Algorithm for sustainable water source and treatment selection process
Adrienne I. Masterton and Brian D. Barkdoll

ABSTRACT

World water supply is lacking in many places, making sanitation and reuse methods important. A new algorithm entitled 'Drinking Water Source and Treatment Selection' (DWSTS) to more sustainably select and compare water sources and treatment methods is introduced and demonstrated. Sustainability factors included in DWSTS include economic, social, and technical. DWSTS charts produced using this new method are an improvement over more traditional performance measures since they compare water sources based on a spectrum of considerations. The DWSTS method is demonstrated in a representative town. In water-scarce Muslim communities, the practice of ablution offers an opportunity for gray water reuse. Treating and reusing ablution gray water (AGW) was evaluated as part of the new DWSTS algorithm. Investigatory tools included in the new method were: household water use surveys, opinion leader interviews, an AGW collection device prototype design, treatment identification and testing, and comparison of attributes to those of existing water sources. Treatment methods examined were locally-made clay pot filter, coagulation and settling using moringa tree seeds, and P&G™ Purifier of Water. The DWSTS charts developed indicate AGW reuse could be socially acceptable, has potential to provide quality water, and would be financially competitive with existing sources. The DWSTS resulted in a more robust and environmentally sustainable solution than the conventional approach of simply considering cost.

Key words | ablution, economic, social, technical, water scarcity, water use

HIGHLIGHTS

- New method to choose water treatment technology.
- First to investigate ablution water for graywater.
- Addresses social and cultural values.
- Helps with international development.
- This new method can be used for any decision, however.

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DOI: 10.2166/ws.2020.158
INTRODUCTION

According to the United Nations (UN) Water Facts, ‘Water is at the core of sustainable development and is critical for socio-economic development, healthy ecosystems and for human survival itself’ (UN 2018). In 2016, the World Economic Forum (WEF) predicted water crises to be the global risk of highest concern for the next ten years, suggesting that despite the UN’s declaration, water needs are not sufficiently addressed in many places around the globe (WEF 2016).

Perhaps in recognition of this discrepancy, the UN World Water Assessment Programme (UN-WWAP) focused on wastewater in their 2017 World Water Development Report (UN-WWAP 2017). They claim that over 80% of the world’s wastewater enters the environment untreated. The associated pollution has implications for public health, ecosystems, industries that depend on natural systems, and drinking water sources. They recommend wastewater management policies include wastewater as an alternative water resource, a practice growing in interest but which is not yet commonplace nor readily accepted (UN-WWAP 2017). Recent issues in sustainability and water quality include coastal pollution. For example, Shamshirband et al. (2019) developed ensemble models with uncertainty analysis for multi-day ahead forecasting of chlorophyll concentration in coastal waters, while Alizadeh et al. (2018) studied the effect of river flow on the quality of estuarine and coastal waters using machine learning models. In addition, Shende & Chau (2019) investigated forecasting the safe distance of a pumping well for effective river bank filtration, and Chau (2005) studied characterization of transboundary POP contamination in aquatic ecosystems of the Pearl River Delta. Another example of sustainability and water quality is suspended sediment load, for which Olyaie et al. (2015) reported on a case study in the USA of a comparison of various artificial intelligence approaches’ performance for estimating suspended sediment load of river systems, and Chen & Chau (2016) investigated a hybrid double feedforward neural network for suspended sediment load estimation.

The selection of a water source(s) should consider at least three criteria, any of which can render the use infeasible or even dangerous to public health. These criteria are (1) sufficient quantity to meet all the users’ needs, (2) sufficient water quality to ensure public health, and (3) economic viability. Water source selection criteria exist for indirect potable use (Wetterau et al. 2013), water supply planning (Griffith & Ickert 2017), and water irrigation systems (Pérez-Sanchez et al. 2017). Sustainability is an important concept that enables the ability of future generations to live in a method unfettered by the depletion of natural resources or environmental pollution and its related illnesses (Global Footprints 2018). In addition, it requires the consideration of many aspects of life, namely the three-legged sustainability stool of economic, social, technical considerations (Environmental Leader 2018). Considering all of these aspects leads to better solutions that are more balanced than considering any of them individually.

Gray water is often not considered for use, but interest in doing so is growing and is feasible (Edwin et al. 2013). Gray water is a category of wastewater of particular interest...
for those promoting the concept that wastewater is a resource. Although there is a wide variety of technical definitions of gray water, most studies agree that gray water is wastewater with only trace amounts of fecal matter. Some researchers impose additional restrictions because of the expectation of excessive fecal matter, perhaps excluding bathing wastewater. Other researchers will restrict the definition based on what is applicable to their area of interest. For example, industrial applications may have a very specific wastewater under consideration. The broadest definition of not being potable for any reason is used here.

In spite of these previous studies, there have been none that aid in the selection of a water source considering all aspects of sustainability, namely social, environmental, and technical (water quality and quantity), as the present study does.

Study objective

The objective here is to present a water source and treatment technology selection algorithm that incorporates the main three aspects of sustainability, namely economic, social, and technical, and to demonstrate the benefits of the new method on an example from a real situation. Specifically, this paper proposes a new assessment tool called ‘Drinking Water Source and Treatment Selection,’ (DWSTS) and demonstrates its use in a representative rural community. The method aids in the selection of both source selection and also water treatment.

METHODS

The study methods are now described, including subsections of Proposed Selection Method, Drinking Water Source and Treatment Selection (DWSTS) and the Demonstration Site.

Proposed selection method, drinking water source and treatment selection (DWSTS)

The new method is introduced here prior to demonstrating its effectiveness in a real situation. The method includes the main three aspects of sustainability, namely economic, social, and technical. The steps proceed one by one in a sequential manner with no need to loop back to previous steps, therefore no flowchart is needed. See the Results section for further details of each step or Masterton (2017) for full details. The steps include:

Step 1. Estimate current total water consumption and activity-specific water consumption volumes with consumer surveys.

Step 2. Determine all current sources, their costs, and any other user investment such as time to obtain the water, making sure to account for seasonal variability. These values will provide comparison to determine whether proposed water sources provide favorable options. Further, the reported uses will determine socially-acceptable uses of the water sources based on what percentage of respondents report using a given source.

Step 3. Test and treat the proposed water source(s) to determine quality parameters based on the water quality regulations in the area and availability of testing. Analyze the results to determine whether any treatments or combinations of treatments may provide potable water. Ask users whether they would feel comfortable using this new water source considering the laboratory testing results. From the testing, costs of treatments and time required to treat during trials, estimate some unit costs and collection times for the proposed source(s) and requisite treatment(s).

Step 4. Estimate social acceptability for each proposed source using more surveys, in-depth interviews, and/or trials and use the user surveys to determine the social acceptability of sources already in use. Interview notes were analyzed qualitatively using thematic coding (Braun & Clarke 2006). This process involves reviewing interview notes and coding the text for frequently used terms or concepts important to the social acceptability of ablation gray water (AGW) reuse. The emerging themes could then be logically analyzed for coherency and consistency to build an initial theory of the social acceptability of the repurposing of treated AGW. This applies no matter what the source is. The categories from this study can be used, or ones more appropriate for the community at hand can be created.

Step 5. Plot each source and treatment's unit active collection time, unit price, and social acceptability levels to see what options make the most sense for the community at hand.

The x-axis of this ‘DWSTS chart’ is the active unit ‘fetch time’, defined as the time required to collect from a given...
source, including time that could be used to do another activity. The ‘active’ time is defined as time required to fetch and/or treat during which a user cannot do anything else. Thus, walking to fetch water is active time, because walking requires the fetcher’s full involvement. On the other hand, settling time of treatment, defined as the time it takes the treatment method to work, would not be considered active since the user can go elsewhere and do other things while the contaminant particulates settle. The ‘unit’ refers to the total active time normalized by volume, which is particularly necessary in locations where water is collected manually in a variety of container types.

The DWSTS chart’s y-axis is the unit cost of water from a certain source. This cost, to the extent possible and where relevant, should include all capital and recurring expenses for the user, including fees charged, purchase of treatment supplies, and fuel for motorized transport. This may require third-party sources for cost information, but to the extent possible should be based on survey comments regarding cost from people’s actual experience. Some assumptions are likely necessary in determining a cost per volume. For example, the cost of water treated using a filter requires an estimate of the filter’s lifetime. Both the x- and y-coordinates for a given source then express the economic component of feasibility, with the origin being ideal as it represents zero cost and zero active collection time for the user.

The social feasibility of a given water source is expressed on the DWSTS chart as the size of the datapoint symbol on the chart. The larger the dot, the greater the social acceptability of that source. The number of unique symbol sizes used and the relative size should be determined based on how precise are the social acceptability data. For sources not currently in use, social acceptability will be estimated and thus has limited precision. This system allows for a fairly standardized categorization based on the community’s opinions of cultural acceptability, but should be adjusted for other communities’ cultural norms.

Finally, technical measures are represented by the shading color of its data point symbol. To distinguish water quality, potable water sources can be shown in a black outline with no fill color, non-potable sources that are minimally turbid are given a gray fill, and very turbid non-potable sources are black. As with social acceptability categorizations, measures of quality can be adjusted for the community of interest.

In this way, a DWSTS chart can show all sustainability factors for all sources in a spectral, rather than binary way. This allows decisions to be based on local cultural standards, individual or family budgets, time investment preferences, as well as quality standards. Household water use surveys and opinion leader interviews were used, since they are the only methods to get social acceptability data. An AGW collection device was the only way to actually test user acceptability of this new device. Treatment identification and testing was used since that is a better way to quantify treatment effectiveness than literature studies. Comparison of attributes was used to enable the new method to be more robust.

Demonstration site

Tong is a town of about 1,600 people in the Karaga District of Ghana’s Northern Region (Masterton 2017). Tong is located about 45 miles northeast of Tamale, the regional capital, and about 3.3 miles west of Karaga, the district capital. The people are primarily Muslim subsistence farmers. The region is arid and experiences one monsoonal rainy season between May and October. During the rainy season, everyone simply collects rainwater from their corrugated zinc roofs. No treatment is applied to make the water potable. As water insecurity is not a problem in this season, water source evaluation focused on the driest part of the year, January through March.

Based on their water scarcity and limited groundwater sources, the town was considering how to be more efficient with current water sources, leading them to investigate which water combination of source and treatment is best, including gray water treatment and reuse options. Cursory research on gray water reuse, as detailed by Masterton (2017), indicated Ablution Gray Water (AGW) could be readily treated with local methods. The results of treatment testing and the DWSTS analysis for dry season water source options are given below.

RESULTS AND DISCUSSION

The results of each step of the DWSTS algorithm demonstration are detailed below. The subsection consists of
each step, 1–5, followed by the DWSTS charts for All Options. See Masterton (2017) for full details.

**Step 1 – Estimate water consumption volumes**

Household surveys were conducted during the dry season with randomly-selected respondents. Water users in each household were ethically (with respondents’ permission and Institutional Review Board approval) surveyed in their home with a series of questions related to water use amounts, water-consuming activities, water sources, gray water amounts, and collection (Masterton 2017). In addition, potable water use was documented.

**Step 2 – Identify and describe current water sources and treatment methods**

Household survey participants identified existing sources and described each source’s time-to-fetch and unit cost of using each source (Masterton 2017). Nearly a dozen different sources were identified, but only sources reported by at least half of respondents and available year-round were included for analysis. This was done because it is possible that a source not currently used is chosen by the algorithm. Sources not available year-round were eliminated since people need water during all seasons. The most commonly used source is the borehole, which feeds four public taps. Nyensobga, a community about 2 km north of the community, also has a borehole visited by more than half of respondents. There are two reservoirs, about equidistant from the center of the community. These are accessed by walking, cycling, motorized transport, or by donkey cart. Human-powered modes of walking and cycling have been grouped into one category for the similarity in time and requisite involvement of the user. Motorized and animal-powered transport have been placed in a separate category as this fetching is usually hired out and thus does not have the same active involvement for the user. ‘Pure water’ is the vernacular for industrially treated and packaged water that is sold in half-liter plastic pouches. The issue of recycling the plastic pouches after use was not considered here since it is not available in this country and is not possible, but could be in future analyses. To keep the information relevant to the local population, costs were recorded as the local currency, cedis (GHS) and volumes were standardized into a ‘garawa,’ a common metal bucket equivalent to 48.5 L.

Treatment methods included the following. The AfriClay filter is a hemisphere of clay, with about a foot and a half diameter and a half foot depth (Pure Home Water 2017). 3M™ Petrifilms™ are ready-to-use E. coli and coliform counting plates (3M 2019a). Moringa, *Moringa oleifera*, is a tropical tree with many uses for its various parts and propagates relatively easily. For water treatment, the seeds, which contain a cationic protein, can be used as a coagulant to treat water (Beltrán-Heredia & Sánchez-Martín 2009).

Since the AfriClay filter can remove metals and the Petrifilms™ (3M 2019b) indicated it could significantly reduce bacteria, it is assumed to be safe for many uses and on any source. During prototype testing, users and passersby were pleased with the water coming from the AfriClay when combined with boiling; boiling is not assumed to affect social acceptability (personal communication with town residents described in Masterton (2017)).

Similarly, the moringa treatment had good test results. The concentration of metals was not reduced to potable levels, but was significantly reduced. The Petrifilms™ results showed that moringa can remove a significant number of bacteria, but not render the water potable. As such, moringa would need to be combined with other treatments for drinking, but for other household tasks, moringa alone would be sufficient.

P&G™ Purifier of Water (P&G 2019) is a packet of powder distributed free of charge in the community by World Vision, a non-governmental organization serving the area. According to the Center for Disease Control (CDC), the powder consists of both flocculant in the form of ferric sulphate and disinfectant in the form of calcium hypochlorite (CDC 2014). Through laboratory and field testing, it has been shown to remove a significant number of microorganisms and particulate matter. P&G™ Purifier of Water had similar quality results as moringa – it could be used solely to produce water clean enough for many tasks, although not drinking. As such, it was considered to provide water for multiple uses. However, P&G™ did not get any positive feedback from users during prototype testing. Nor did interviewees specify P&G™ as particularly favorable, perhaps due to unreliable supply. No reasons were recorded for the negative responses, however.
Untreated gray water was originally considered to be a non-acceptable source. However, those interviewed noted that people actually already use this water for construction but it was not considered feasible for other uses.

**Step 3 – Assess the proposed water sources and treatment methods**

Sources were tested for several components including turbidity, pH, solids, total coliform or total heterotrophic bacteria, and several minerals and metals. These were chosen on availability of testing and government regulations (MWR 2015). There are hundreds of possible constituents to test for, but time and money did not allow for additional testing than was done.

To assess AGW, with comments from surveys giving recommendations from villagers, an AGW collection device was invented. The design was based on several factors. The size allowed the device to sit easily over basins, a common container in the community, while simultaneously sitting low enough for users to perform ablution above the drainage plate. The metal construction makes it light enough to be carried around from user to user but sturdy enough to survive repeated use. The top plate had a hole at the center for AGW to drain through to the basin below. Respondents indicated that they would be willing to pay 50 GHS or construct one themselves. The one used in the study cost 40 GHS and was constructed by a trained welder.

After ablation, AGW was collected using the above-mentioned device, testing was performed on untreated and treated AGW (Masterton 2017). Treatment methods suitable for the community were selected based on availability, affordability, and potential for effectiveness. Methods used were an AfriClay filter, coagulation and settling with moringa seeds, coagulation, settling, or sterilizing with P&G™ Purifier of Water. Only one method was tried at a time. These methods were significantly less expensive than conventional water treatment plants. Test results were compared to water prior to use in ablation and also to Ministry of Water Resources (MWR) national standards (MWR 2015). MWR Standards were used since they are the only national standards that exist in the country. Samples showed that treatment did improve water quality, but not to potable standards (more details on treatment methods, test methods, and uncertainty in Masterton 2017).

For the reservoir sources, the pre-use, non-treated reservoir sample shows that even before use, the most commonly used dry season source does not meet MWR standards for total coliforms, iron, or manganese. As expected and shown by the untreated AGW sample, performing ablution with the water did not improve quality. No AGW treatment met all MWR drinking water biological parameter standards, and only the AfriClay filter consistently reduced iron and manganese to acceptable levels. Drinking of AGW would only be possible, therefore, with a combination of treatments including at least boiling to successfully remove biological contaminants and the AfriClay filter to remove metals.

Boiling in the community is most often completed using either firewood or charcoal. Although moringa did not treat water to acceptable standards, it could be used as a pretreatment to the AfriClay to speed up filtration, reduce the frequency of filter cleanings, and increase the life of the filter. Moringa can be obtained by either collecting seeds from one’s own tree or by purchasing the seed cake. These options result in several combinations of AGW treatment options and a variety of associated unit costs and fetch times. A detailed description of assumptions and calculations are provided by Masterton (2017).

**Step 4 – Estimate social acceptability**

The social acceptability of treated AGW is also necessary to complete the DWSTS charts using the following four categories of social acceptability:

- **Proven Acceptability** – at least half of survey respondents report they already use this source for any use without treatment
- **Limited Proven Acceptability** – at least half of survey respondents report they already use this source but for only certain uses or only after treatment
- **Unproven Promising Acceptability** – not in current use but feedback from trial participants and water quality testing suggest it would be acceptable for broad application
- **Unproven Limited Acceptability** – not in current use and feedback from trial participants and water quality testing
suggest it may not be readily accepted for more than one or two applications.

All sources described by respondents were placed in the first two categories, as their mention by participants meant they were in current use. Currently used sources were further broken down based on how respondents were willing to use water from that source. For example, many people were willing to drink reservoir water but only if it were treated first. Thus, their use was limited due to its poor quality. Since AGW treatment is not currently in use, these options were placed in one of the latter two categories using a different method. Rather than what uses are currently accepted, as was done for existing water sources, AGW treatments were measured based on the potential for use as dictated by the water quality results. ‘Multiple uses’ does not necessarily include drinking, since not all treated AGW is potable, but it does include most household chores like laundry, washing dishes, and cooking. If a treatment provides water acceptable for only a couple of uses, it is not considered to provide water for ‘multiple uses.’ Treatments were also assessed by the feedback received from users and observers during testing and statements from interviewees. Full details of the survey results are available in Masterton (2017).

Step 5 – Plot DWSTS charts for potable options

Results show (Figure 1) that the cost ranges from 0.10 to 16.34 GHS/barawa, the Fetch Time from 14 to 729 minutes, and the Social Acceptability from Proven to Unproven Promising.

Results show that, as expected, the purchasing of pure water pouches is far and away the most expensive per volume. People in the community frequently purchase them nonetheless, likely because it is sold cold and is purchased in very small, inexpensive amounts spread over a long period. People in the community typically buy less than a cedi (a unit of the local currency, equivalent to 100 pesewas and to 0.23 USD) at a time and thus do not associate such a high expense with pure water pouches.

Comparatively, it is also easy to see why people in the community use their borehole frequently in the dry season. The borehole requires minimal active time to fetch and has a relatively low cost. That said, the time spent at the borehole, although considered passive for the purposes of the DWSTS chart, is still limited in some ways. For example, if one walks away from the vicinity, they will lose their spot in line. However, one can be sitting, braiding hair, selling small items, or dozing off and thus the waiting time is still preferable to other water sources.

Despite the distance, people use the borehole in Nyensobga, a small community about 2.5 miles northwest of the community. If insufficient water is collected from the main borehole, a nearby borehole is a good second option. It is farther than the reservoirs, but it provides high-quality water. It is not free, like reservoir water, but its price is the same as water from the main borehole.

The AGW treatment options have a variety of unit costs and times. The least favorable is clearly the AfriClay filter without pretreatment supplemented by boiling with charcoal, contrary to initial favorable results mentioned earlier in prototype testing. The unfavorable response was due to the fact that charcoal is costly unless made by the household and that the filter without pretreatment takes too long. AGW is used for non-potable uses, while the main borehole is used for potable use.

For a potable water source, pretreatment with one’s own moringa, then filtering with the AfriClay, and then boiling with firewood is a reasonable option. It is more expensive and takes more active involvement than the main borehole, but when the borehole runs dry and people start looking for a secondary source of potable water, AGW treatment with this combination is competitive with existing options. Users were willing to spend time if it is the only realistic course of potable water in the dry season but not for non-drinking uses. The option comprising moringa, AfriClay, and boiling combination has a cost saving of more than 30 fold over pure water pouches. The cost of such treatment is almost five times as much as the Nyensobga borehole, but the treatment saves approximately two and a half hours for each garawa (approximately 48 L). The upfront cost of the AfriClay filter poses a barrier to adoption at the onset but, if adopted, the regularly observed cost to the user is negligible since all cost is taken care of with the initial purchase. Future costs have not been considered in this study due to their uncertainty.
All options are plotted in a DWSTS chart in Figure 1. As seen with the potable sources, the two boreholes offer low prices. The main borehole requires less than 15 minutes of active time to fetch a garawa, but the passive waiting time, sometimes up to several hours, is prohibitive. The Nyensobga borehole is also fairly inexpensive, but it requires over two hours of active fetching time for one garawa.

The dams are currently widely used. It takes about an hour and a half, round trip, to fetch a garawa from the reservoir if walking. It is free but it is also of poor quality, both by national standards and local opinion. Most people in the community currently treat it with alum, which adds cost. Not treating, however, reduces social acceptability. The other option for fetching water at the reservoir is hiring a donkey or motorized vehicle. This requires minimal active time for the user, but it does cost much more than most options, at almost a cedi for one garawa compared to just 0.82 GHS for the next most expensive option (purchased moringa). Despite the extra cost, the water quality is very low and will likely require the use of alum, adding to the already-high cost.
AGW treatment options for non-drinking uses can potentially be used on their own. The AfriClay performs better in cost and price when pretreatment is included. The average time investment is less than a minute for a garawa; the price, not including the cost of pretreatment, is almost 0.50 GHS for a garawa. For uses that do not involve ingestion, the AfriClay may not be necessary. Although it clarifies water, clarification beyond that done by moringa is not as significant and would come at a relatively high cost. The AfriClay may only be worth the cost if one needs to remove the iron and manganese before ingesting.

Moringa used on its own is a very cost-effective choice. It is free when gathered from one's own tree and requires only about 25 minutes to treat an entire garawa, providing far less turbid water in less time than by walking to the reservoirs.

P&G™ Purifier of Water did not produce water that looked as good as the water treated with the AfriClay or the moringa. As such, its use would likely be very limited when used to treat AGW. Because it is free, it may still be beneficial for certain uses like treating reservoir water instead of purchasing alum.

Untreated AGW has very limited use, as it is only acceptable for construction, something a household requires only about a few weeks every few years. However, as it is free and does not require any treatment time, it can be useful for the years in which a household does construction.

CONCLUSIONS

The new DWSTS algorithm and its demonstration in a real community provide more sustainable and balanced selection. Many communities or aid agencies working on clean water projects would likely not consider AGW treatment and reuse on either technical or cultural basis. However, incorporating economic and social performance measures into the analysis and sharing these holistic results with community members revealed a surprising openness to AGW reuse. In places like this community, where traditional water projects have fallen short, having a tool like the DWSTS to evaluate unorthodox water solutions on all three main components of sustainability aids the identification and development of locally relevant options. From its DWSTS, the community saw that gray water can be a cost-competitive and high-quality resource when compared in a more sustainable way – by accounting for the locally-defined economic, social, and technical aspects of each water option. The new DWSTS algorithm should be considered by other communities seeking a new water solution. The DWSTS resulted in a more robust and environmentally sustainable solution than the conventional approach of simply considering cost, although it needs more information.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories at https://digitalcommons.mtu.edu/etdr/522/.

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First received 20 April 2020; accepted in revised form 7 July 2020. Available online 20 July 2020