Although the acceptance of point-of-use (POU) and point-of-entry (POE) systems is still being debated, it is generally acknowledged that the systems have a role to play in drinking water treatment. Certified systems being marketed today incorporate proven technologies that have been engineered to achieve defined contaminant removal targets. Although this is of paramount importance, there is value in assessing the sustainability of such treatment alternatives. This article investigates issues related to the implementation, management, and environmental effects of POU/POE systems and presents a framework for sustainability assessment of those systems. A set of sustainability criteria—technical, economic, environmental, and sociocultural—is defined. Quantitative and qualitative indicators are proposed to promote the practical use of these criteria for comparing and selecting among POU/POE systems. Survey results of experts’ judgment on the effectiveness of the developed indicators are presented.

The framework on integrated water resources management (IWRM) represents a paradigm shift in how water systems are perceived and what should be expected from management practices. IWRM has been defined as “a process [that] promotes the coordinated development and management of water, land, and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (GWP, 2000). This vision of IWRM includes the promotion of water system sustainability. Therefore sustainability should be applied regardless of the scale of water treatment, including comparing alternatives to select the treatment that is more sustainable.

Nontraditional water supply systems have entered the water supply arena (Raucher et al, 2004; Cotruvo & Cotruvo, 2003). As with most nontraditional methods, these systems often evoke contradictory opinions and perceptions from stakeholders in water supply—ranging from total rejection to a recommendation for their implementation. Of these nontraditional alternatives, point-of-use (POU) and point-of-entry (POE) systems have been the focus of many studies and investigations, primarily regarding their capabilities to assist in complying with water regulations. However, the sustainability of such systems still needs investigation. Sustainability is often described as having three main components: environmental protection, social well-being, and economic well-being. The objective is to strike a balance when using resources so that the contribution to local and global problems is minimized or at least known and accounted for.

A framework for selecting POU/POE systems

MOHAMED A. HAMOUDA, WILLIAM B. ANDERSON, AND PETER M. HUCK
The growing interest in POU/POE units has led to increased numbers of commercial units being marketed as potential solutions to real or perceived water problems that are often aesthetic in nature. This leaves community water suppliers with the difficult task of choosing among these units. Many of these units go through rigorous testing procedures to ensure their proper functioning, and units that pass these tests become certified. A POU/POE system is typically a treatment train that can either be an integrated off-the-shelf product or an assembled line of individual products.

An increasingly relevant question is whether centralized (municipal) systems are the most sustainable form of water treatment or whether in certain situations it may be advantageous to implement or switch to decentralized and POU/POE systems. Before this question can be answered, investigations concerning the sustainability of different POU/POE systems need to be conducted.

This article does not investigate the feasibility and sustainability of POU/POE water treatment as an alternative to central water treatment for particular applications. Although this article has global implications, it has been prepared from the perspective of how to proceed after the decision is made to use a POU or POE system to assist North American water purveyors and consultants in selecting the most suitable system. The aspects of sustainability for which a particular POU/POE system should be assessed before being implemented are investigated. Only certified POU/POE units are considered. In addition, this investigation focuses on setting a framework for comparing and selecting among the different POU/POE alternatives on the basis of sustainability. The work presented here is the basis for a user-friendly decision support system that is under development.

POU/POE WATER TREATMENT

Recent POU/POE technologies offer a range of alternatives to replace or complement central water treatment in certain situations. POU/POE units are designed to reduce specific contaminants in drinking water, including heavy metals, pesticides, particulates, and pathogens (Chaidez & Gerba, 2004). POU/POE systems can be effective in removing or inactivating waterborne pathogenic bacteria, viruses, and protozoa if they are properly designed, engineered, operated, and maintained (Abbaszadegan et al, 1997). Most treatment technologies can be implemented on a POU/POE scale, including activated carbon, distillation, membrane filtration, and ultraviolet disinfection. Regulation 170/03 of the Ontario Safe Drinking Water Act defines a POE system as one that provides primary disinfection (but no chlorination), is installed at or near where water enters a building, and is connected to the plumbing (OMOE, 2002). NSF/ANSI standards add that flow of a POE system should be > 15 L/min (4 gal/min) at a 103-kPa (15 psi) pressure drop and 18±5°C (64.4±9°F) temperature (NSF/ANSI Standard 53, 2007). A POU system, on the other hand, is installed at or near where water is directly used and may or may not be connected to plumbing.

The most important factor in the rising use of POU/POE treatment is increased consumer awareness about water issues, including aesthetic considerations and perceptions about the safety of centrally treated water. Studies show that a considerable number of consumers in North America have concerns about water safety (Dupont, 2005; Jones, 2005; Turgeon et al, 2004; Odoi et al, 2003). Taste and odor issues are often the causes of consumer concern; a survey reported 66% of adults in the United States were worried about their water’s aesthetic quality and that 41% used POU/POE treatment units in their homes (WQA, 2001). Concerns are exacerbated when water originates from a private source; a survey of a Canadian community showed that 56% of respondents used in-home treatment to polish water from their wells (Jones et al, 2006).

There has also been an interest in POU/POE systems as a means of reducing risk and providing a sense of security. POU/POE systems have been advocated as being an appropriate final barrier in the multibarrier approach to drinking water treatment (McCencroe, 2007; Lykins et al, 1995). They may provide protection from microbial and chemical contaminants entering a distribution system as a result of cross connections, backflow, equipment failure (pumps, pipes), accidental damage (excavating, landscaping), unacceptable installations (those in or near septic tanks, tile fields, or subsoil treatment systems), chemical dosing problems (fluoride, disinfectants), disinfection by-products (trihalomethanes), corrosion or leaching from surfaces in contact with water (copper, aluminum, lead), reservoir management practices, reservoir contamination by wildlife, or even intentional introduction of contaminants (exploiting these vulnerabilities or devising new opportunities) (USEPA, 2006; Smith et al, 2001; Srinivasan et al, 1999; Williams et al, 1997).

POU/POE units have also been proposed as a direct water treatment alternative for small, rural, or remote communities, especially where groundwater is the source (Anderson & Sakaji, 2007; McCencroe, 2007; Cotruvo & Cotruvo, 2003; Kuennen et al, 1992). In this case, the systems are more complex than devices certified for use with treated water, and the level of control and monitoring required for these units is far more strict. POU/POE
devices represent an alternative for small water systems with limited financial resources and expertise to comply with increasingly strict regulations (Jones & Joy, 2006). Furthermore, small and rural water systems are distributed by nature when homes are too far apart to be connected with water networks, making a decentralized or distributed water treatment system more feasible.

Research and scientific advances in attribution of health implications of the existence of certain compounds in drinking water and improvements in detection capabilities have led to the lowering of the maximum acceptable concentration of known compounds (e.g., arsenic, lead) and the introduction of new contaminants to regulations (e.g., methyl tertiary-butyl ether). Municipalities may modify water treatment plants, build new ones to comply with new standards, or potentially adopt a decentralized water treatment strategy in which some contaminants can be removed at the small or POU level.

**POU/POE GOVERNANCE AND MANAGEMENT**

When it comes to using POU or POE water treatment to satisfy drinking water safety standards, six main entities are important to include when implementing such treatment systems.

**Government monitoring agency.** In Canada, the overseeing agency that ensures that the POU/POE implementation strategy functions properly is either the provincial Ministry of Health or the ministry responsible for the drinking water provision. In the United States, the overseeing agency is the US Environmental Protection Agency (USEPA); however, states may assume primacy by promulgating regulations that are at least as if not more restrictive than those of the USEPA.

![Figure 1](image-url)

**FIGURE 1** Timeline for the evolution of governance and management practice of POU/POE water treatment: regulatory (A), certification and industry (B), and research (C)
Water purveyor (municipality or private company). This entity is responsible for the operational plan for implementing POU/POE treatment systems on a local scale.

POU/POE systems supplier/manufacturer associations. In North America these are the Water Quality Association (WQA) and the Canadian Water Quality Association, which are not-for-profit trade associations representing the residential, commercial, industrial, and small community water treatment industries. These groups represent suppliers and provide guidance on product marketing and performance claims.

Independent certification organization. Standards are developed to test drinking water treatment systems, their components, and the materials used in them to ensure that they meet the minimum requirements for performance (mainly contaminant reduction claims) and structural integrity from plumbing, electrical, mechanical, and material toxicity perspectives. NSF is the organization accredited by ANSI to develop such standards in North America. In addition to NSF, other entities test and certify the units to NSF/ANSI standards.

Water associations. These organizations (which may include those also playing an advocacy role) promote research and consumer awareness regarding water treatment alternatives and the strategies and responsibilities they entail (e.g., AWWA, Canadian Water and Wastewater Association, Safe Drinking Water Foundation).

Consumer organizations. Representing consumer concerns and interests, these organizations are responsible for consumer awareness regarding new strategies and the responsibilities they entail. They can also be water supply cooperatives delivering drinking water to communities. Some of these entities play a limited role in the POU/POE industry, but it is believed that their involvement will increase.

Regulatory agencies have traditionally adopted a stronger position against POU treatment devices than POE systems. However, a closer look at the timeline in Figure 1, which depicts the changes in positions toward POU/POE systems, shows that there has been a gradual shift in the consideration of POU/POE systems in regulations (Figure 1, part A). Several water regulations have included acceptance of POU/POE treatment as an alternative to comply with maximum contaminant levels, including the following:

- US Safe Drinking Water Act, section 1412(b)(4)(E)(ii), instructs the USEPA to include POU/POE systems in the list of technology alternatives for achieving compliance with maximum contaminant levels in small water systems (i.e., those serving a population of fewer than 10,000 people). This section sets a limit on using POU units by prohibiting their use to achieve compliance with a maximum contaminant level or treatment technique requirement for a microbial contaminant (or an indicator of a microbial contaminant).

A survey reported that 66% of adults in the United States were worried about their water’s aesthetic quality.

### Table 1

<table>
<thead>
<tr>
<th>Standard</th>
<th>Title</th>
<th>POE</th>
<th>POU</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSF/ANSI 42</td>
<td>Drinking water treatment units—aesthetic effects</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>NSF/ANSI 44</td>
<td>Residential cation exchange water softeners</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>NSF/ANSI 53</td>
<td>Drinking water treatment units—health effects</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>NSF/ANSI 55</td>
<td>Ultraviolet microbiological water treatment systems</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Class A: systems (40,000 μW-s/cm² [40 mJ/cm²]) designed to disinfect and/or remove microorganisms from contaminated water, including bacteria and viruses, to a safe level</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Class B: systems (16,000 μW-s/cm² [16 mJ/cm²]) designed for supplemental bactericidal treatment of public drinking water or other drinking water that has been deemed acceptable by a local health agency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NSF/ANSI 58</td>
<td>Reverse osmosis drinking water treatment systems</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>NSF/ANSI 60</td>
<td>Drinking water treatment chemicals—health effects</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>NSF/ANSI 61</td>
<td>Drinking water system components—health effects</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>NSF/ANSI 62</td>
<td>Drinking water distillation systems</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>NSF/ANSI 177</td>
<td>Shower filtration systems—aesthetic effects</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>NSF/ANSI P231</td>
<td>Microbiological water purifiers</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

POE—point of entry, POU—point of use

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The Ontario Safe Drinking Water Act Regulation 170/03 (Drinking Water Systems) Schedule 3 identifies POE as compliance technology for small municipal residential systems (defined as systems serving fewer than 101 private residences).

The British Columbia Drinking Water Protection Act (DWPA), section 3.1, stipulates that a small water system in which each recipient of the water has POE or POU treatment that makes the water potable is exempt from section 6 of the DWPA (which requires a water supply system to provide potable water; BCMOH, 2003). It is notable that of the few reviewed regulations, the British Columbia DWPA is the only one that does not set limitations on the use of POU units for compliance.

In response to the increased adoption of POU/POE treatment units in 1968, NSF was assigned the task of developing certification standards under ANSI. However, there is more than one entity that can certify units to these standards, including the WQA, the Canadian Standards Association International, Underwriters Laboratories, the Quality Auditing Institute, and the International Association of Plumbing and Mechanical Officials. The evolution of NSF standards over the past few decades is shown in Figure 1 (part B) and Table 1. NSF certification requires a POU/POE water treatment unit to meet the following requirements:

- Contaminant reduction claims must be verified.
- Materials and components of the system must not add anything harmful to the water.
- The system must be structurally sound.
- The advertising, literature, and product labeling must not be misleading.
- The materials and manufacturing processes used cannot change without recertification.

Although research began a decade after NSF and WQA efforts were implemented to coordinate and manage the industry, it may have helped in the acceptance of POU/POE systems for compliance with regulations (Figure 1, part C). The time line of research activities on POU/POE shows that sustainability-focused investigations of these treatment methods are timely.

SUSTAINABILITY CONCERNS WITH POU/POE TREATMENT

Several sustainability concerns regarding the implementation of POU/POE systems are outlined in reports and research studies.

- Logistical challenges are typical of all decentralized systems—and POU/POE systems are decentralized systems that demand the distribution of responsibilities among stakeholders. Although regulations assign most of the responsibilities to water service providers, educating all interested stakeholders on their roles and responsibilities is a crucial factor in determining the success of POU/POE treatment systems (USEPA, 2002).
Stakeholder involvement is important in POU/POE systems decision-making processes. Substantial involvement is needed to deliver water systems that users “buy into.”

- Risk of failure either from improper operation of or unit malfunction in POU/POE systems can have serious health implications (Anderson & Sakaji, 2007). Moreover, units vary considerably in their efficiency and operation and maintenance requirements. Thus, such systems may require trained operators and maintenance personnel, who may or may not be available, despite the fact that the equipment is fairly simple to operate and maintain.

- The costs of implementing POU/POE treatment systems vary depending on the level of treatment and the quantity of water treated (USEPA, 2007; Craun & Goodrich, 1999).

- There is a lack of information about how to choose among a multiplicity of units, given the limited scope of POU/POE certification programs (Craun & Goodrich, 1999). The selection process requires information regarding a unit’s components that is often unavailable (e.g., life cycle, operation and maintenance requirements, and generated residuals). However, depending on the technology incorporated in a POU/POE unit, the expected performance and removal efficiency of the unit can be estimated.

- The market growth of POU/POE units is overwhelming. Worldwide, there are about 380 manufacturers of certified POU/POE units listed by NSF, producing approximately 5,700 drinking water treatment products. Only 2,356 of these products are treatment units; the remaining products are accessories and replacement elements such as faucets, filter cartridges, housing adapters, membranes, valves, pumps, and tanks. There are varying configurations of POU units available on NSF’s list of certified treatment units (NSF, 2008). Figure 2 shows that certified plumbed-in units represent ~75% of total certified products. In 1999, a survey of drinking water units in Canada showed that certified products account for only 34% of the POU/POE market (Lavoie, 2000).

- Waste management plans should be designed to dispose of spent cartridges, media, membranes, bulbs, and filters at the end of their useful life. In addition, waste brines from POU and POE reverse osmosis systems and POE ion exchange systems and backwash from POE activated alumina and granular activated carbon systems must also be disposed of (USEPA, 2002). Therefore, before a treatment technology is selected, the potential difficulties associated with the disposal of these wastes must be considered.

A FRAMEWORK FOR SUSTAINABILITY ASSESSMENT OF POU/POE SYSTEMS

The difficulties that water service providers may face during the selection of POU/POE systems, particularly with regard to sustainability considerations, should also be considered. The proposed framework is intended to be

![Figure 4: Scope for the system analysis for POU/POE sustainability assessment](image-url)
Choosing among a variety of treatment alternatives is generally based on the constraints posed by both the objectives and the characteristics of the treatment operation. For the choice to be sustainable, the selection or decision-making process itself must incorporate a sustainability aspect (Starkl & Brunner, 2004). Researchers and designers refer to the factors that help in selecting a treatment alternative as criteria, factors, or parameters. These criteria are usually hard to assess or measure, which leads researchers to use sets of proxy indicators, variables, constraints, or functions that best assess the criteria. The framework shown in this article provides a selection process for sustainable POU/POE treatment trains that comprises the five stages outlined in Figure 3 and explained in the following paragraphs.

**Stage 1.** System analysis and problem structuring involve identifying the stakeholders in POU/POE water treatment and their interests, the definition of issues, and the identification of objectives (Flores et al, 2007). The analysis is translated into preferences and constraints of various POU/POE alternatives and is coded into the process of selecting sustainable treatment systems. For example, a technical constraint can be triggered when the feedwater has a high chlorine content, which would rule out reverse osmosis membranes that have no prefilters. The advantage of using the system analysis approach is that it accounts for the multidimensional aspects of sustainability (Hamouda et al, 2009). Figure 4 outlines relevant information needed in selecting a POU/POE system. Under ideal circumstances, all relevant information should be considered in the developed selection framework; however, this may not be attainable because of a lack of data.

**Stage 2.** Sustainability criteria are defined as factors that may be used to assess which of a range of POU/POE treatment trains offers the greatest contribution to achieving sustainability objectives. To increase the comparability among different alternatives, indicators are used to convert data into knowledge that can evaluate performance against the sustainability criteria. The main difficulty in using this approach is that different stakeholders will devise different criteria. It is difficult to have stakeholders buy into using predefined criteria and indicators to select among the POU/POE topologies. A compromise is to let stakeholders decide on the criteria/indicators and their relative importance. Stakeholder involvement can be accomplished through structured interviews, questionnaires, or focus groups. This way, the developed list of criteria and indicators can be applicable to all situations in which POU/POE systems are being considered.

**Stage 3.** POU/POE certification lists are valuable in setting up a database of the available units and their...
treatment claims, which can help in selecting suitable treatment systems tailored to remove target contaminants. However, developing the POU/POE knowledge base for use in the selection process will require further investigation in order to include other nontechnical aspects of sustainability for each treatment unit. Furthermore, treatment trains rather than individual treatment units need to be considered in the overall framework of the selection process. In the course of selecting among treatment alternatives, the first step is to prepare predefined common treatment trains, such as the one shown in Figure 5. These trains take into consideration restrictions associated with sequencing treatment processes.

The knowledge base can include: (1) treatment unit type and description, (2) reduction claims and target contaminants, (3) incidental effects (e.g., other contaminants), and (4) operational and maintenance considerations. The selection process should consider the following steps:

1. **Preparation of Treatment Trains**: Develop common treatment trains based on the requirements and restrictions of the process. These trains should include the following components:
   - **Treatment Unit Type and Description**: Identify the type and description of each treatment unit.
   - **Reduction Claims and Target Contaminants**: Specify the reduction claims and target contaminants for each unit.
   - **Incidental Effects**: Consider other contaminants that may be generated or affected by the treatment process.
   - **Operational and Maintenance Considerations**: Include operational and maintenance considerations.

2. **Selection of Treatment Trains**: Evaluate the treatment trains based on the criteria defined in the knowledge base. The criteria can include:
   - **Technical**: Treatment modules' removal efficiency score, environmental impact, pollutants removal, performance efficiency, treatability, flexibility/adaptability, reliability, and robustness.
   - **Economic**: System cost, operating cost, cost functions, construction cost, land area, floor space, and economic indicators.
   - **Environmental**: Energy use, energy balance, and environmental indicators.
   - **Sociocultural**: Cultural acceptance, institutional requirements, availability, expertise, and sociocultural indicators.

3. **Final Selection**: Choose the most suitable treatment train based on the evaluation criteria and the specific requirements of the project.
nants removed, variation in pH), (4) maximum and minimum flow, (5) conditions that increase/decrease efficiency (e.g., presence of a specific contaminant that impedes the efficient performance of the device), (6) service life, and (7) a document that includes installation instructions, including required permits for construction, operation, and pilot-study and water quality monitoring and reporting procedures.

Stage 4. To encompass all aspects of a POU/POE treatment system and properly assess its sustainability, the decision-maker is left with a set of indicators that has disparate and incompatible units of measurements. To avoid comparing a large number of treatment alternatives, constraints can be used to screen out nonfeasible alternatives. A screening algorithm can be developed by superimposing known case-specific constraints. The constraints used can be user-defined (e.g., eliminating POU treatment as an alternative and focusing on POE in a particular situation) or a technology characteristic. These technical constraints include limits on the influent turbidity, influent hardness, and influent pH.

After screening out infeasible alternatives, the remaining alternative systems can be rated and ranked according to their fulfillment of sustainability objectives. The most common approach to rate and rank alternatives is to follow a multicriteria decision analysis (MCDA) (Lai et al, 2008). The simplest form of MCDA is to quantify the evaluation criteria and calculate the weighted sum score for each alternative. An MCDA can become more complex when there are conflicting objectives and limiting constraints. The objective is to rank a large number of systems according to sustainability ratings. A range of MCDA methods can be used in ranking alternatives. It can be done through a pairwise comparison of alternatives using an analytical hierarchy process or other methods such as ELECTRE (Elimination Et Choix Traduisant la Réalité [elimination and choice expressing reality]), simple multiattribute rating technique (SMART), or Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE); these methods have been reviewed elsewhere (Hamouda et al, 2009; Ashley et al, 2008; Lai et al, 2008). The selection framework output

<table>
<thead>
<tr>
<th>Sustainability Objective</th>
<th>Indicator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>Removal efficiency</td>
<td>Reduction efficiency (%) of treatment train for target contaminant (chemical and microbial) as certified to NSF/ANSI standards</td>
</tr>
<tr>
<td></td>
<td>IE</td>
<td>Additional removal of contaminants other than those targeted in the influent water, IE = (Ct – Cw)/Ct (range 0–1), in which Ct represents the number of contaminants removed by the train (as certified by NSF) (e.g., 5) and Cw represents the target number of contaminants in influent water (e.g., 3), so that IE = (5–3)/5 = 0.4</td>
</tr>
<tr>
<td>Reliability</td>
<td>Sensitivity to malfunctioning</td>
<td>Reliability = (Pf – 1)/Pf, in which Pf represents the number of individual processes in train removing target contaminant; e.g., for a train having GAC and RO used to remove arsenic Reliability = (2 – 1)/2 = 0.5</td>
</tr>
<tr>
<td>Robustness</td>
<td>A qualitative assessment of sensitivity of a treatment train concerning toxic contaminants, shock loads, and seasonal effects (rating of low, moderate, or high robustness)</td>
<td></td>
</tr>
<tr>
<td>Microbial regrowth risk</td>
<td>An indication of the potential for increased heterotrophic bacteria and the existence of a mitigation technique (rating of low, moderate, or high risk)</td>
<td></td>
</tr>
<tr>
<td>Service life</td>
<td>Estimated service life until retirement in litres</td>
<td></td>
</tr>
<tr>
<td>Implementability</td>
<td>Installation skill</td>
<td>A qualitative assessment of the level of skill required to install the train Low: installed by homeowner Moderate: unit distributor is required High: professional plumber and/or electrician required</td>
</tr>
<tr>
<td></td>
<td>Installation time</td>
<td>Average time to install the train (hours)</td>
</tr>
<tr>
<td></td>
<td>System complexity</td>
<td>A qualitative assessment of the complexity of a treatment train that considers the number of processes and accessories (rating of low, moderate, or high complexity)</td>
</tr>
<tr>
<td></td>
<td>System footprint</td>
<td>Indication of average volume (or area) occupied by the train</td>
</tr>
<tr>
<td>Operability</td>
<td>Operation skill</td>
<td>A qualitative assessment of the level of skill required to operate the treatment train Low: no formal training required Moderate: training is useful High: operator training required</td>
</tr>
<tr>
<td></td>
<td>Maintenance frequency</td>
<td>Indication of frequency of maintenance required, expressed by: number of maintenance hours/year + number of components to change/year</td>
</tr>
</tbody>
</table>

IE—incidental effect, GAC—granular activated carbon, RO—reverse osmosis
will rank the more sustainable systems recommended for implementation from the alternatives knowledge base.

Stage 5. A sensitivity analysis is needed to validate the implemented sustainability assessment framework. Sensitivity assesses the change in the outcome of the framework as affected by the tradeoffs made by choosing different technologies, different technology combinations, or different weights on the sustainability indicators. The results of the sensitivity analysis will help improve the framework through a feedback loop that highlights aspects needing change or improvement (e.g., improving data quality, changing an indicator or its evaluation method, changing the entire sustainability-rating procedure; Figure 3). The following section describes one of the cornerstones of the sustainability assessment framework, which is to determine the criteria to be used in the assessment.

**SUSTAINABILITY CRITERIA AND INDICATORS**

Sustainability in water and wastewater management has been studied by many researchers, either by comparing various technologies in terms of sustainability or by outlining approaches for selecting sustainable solutions (Sahely et al, 2005; Balkema et al, 2002; Hellstrom et al, 2000; Lundin et al, 1999; Mels et al, 1999; Otterpohl et al, 1997). Several studies have established indicator sets for sustainable water and wastewater treatment (Table 2). The classification of indicators shown in Table 2 differs from one study to another. Nevertheless, most sets include health-related, environmental, economic, sociocultural, and technical criteria.

The traditional framework for sustainability assessment translates the demands of the end user (consumer, government, or organization) into functional criteria that must be fulfilled by the technology. This framework does not claim that the selected alternative is the optimum or best alternative; rather, it claims that the selected alternative is the highest ranking when evaluated by a defined set of criteria (Ashley et al, 2008). The multiplicity of criteria and indicators being developed in the field of water and wastewater treatment shows the importance of focusing on a conceptual basis for sustainability assessment. In theory, criteria and their respective set of indicators should reflect the sustainability issues of the problem at hand. The aggregation function for the indicators categories forms clusters of indicators, which in turn are the components of a sustainability index that represents a rating of the system (Afgan, 2008).

A proper indicator has to use quantifiable, reliable data to assess any aspect of sustainability. The aggregation of indicators depends on the ultimate goal of the sustainability assessment. In the case of this research, the goal was to select among different alternatives; therefore,
comparability is a key feature of the designed sustainability assessment scheme. It is clear from Table 2 that most technical and economic indicators are similar, whereas the views about environmental and social indicators are different. Even for similar factors, the assessment method may differ. For example, when evaluating the environmental merit of an alternative, some researchers assess quantitative indicators such as energy use (Balkema et al., 2002; Mels et al., 1999), whereas others are more interested in a qualitative judgment of environmental friendliness.

**Sustainability criteria for selecting among POU/POE systems.** POU/POE treatment systems need their own sustainability criteria to assess alternatives. A tentative list of the sustainability criteria, underlying objectives, and proposed indicators to be used in assessing sustainability is shown in Figure 6. The criteria used to rate various systems include: (1) technical criteria, which define the technical performance, implementability, and operability of an alternative; (2) economic criteria, which can be a constraint when choosing a particular treatment train (including purchase and installation costs and operation and maintenance costs); (3) environmental criteria, which are often overlooked on such a small scale (nevertheless, the environmental effect can be evaluated by assessing resource use and possible residuals resulting from the treatment train); and (4) sociocultural and institutional criteria, which are rarely considered in sustainability assessment of water treatment processes; however, because they play an important role, indirect measures of consumer acceptability and availability of products can be used.

The developed indicators can be used to assess the sustainability of treatment trains. The treatment train is defined by the type and number of processes. However, before applying these indicators, their effectiveness and the extent to which they include the various sustainability issues must be examined. Because several of the indicators proposed in this framework were developed by the authors, it was necessary to validate indicator effectiveness. A questionnaire was designed to obtain feedback and develop consensus on the final list of indicators. Fifteen experts in water treatment—particularly POU/POE systems—were approached. Eleven responded, generating 52 comments. The experts were employees of consulting firms, NSF, WQA, and Underwriters Laboratories Inc.; professors specializing in water research; municipal water providers; employees or former employees of the Canadian Standards Association International; and those from Canadian federal or provincial departments or ministries involved with the provision of drinking water. The questionnaire was not designed to allow extensive statistical analysis of the results but to evoke a discussion of the proposed indicators.
Sustainability indicator discussions. Figure 7 provides a summary of the experts’ judgments on the effectiveness and appropriateness of the developed indicators. Most of the indicators were thought to be important by more than 50% of the respondents. Although this implies that the developed indicators were well received by the experts, the 50% acceptance rate alone should not be used to decide whether to use these indicators. The experts’ comments contributed to the decision to remove, modify, or adopt a particular indicator. Nevertheless, Figure 7 suggests that indicators such as incidental effect, microbial regrowth risk, installation time, system complexity, and bulk purchase discount should be revisited to assess their relevance and effectiveness because fewer than 50% of the experts thought of them as effective indicators. However, the relatively high or low level of support for some of these indicators may be related to the makeup of the expert panel. Each decision-making entity (utility or regulatory agency) that uses the selection framework should consider assigning relative weights based on their local situations or values.

Technical indicators. There was little disagreement among the respondents on the importance of technical indicators, and removal efficiency remained the top technical concern (Table 3, Figure 7). The incidental effect indicator was considered by some respondents to be of low importance because a system is usually selected to remove a target contaminant. However, the authors argue that all indicators being equal among competing products, the ability of a treatment system to remove additional contaminants is important. This applies in situations in which some contaminants can potentially remain undetected or in which there is a desire to protect against the risk of intentional introduction.

Comments by the respondents on other technical indicators included concerns regarding codependence. The installation time indicator was thought to be a dependent of installation skill; therefore, it was decided to remove it from the final list of indicators. System complexity seems to overlap with three indicators (operator skill, installation skill, and system footprint); therefore, it was removed from the list to avoid the risk of overemphasizing some

<table>
<thead>
<tr>
<th>Sustainability Objective</th>
<th>Indicator</th>
<th>Description</th>
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<tbody>
<tr>
<td>Life cycle cost</td>
<td>Capital cost</td>
<td>A qualitative assessment of the cost of purchase and installation (rating of low, moderate, or high)</td>
</tr>
<tr>
<td></td>
<td>Operations and maintenance cost</td>
<td>A qualitative assessment of the operations and maintenance cost (rating of low, moderate, or high)</td>
</tr>
<tr>
<td></td>
<td>Disposal cost</td>
<td>A qualitative assessment of the residuals disposal and decommissioning costs (rating of low, moderate, or high)</td>
</tr>
<tr>
<td></td>
<td>Bulk purchase discount</td>
<td>A qualitative assessment of the potential discount on train bulk purchase (rating of low, moderate, or high)</td>
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<table>
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<tr>
<th>Sustainability Objective</th>
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<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Resource consumption</td>
<td>Energy use</td>
<td>Energy used by train per unit of treated water. A qualitative assessment of chemicals used by train per unit of treated water. Low: chemicals used are of small quantity and mild or no impact Moderate: chemicals used are of larger quantity or of higher impact High: chemicals used are of larger quantity or of higher impact</td>
</tr>
<tr>
<td></td>
<td>Chemical use</td>
<td>A qualitative assessment of the treatment train production of solid waste per unit of treated water. Low: residuals can be disposed of in a standard solid waste management system or the manufacturer provides a residuals collection system Moderate: residuals can be disposed of for a small cost High: residuals are hazardous and need special and costly treatment</td>
</tr>
<tr>
<td>Environmental footprint</td>
<td>Solid residuals</td>
<td>A qualitative assessment of the treatment train production of liquid waste per unit of treated water; rating is similar to that of solid residuals</td>
</tr>
</tbody>
</table>

TABLE 4 Description of economic sustainability indicators and methods of evaluation

TABLE 5 Description of environmental sustainability indicators and methods of evaluation
factors over others. Other comments stemmed from a failure to acknowledge that indicators are developed considering all possible cases. The importance of a particular indicator in a given case is reflected in the weight that can be assigned to it. For example, there was an argument against the indicator of microbial regrowth risk based on the knowledge that such regrowth would be more risky to the immunocompromised than to otherwise healthy consumers. It was explained that whether an indicator is judged to be of importance (i.e., higher weight) will be dependent on the case (i.e., if the case includes a system intended to serve immunocompromised individuals, the indicator should be assigned a high weight, whereas if it is to serve healthy individuals it should have a low weight—perhaps even a weight of zero).

**Economic indicators.** Similar to technical indicators, there was consensus on the importance of economic indicators (Table 4). One comment suggested adding a dollar value to the indicators’ assessment, which was done at each level of assessment (i.e., a low capital cost ranges from $0 to $50). Disposal cost was thought to be more appropriately included in the operations and maintenance cost category. Additionally, it was recommended that the bulk purchase discount indicator be linked to the number of systems to be installed.

**Environmental indicators.** The environmental indicators were well received by the respondents because they also addressed safety issues, especially chemical use (Table 5). However, a perceived overlap between the energy use indicator and the cost indicators was raised. Energy use is included as an indicator of environmental effect, not cost. For instance, if lowering the environmental effect instead of the cost is the primary concern in a particular case, then although the economic indicators will be assigned low weights, the energy use indicator will be assigned a high weight. In this case, the two indicators may be independent.

**Sociocultural indicators.** The experts thought these indicators were of high importance, especially when dealing with a consumer who is not a water professional (Table 6). Nevertheless, concerns were raised about the ability to assess the indicators, especially those that require marketing data. Although a rigorous quantitative assessment of market factors can be very difficult and perhaps unjustified, the suggested assessment relies on a qualitative assessment to compensate for lack of data.

**CONCLUSIONS**

To enable decision-makers to choose sustainable POU/POE water treatment systems, insights into the multidisciplinary nature of sustainability are needed. This necessitates the comparison among alternative treatment trains and units on technical, economic, environmental, and sociocultural grounds. Existing standards, reports, and guidelines provide knowledge to assist with selecting and implementing POU/POE systems. Nevertheless, they require expert interpretation, whereas marketing techniques are designed to appeal to consumers regardless of their knowledge, and in some cases the actual need for a supplementary device. It is important to rely on objective and professional resources when making an educated decision regarding which treatment system to use. This

<table>
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</tr>
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<tbody>
<tr>
<td>Consumer acceptance</td>
<td>Aesthetics*</td>
<td>An indication of the aesthetic issues associated with water produced by the system, including issues such as warm or low-pressure water (rating of low, moderate, or high aesthetic quality)</td>
</tr>
<tr>
<td></td>
<td>Configuration</td>
<td>A rating of satisfaction with the system configuration, e.g., under the sink, countertop, pitcher (rating of low, moderate, or high satisfaction)</td>
</tr>
<tr>
<td></td>
<td>Cosmetics</td>
<td>An indication of the attractiveness and communication of the system with the user—decorative shape and color, transparent versus solid casing, display of system performance; (rating of low, moderate, or high attractiveness)</td>
</tr>
<tr>
<td>Product availability</td>
<td>Market availability</td>
<td>A qualitative assessment of the market availability of a unit indicated by the coverage of the chain of stores in which it is sold (e.g., national chains, corner stores, or units sold online)</td>
</tr>
<tr>
<td></td>
<td>Market penetration</td>
<td>A quantitative assessment of the treatment train availability in the market expressed by the number of units certified to NSF/ANSI standards that fit the treatment train (e.g., number of certified units that fit the train prefilter–GAC–RO–UV)</td>
</tr>
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</table>

GAC—granular activated carbon, RO—reverse osmosis, UV—ultraviolet

*Assuming that the device functions properly (i.e., it passes performance indicators), taste, odor, and suspended particles should no longer be an aesthetic measure of the system but are included in the system performance screening (i.e., if the source water has a taste and odor problem, only treatment systems that can remove taste and odor will be considered).
is a clear goal, especially in a marketing-intensive industry such as that of POU/POE devices, where advertising seems to dominate the decision-making process.

The framework proposed in this article provides a reliable approach for identifying sustainable treatment trains when provided with the various requirements and constraints for a specific case. The proposed framework will assist drinking water policy-makers, water purveyors, and consultants in selecting sustainable POU and POE treatment systems.

The process of developing the indicators helped to determine the important tenets of sustainability. The developed indicators strive to capture as many aspects of sustainability of POU/POE treatment as possible. The appropriateness of the indicators was investigated by soliciting expert opinions and incorporating their comments into a refined list (Tables 3–6, with the system complexity and installation time indicators removed for reasons of redundancy).

The framework is being further developed into an interactive, user-friendly, updatable decision support system to select sustainable certified POU/POE systems. Unlike the more complex sustainability assessment presented in this article, it is anticipated that the decision support system will be sufficiently simple that it can be used by all stakeholders, including individual consumers. The real test of the effectiveness of the developed indicators and the selection framework in capturing aspects of sustainability is to apply them to a real-world case study and to analyze the performance of the selected POU/POE treatment systems. Future research should show large gaps between the theoretical and practical aspirations of decision-making for the selection of sustainable POU/POE treatment systems.

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