Water Treatment Technology Selection Guide

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Abstract

In a world where more than 1.1 billion people still lack access to improved sources of water, the information barrier to selecting the appropriate water treatment technology for resource-poor communities has not been effectively lowered. Current technology selection guides tend to focus on providing information on treatment technologies based on contaminant removal requirements, while ignoring the realities of resource-constraints and skill-constraints of communities, and without consideration of sustainable engineering practices. An expert guidance tool is needed to empower people to improve their water treatment. The goal of this project is to develop the framework and decision-making methodology for such a decision-support system, and to implement a platform for usage.

1 Background

According to a World Health Organization (WHO) monograph[6], in resource-poor communities, more health benefits can be gained from money spent on a water-supply program than in any other way. For community leaders and government officials, selecting the right technology to optimize the limited resources available has often proved challenging, particularly in communities where individuals with technical expertise are not available.

Currently, institutions like National Research Council (NRC)[2], National Academy of Sciences (NAS)[3], and WHO have provided information and guidance on the technical capabilities of established treatment technologies. However, what is distinctly lacking is a platform to synthesize all the available public-domain information into a decision-support system (DSS) - one that a layperson can easily interface with, and which promotes the idea of sustainable engineering practices. Ideally, such an expert guidance tool should consider both technical and social-economic factors, and on a case-by-case basis generate a useful output that a layperson can relate to and apply.

The goal for the Water Treatment Technology Selection Guide team in Fall 2011 is to conduct an extensive literature review, codify the available information with respect to alternative treatment processes as well as process sequences, determine their limitations and capabilities, and develop a multi-criteria scoring model for direct implementation.

2 Approach to Creation of a Water Treatment Technology Selection Guide

Designing a DSS is akin to solving a water treatment design problem, where the developer has to address three major areas – i) problem analysis, ii) knowledge acquisition and identification of alternatives and iii) decision optimization. The 'optimal solution' would need to be acceptable to the user and, if not, additional constraints on the design would need to be considered. The scope of the Technology Selection Guide project in Fall 2011 is to synthesize information from water treatment guides, databases, case-studies, etc., into useful knowledge for decision-making.

2.1 Water Treatment Problem Analysis

From the many factors to be considered when selecting a water treatment process, the majority of DSSs available on the internet focus on technical and economic factors, such as the extent of contaminant removal and capital cost of technology. Non-technical factors such as acceptability of technology, availability of resources, social costs, etc. are often difficult to quantify and the impact of such factors is subjective. However, these issues remain important for the chosen technology to operate on a sustainable basis. Our efforts in this project are directed towards establishing a holistic set of criteria, including non-technical factors - that will form a basis for a generic water treatment technology selection tool. With a focus on small, resource-poor communities, the following set of criteria has been developed to be broadly applied in assessing the solution to a generic water treatment problem:

Criteria for Technology Assessment

1. Effectiveness of Technology
   (a) Water Quality: What contaminants can be removed? - Turbidity, Algae, Protozoa, Bacteria, Viruses, Heavy Metals, etc.
   (b) Ability to meet effluent guidelines (WHO/US-EPA guidelines) and/or regulatory standards (local laws)
2. Appropriateness of Technology
   (a) Manufacturing requirements:
      - Skills available required to implement technology (e.g. masonry, carpentry, metal-working, etc.)
   (b) Access to materials (e.g. Alum, PACl, Ferric Salts, Chlorine, Sand, Gravel, PVC Pipes, Float Valves, etc.)
   (c) Degree of skilled labor needed
3. Acceptability of Technology
   (a) Removal of taste, odor and color
   (b) Household expenditure savings and/or increased willingness to pay for safe drinking water
   (c) Existing water-related health problems vis-a-vis contaminants to be removed
4. Cost of Technology
   (a) Capital cost of project budgeted
   (b) Recurring operation cost per year

For each combination of technologies within the DSS, the extent of compliance with the above set of criteria will form the basis of decision-making (see Section 2.3).

2.2 Knowledge Acquisition and Representation

After a set of criteria is developed to evaluate a particular water treatment technology, the next logical step is to initiate a knowledge acquisition process. In this step, critical information necessary for decision-making needs to be codified within the DSS. This information pertains to quantitative and qualitative descriptors of the criteria established in Section 2.1, and will be utilized in the decision-making process (illustrated in Section 2.3). The main categories of information are as follows:

User Inputs - Understanding the User's Context

Questions shall be posed to users in the DSS to understand what situation they face and their water quality requirements. These questions are organized into five categories. The following list describes the categories and provides an example for each type of the questions that are asked:

1. General information on water source
   - Example: What is your source of raw water?
2. Raw water quality
   - Example: Which of the following pictures best illustrate the turbidity level of the raw water?
3. Desired water quality,
   - Example: Are you aware of the drinking water standards in your country? If not, which standards (WHO / US-EPA) would you like to meet?
4. Available resources (chemical and manpower)
   - Example: Are masons, carpenters and metal workers available in your community?
5. Cultural preferences
   - Example: How important is the taste of water?

Performance of Unit Treatment Processes

In the development of a DSS, gathering up-to-date performance data on the treatment processes of interest is often the most time-consuming step. In this project, focus is placed on selecting sustainable treatment technologies befitting use in resource-poor communities. From an extensive literature review, the following 5 Unit Treatment Processes (UTPs) are chosen based on their ease of implementation, and established track record for use in developing countries.

Visual illustration of Turbidity Levels (in user interface)

1. Roughing Filter
2. Coagulation & Flocculation, coupled with Sedimentation
3. Coagulation & Flocculation, coupled with Stacked Rapid Sand Filtration (SRSF)
4. Stacked Rapid Sand Filtration
5. Chlorination

From literature[8], the removal efficiencies of the unit treatment processes are as listed in Table 1, and are codified within the DSS:

Table 1: Performance (Removal Efficiencies) of Unit Treatment Processes

Parameters	Roughing Filter	SRSF	Coagulation, Flocculation & Sedimentation
Turbidity	60.0% - 90.0%	70.0%	80.0%-89.0%
Cryptosporidium	60.0% - 90.0%	70.0%	90.0% - 95.0%
Total Coliform	93.0% - 99.5%	1.0% - 50.0%	90.0% - 95.0%
Rotavirus	0.0%	1.0% - 50.0%	90.0% - 95.0%
Cadmium	0.0%	0.0%	70.0%
Total Chromium	0.0%	0.0%	90.0%
Mercury	0.0%	0.0%	70.0%
Selenium	0.0%	0.0%	40.0%-80.0%

Table 1: Performance (Removal Efficiencies) of Unit Treatment Processes (Contd.)

Parameters	Coagulation, Flocculation & SRSF	Chlorination
Turbidity	97.0%	0.0%
Cryptosporidium	99.9%	0.0%
Total Coliform	96.0%	99.9%
Rotavirus	87.4%	99.9%
Cadmium	70.0%	0.0%
Total Chromium	90.0%	0.0%
Mercury	70.0%	0.0%
Selenium	40.0%-80.0%	0.0%

WHO and US-EPA Drinking Water Standards

Based on the removal efficiencies and the user inputs on water quality expectations, the final water quality (turbidity, protozoa, bacteria, viruses and heavy metal contaminants) at the end of the treatment processes can be projected. In the decision-making process that follows, the water quality data will then be compared with either the local standards (input from the user), or the WHO or the US-EPA

Drinking Water Standards to determine if the proposed treatment process or process sequence is effective in treating water to desired standards/guidelines. Relevant WHO guidelines[9] and US-EPA[5] Drinking Water Standards are thus codified within the DSS (see Table 2 below):

Table 2: WHO / US-EPA Drinking Water Standards

Parameters	WHO	US-EPA	Units
Turbidity	5	0.3	NTU
Cryptosporidium	1.3 e-5	0	Organisms/L
Total Coliform	0	0	Organisms/L
Rotavirus	1.1 e-5	0	Organisms/L
Cadmium	0.003	0.005	mg/L
Chromium	0.05	0.1	mg/L
Mercury	0.006	0.002	mg/L
Selenium	0.04	0.05	mg/L

Resource Considerations

As highlighed by Schultz and Okun[4] - design practice in any locality should strive to optimize the total available capital, material, human resources, recognizing the limitations that may exist. When focusing on resource-poor communities, it is especially important that the chosen technology operate on a sustainable footing. For example, while automation is desirable in the control of mechanical plants, the lack of vendor support for the automation technology, and lack of skilled operators to remedy faults may result in abandonment of automated technology. Conversely, the adoption of hydraulic-based treatment technology with simple manual controls will likely be something plant operators can understand and repair. This is likely to result in a higher community acceptance and willingness to pay for cleaner drinking water.

Through an examination of the requirements of the unit treatment processes, and from the inputs of Señor Antonio Elvir (Agua Para el Pueblo technician working with AguaClara in Honduras), the resource requirements for combinations of UTPs under consideration are as follows:

Resource Requirements	1. C	2. SRSF + C	3. RF + SRSF + C	4. CF + SRSF + C	5. CFS + C
Chlorine	✓	✓	✓	✓	✓
PACl				✓	✓
Alum				✓	✓
Ferric Chloride				✓	✓
Sand		✓	✓	✓	✓
Gravel		✓	✓	✓	✓
Cement		✓	✓	✓	✓
Bricks		✓	✓	✓	✓
PVC Pipings	✓	✓	✓	✓	✓
Float Valves	✓	✓	✓	✓	✓
Masons		✓	✓	✓	✓
Carpenters		✓	✓	✓	✓
Metal Workers		✓	✓	✓	✓
Local Manpower Skill Level	LS	BS	BS	IS	IS

Resource Requirements	6. CFS + SRSF + C	7. SRSF	8. RF + SRSF	9. CF + SRSF	10. CFS	11. CFS + SRSF
Chlorine	✓					
PACl	✓			✓	✓	✓
Alum	✓			✓	✓	✓
Ferric Chloride	✓			✓	✓	✓
Sand	✓	✓	✓	✓	✓	✓
Gravel	✓	✓	✓	✓	✓	✓
Cement	✓	✓	✓	✓	✓	✓
Bricks	✓	✓	✓	✓	✓	✓
PVC Pipings	✓	✓	✓	✓	✓	✓
Float Valves	✓	✓	✓	✓	✓	✓
Masons	✓	✓	✓	✓	✓	✓
Carpenters	✓	✓	✓	✓	✓	✓
Metal Workers	✓	✓	✓	✓	✓	✓
Local Manpower Skill Level	IS	BS	BS	IS	IS	IS

Legend:
C: Chlorination
RF: Roughing Filter
CF: Coagulation & Flocculation
CFS: Coagulation & Flocculation + Sedimentation
LS: Lowly-Skilled
BS: Basic Skills
IS: Intermediate Skills

2.3 Decision Optimization

The above sections discuss the criteria for accessing individual UTPs, in tandem with how real-world requirements such as treatment standards, efficiencies and resource requirements influence the final decision. The technology-selection problem is one that demands a multi-criteria decision-making (MCDM) methodology. Often, some criteria will conflict with others - thus a trade-off is needed based on expressed preferences and utility of the individual or community being considered.

In the technology-selection process, a weight can be assigned to each criteria as a measure of its relative importance. The weight can then be multiplied by a score for a particular criteria - dependent on whether the criteria is met. The total score for each treatment combination is then given by:

$$Totalized\,Score\,for\,Treatment\,Combination\,j\ = \sum_i w_i Score_{i,j}$$

In the DSS, based on the UTPs being considered, all possible meaningful treatment combinations are constructed and evaluated with the above scoring methodology. The current main categories and their associated weights are:

1. Contaminant Removal Ability (35%)
2. Final Product Water Quality (35%)
3. Resource Considerations (10%)
4. Community Preferences (5%)
5. Costs (15%)

Within each category, there are sub-categories that are also assigned weights. For example, the 'Costs' category is made up of capital costs (30%) and operating costs (70%), while 'Resource Considerations' is made up of a listing of resources, such as PVC pipes, cement, bricks, etc, each with its own weight.

With a list of the total scores for each treatment combination, conventional MCDM recommends that the user adopt the option with the highest score - as it is more sustainable. However, this ignores the real-world resource constraints, e.g. there may be a lack of chlorine supply in the community, thus preventing the use of chlorination. In this DSS, the absolute compliance to resource requirements can be represented by an additional filtering stage. The filtering stage involves screening the top-ranked option to ensure resource compatability, and moving on to the next option if there is a lack of a particular resource. After this filtering stage, the user will be presented with the highest ranked option, that has its associated resource requirements completely met.

In the DSS, users are empowered to choose the mode of decision making - MCDM, or MCDM with absolute-resource compliance.

3 DSS on Microsoft Excel Platform

Using the approach described above, a user interface is being developed in Microsoft Excel software. The Microsoft Excel software provides a convenient plaform for implementation using Visual Basic for Applications (VBA) language, and the DSS file can be easily disseminated for offline usage. The capacity for offline use is especially beneficial for resource-poor communities, which are likely to have intermittent internet access.

The DSS consists of the following components:

1. Main Menu (see screenshot in Figure 1 of Appendix) - where users can choose between 'Understanding Your Treatment Options', 'Choosing A Water Treatment Technology' and 'Top 15 Questions to Ask Technology Vendors'. Further descriptions of each selection can be found below.
2. 'Your Treatment Options' page (see screenshot in Figure 2 of Appendix). Here, users can click on tabs which are linked to simple and educational write-ups about technologies such as Roughing Filter, Coagulation and Flocculation, Sedimentation, Stacked Rapid Sand Filtration, and Chlorination. This section is for users who would like to understand more about the technologies.
3. A user interface where users respond to questions to allow the DSS to acquire information about their context (see screenshot in Figure 3 of Appendix).
4. A scoring matrix that determines the treatment process permutation that best satisfies the user's requirements.
5. Output which will consists of the following:
   (a) Recommended Treatment Process Combination. The user will be allowed to explore alternatives, that gives reduced performance (at lower cost) and improved performance (at higher cost).
   (b) Projected removal efficiencies with focus on parameters such as Turbidity, Cryptosporidium, Total Coliform, Rotavirus, Cadmium, Chromium, Mercury and Selenium
   (c) Estimated site area required (referencing the AguaClara Design Tool)
   (d) Estimated capital and operating costs for the recommendation

4 Case Study: Using the DSS

To illustrate the use of the DSS that has been developed, a hypothetical problem was presented to the DSS. The details used for the simulation is as follows:

Parameter	Value	Units
Turbidity	25	NTU
Cryptosporidium	0.0001	Organisms/L
Total Coliform	0.00022	Organisms/L
Rotavirus	0.00013	Organisms/L
Cadmium	0.007	mg/L
Mercury	0.009	mg/L

Resource	Availability
Chlorine	No - Cannot be obtained easily
PACl	Yes - Can be obtained within community
Cement	Yes - Can be obtained within community
Bricks	Yes - Can be obtained >10km away in Country
Masons	Yes - With Basic Skills

The user has specified that the drinking water should comply with WHO Drinking Water Guidelines. From the treatment combinations within the DSS, the scoring matrix calculates the following ranked solutions:

Rank	Treatment Combination	Score
1	Coagulation & Flocculation - Sedimentation - Chlorination	66.71%
2	Coagulation & Flocculation - Sedimentation	63.75%
3	Coagulation & Flocculation - Sedimentation - Stacked Rapid Sand Filtration	62.31%
4	Coagulation & Flocculation - Sedimentation - Stacked Rapid Sand Filtration - Chlorination	61.27%
...	...	...

From the ranked solutions, users are allowed to choose between 2 types of recommendations within the DSS - firstly, one that is associated with the highest score based on the MCDM methodology, and a second solution that factors in absolute resource constraints. In this case, the user understands that he has no means of obtaining any form of chlorine, and thus he is obliged to choose a resource-compliant recommendation.

Based on the resource-compliant recommendation, the projected water quality is:

Parameter	Source Concentration	Overall Removal Efficiency	Final Water Quality	WHO Guidelines	Compliance
Turbidity	25 NTU	84.50%	3.875 NTU	$<$ 5 NTU	✓
Cryptosporidium	0.0001 Organisms/L	92.50%	0.000008 Organisms/L	$<$ 0.000013 Organisms/L	✓
Total Coliform	0.00022	92.50%	0.000017 Organisms/L	0	×
Rotavirus	0.00013 Organisms/L	92.50%	9.75 E-06 Organisms/L	$<$ 0.000011 Organisms/L	✓
Cadmium	0.007 mg/L	70.00%	0.0021 mg/L	$<$ 0.003 mg/L	✓
Mercury	0.009 mg/L	70.00%	0.0027 mg/L	$<$ 0.006 mg/L	✓

From the table above, while it is observed that Total Coliform requirement does not conform to the stringent WHO Guidelines, it is noted that the coliform concentration is very close to zero. The water is thus safe for drinking, as based on general guidelines of less than 10 Organisms/liter.

5 Conclusion & Recommendations

With the systematic approach outlined above, a Decision Support System has been developed to empower resource-poor communities in choosing a sustainable water treatment solution for their context. The DSS considers the use of 5 unit treatment processes (and their combinations), and all proposed solutions can be implemented in fully hydraulic-based configurations. The over-arching theme of sustainability has been the key differentiating factor from other DSS available in the internet. The DSS that has been developed also provides a more holistic assessment of the user's context, intimately considering the lack of key resources in decision-making. The resultant solution/recommendation to the user is thus robust and sustainable - considering i) treatment ability/performance ii) resource requirements, iii) life-cycle costs and iv) acceptability of the proposed solution.

To further enhance the functionalities of the DSS, the following aspects should be explored:

1. To continue to update the removal efficiency figures of the UTPs featured in the DSS - for example, the performance data for the SRSF should be updated in the DSS after operations have stabalized
2. To include other combinations of UTPs in the DSS
3. To develop a database of regulatory guidelines/standards pertaining to drinking water within the DSS
4. To explore synergies between the use of the DSS and the AguaClara Program. One approach could be to develop a web-based version of the DSS, directly linking prospective communities to the AguaClara Program if there is a match in solution and needs.

6 References

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7 Appendix

Figure 1: Screenshot of Main Menu page

Figure 2: Screenshot of 'Your Treatment Options' page

FIgure 3: Screenshot of User Interface

Water Treatment Technology Selection Guide

Who Are You?

Name:	
Occupation / Designation:	
Country:	
State:	
City:	

Improving Your Water

How many people will this system need to serve on a daily basis?	6000	people
How much water does one person approximately use daily? *(typical: 150litres/day)*	150	litres/day
What is your source of raw water?	Stream	
How much water can be collected from this source per day?	1000000	litres/day

How does the volume of the raw water change with the weather (e.g. storm, dry season, etc.)

Dry Season	40	%
Normal Weather	100	%
Wet Season	150	%

Figure 4: Screenshot of Scoring Matrix (partially shown below)

Category	User Interface Data	Unit	Boolean/Scale Interpretation	Weighted Score	Option 1: Chlorination	Option 2: Stacked Rapid Sand Filtration + Chlorination	Option 3: Roughing Filter + Stacked Rapid Sand Filtration + Chlorination
Virus: Rotavirus	0.1	Organisms/Liter	1	25	1	1	1
Iron	0.2	mg/L	1	25	1	1	1
Manganese	0.4	mg/L	1	25	1	1	1
Antimony	0.2	mg/L	1	25	0	0	0
Arsenic	0	mg/L	0	25	0	0	0
Beryllium	0.2	mg/L	1	25	0	0	0
Cadmium	0.3	mg/L	1	25	0	0	0
Total Chromium	0.2	mg/L	1	25	0	0	0
Cyanide	0	mg/L	0	25	1	1	1
Mercury	0.1	mg/L	1	25	0	0	0
Selenium	0.1	mg/L	1	25	0	0	0
Meeting Standards	No	Boolean	0	*(0 - WHO Standards, 1 - USEPA Standards, 2 - Local Standa*			
Turbidity	0	NTU	1	200	0	1	1
TOC	0	mg/L	1				
pH	0	pH Scale	1				
Protozoa: Cryptosporidium	0	Organisms/Liter	1	25	0	0	0
Bacteria: Total Coliform	0	Organisms/Liter	1	25	0	0	0
Virus: Rotavirus	0	Organisms/Liter	1	25	0	0	0
Cadmium	0	mg/L	1	25	0	0	0
Total Chromium	0	mg/L	1	25	0	0	0
Mercury	0	mg/L	1	25	0	0	0

Figure 5: Screenshot of Evaluation Table

Score	Option 1: Chlorination	Option 2: Stacked Rapid Sand Filtration - Chlorination	Option 3: Roughing Filter - Stacked Rapid Sand Filtration - Chlorination	Option 4: Coagulation & Flocculation - Stacked Rapid Sand Filtration - Chlorination	Option 5: Coagulation & Flocculation - Sedimentation - Chlorination	Option 6: Coagulation & Flocculation - Sedimentation - Stacked Rapid Sand Filtration - Chlorination	Weightage (%)
Contaminant Removal Ability Score (25%)	7.35	13.24	13.24	13.24	22.06	22.06	25
Actual Removal Performance Score (25%)	0.00	11.76	11.76	14.71	16.18	18.33	25
Resources Requirement Score (25%)	19.53	20.83	20.83	21.67	21.67	21.67	25
Community Preferences Score (5%)	0.00	0.00	0.00	0.50	-1.50	-1.50	5
Costs (20%)	18.00	15.70	8.30	11.90	9.40	7.20	20
Percentage Score	44.88	61.53	54.13	62.01	67.80	67.76	