 2013). The research investigates the responses households give about their "primary water source." The term "primary water source" is used in this study to reflect the respondent's, self-identified first choice (source type) from which their household collects drinking water. The analysis of survey data related to water source choices is not included in this study since the goal of the study is to link the households' perceptions to the evaluation of environmental impacts associated with water provision and household treatment.

The next portion of questions has two goals. The first is to characterize water treatment methods and quantify water usage. These answers are used to provide some of the quantitative data for the life cycle assessment of the household's chosen water source and treatment method(s) for drinking water. Specifically, the questions focus on the amount, frequency, and materials used for the household's water treatment method(s). The second goal is less technical and more qualitative as the study investigates local perceptions of water quality; how do these perceptions motivate a household to treat their drinking water and through what method(s) (Prouty, 2013).

To analyze the survey data, the qualitative information was grouped and coded based upon recurring themes or expressions. In some cases, the quantitative data was estimated based upon measurements community members used most comfortably (i.e. 1 jerrycan, 2 cups, or 1 kettle of water). In these circumstances, the researcher estimated volumetric quantities based upon the dimensions of the containers and validated these estimates with personal observations. Lastly, qualitative responses and observational field notes are distinguished throughout the results and discussion portion by indenting and italicizing the text.

3.3 Water quality tests

Two water samples were collected from a typical site of each of the five primary sources. These sites were determined by (1) the granting of permission from the owner of the source (if necessary), (2) the availability of water at the site, and (3) the source being expressed as a popular site among survey respondents. These samples were taken to the Ugandan National Laboratory in 250mL sterile plastic containers (which the laboratory provided) where basic water quality tests were conducted (e.g. turbidity, conductivity, total dissolved solids, pH, total fecal coliforms, and total suspended solids). Each container was first labeled prior to sampling in duplicate. Proper field data collection procedures were taken to minimize sampling errors. After samples were collected, within two hours they were taken to the Ugandan National Laboratory (UNL) for testing. It is assumed that in order to assure the integrity of the results, the samples were properly stored in the National Laboratory until the tests were conducted.

4.0 Results and discussion

4.1 Measured water quality versus perceived water quality

In this study, objective water qualities for each source in Nalugala and Kitale were measured based on the six water quality parameters listed in Table 4. Although samples from each source were collected in duplicate, when tests were conducted at UNL, only one set (from each source) was tested for all the parameters. The incomplete test results from one set of samples were not used for analysis in this study, so all data presented are direct, measured values instead of average values. Table 4 represent one complete set of water quality tests.

Table 4

According to the WHO Guidelines for Drinking Water, thresholds considering human health are set for TDS (< 600 mg/L), E.coli (0 CFU/100 mL), and turbidity (<1 NTU) (WHO, 2011). Based on measured parameters (Table 4), tap water has the highest quality because the concentrations of TDS, turbidity, and E. Coli all fall below the WHO threshold levels. The protected spring has lower water quality because it has the highest value for TDS and high turbidity; however, there is no detectable fecal contamination. The turbidity measurement for water from the borehole is comparable to the value for the protected spring, but the TDS is much lower compared with the protected spring. For surface water, although the turbidity (2.4 NTU) is fairly close to the measurements for both the protected spring and the borehole, it has excessive fecal contamination with a high E. Coli value (178.5 CFU/100mL). In a similar fashion, rainwater also has a high T. Coliform measurement, an E. Coli measure above the threshold, the highest turbidity, and relatively high TDS. This result reflects the lack of the “first flush” process in these villages. This practice involves the installation of a system or manual purging of the water from a first rainfall that oftentimes fills the households’ tanks with large amounts

of debris (Mihelcic et al., 2009). Rather, community members in Nalugala and Kitala explained that they performed a yearly (or less) clean-out of their rainwater systems. The accumulated debris led to rainwater's poor measured water quality results listed in Table 4. Based on measured water quality, the five sources are grouped in the following ways according to the WHO Guidelines for Drinking Water standards: tap, borehole, protected spring adhere to the standard for E. coli while surface water and rainwater do not. Additionally quantitative and qualitative information from household surveys were combined to reflect their perceptions of water quality. Households were asked, "What drinking water treatment method(s) do you use?" and, "Why is this method chosen?" Figure 2 shows the quantitative responses to the factors (i.e. cost, convenience, quality, only method available, and others) that impact household water treatment choice. The primary factors influencing a household's choice for drinking water treatment method are convenience, cost, and quality (51%, 25.5%, 9.5% respectively).

Figure 2

Furthermore, the number of treatment steps taken at the household level also helped to reveal households' perceptions; when water quality was perceived poorly, there were more steps involved in household water treatment. Finally, qualitative information provided the households' rationales for their choices. Consider the water quality tests in Table 4 that indicate that tap water has the highest measured quality. However, community members perceived tap water as one of the lowest quality sources. This notion is partly evidenced by (1) the vast number of survey respondents (greater than 90%) answering "Yes" to treating their tap water at the household level, (2) the number of treatment steps taken before drinking, and further, (3) by qualitative responses that reflect such a perception.

One respondent said his poor perception of the quality of tap water was due to the leaky drinking water pipes that passed through unsanitary areas of Kampala (i.e. open sewage, drainage ditches with stagnant water). He knew there was “medicine” (NaOCl) in the water for disinfection, but remained skeptical about the government’s ability to operate and maintain a safe drinking water system even after laboratory tests proved it to be potable.

The protected spring and borehole had similar measured water quality that is poorer than tap water. Qualitative responses from community members, however, clarified that both the borehole and protected spring’s qualities are considered better than tap water.

Those sources were mentioned to be “safer [and] cleaner” compared to tap water because they have “more natural [treatment] without chemicals.”

Furthermore, the perceived water quality of the protected spring and borehole is different as evidenced by the number of household treatment steps—boiling for the borehole and a combination of boiling and filtering for the protected spring. Information about these sources’ physical infrastructure and comments about their susceptibility to contamination further informed the households’ behaviour.

Community members pointed out the basic, locally available eucalyptus boards around the protected spring, and mentioned that they provide less guard against impurities as compared to the borehole that has a concrete apron and metal piping.

Next, the perceived quality of the surface water appeared to be similar to the borehole because the same household treatment methods were mentioned—boiling. However, for the case of surface water, the qualitative responses and household treatment methods

were inconsistent. The qualitative responses revealed that community members perceived surface water as undesirable because it is exposed to severe, direct contamination.

“We see [open defecation] from animals being watered on the banks and people right there bathing or washing clothes.”

However, based on further observations and discussions during community surveys, the inconsistencies in the qualitative responses and household treatment were justified.

Households mentioned that they rarely relied on this source for drinking water, mostly when they were constrained for time. Instead, the most common scenario was that households were forced to use it for drinking purposes when other, more preferable, sources were low yielding, too expensive, or dysfunctional.

Lastly, the rainwater source had measured water quality below that of the WHO Guidelines for Drinking Water for E.coli and turbidity. However, qualitative survey data revealed an inconsistency between perceived and measured quality.

There was a consensus that as long as the rainwater had not become stagnant in the tank during the dry season “when it over-shines,” it was pure to drink without treatment.

Community members also mentioned this source as having a preferable taste to others that were available.

However, there was no standardized rule or guideline to determine the amount of time the water could remain in the tank (i.e. when would it be considered stagnant?).

Based on perceived water quality (as determined through survey questions and the number of household treatment steps) the five sources rank in the following order (from best to worst): rainwater, borehole, protected spring, surface water, and tap.

4.2 Environmental impacts of water provision based on perceived water quality

The discrepancies between measured and perceived water qualities affect the household-level treatment methods. These treatment methods, in turn, have different environmental impacts. This section details the environmental burden of the water sources and household treatment associated with perceived water quality (Figure 3a).

Rainwater has the lowest impact due to the community members' perception of rainwater as a natural, high quality source. As a result, no treatment was practiced at the household level. The stage that contributes primarily to the impact is related to rainwater storage. In Kitala and Nalugala, the most common materials used for constructing 3,000-5,000 L rainwater collection vessels are corrugated metal sheets. The impact is associated with the extraction, production, and transport of the materials for these tanks. While the construction of a rainwater harvesting system is initially a material-intensive endeavour, after installation, there were rarely extra resources required for operation and maintenance. Figure 4 shows the individual impact categories for a rainwater harvesting system, and the category of carcinogens presents the highest impact. This is due to the emission of carcinogenic substances such as asbestos in the fabrication of the corrugated sheets under high heat (Siemiatycki et al., 2004).

In comparison, the borehole, protected spring, surface water, and tap all have comparable environmental impacts because of similar household treatment methods based on perceptions. For those sources, the most significant stage contributing to the overall environmental impact is the treatment at the household level. While centralized water treatment systems use many more resources, they are treating a much larger volume of water. As such, the environmental impact of water treatment per functional unit is lower for the centralized treatment process as compared to the household level. Figure 4 shows

the categories having highest impacts are land use and climate change since households are boiling their drinking water using charcoal.

Figure 3

Figure 4

4.3 Environmental impacts of water provision based on measured water quality

To ensure the safety of drinking water, additional treatment at the household level is required for all sources except tap water based upon the measured water quality presented in Table 4. These prescribed treatment methods simulate theoretical steps that would be necessary at the household level to bring each source to the WHO drinking water standards (see Table 4 “Measured” column).

Tap water had the best quality of the five sources and was tested to meet potable standards (see Table 4). As a result, water from the tap requires no treatment at the household level. This leads to the low environmental impact for tap water based on measured water quality (Figure 3b). The impact is primarily due to the source (i.e. centralized water treatment facility and distribution to community). Figure 5 shows the category with the highest impact is fossil fuels. This is associated with the production and transport of chemicals and the operation of pumps and generators at the treatment plant.

Figure 5

In contrast to the tap, rainwater was evaluated to have poor measured water quality due to the high turbidity, dissolved solids (TDS), and fecal coliforms. The prescribed treatment method involves settling, filtration, boiling, and dosing with a sodium hypochlorite (NaOCl) solution (see Table 4; CDC, 2012). The addition chlorine provides some residual protection from recontamination (Mihelcic et al., 2009). This is particularly

395 important for young children or those living with immunocompromised diseases (i.e.
396 HIV, AIDS). These populations must have adequate volumes of the highest quality of
397 water to consume without serious risks to their health. As a result, the overall
398 environmental impact associated with household treatment based on the measured quality
399 of rainwater is magnitudes higher in comparison to the impact associated with rainwater
400 supply based on perceived water quality. Figure 3b also reveals that the impact is
401 primarily associated with the treatment stage at the household level instead of the
402 rainwater collection vessel. This finding is consistent with the results from Figure 5 that
403 shows the largest impact categories are land use and climate change – the expected
404 categories for households which treat their water by boiling with charcoal.

405 Furthermore, surface water requires household treatment that is similar to rainwater, but
406 is reduced by one step—settling. As a result, the environmental impacts of treatment—
407 filtering, boiling and dosing with NaOCl to eliminate E. Coli—yield impact categories
408 that are consistent with those for rainwater treatment. However, the impacts for surface
409 water treatment based on perceived water quality only considered boiling at the
410 household level. As a result, the environmental impacts attributed to treatment based on
411 measured water quality are greater because of contributions from filtering and dosing
412 with NaOCl (which are steps not included for treatment based on perceived water
413 quality).

414 At the same time, the measured water qualities of both the borehole and protected spring
415 require households to filter water in order to reduce the sources' turbidity. This filtering
416 results in the lowest environmental impacts among all tested sources. However, due to
417 the difference in infrastructure between the borehole and protected spring (see Table 2),

the protected spring has a lower environmental impact because the protection structure is constructed using basic and locally sourced materials. Overall, since fossil-based energy is not used for household treatment, environmental impacts associated with both sources are very low.

For treatment methods based on measured water quality, surface water and rainwater that require many treatment steps, particularly boiling, have the highest environmental impacts. In contrast, the other options that do not require energy intensive household level treatment or require no treatment at all (i.e. borehole, protected spring, tap water), yield very low impacts.

4.4 Influence of people's perception and its implication

As shown in Figure 3a, the impacts associated with household treatment based on perceived water qualities can be considered the status quo (these are impacts evaluated based on a household's normal practices). In contrast, the impacts shown in Figure 3b are associated with theoretical treatment scenarios that are based on measured water quality. It was observed from the field studies in Nalugala and Kitale, tap water is being systematically "over-treated" at the decentralized level. Households are using scarce economic resources to purchase charcoal for boiling water that is already potable. Calculations based upon surveys, household income, and observations revealed that ~7% of a household's take-home pay was being used to purchase charcoal for boiling (UBOS, 2010; Prouty, 2013). Aside from spending money that could be allocated towards other necessities, boiling as a decentralized treatment method is a primary contributor to a significantly higher environmental impact as compared to centralized treatment. These results are consistent with a study from Vietnam (Homaki, 2003) that showed boiling tap

water had the greatest impact when performing an LCA of Hanoi's drinking water provisions. Based on the community's feasible alternatives (improvements/expansion of the centralized system, bottled water, or boiling at the household level), a comparative study revealed that consuming water directly from the Hanoi treatment plant (filled in 5 L recyclable containers) would have the lowest environmental impact (Homaki, 2003). Furthermore, when boiling water at the household level incomplete combustion of charcoal increases volatile organic compounds and contributes to more particulate matter in the air, both degrading indoor air quality (Homaki et al., 2003; Rehfuss et al., 2006). On the other hand, households in Nalugala and Kitale are consuming rainwater without any household level treatment. While the associated environmental impact is very low, the "under-treatment" of this source has severe human health implications due to the likelihood of waterborne illnesses, such as diarrhea or cholera (Mintz et al., 2001; Lee & Schwab, 2005; Montgomery & Elimelech, 2007; Dean & Hunter, 2012). Overall, aligning perceptions of water quality with the measured quality provides the best situation for appropriate household treatment methods to be used. This alignment will have economic, environmental, and public health implications including fewer financial resources being spent on unneeded charcoal, lower environmental impacts due to the decreased consumption of fossil fuels, and improved health due to adequate treatment of lower quality water sources.

5.0 Conclusion

In this study, community surveys in the villages of Nalugala and Kitale revealed the influence that perceived water quality had on household treatment practices. The

environmental impacts of local water sources in combination with household treatment methods were investigated by considering both perceived and measured water qualities. A couple of limitations exist due to the researcher's limited timeframe and financial resources. First, with respect to the measured water quality, the sample size was small. Additionally, this study only takes into consideration one (i.e. perceived water quality) of the multiple factors that influence households' choices for drinking water treatment methods. Finally, convenience sampling was employed, rather than other quantitative sampling approaches because the aim was to provide a general insight into the social implications of life cycle assessments for decentralized drinking water provisions in developing countries. Therefore, given the combination of these limitations, the results cannot be extrapolated to be representative of the population as a whole. In particular, the small sample size of water quality tests may not statistically represent the quality of the various types of water sources. Consequently, future studies should collect qualitative and quantitative data (e.g. surveys, water quality analysis) statistically representative using an approach like the Rapid Assessment of Drinking-water Quality (RADWQ) implemented by the WHO/UNICEF Joint Monitoring Programme (JMP) on Water Supply and Sanitation. This approach outlines considerations for the survey design such as, calculation of the sample size, definition of the sample clusters, and identification of sources for water quality testing (WHO & UNICEF, 2012).

When considering measured water quality, tap water from the centralized treatment system has the lowest environmental impact. However, survey data revealed that community perceptions of tap water were poor, resulting in over-treatment at the household level, thereby resulting in a high environmental impact as compared to other

water sources. The dominant impact categories in the life cycle assessment were land use and climate change when considering perceived water quality because charcoal was used for boiling during the household treatment stage. On the other hand, the fossil fuels category is the dominant impact category for measured water quality because the source (centralized treatment) was the largest contributing stage.

In contrast, rainwater posed the opposite scenario. When considering perceived water quality, survey respondents generally explained that rainwater was a clean, pure source with a preferable taste. As a result, there was no treatment practiced at the household level, thus yielding a very low environmental impact. However, rainwater actually had the poorest quality based on the measured quality parameters and required the most steps at the household level for treatment, resulting in the highest environmental impact. The primary impact category for water provision based on the perceived water quality was carcinogens due to the manufacturing of the storage vessel (source stage), whereas the main impact category based on measured water quality was land use and climate change generated by charcoal consumption for boiling during the treatment stage.

This research demonstrates how community perceptions should be included in technical studies to reveal the environmental impacts of their behaviour. While the scope of factors impacting household water treatment is multivariate, this study narrowed its focus singularly on perceived water quality and linked this factor with consequential environmental implications. However, it must be noted that a change in other factors, such as the cost or convenience of a treatment method, may also influence the resulting environmental impacts; to determine such influences, more research must be conducted.

Perceptions of water quality in comparison with measured water quality revealed the over/under treatment of some drinking water sources at the household level. To better mitigate these discrepancies in perceived and measured water qualities, educational and outreach efforts should be developed to increase public awareness of the measured water quality associated with each source. One impact of such knowledge is the conservation of economic and natural resources from unnecessary use during household treatment. However, to protect human health it is also important for households to be educated about the risks of recontamination of their drinking water. Mihelcic et al. (2009) explains that potable quality water can be recontaminated during collection, transport, or household storage, such as collection by unwashed hands, storage in containers with wide openings that allow dust particles and debris to enter, and distribution of water by vessels contaminated with fecal matter. Overall, an alignment of perceived and actual water qualities could conserve economic and environmental resources and protect public health.

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742 Figure 1: Geographic context of the study and population density of Wakiso District with
 743 units of people/km² (Ministry of Water and Environment, 2010).
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Figure 2: Households' responses to the survey question "why is this drinking water treatment method chosen?"

Figure 3: (a) Environmental impact associated with different stages of water provision for each water source and household treatment method based upon perceived water quality. (b) Environmental impact associated with different stages of water provision for each water source and household treatment method based upon measured water quality

Figure 4: Contribution of individual impact categories to the overall environmental impacts of water sources and household treatment based on perceived water quality

Figure 5: Contribution of individual impact categories to the overall environmental impacts of water sources and household treatment based on measured water quality

762 Table 1. Information about Kitabi Sub-county, water sources, and functionality

Category	Quantity
Population	80,000
Population density (people/km ²)	1,001-1,500
Population served by improved water sources (people)	62,262
Percentage with access to improved water sources (%)	78
Percentage of functional improved water sources (%)	80
Protected springs	15
Wells	83
Boreholes	15
Rainwater harvesting tanks	30
Tap	198

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Table 2. Characteristics and performance information for each community water source

Community water source	Characteristics and specifications
Borehole with hand pump	<p>Requires community members to pump manually to lift groundwater to the surface</p> <p>Uses a concrete base, metal piping/lever, and typical lifespan between 20-50 years</p> <p>Production capacity varies with the depth of the water table and aquifer capacity, ranging from 0.1-10 L/sec (Danert & Armstrong, 2010).</p> <p>Suggested population served by this technology is 300 people (Danert & Sutton, 2010).</p>
Protected spring	<p>The spring is protected through the use of locally available eucalyptus boards covering the source to prevent contamination at the collection point.</p> <p>Serves approximately 50 households.</p>
Rainwater	<p>An unpredictable water provision due to Uganda's increasingly sporadic rainy seasons (March to May, September to November). During the rainy seasons, the average rainfall is about 185-190 mm per month (UBOS, 2010).</p> <p>The two most common household collection and storage vessels are recycled metal oil drums (~200L) or locally fabricated metal/plastic tanks (5000 L)(Blanchard, 2012).</p>
Surface water	<p>Lake Victoria is the primary surface water source for Nalugala and Kitale.</p> <p>There is no protection of Lake Victoria from contamination. The lake's banks are frequently used for watering animals, washing clothes, and sometimes as a point of open defecation.</p> <p>Community members use jerrycans to collect stagnant water near the banks.</p>
Tap water	<p>These sources are typically exposed tap stands (pipes) outside the home, but can be piped into the bathroom or kitchen (less common option).</p> <p>An outdoor tap stand typically serves about 20 households, particularly when owners are selling water to neighbors to generate income.</p> <p>The water treatment facility can functionally treat ~5 MGD (20,000 L/day) but averages closer to 3 MGD (11,400 L/day)(Ministry of Water and Environment, 2010).</p>

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Stage	Item	Input	Amount	Units	Source
Source	Borehole	Groundwater	3.57E+00	L	(IRC, 1991), (UNICEF, 2002), (Danert & Armstrong, 2010), (Sloots et al., 2010), SimaPro database
		Pump	1.46E-06	USD	
		PVC pipe	2.24E-09	kg	
		Transport	1.12E-10	tkm	
		Valves	1.13E-06	USD	
			3.57E+00		
	Protected spring	Groundwater	0	L	(Prouty, 2013), Sima Pro database
		Eucalyptus planks	1.97E-11	m ³	
	Rainwater harvesting	Rainwater	3.57E+00	L	(Ministry of Water and Environment, 2011), (Prouty, 2013), Sima Pro database
		Metal sheets	5.97E-04	kg	
		Transport	1.68E-05	tkm	
	Surface water	Surface water	3.57E+00	L	Sima Pro database
			0		
	Tap	Tap water	3.57E+00	L	Sima Pro database
			0		
Collection	Jerrycan	Plastic for container	4.93E-01	kg	Sima Pro database
		Transport	1.39E-02	tkm	
		Plastic for NaOCl bottle	2.46E-02	kg	
	Disinfection with NaOCl	Sodium hypochlorite (NaOCl)	1.67E-01	kg	(CDC, 2012), Sima Pro database
		Transport	5.39E-03	tkm	
Treatment	Filtration	Plastic	6.24E-02	kg	Sima Pro database
		Transport	1.76E-03	tkm	
			2.64E-03		
	Boiling	Aluminum	13	kg	Sima Pro database
		Charcoal	3.45E-	kg	

	02	(Rugumayo, 2005),
	1.39E-	(Akena, 2012),
Transport	02	(Prouty, 2013)
	2.78E-	
Electricity	01	kWh
	1.99E-	
Propane	02	kg
	5.92E-	
Firewood	02	kg

768 Table 3. Life cycle inventory for each stage of water supply based on the defined functional
769 unit
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771 Table 4. Measured water quality parameters and household treatment methods
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Water Source	TDS (mg/L)	TSS (mg/L)	Turbidity (NTU)	E. Coli (CFU/100 mL)	T.coliforms (CFU/100m L)	Conductivity (μS/cm)	Utility water (L)	Drinking water (L)	Household treatment based on perceived water quality	Household treatment based on measured water quality
Borehole	85	0	2.1	< 1	< 1	122	58.38	2.01	Boil	Filter
Protected Spring	151	0	2	< 1	< 1	215	64.38	4.38	Filter + boil	Filter
Rainwater	76	0	3.4	3	>2420	108	87.92	3.47	No treatment	Settle + filter + boil + dose with NaOCl
Surface Water	60	1	2.4	178.5	>2420	85	89.93	4.37	Boil	Filter + boil + dose with NaOCl
Tap	66	0	0.6	< 1	< 1	94	69.84	3.61	Filter + boil + dose with NaOCl	No treatment