

## System Life Cycle Evaluation<sup>SM</sup> (SLiCE): harmonizing water treatment systems with implementers' needs

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### ABSTRACT

One of the methods proposed to improve access to clean drinking water is the mobile packaged water treatment system (MPWTS). The lack of published system performance comparisons combined with the diversity of technology available and intended operating conditions make it difficult for stakeholders to choose the system best suited for their application. MPWTS are often deployed in emergency situations, making selection of the appropriate system crucial to avoiding wasted resources and loss of life. Measurable critical-to-quality characteristics (CTQs) and a system selection tool for MPWTS were developed by utilizing relevant literature, including field studies, and implementing and comparing seven different MPWTS. The proposed System Life Cycle Evaluation (SLiCE) method uses these CTQs to evaluate the diversity in system performance and harmonize relevant performance with stakeholder preference via a selection tool. Agencies and field workers can use SLiCE results to inform and drive decision-making. The evaluation and selection tool also serves as a catalyst for communicating system performance, common design flaws, and stakeholder needs to system manufacturers. The SLiCE framework can be adopted into other emerging system technologies to communicate system performance over the life cycle of use.

**Key words** | emergency water supply, life-cycle analysis, relief agency, water treatment selection

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### INTRODUCTION

Almost one-tenth of the global disease burden, mainly in developing countries, could be prevented by water, sanitation, and hygiene interventions. The economic return of investment for a local community in improved access to safe drinking water is almost 10-fold (Fewtrell *et al.* 2007). These figures implore innovation, and the overall effect of low access to clean water is only compounded in emergency situations (Connolly *et al.* 2004). One such innovation that addresses the need for clean water is the mobile/modular packaged water treatment system (MPWTS), which is currently in use by the Red Cross, Oxfam, UNICEF, and many other relief agencies (Ljungqvist & Schwin 2005; Steele & Clarke 2008; Baillie 2010). An MPWTS will be defined as a mobile system that can treat 2,000 L/day (100 people at WHO standard of 20 L/day) of water to conform to WHO water quantity

standards for drinking and cooking in emergencies (WHO 1996). The MPWTS technology landscape is varied, and organizations have found success with different systems in different locations (Steele & Clarke 2008). As technology continues to advance, more progressive systems continually become available (Clarke *et al.* 2004; Daigger *et al.* 2005; Dorea *et al.* 2006; Ebie *et al.* 2006; Schin & O'Melia 2006; Shannon *et al.* 2008; Clarke & Steele 2009; Peter-Varbanets *et al.* 2009). Before MPWTS can be fully embraced by relief agencies, a systematic review is necessary, similar to reviews of point-of-use (POU) treatment (Souter *et al.* 2003; Crump *et al.* 2004; Lantagne *et al.* 2006; Albert *et al.* 2010). For a systematic review to be possible, we must first 'establish a method of standardizing and creating a benchmark for developing new [mobile package water treatment] technologies'

(ELHRA 2010). A standardized evaluation method has a high potential to integrate communication channels between industry, academia, and humanitarian agencies by promoting collaboration and increasing knowledge transfer of how each sector operates (Steele & Clarke 2008; Ellis & Garelick 2009; Personal communication: V. Cuellar, Public Health Analyst, Center for Disease Control, 2010; ELHRA 2010; Personal communication: O. F. Suntura Yujra & A. Terrazas Vargas, Fundación Sumaj Huasi, 2010).

One of the difficulties of designing such an evaluation is that every intervention has different requirements. The inability of MPWTS to cope with the diverse physical and anthropological aspects of operating in emergency and/or community settings has led to their slow uptake by relief agencies (Steele & Clarke 2008; Clarke & Steele 2009; Personal communication: J. Parker, Environmental Health Regional Technical Advisor, IRC Africa, 2009; Personal communication: V. Cuellar, 2010; Personal communication: O. F. Suntura Yujra & A. Terrazas Vargas, 2010). Yet often, as case studies show, the issue is not the inability of MPWTS to cope with diverse conditions, but the difficulty for a system to cope with conditions different than its intended use (Momba *et al.* 2004; Ljungqvist & Schwin 2005). The few previous comparison methodologies of MPWTS have utilized evaluation methods lacking robustness by not employing a life-cycle multiple criterion approach (MCA) and not evaluating the set of critical factors from sourcing to decommissioning of a system that may significantly affect stakeholders (Snoad 2005). The objective of this paper is to propose a standardized life-cycle MCA evaluation and selection tool by reviewing publications on performance and testing of MPWTS, collaborating with industry, relief agencies, and academia, and actively participating in the life cycle of an array of MPWTS at a field site. In developing the System Life Cycle Evaluation (SLiCE) methodology and selection tool, we followed advice from Steele and Clarke: 'a detailed and inclusive, technical and operational study involving a range of agencies would need to be carried out to develop an effective system selection methodology' (Steele & Clarke 2008).

## METHODS

Achieving the objective of providing drinking water to 100 people in a sustainable and timely manner is influenced by

the system's performance in the life-cycle stages: sourcing, installation, commissioning, operation, maintenance, winterization, and decommissioning. Each life-cycle phase was found to have different critical-to-quality characteristics (CTQ) through a multi-method approach including a literature review, in person correspondence with stakeholders and field-testing. Every CTQ has the potential to affect system performance and thus must be assessed to score systems. Therefore, each CTQ was translated into a set of measurable key performance indicators (KPIs). The life-cycle phases of seven MPWTS were then tested using the developed KPIs. Alongside testing, KPIs were refined, and CTQs were added to reflect differences in system performance.

Few similar multi-criteria evaluation studies of MPWTS in the literature were found and thus CTQs were adapted from best practices, and evaluations of point of use (POU) water-treatment systems and lessons learned from specific case studies (Souter *et al.* 2003; Crump *et al.* 2004; Lantagne *et al.* 2006; Sobsey *et al.* 2008; Albert *et al.* 2010; Kim 2010). Collaboration, via key informant interviews with industry experts, system manufacturers, emergency relief implementers, and other researchers was used to further refine the list of key CTQs (Personal communication: J. Parker, 2009; Personal communication: V. Cuellar, 2010; Personal communication: G. Hodgkin, Executive Director, Tomorrow's Peacekeepers Today, 2010; Huttinger 2010; Personal communication: J. Kim, Assistant Professor, Georgia Institute of Technology, 2010; Personal communication: D. C. Moe, Director, Center for Global Safe Water at Emory University, 2010; Personal communication: O. F. Suntura Yujra & A. Terrazas Vargas, 2010). In addition to collaboration with agencies, this study utilized an email questionnaire with manufacturers of water treatment systems to give insight into the situations in which these systems are currently in use, how they are usually deployed, their intended use, and their documented efficacy (Personal communication: P. Blackburn, Operations Managers, Blue Future Filters, 2010; Personal communication: L. James, Projects Director, SkyJuice Foundation, 2010; Personal communication: R. Rippo, Export Department, LMS France World Water Treatment, 2010). This communication and research identified a broad set of CTQs that fall under the following categories: social, economic, environmental, and technical.

To meet the deployment objective, an MPWTS should fulfill specific CTQs during unique life-cycle phases. Consequently, the deployment life cycle was segmented into discrete phases for evaluation. Each life-cycle phase was first identified, and its scope was defined, entailing precise identification of all steps and periods that encompassed a particular life-cycle phase. Separate evaluation rubrics were created for the sourcing, installation, commissioning, operation, maintenance, winterization, and decommissioning life-cycle phases.

For each life-cycle phase, CTQs were identified, and KPIs were defined to provide quantifiable assessment of the ability of MPWTS to fulfill a unique CTQ. For example, CTQs from the literature such as 'consistently produces sufficient quantities of microbiologically safe water' and 'relatively small user time to treat water' were translated into the KPIs: average measured flow rate, guarantee of safe water, availability, and operator time requirement (Sobsey *et al.* 2008). A 1–5 scale quantifying system performance and measurement procedures was defined for each KPI with 1 being very weak performance and 5 being very strong performance. Specific descriptions of system performance were provided for each possible numerical score, with the range of descriptions spanning anticipated system performance. Scoring rubrics also included spaces for comments, allowing for justification of the given scores and documentation of lessons learned.

Given that no existing methodology adequately captures KPIs throughout the life cycle, the methodology under development was tested and refined through a side-by-side comparison of seven MPWTS at a site which simulated likely conditions by having a source of non-potable water (to be treated), a lack of amenities (running water, electricity) and secure outdoor space (Personal communication: K. Bauer, Director of Global Programs, GE, 2010; Personal communication: D. C. Moe, 2010).

The seven systems selected for methodology testing and refinement were based on a survey of commercially available and commonly used MPWTS are shown in Table 1 (Personal communication: K. Bauer, 2010; Personal communication: D. C. Moe, 2010). A wide range of systems were selected in order to be a representative cross-section of the span of options currently available on the market. The scope of the systems varied from stand-alone filters

**Table 1** | MPWTS tested in the case study

System code	Treatment scheme	Scope	Flow rate (gpm) <sup>a</sup>	Cost (\$)
CMC	Coagulation, media, membrane, and chlorination	Source to pipe	17.6	7,265
SSF	Slow sand filtration (media)	Filter	1.2	12,179
CFMC1	Coagulation, flocculation, media, and chlorination	Source to pipe	19.0	23,500
HP-UFM1	Granular activated carbon, high pressure ultra-filtration membrane	Filter	4.5	2,858
CFMC2	Coagulation, flocculation, media, and chlorination	Source to tap	17.6	19,495
LP-UFM	Low pressure ultra-filtration membrane	Source to tap	3.6	5,921
HP-UFM2	High pressure ultra-filtration membrane	Source to pipe	6.5	NA

<sup>a</sup>Gallons per minute.

(filter) to complete source to tap filters, and systems ranged in price from US\$2,858 to US\$23,500.

Further, multi-criteria decision making methodology was used to aggregate the KPIs in a system selection tool. Researchers used this tool, explained further in the results to refine SLiCE and ensure the aggregated KPIs highlight differences in overall system performance.

## RESULTS AND DISCUSSION

To facilitate analysis of all aspects of MPWTS, a multi-faceted SLiCE tool was developed. The SLiCE system provides a format for evaluating the phases of a system's lifecycle most likely to impact the project outcome. The phases in scope include sourcing, installation, commissioning, operation, maintenance, winterization, and decommissioning.

The sourcing phase addresses system acquisition. Sourcing evaluation starts with initial inquiry to the MPWTS manufacturer and ends with system delivery. Table 2 shows the rubric with defined KPIs for the sourcing phase.

**Table 2** | Sourcing rubric

Performance indicator	Scale
Cost (US\$)	1. >25,000 2. 18,000–25,000 3. 11,000–18,000 4. 4,000–11,000 5. <4,000
Ease of shipping	1. Heavy enough to require forklift 2. Does not require forklift but takes many people 3. Can be moved by 3 or 4 people 4. Can be moved by 2 people 5. Can be moved by 1 person
Product availability	1. >10 weeks 2. 7–10 weeks 3. 4.5–7 weeks 4. 2–4.5 weeks 5. <2 weeks
Purchasing contact accessibility	1. Many attempts required (5+), contact not responsive 2. Infrequently responsive and very delayed in response 3. Moderately responsive and some delay in response 4. Often responsive and timely response 5. Responds to initial request in rapid response time
Required purchasing communication	1. Frequent communication required 2. >5 points of contact required 3. 3–5 points of contact required 4. <3 points of contact required 5. Purchase order is sent and order is completed after initial contact
Total procurement time	1. >12 weeks 2. 9–12 weeks 3. 6–9 weeks 4. 3–6 weeks 5. <3 weeks
Aesthetics	1. Very unattractive 2. Unattractive 3. Average 4. Attractive 5. Very attractive

**Cost** is based on the market price at the time the system was procured and only includes the scope of the system purchased from the manufacturer. Additional costs were required for some systems that were not full scope systems.

**Ease of shipping** is based on the weight of the system assuming that the weight will dictate the relative cost and

effort regardless of the destination. In some regions, other factors, such as size, may influence shipping cost.

**Product availability** is the provided availability of the system at time of purchase from the manufacturer. This is on the basis of our experience with each manufacturer during the onetime purchase.

**Purchasing contact accessibility** is how quickly the system contact responded to our purchasing enquiry.

**Required purchasing communication** measures the number of times the company had to be contacted before the transaction was completed.

**Total procurement time** is the elapsed time from completed order of a system until the system's arrival on site.

**Aesthetics** includes visual appeal of the system and supporting documentation.

**Overall** is an average score for the system during this phase.

The installation phase entails any construction, plumbing, electrical, or other activities required for system use on site. This starts with the unpacking of a system from its shipping container and ends with system being ready for commissioning. Table 3 shows the rubric with defined KPIs for the installation phase of the life cycle.

**Instructions** are the printed documents provided by the company either published or given specifically to us.

**Tools required** are the necessary tools to fulfill any task during this phase of evaluation; this indicator takes into account both quantity and difficulty of obtaining the tools in this experiment's environment.

**Additional materials** include all other parts or consumables used to fulfill any task during the specific phase of evaluation not already accounted for in 'tools required'.

**Required technical expertise** is the required amount of training, education, or experience required of a technician to fulfill tasks in this phase.

**Ease of procedure** rates the difficulty of tasks during the specified phase. Deviations and modifications from instructions are used to rate difficulty.

**Time required** is the elapsed time of a four-person team to complete the current phase. This includes wait time of procuring necessary tools and materials that were not on hand when the phase was begun. This time is contingent on the research team, the weather, and the availability of parts specific to our testing.

**Table 3** | Installation rubric

Performance indicator	Scale
Instructions	<ol style="list-style-type: none"> <li>1. Convoluted, incomplete and resulting in major errors; or non-existent</li> <li>2. Incomplete and convoluted</li> <li>3. Incomplete or convoluted</li> <li>4. Complete, but not concise</li> <li>5. Concise, clear, complete description</li> </ol>
Tools required	<ol style="list-style-type: none"> <li>1. Many hard to find tools required</li> <li>2. Few hard to find tools required</li> <li>3. Many common tools required</li> <li>4. Few tools missing or low quality tools provided</li> <li>5. All tools included</li> </ol>
Additional materials	<ol style="list-style-type: none"> <li>1. Many hard to find materials required resulting in incomplete installation</li> <li>2. Few hard to find materials required</li> <li>3. Many common materials required</li> <li>4. Few common materials missing</li> <li>5. All materials included</li> </ol>
Required technical expertise	<ol style="list-style-type: none"> <li>1. Licensed professional required</li> <li>2. Highly skilled or certified technician</li> <li>3. Some plumbing, electrical, or construction knowledge</li> <li>4. Basic tool knowledge</li> <li>5. No prior training required</li> </ol>
Ease of procedure	<ol style="list-style-type: none"> <li>1. Significant modifications required</li> <li>2. Some modifications required</li> <li>3. No modifications, some difficulty encountered</li> <li>4. Easy execution with deviations from instructions</li> <li>5. Easily executed per non-technical instructions</li> </ol>
Time required (with 4-person team)	<ol style="list-style-type: none"> <li>1. Multiple days</li> <li>2. Less than 2 days</li> <li>3. 8–12 hours</li> <li>4. 4–8 hours</li> <li>5. Less than 4 hours</li> </ol>
Site requirements	<ol style="list-style-type: none"> <li>1. Large area of specified grade with utilities required</li> <li>2. Large area of specified grade or utilities required</li> <li>3. Adapted to sites with simple modifications</li> <li>4. Can be adapted to most sites</li> <li>5. No site requirements</li> </ol>
Scope of system	<ol style="list-style-type: none"> <li>1. Stand alone filter</li> <li>2. Major components required</li> <li>3. Additional components required</li> <li>4. Additional components preferable</li> <li>5. Full source to cup system</li> </ol>

**Site requirements** are the necessary utilities or environment requirements to complete the phase.

**Scope of system** defines how many extra components may be required to achieve a full source to cup system, which includes water procurement, water treatment, and water output in a form that can be captured by a cup.

The commissioning phase entails the processes necessary to ensure that the system performs as desired by stakeholders. It begins with the completion of installation and ends when the system is ready for operation. Commissioning includes activities like flow rate adjustments, chemical proportioning, and first time start-up procedures. The KPIs for the commissioning rubric are: Instructions; Tools required; Additional materials; Required technical expertise; Ease of procedure; and Time required, which are all described in the installation phase.

The operation phase entails the daily procedures for the system to produce drinking water. It begins after commissioning is complete and ends when either the deployment is complete or the system can no longer meet requirements. Maintenance happens between operational periods except for routine maintenance, which is included in daily operational procedures and therefore is included in the rubric and KPIs for the operation phase shown in [Table 4](#).

**NTU** is nephelometric turbidity units; **dB** is decibels; **gpm** is gallons per minute; **BTU** is British thermal units.

**Start up and shut down** is multiple operators' experience of starting and shutting down the system over many months of operation.

**Reliability** is the average runtime of the system in between failures, measured in hours. This metric does not take into account the severity of failure reached or how quickly the system becomes operational again.

**Availability** is measured as the ratio of uptime to total time, with total time being the aggregate accumulation of man-hours put into a system plus the run time, maintenance, and operational procedures time.

**Operator time** is a percentage of the time of an eight-hour day an operator spends operating and/or monitoring a system.

**Consumable materials** are the materials consumed in order to operate a system over the entire life cycle.

**Guarantee of safe water** is metric that ranks possibilities of three attributes used to guarantee safe drinking water – Robustness: ability to intake a wide range of source water

Table 4 | Operation rubric

Performance indicator	Scale
Start up and shut down	<ol style="list-style-type: none"> <li>1. Occasional unsuccessful start up</li> <li>2. Complicated and difficult to learn</li> <li>3. Complicated or difficult to learn</li> <li>4. Easily executed with numerous steps</li> <li>5. Straightforward and easily learned</li> </ol>
Reliability (avg. runtime between failures)	<ol style="list-style-type: none"> <li>1. &lt;1 hour</li> <li>2. From 1 to 40 hours</li> <li>3. From 40 to 100 hours</li> <li>4. &gt;100 hours</li> <li>5. No failure as of yet</li> </ol>
Availability (ratio of uptime to total time)	<ol style="list-style-type: none"> <li>1. &lt;0.1</li> <li>2. 0.1–0.4</li> <li>3. 0.5–0.74</li> <li>4. 0.75–0.94</li> <li>5. &gt;0.95</li> </ol>
Operator time (percentage of operator time of 8 hour day)	<ol style="list-style-type: none"> <li>1. &gt;50%</li> <li>2. 30–50%</li> <li>3. 20–30%</li> <li>4. 10–20%</li> <li>5. &lt;10%</li> </ol>
Consumable materials to operate	<ol style="list-style-type: none"> <li>1. Hard to find materials required for daily operation</li> <li>2. Easy to find materials required for daily operation</li> <li>3. Easy to find materials or fuel required for daily operation</li> <li>4. All consumable materials included for at least 1 month including fuel</li> <li>5. No consumable materials needed</li> </ol>
Guarantee of safe water: Robust, Tunable, Detection (RTD) <sup>a</sup>	<ol style="list-style-type: none"> <li>1. RTD: H, L, M</li> <li>2. RTD: MHH, MHM, HLL</li> <li>3. RTD: MMM, MMH</li> <li>4. RTD: MLM, MML, MML, LMM</li> <li>5. RTD: LLM, LML, MLL</li> </ol>
Water quality	<ol style="list-style-type: none"> <li>1. No thermotolerant coliforms at &lt;5 NTU</li> <li>2. No thermotolerant coliforms detected in 100 mL sample when source water is 5–30 NTU</li> <li>3. No thermotolerant coliforms detected in 100 mL sample when source water is 30–100 NTU</li> <li>4. No thermotolerant coliforms detected in 100 mL sample when source water is 100–200 NTU</li> <li>5. No thermotolerant coliforms detected in 100 mL sample when source water is 200–300 NTU</li> </ol>

(continued)

Table 4 | continued

Performance indicator	Scale
Taste, odor, and appearance	<ol style="list-style-type: none"> <li>1. Low acceptability at &lt;20 NTU</li> <li>2. Medium acceptability at &lt;20 NTU</li> <li>3. High acceptability at &lt;20 NTU</li> <li>4. High acceptability &lt;100 NTU</li> <li>5. High acceptability 200–300 NTU</li> </ol>
Noise	<ol style="list-style-type: none"> <li>1. &lt; 90 dB causes hearing loss</li> <li>2. 80–90 dB disrupts a community</li> <li>3. 70–80 dB bothersome</li> <li>4. 30–70 dB audible, but not bothering anyone</li> <li>5. &lt;30 dB runs silently</li> </ol>
Flow rate	<ol style="list-style-type: none"> <li>1. &lt;1 gpm</li> <li>2. 1–5 gpm</li> <li>3. 5–10 gpm</li> <li>4. 10–20 gpm</li> <li>5. &gt;20 gpm</li> </ol>
Power efficiency	<ol style="list-style-type: none"> <li>1. &gt;50 BTU/gallon</li> <li>2. 35–50 BTU/gallon</li> <li>3. 20–35 BTU/gallon</li> <li>4. 10–20 BTU/gallon</li> <li>5. &lt;10 BTU/gallon</li> </ol>
Water efficiency (treated gallons/total gallons)	<ol style="list-style-type: none"> <li>1. &lt;0.5</li> <li>2. 0.5–0.8</li> <li>3. 0.8–0.9</li> <li>4. 0.90–0.99</li> <li>5. &gt;0.99</li> </ol>

<sup>a</sup>Each attribute is ranked High, Medium, or Low.

quality; Tunability: the ability of a system to tune to different source water qualities; and Detectability: the presence of a detection method or device to alert an operator when water quality drops below a standard. Each attribute is ranked High, Medium, or Low and then the combinations are scaled 1–5 as indicated in the table.

**Water quality** is the performance of each MPWTS in producing safe water to the WHO standard of not detecting thermotolerant bacteria in a 100 mL sample based on varying initial water quality.

**Taste, odor, and appearance** is the performance of each MPWTS in producing publicly acceptable water at varying levels of initial water quality.

**Noise** is the level of sound produced by the system within 5 feet of the pump during operation, in decibels.

**Flow rate** is the observed average flow rate for a system over the testing period, in gallons per minute.

**Power efficiency** is a ratio of the amount of power used to operate the system to how many gallons of clean water the system is producing, measured in BTU/treated gallons.

**Water efficiency** is a ratio of the amount of clean water produced to the total amount of water provided to the system.

The maintenance phase is the process of maintaining a system to operate at desired performance. Maintenance falls under two main categories: planned and unplanned. Both are considered in the maintenance rubric. Planned maintenance begins as instructed by system instructions and unplanned maintenance begins when a failure is identified. Maintenance ends when the system is returned to desired performance. The KPIs for the maintenance rubric are: Instructions; Tools required; Additional materials; Required technical expertise; Ease of procedure; Frequency of planned maintenance; and Ease of unplanned maintenance. Table 5 shows the maintenance rubric and KPIs not previously mentioned. Excluded KPIs are described in the Installation phase.

**Frequency of planned maintenance** is how often a system requires maintenance.

**Ease of unplanned maintenance** is the difficulty of trouble-shooting during reactive maintenance.

Winterization is the phase of preparing and storing a system for temperatures below freezing. It begins when the system is removed from operation and ends when it is returned to operation. The KPIs for the winterization rubric are: Instructions; Tools required; Additional

materials; Required technical expertise; Ease of procedure; Time required; and Environmental requirements for winter storage. Table 6 gives the winterization rubric; the other KPIs mentioned were described in the Installation section.

**Environmental requirements** are the necessities for storing the system over a long time during winterization.

The decommissioning phase refers to the point when an MPWTS has finished its operational time in a specific site. This can refer to either transporting the system to a new site or retiring the system. The KPIs for the decommissioning rubric are: Instructions; Tools required; Required technical expertise; Ease of procedure; and Time required. These KPIs were described in the installation phase.

The comparison of seven different systems to test and refine SLiCE, involved scoring all the systems on each KPI. Figure 1 shows a sampling of scores from the installation phase to demonstrate how system performance varied across the possible spectrum (1–5) within KPIs and between systems.

Once the systems have received scores for each KPI, the system selection can be populated. The system selection tool facilitates selection of a system meeting a specific implementer and site's requirements by allowing the implementer to rank the importance (on a 1–5 scale) of individual KPIs. Once rankings of importance have been provided, the tool multiplies each KPI score by the importance ranking and totals these weighted KPI scores for each life-cycle phase. The implementer then has the option to provide importance rankings for each life-cycle phase if desired. Finally, the system's total score for each life-cycle phase and overall score is divided by the highest

**Table 5** | Maintenance rubric

Performance indicator	Scale
Frequency of planned maintenance	1. More than once a week 2. 1–4 times a month 3. 3–6 month interval 4. 6 months–1 year 5. 1 year or longer
Ease of unplanned maintenance	1. Significant modifications required 2. Some modifications required 3. No modifications, some difficulty encountered 4. Easy execution with deviations from instructions 5. Easily executed per non-technical instructions

**Table 6** | Winterization rubric

Performance indicator	Scale
Environmental requirements for winter storage	1. Many hard to meet conditions required 2. Few hard to reach conditions required 3. Many requirements able to fulfill on site 4. Few easily fulfilled requirements on site 5. No site requirements

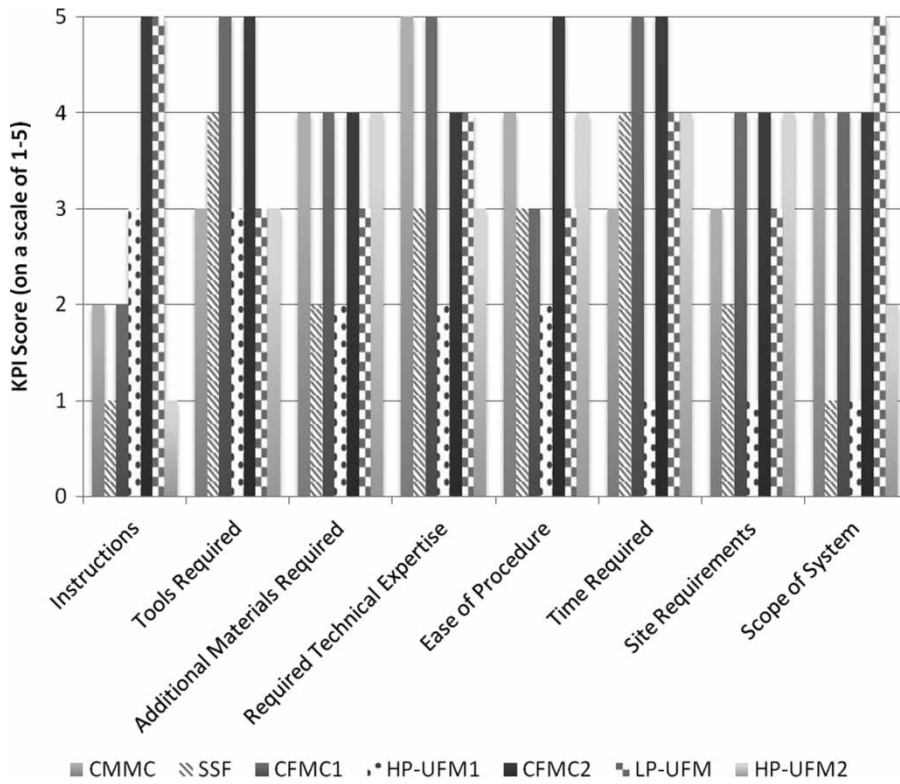


Figure 1 | System scores for all KPIs in the Installation phase of the side-by-side system comparison (see Table 1 for meaning of system codes).

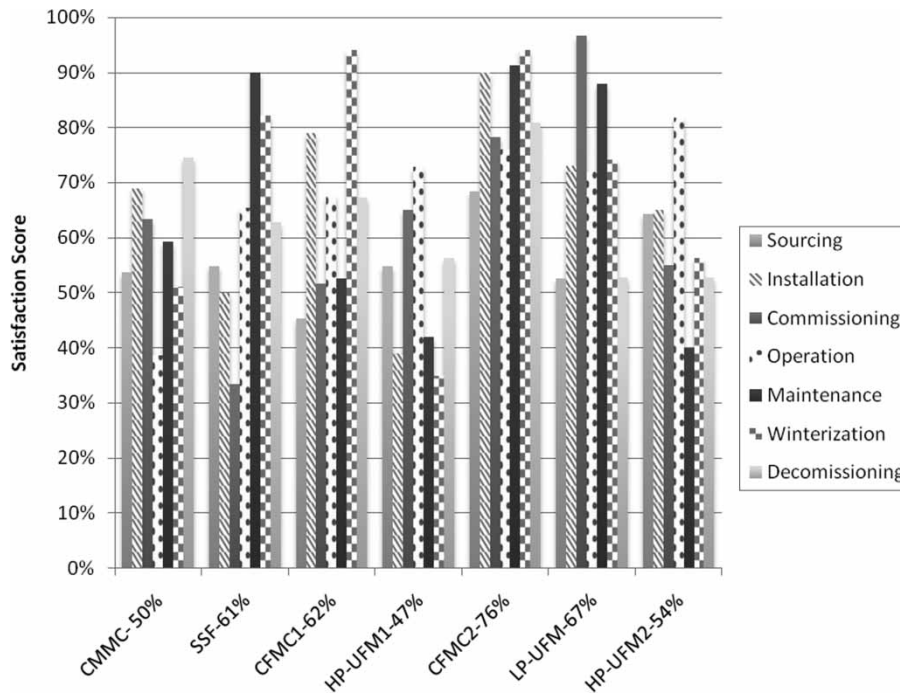


Figure 2 | Satisfaction scores of system and respective life-cycle phases where system selection tool was weighted for a sample implementation (see Table 1 for meaning of system codes).



possible score to be aggregated into a satisfaction score. Figure 2 shows an example of the overall satisfaction score of a system and of its life-cycle phases.

SLiCE is a methodology developed to objectively compare multiple systems by considering the entire life cycle of the system and analyzing and rating each of the major KPIs at every process in the system's life cycle. Researchers attempted to address every stakeholder CTQ for MPWTS but recognize that some may be overlooked. The amenability of SLiCE allows future evaluators to easily add CTQs and KPIs; however, it is not recommended that KPIs be removed from the list above, as then it will no longer capture the CTQs of MPWTS' full life cycle. To increase the knowledge dissemination and trust between sectors (i.e., academia, industry, relief agencies), all future evaluations of MPWTS should use SLiCE as a baseline evaluation. While certain KPIs may not be relevant in certain applications, this decision is one that should be made by the users of the information and not by evaluators.

SLiCE provides a way to compare MPWTS across a wide range of parameters and attempts to discern the system most likely to achieve the desired outcome under site-specific operating conditions. Humanitarian relief organizations want to know which system will perform the best for their specific site parameters and research has shown that choosing an appropriate MPWTS requires a decision based on initial conditions, parameters, and priorities (Personal communication: V. Cuellar, 2010; Personal communication: G. Hodgins, 2010; Personal communication: O. F. Suntura Yujra & A. Terrazas Vargas, 2010). To help a consumer choose the correct MPWTS for their situation, the system selection tool was created. This allows the user to individually weight KPIs based on their predicted importance. If a certain KPI is not important then the user can rank it as 1, whereas the most important KPIs would receive a 5. These weightings are then multiplied by each KPI, summed, and divided by the total possible score to provide a composite score for each system to inform decision-making. For instance, in an extreme emergency setting where the MPWTS needs to provide water to hundreds of people immediately for a short time, the relief agency would put the highest preference on flow rate, speed of arrival, and ease of the procedure for installation and commission. This same situation would

put low preference on KPIs like daily consumables or operator time. This system selection tool empowers stakeholders to discern the suitability of different MPWTS and weight the data to best meet their needs.

Not only will SLiCE provide humanitarian relief organizations with decision support on what MPWTS is most effective for the situation, but also provide baseline design targets for MPWTS manufacturers. Manufacturers, while biased, will be able to rate their systems and compare them with other reviewed systems on the market. SLiCE will continue to highlight settings and parameters for which an MPWTS is not proficient. Manufacturers will then be able to use their resources more efficiently by designing a system to meet a certain niche instead of replicating and marketing a design that already exists. With improvements in technology and manufacturers' design, a certain MPWTS may become effective for a wide variety of site parameters. Statistically this could be shown using Monte Carlo analysis on the weighting factors in the SLiCE tool.

The development and pilot utilization of SLiCE had some limitations. As this study was the first application of SLiCE and was developed at a simulated field site rather than in an actual emergency or remote setting in a developing region, not all potential failure modes were recognized. Research at an actual field site would help to further refine the rubrics.

The scales used in the evaluation rubrics are described at a level of detail intended to capture significant differences in performance. Because significant differences in performance are often determined by factors including whether materials needed are 'easy to find' or 'hard to find', scoring can sometimes depend on reviewers' expectations of what may be easy or hard to find; while reviewers should have the background to be able to make reasonable assumptions, this can introduce some subjectivity. Therefore, systems should be evaluated by experts who can use knowledge and experience to make consistent judgments across systems. This limits who can make use of the SLiCE method but reduces the possibility of variability in system scores and therefore enhances the credibility of the system selection tool.

Another source of subjectivity is that the life-cycle phases are not always discrete. For example, daily operation

often includes activities that might be counted as preventive maintenance: backwashing, cleaning, or simply observing the system during runtime. This overlap of life-cycle phases could lead to excluding or duplicating some CTQs and the activities included in each phase should be defined to guarantee valid results. To address the blurred line between 'operation' and 'maintenance', for example, a temporal frequency of maintenance (one week) was chosen as the dividing line between 'operation' activities (performed one per week or more) and 'maintenance' activities (performed less than once per week).

## CONCLUSION

This study documents the method of evaluating systems through SLiCE analysis and proposes a system selection tool. The method of selecting and refining CTQs that span the full life cycle of a system, scoring systems against these indicators, and translating these scores into a system selection tool is outlined and fully replicable. This method can be applied to systems in many fields outside of water treatment, and this report can serve as an instructional document.

The application of SLiCE to MPWTS technology has the potential to change the field of emergency water treatment as more systems are measured through this lens and the results are published. The identification of CTQs and the publication of KPIs in the evaluation rubrics will assist aid organizations and MPWTS manufacturers alike in identifying important factors that should be considered about each system. For aid organizations, this will facilitate consideration to all factors of system performance that may or may not meet their particular needs and restrictions. This consideration will increase the likelihood of appropriate system selection and thus successful and sustainable implementation. For manufacturers, the KPIs outlined in this SLiCE analysis will inform future designs by bringing to attention performance factors that may not have been previously considered but could be improved through modifications to future designs.

The SLiCE rubrics that have been developed for MPWTS can be further refined through a continuation of this study.

Addressing the limitations encountered in this study will yield more conclusive scores for the KPIs. The SLiCE tool provides a method to thoroughly evaluate and compare the performance of systems, and with continued application, SLiCE provides valuable insight in the field of emergency water treatment and other emerging technologies.

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