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Sustainability of wastewater treatment technologies

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Abstract

A set of indicators that incorporate environmental, societal, and economic sustainability were developed and used to investigate the sustainability of different wastewater treatment technologies, for plant capacities of <5 million gallons per day (MGD) or 18.9×10^3 cubic meters (m^3/day). The technologies evaluated were mechanical (i.e., activated sludge with secondary treatment), lagoon (facultative, anaerobic, and aerobic), and land treatment systems (e.g., slow rate irrigation, rapid infiltration, and overland flow). The economic indicators selected were capital, operation and management, and user costs because they determine the economic affordability of a particular technology to a community. Environmental indicators include energy use, because it indirectly measures resource utilization, and performance of the technology in removing conventional wastewater constituents such as biochemical oxygen demand, ammonia nitrogen, phosphorus, and pathogens. These indicators also determine the reuse potential of the treated wastewater. Societal indicators capture cultural acceptance of the technology through public participation and also measure whether there is improvement in the community from the specific technology through increased job opportunities, better education, or an improved local environment. While selection of a set of indicators is dependent on the geographic and demographic context of a particular community, the overall results of this study show that there are varying degrees of sustainability with each treatment technology.

Keywords: Wastewater treatment; Activated sludge; Lagoon; Land treatment; Sustainable development; Indicators; Design

1. Introduction

Improvement in global health and sanitation and consequent reduction in the spread of disease depends largely on good hygiene practices, availability of health facilities, and reliable collection and treatment of wastewater. The World Health Organization (WHO) estimates that 2.4 billion people lack access to any type of sanitation equipment (WHO and UN Children's Fund, 2000).

Wastewater collection systems (i.e., sewer networks) and centralized and decentralized treatment systems are designed and managed primarily to protect human and environmental health. Though their benefits are widely recognized, there are other aspects of this infrastructure and associated technologies that are not so obvious and hence less acknowledged, yet they impact communities and the surrounding environment. For example a positive aspect of the sewer network is the collection and transport of wastewater to appropriate treatment facilities, whereby pathogens and chemical constituents such as oxygen-depleting organic matter and phosphorus are removed before the treated water is returned to the environment. A negative aspect of such a network is that it can create an imbalance in water and nutrient fluxes and therefore distort natural hydrological and ecological regimes. For instance the discharge of large volumes of treated wastewater that contains low concentrations of chemical constituents may still lead to an excessive input of nutrients in a receiving water body, thus, leading to a water quality problem.

Transport of water and wastewater across watershed boundaries not only increases the embodied energy of a material and requires extensive infrastructure needs, but it may also result in adverse changes in an ecosystem's hydrology. In addition, treatment facilities, while they treat wastewater to a quality deemed safe for discharge, also consume considerable energy during their operational life, and consequently contribute to atmospheric carbon

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dioxide emissions. These impacts, whether positive or negative, greatly affect local and global sustainability, be it in the construction, operation, or dismantling life stage and hence deserve discussion. In an era where there is growing concern of the local and global impact of our current environmental management strategies, and the need to reduce sanitation problems, disease, and poverty, there is a greater need to develop more environmentally responsible, appropriate wastewater treatment technologies whose performance is balanced by environmental, economic, and societal sustainability.

While there is no consensus on the definition of sustainability, what is clear is that it strives for the maintenance of economic well being, protection of the environment and prudent use of natural resources, and equitable social progress which recognizes the just needs of all individuals, communities, and the environment. Furthermore, it recognizes the need to design human and industrial systems that ensure humankind's use of natural resources and cycles do not lead to diminished quality of life due to either losses in future economic opportunities or adverse impacts on social conditions, human health and the environment (Mihelcic et al., 2003).

Although collection systems are important to overall wastewater management, this study is limited to wastewater treatment. Thus in light of the main aspects of sustainability, questions that deserve further analysis are how selection of a particular wastewater treatment technology affects overall sustainability and are there certain aspects of a particular treatment technology that makes it more balanced in terms of economic, environmental, and social sustainability?

Sustainability of wastewater treatment systems can be assessed through different assessment tools such exergy analysis, economic analysis, and life cycle assessment (LCA). For this study, the use of a balanced set of indicators that provides a holistic assessment was chosen for evaluating the sustainability of the different wastewater treatment technologies. These wastewater treatment technologies include mechanical systems, lagoons systems, and land treatment systems. Mechanical systems such as activated sludge utilize physical, chemical and biological mechanisms to remove nutrients, pathogens, metals and other toxic compounds. Lagoon systems primarily use physical and biological processes to treat wastewater, while land treatment systems utilize soil and plants, without significant need for reactors and operational labor, energy, and chemicals (Metcalf and Eddy, 2003).

Selection of a particular set of indicators may vary from community to community depending on geography, culture, and population served. Several lists of sustainability indicators have been proposed to assess wastewater management and wastewater treatment technologies (Nilsson and Bergstrom, 1995; Balkema, 1998; Lundin et al., 1999; Balkema et al., 2002). These studies use a comprehensive, multi-disciplinary set of indicators; however, they have focused on evaluating one treatment technology and have not compared different treatment technologies as proposed in this study. Furthermore, these studies were one dimensional in terms of evaluating sustainability because they only evaluated environmental stressors. Other studies measuring environmental and/or economic issues associated with wastewater treatment (Emmerson et al., 1995; Nilsson and Bergstrom, 1995; Hwang and Hanaki, 2000; Tsagarakis et al., 2002; Dixon et al., 2003) do not address societal issues; thus, they do not fully capture the overall sustainability that should be inclusive of a balance of economic, environmental and social considerations.

Selection of a particular wastewater treatment technology should not be based primarily on technical insight, but should also integrate the human and environmental activities that surround it. Accordingly, this paper initiates a discussion on this topic by first developing a set of indicators and then evaluating the environmental, economic, and societal impacts of three different wastewater treatment technologies that treat less than 5 million gallons per day (MGD) ($18.9 \times 10^3\,m^3$).

We acknowledge that the selection of indicators and evaluation of particular technologies in this paper is dependent on the geographic and demographic particulars of a community. Here, the results pertain to small communities ($<$ 5 MGD or $18.9 \times 10^3\,m^3$) who wish to integrate the selection of an economically and environmental viable wastewater treatment technology with social attributes such as workforce education level, employment, and open space; while also being concerned with localized warming from a built up infrastructure. The delicate balance associated with these attributes differs by community, region, and country. For example, higher labor costs may prohibit employment of additional workforce at a treatment plant and urban heat island stresses may not impact communities located in colder regions. Furthermore, this paper does not advocate analyzing a treatment technology only through use of sustainability indicators. Other tools such as LCA exist and can be utilized. This paper merely attempts to initiate a discussion on how to address a more integrated evaluation of the overall sustainability of wastewater treatment technologies.

2. Methodology

There currently exists a plethora of different frameworks to select sustainability indicators. Commonly used frameworks include those developed by the Organization for Economic Co-Operation and Development (OECD, 1998) and the United Nations Commission on Sustainable Development (UNCSD, 1996). However, some problems associated with selection and application of indicators exist, for example, indicators produced by one group may not be applicable to another, thus they may not be widely implemented. Geographical diversity of urban, rural and peri-urban areas may mean that an indicator appropriate to one locality may be inappropriate to another (Mitchell, 1996). Other reasons include difficulty of data availability (Bell and Morse, 2004; Mitchell, 1996), the numerous methodologies available for deriving sets of sustainability indicators (Bell and Morse, 2004) and lack of consensus among peers regarding the definition of sustainability and indicators (Spangenberg, 2002).

In any case an indicator should refer to specific targets chosen, be able to indicate the success or lack of it in approaching them, and be sensitive and robust in their construction. Indicators should also be easy to fathom and be limited in number (UNDPCSD, 1995). Moreover, indicators should be linked to a target or goal that is ecologically sustainable (Meadows, 1998) and be able to 'stand the test of time.''

The first step in this process was deciding on a suitable treatment plant capacity, over which all three different types of technologies exist. In determining the most appropriate plant capacity to perform this study, 16,255 US wastewater treatment plants were reviewed (U.S. EPA, 2004a). Over 80% of existing plants have a capacity less than 5 MGD ($18.9 \times 10^3\,m^3$) and this was the size range selected for this study.

The set of indicators selected were based on: (1) the relevancy of the indicators to different wastewater treatment technologies, and (2) their ability to indicate progress towards balanced sustainability or away from it, that is equal inclusion of economic, environmental and social aspects. The United Nations Department of Policy Coordination and Sustainable Development's criteria (UNDPCSD, 1995) were used to select the most appropriate indicators. Indicators in general should be (i) based on a sound scientific basis and widely acknowledged by scientific community; (ii) transparent, e.g., their selection calculation and meaning must be obvious even to non-experts; (iii) relevant, e.g., they must cover crucial aspects of sustainable development; (iv) quantifiable, e.g., they should be based on existing data and/or data that is easy to gather and to update; and, (v) limited in number according to their purposes they are being used for (UNDPCSD, 1995).

From the above criteria a set indicators useful for evaluating wastewater treatment technologies were selected. They are presented in Table 1 along with their unit of measure. These indicators measure the economic, environmental and social sustainability of the treatment system; however, readers should understand that the selection and interpretation of these indicators is context specific and based on opinions of the authors. Data related to each indicator were then obtained from sources that included government, professional societies, and academic textbooks.

A final consideration is the life stage over which the indicators are applied. The operational life stage of wastewater treatment was chosen for this study, primarily because of its length of time relative to the other life stages and its environmental impacts are believed to be greater than those during construction and end-of-life stages (Emmerson et al., 1995). For example, the operational stage has the highest energy consumption (95%) compared to construction and refurbishment/demolition stages (Emmerson et al., 1995). This is significant because energy production and its use are associated with a large number of environmental problems including release of airborne pollutants associated with global warming and acidification. Moreover, environmental impacts from the construction stage account for only 5% of the total environmental impact (Emmerson et al., 1995).

Table 1
Set of indicators developed in this study for assessing sustainability of wastewater treatment technologies

Indicator	Unit of measure
Economic	
Capital costs	$/GPD
Operation and management	$/MGD
User cost	$/month
Environmental	
Energy use	kWh/MGD (kWh/m^3)
Biochemical oxygen demand (BOD)	% Removal
Total suspended solids (TSS)	% Removal
Nitrogen (NH_3)	% Removal
Phosphorus	% Removal
Pathogens	% Removal
Societal	
Public participation (in selecting treatment technology)	Qualitative measure
Community size served	Population/MGD
Aesthetics	Measured level of nuisance from odor
Staffing required to operate plant	Staff/MGD
Level of education	Operational requirements (operator license)
Open space availability	Acre/MGD

Selection and interpretation of indicators will be based on the geographic and demographic context of a particular setting.

3. Results and discussion

3.1. Economic sustainability

3.1.1. Capital costs

Fig. 1a shows comparable capital costs for the different wastewater treatment technologies. These costs are based on a gallon per day (GPD) or cubic meters per day (m^3/day) of wastewater treated. Due to unavailability of data for higher capacities (i.e., 1–5 MGD) ($3.8 \times 10^3 - 18.9 \times 10^3\,m^3$), data were only available for plant capacities ranging from 0.1–1 MGD ($3.8 \times 10^2 - 3.8 \times 10^3\,m^3$). Fig. 1a shows there is significant difference ($10.50/GPD versus $4/GPD) ($2770/m^3 per day versus $1060/$m^3$ per day) in capital construction costs between a more costly mechanical and less costly lagoon system at the higher expected range. At the lower range of cost, there is a much smaller difference ($3/GPD versus $1/GPD) ($790/m^3 per day versus $260/$m^3$ per day) between both technologies (UNEP, 1997); however, mechanical systems are still more expensive.

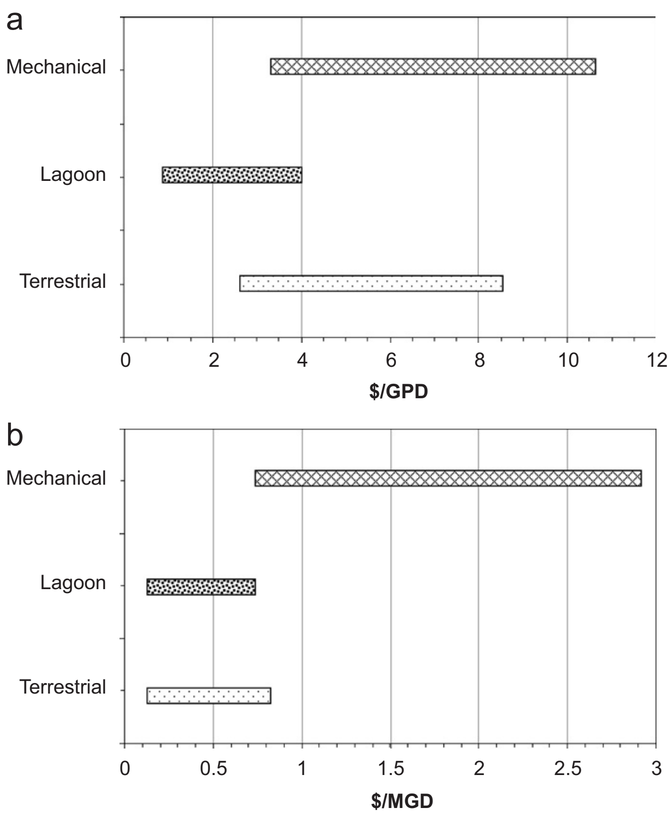

Fig. 1. (a) Comparative capital cost for the different wastewater treatment technologies. Plant size is 0.1–1.0 MGD ($3.8\times10^2-3.8\times10^3\,m^3$/day) (UNEP, 1997). (b) Comparative operations and management cost for the different wastewater treatment technologies. Plant size is 0.1–1.0 MGD ($3.8\times10^2-3.8\times10^3\,m^3$/day) (UNEP, 1997).

3.1.2. Operation and management

Operating and maintenance costs associated with wastewater treatment include labor, energy, and purchase of chemicals and replacement equipment. Fig. 1b shows this cost for mechanical treatment is approximately 4–5.5 times higher than a lagoon system and 4–6.5 times greater than a land treatment system. This can be attributed to more highly mechanized equipment and complex processes that require considerable energy inputs.

3.1.3. User costs

Wastewater treatment costs are usually dependent upon the type of treatment technology, its efficiency, and the discharge option used. Another factor is the population size served. About 70% of the US population is serviced by secondary or greater treatment level (U.S. EPA, 2004a). A majority of this population reside in urban areas.

The cost of wastewater treatment for a resident of a smaller population serviced by a treatment plant capacity of <9.8 MGD ($<37\times10^3\,m^3$), is much higher ($0.10–$1.24) then a resident of a larger population serviced by a larger plant capacity (>187 MGD) ($>708\times10^3\,m^3$) using similar treatment systems (Raftelis Financial Consulting, 2004), even when normalized on a per capita basis. These costs can translate to affordability problems of residents in smaller communities, especially low-income residents (income of $15,000 per annum), which may be evident through late or nonpayment of bills, disconnect notices, and service terminations.

Affordability problems are more pronounced in developing countries with expanding economics, where the average annual household income is well below US$300, and the cost for conventional treatment (mechanical systems) may range from US$300–1000. Cost-effective treatment technologies such as lagoon and land treatment systems have the potential to reduce these costs by at least one-half (reduced costs to the order of US$100 per household) (Helmer and Hespanbol, 1997). These alternatives are beneficial in terms of money saved that could be spent elsewhere, for example on health care, education, or other environmental initiatives. As for developing countries, this monetary savings could be spent on improvements in the water supply with further benefits of reduced illnesses and hence cost savings in health care and enhanced economic activity (WHO, 2005).

3.2. Environmental sustainability

3.2.1. Energy use

A majority of operation and maintenance costs may be attributed to energy consumption during aeration and pumping of water and solids. Fig. 2 shows the energy requirements of a combination of various wastewater treatment technologies, excluding the use of methane gas from digesters as an energy source. The data clearly show that activated sludge requires more energy than either lagoon or land treatment systems. Aeration of lagoon systems may increase energy use considerably, by 3 times for a 0.1 MGD ($3.8\times10^2\,m^3$) plant capacity, and 5 times for a 5 MGD ($18.9\times10^3\,m^3$) plant capacity (Middlebrooks and Middlebrooks, 1979).

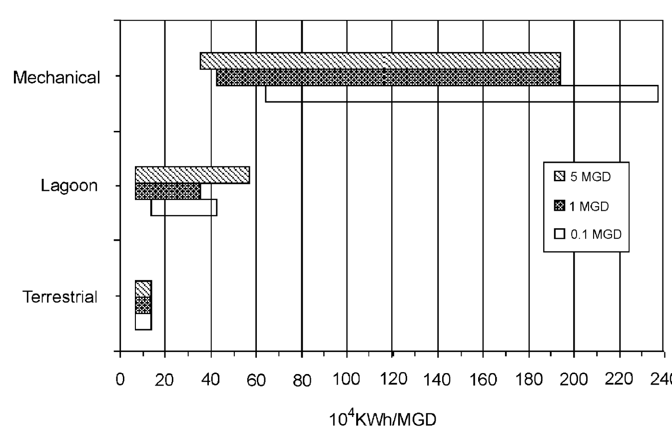

Fig. 2. Total energy requirements for various sizes and types of wastewater treatment plants located in the intermountain areas of the US. Total electricity requirements measured in kWh/MGD at various flow rates (Middlebrooks and Middlebrooks, 1979).

Some activated sludge systems may have lower energy consumption because of internal energy combustion of methane gas produced in-house, particularly from anaerobic digestion. In future studies, energy production related to waste management could be included as an attribute of a sustainable technology.

Energy use is often associated with global environmental problems such as carbon dioxide emissions. For example, an activated sludge system serving a population of 1000 people (<1 MGD or $<3.8 \times 10^3\,m^3$) has the potential to produce up to 1400 ton of carbon dioxide for operation and 50 ton of carbon dioxide for maintenance over a 15-year life (Emmerson et al., 1995).

Various opportunities exist in reducing energy use and associated impacts. These include the type of wastewater treatment technology selected; use of recycled materials for construction; correct sizing and rating of equipment for operation, especially for pumping requirements; and reuse of waste aggregate from demolition. Plant design can also more carefully incorporate issues of energy conservation and as mentioned previously, use of in-house methane production may reduce external energy needs.

There are also energy issues associated with materials that go into a treatment technology. For example, concrete is the primary component in many mechanical treatment systems and has embodied energy estimated between 70 and 6000 MJ/Mg (Horvath and Hendrickson, 1998). Building-related demolition debris is estimated at around 65 million tons annually in the United States (Franklin Associates, 1998). Two thirds of it by weight and about one half by volume is cement-based concrete (Wilson, 1993). Although mechanical treatment systems use more concrete than lagoon and land treatment systems they can reduce their overall environmental impact if designers consider recovery and reuse of any waste aggregate during the end-of-life stage.

3.2.2. *Removal of water quality constituents*

The conventional water quality constituents associated with wastewater treatment are: BOD, TSS, phosphorus, nitrogen and fecal coliforms. There are some major differences in removal efficiencies of each treatment technology. Mechanical treatment has high removal efficiency of BOD (90–95%), TSS (90–95%), and fecal coliforms (92–99.99%) but has low removal efficiency of phosphorus (10–20%) and total nitrogen (15–25%). Lagoon treatment has comparable high removal efficiency of TSS (90–95%), and fecal coliforms (90–99.90%) but has medium to high removal efficiency of BOD (75–95%), and low to medium removal efficiency of phosphorus (10–50%) and total nitrogen (10–60%). A land treatment system has a guaranteed high removal efficiency of fecal coliforms (90–99.90%) but has varying efficiencies for the other constituents. It has medium to high removal efficiency for BOD (67–100%), TSS (58–99%), and low to high removal efficiency of phosphorus (40–99%) and total nitrogen (38–95%) (U.S. EPA, 1975; Gilbert, 1976; Leach et al., 1980; U.S. EPA, 1981, 1982; Pettygrove and Asano, 1984; Hannah et al., 1986; Reed, 1991; Reed et al., 1995; UNEP, 1997; Crites et al., 2000; U.S. EPA, 2002; Metcalf and Eddy, 2003). These effluent qualities ultimately determine if further treatment is required, what type of discharge options can be used and most importantly their potential for reuse.

Removal efficiencies for a lagoon are dependent on whether the lagoon is operating aerobically or facultatively. Aerobic lagoons have detention times of 3–10 days and facultative lagoons, 5–30 days (Reed et al., 1995). While both have high removal efficiencies, the longer detention time of facultative lagoons often leads to higher removal efficiencies of such constituents as nitrogen and pathogens (WEF, 1992). Furthermore, comparison of synthetic organic compound removal in facultative and aerobic lagoons show that a facultative lagoon is capable of removing between 77 and 96% (average of 86%), whereas as an aerobic lagoon can remove between 61 and 80% (average 68%) of the same organic compounds (WEF, 1992). Careful design of a facultative lagoon can reduce the detention time to 10–15 days, while still achieving high removal of pathogens (Oakley, 2005). Properly designed lagoon systems have the capability of removal efficiencies comparable to mechanical systems.

In terms of heavy metal removal, mechanical systems have a comparative removal performance (24–82%) to a lagoon system (32–79%) (Hannah et al., 1986). No data were obtained on metal removal for land treatment systems. In terms of volatile organic chemical removal, the land treatment system had a high removal efficiency of 82–99.99%, while the mechanical system had removal efficiency of 74–94%, and the lagoon system 60–80% (Crites et al., 2000).

Fate and removal of hazardous and toxic compounds is a generally accepted challenge in wastewater treatment and indicators that carry information on emissions or flows of these compounds are often recommended (e.g., Lundin et al., 1999; Malmqvist and Pamlquist, 2005; Palme et al., 2005). If wastewater treatment is to be sustainable in the long-term, better waste management strategies may have to be developed that integrate local economic activity, eliminate the use and improper disposal of household hazardous waste, and partner with health providers that prescribe pharmaceutical chemicals. The use of barriers at various points in wastewater treatment systems can have a tremendous impact in managing hazardous substances. For example, the decision to design a wastewater treatment system with either a combined or separated system (systems that combine gray black water versus systems that separate gray black water at the source, usually in the houses), has the potential to reduce cadmium inputs by 114 g per year (combined system) and 40 g per year (separated system) (Malmqvist and Pamlquist, 2005).

Furthermore, removal efficiencies of pathogens, heavy metals, and other toxic compounds have major implications on water reuse schemes. The specific type of wastewater reuse initiatives ultimately defines the quality of wastewater required and the subsequent treatment processes needed to achieve this quality. In the US, these reuse schemes such as agricultural irrigation are guided by EPA guideline criteria for wastewater reuse (U.S. EPA, 2005a), which include the control of conventional parameters such as BOD, turbidity, coliforms, pH and residual chlorine, in order to protect public and the environmental health. The WHO has set other guidelines specifically for pathogen control (WHO, 1989). All three systems evaluated have the capability of producing effluent quality within the suggested EPA and WHO guidelines for reuse.

3.3. Societal sustainability

3.3.1. Public participation

Public participation is often a neglected aspect when selecting the most appropriate wastewater treatment technology for a particular community. While some regulations designate a specific technology through a ''best technology'' process, the perceptions and preferences of the public for the selection and implementation of a particular technology is important if technology is to be integrated with local and broader sustainability concerns. In the US community, participation is embedded in the regulatory process through requirements of public hearings and it does not appear that a particular treatment technology has an advantage to encourage more community participation in the decision making process. We acknowledge this is a difficult indicator to quantify. Palme et al. (2005) suggest a more measurable indicator as percentage (%) of users that are ''aware and responsible''.

The elements considered important in selecting a sustainable treatment system will vary from community and region because of geographical and demographical realities specific to a locality. In any case, the elements currently used in wastewater treatment selection are usually performance and affordability. In developed countries a wastewater treatment plant's efficiency, reliability, sludge disposal and land requirements are considered critical over affordability (Sperling, 1996). Hence there is a tendency to select mechanical systems over alternative treatment systems. In developing countries, affordability and the appropriateness of the technology is considered critical. Thus these countries often select simple, cost-effective appropriate technology, over more mechanized technology (Sperling, 1996). Selecting a sophisticated treatment system for a community with low-income families may place undue financial hardship on them.

3.3.2. Community size served

The size of a community can dictate the type of treatment system selected, its capacity, and hence its sustainability. Increase in population often means a larger plant capacity is required. Mechanical and lagoon systems are more capable of servicing a larger population than land treatment systems. However, mechanical systems are often chosen over lagoon systems to service these populations. A deciding factor in choosing mechanical systems that serve large populations, especially in urban areas is the land requirement or open space availability.

But how does community size relate to the sustainability of a technology that is selected for a particular community? Greater municipal pollution loadings are associated with urban areas because of their large material inputs and outputs compared to smaller communities. This may create a burden on the surrounding environment to which dissolved and solid residuals are returned because the surrounding has limits on how much pollutant loading it can accept. Accordingly, if wastewater systems are to be sustainable, then considerations of material balances, particularly water and chemical fluxes, are required to maintain a proper balance of nutrients in the environment; avoiding the accumulation of pollutants in one ecosystem or deficiency of nutrients in another.

3.3.3. Nuisance from odor

Wastewater treatment facilities, regardless of how well designed, at one time or another may generate odor as by-products of the wastewater collection and treatment process. The presence of odor in any wastewater treatment facility is typically an aesthetic problem that usually evokes public intervention and sometime regulatory agency involvement. All the treatment systems have the potential to produce odorous emissions.

Land treatment systems have the lowest odor potential than mechanical and lagoon systems, due to pre-treatment of the wastewater before land application. Odor problems may also arise, if large solids and algae have not been removed prior to land treatment. Principle odor problems typically occur at pumping stations, inlet and outlet piping, and manholes if any are present. Odors from lagoon systems may also be due to overloading or excessive surface scum that has been allowed to accumulate. Sludge accumulation from lagoon systems may also contribute to the problem, however this should not be the case, as sludge builds up slowly over a period of 10–15 years and removal is required at end of this period (U.S. EPA, 2002).

Table 2 indicates that mechanical systems have a greater potential for odor problems than lagoon systems. Common locations in these facilities from which odors are released include preliminary and primary treatment, sludge processing facilities, and sludge disposal. Of these locations, severe odor problems can occur at the headworks facilities (wet wells, screening facilities, and grit chambers), and more recently, sludge storage, thickening, stabilization, and dewatering facilities. Industrial waste discharged to these mechanical systems can also generate significant odorous emissions, some of which, if emitted at high concentrations, pose serious health and safety risk to plant personnel (WEF, 1992). Table 2 shows other unit processes that have odor potential. Odors from sludge conditioning, transport, and disposal are a common problem. Scum and foam buildup, filamentous growth and solids settleability also

Table 2
Odor potential for typical unit processes in a wastewater treatment plant

Unit processes	Odor potential
Treatment plant	
Primary clarifiers	High
Trickling filters	High
Aeration	Low
Lagoons	Moderate
Terrestrial	Low/Moderate
Secondary clarifiers	Low/Moderate
Sludge handling	
Thickening/Holding	High
Aerobic digestion	Moderate
Sludge storage basins	Moderate/High
Dewatering	High

Source: WEF, 1992.

Table 3
Staffing required to operate a wastewater treatment plant for a given plant capacity

Plant capacity MGD (m^3/day)	Average capacity MGD	Plant staffing (Average)	Staffingper Ave. capacity
<1.0 ($<3.8\times10^3$)	0.4	3.9	10.0
1.0–5.0 ($3.8\times10^3-19\times10^3$)	2.5	8.4	3.4
5.0–10.0 ($19\times10^3-38\times10^3$)	7.5	17.6	2.4
10.0–50.0 ($38\times10^3-190\times10^3$)	25.1	50.6	2.0
50–100 ($190\times10^3-380\times10^3$)	68.1	129.4	1.9
>100 (380×10^3)	181.7	314.7	1.7

Source: WEF, 1992.

contribute to the problem. Overall, mechanical systems appear to have the greatest odor potential, followed by lagoon systems, and land treatment systems.

3.3.4. Staffing required to maintain infrastructure

Table 3 indicates the number of staff required to operate and maintain a wastewater facility based on plant capacity. An average staff of 4 is required to maintain a plant capacity below 1 MGD ($3.8\times10^3\,m^3$), while an average staff of 8.4 and 18 is required to maintain a 1.1–5 MGD (4.2×10^3–$18.9\times10^3\,m^3$) and 5–10 MGD (18.9×10^3–$37.9\times10^3\,m^3$) plant capacity, respectively. Plant capacities >100 MGD ($>378.5\times10^3\,m^3$) require the most staff with an average staffing of 315 (WEF, 1992). This indicates that smaller plants serviced by lagoon, land treatment and some mechanical technologies require the least number of staff to maintain, and that large plants served predominately by mechanical systems require the most number of staff to maintain. However, when staffing is normalized to capacity, the results show a decrease in staffing as plant capacity increases. Considering the staffing per MGD, less mechanized systems such as lagoon and land treatment systems, which constitute a majority of smaller treatment plants (<5 MGD or $<18.9\times10^3\,m^3$), have the greatest potential to impact social and economic development through increased employment in the community than larger treatment plants of mechanical systems that may be located outside of the community where the wastewater is generated.

3.3.5. Level of education

Increased education is generally valued as an important indicator for sustainability. The level of mechanization of a treatment system often dictates the level of operator qualification required to operate the plant, and thus their education level. Licensing required by each state depends on the type of treatment plant, complexity and size (U.S. EPA, 2004b). A high school diploma or general equivalency diploma (GED) may be necessary for less complicated systems, like a lagoon or land treatment system. Higher education is required to operate and maintain complex, sophisticated treatment systems such as activated sludge.

Each state has a tiered system for operator licensing. For example in Michigan the tiered system for operator licensing is from Class A to D. The level of education is important in determining the type of wastewater treatment plant an individual can operate and the type of license required. More complex and sophisticated processes such as mechanized treatment systems require a higher level of education for licensing and operation, than less mechanized processes like lagoon and land treatment systems. The more mechanized wastewater treatment system, (e.g., activated sludge system) usually requires a higher class license, (Class A or B), while less mechanized systems (e.g., lagoons, land treatment) require a lower class license (Class C or D).

Results of an EPA survey of 150 small treatment plants with debilitating problems, show that poor operator understanding and application of process control is the most frequently occurring problem that limits treatment plant performance (WEF, 1992). Smaller treatment facilities are more likely to gain from higher level of education and additional training as these facilities are not often reached by professional networks that can offer trouble shooting advice in the event of a process upset or failure. An operator with relevant knowledge of the processes within a facility can reduce the risk of a process failure, protect worker safety, and solve debilitating problems by responding promptly to any problems, then one who does not. Even the perfect plant design will not perform adequately without informed operation and responsible administration.

3.3.6. Open space availability

Mechanical treatment systems have lower hydraulic retention time of 3–8 h (Metcalf and Eddy, 2003), which

Table 4
Land required by the different treatment technologies to treat 1 million gallons per day (MGD) ($3.8 \times 10^3\, m^3$/day)

Treatment technology	Required land area Acre/MGD
Mechanical treatment (conventional activated sludge)	0.4
Lagoon treatment	
Facultative	49–161
Aerated ponds	5–16.3
Partial-mix aerated ponds	28–49
Land treatment	
Slow rate (loading rate, 2–18 ft/yr)	60–700
Rapid infiltration (loading rate, 18–360 ft/yr)	3–60
Overland flow (loading rate, 10–70 ft/yr)	16–112

Sources: Crites and Tchobanoglous (1998), Metcalf and Eddy (2003), National Research Council (1993).

translates to smaller land requirements compared to lagoon and land treatment systems that require a longer detention time and hence more land area (Table 4). Smaller land requirements can mean that land can be used for other economic or environmental purposes. We have stated previously that the value and use of open space requires context-based interpretation. Here it is assumed that open space is a benefit to the community. Although minimum land requirement may be seen as a benefit, especially in urban areas where land is at a premium, increased land area can also be considered a benefit as assumed in this study as this provides more open, green spaces to a community and hence increased ecological and social benefits. These open spaces have many climatic purposes, such as maintaining the ambient temperature at an optimum. Land can also serve as a buffer between a community and aesthetic concerns associated with wastewater treatment.

In Atlanta, Georgia, the estimated annual economic value of tree cover in improving Atlanta's air quality was valued at $15 million. Additional annual economic benefits in improved air quality of $7 million could be realized if Atlanta's tree cover were increased to 40% (Trust for Public Land, 2005). Lagoon and land treatment systems that require more land area, and hence contribute to green space, also may provide habitat for waterfowl and other wildlife, as well as areas for public education and recreation (U.S. EPA, 2005b). This is important in an economic sense because in 1990, it was estimated that outdoor recreation contributed $40 billion to the US economy. Furthermore, recreation is ranked number 2 among all economic activities on US Forest Service lands (Trust for Public Land, 2005). Such green spaces attract visitors who for example, enjoy bird watching or open areas in general, and also encourage social encounters among different members of a community that is another valued benefit.

3.4. Overall sustainability

As seen in this study, the sustainability of the different wastewater treatment technologies evaluated varied with each sustainability indicator. These selected indicators were used to measure the economic, environmental and societal sustainability of a treatment system. Hence, in order to compare results and show the overall sustainability of each treatment system, the individual results from the three treatment technologies were displayed using target plots. Target plots have been used historically in LCA and environmental product design to evaluate overall sustainability. The plots make it easy to single out points that are far removed from the plot's center that require special attention. Furthermore, in this study they enable quick visual comparisons of environmental, economic and social attributes.

The target plot shown in Fig. 3a displays the three dimensions of wastewater sustainability, the scale of impact from these dimensions, and the sustainability indicators used in this study. The impact values for each sustainability indicator for the different treatment systems were rated on a scale of 1–3, with a scale of 1 being more preferable and thus situated closer to the center of the plot. Again, the rating is a context-based decision that can change with a community, region, and country. Due to space limitations the conversion of the data to the target plots is not shown. However, the authors can be contacted for supplemental information that explains the method. Figs. 3a–d indicate that using the indicators, mechanical treatment systems are overall less sustainable than lagoon and land treatment systems (i.e., greater area of the plot is taken up by the shaded area). This is especially true in the economic and societal indicators identified for this study.

The greatest economic impacts for mechanical systems arise from their higher capital, operation and management, and resulting user costs. The greatest environmental impact for such technology originates from its high energy use compared to other technologies. Mechanized processes may compromise aesthetics (i.e., odor forming potential) to a greater extent compared to the other technologies and contribute less to the economy of a community by employing the least number of staff per plant capacity, than other treatment systems. Despite these setbacks in attaining sustainability, mechanical systems are very efficient removing biochemical oxygen demand, total suspended solids, and pathogens.

Lagoon treatment systems can provide open space to a community along with having a low user cost and less odor forming potential while providing sufficient removal of nitrogen and phosphorus, and less compromising aesthetics. The user cost depends on whether the lagoon is aerated or not, usually reflected in operational and management costs. Aerating a lagoon (including power) costs $350 to $500 per year, in operational and management costs, whereas a facultative lagoon costs less than $100 per year (U.S. EPA, 2002). In lagoons, the presence of

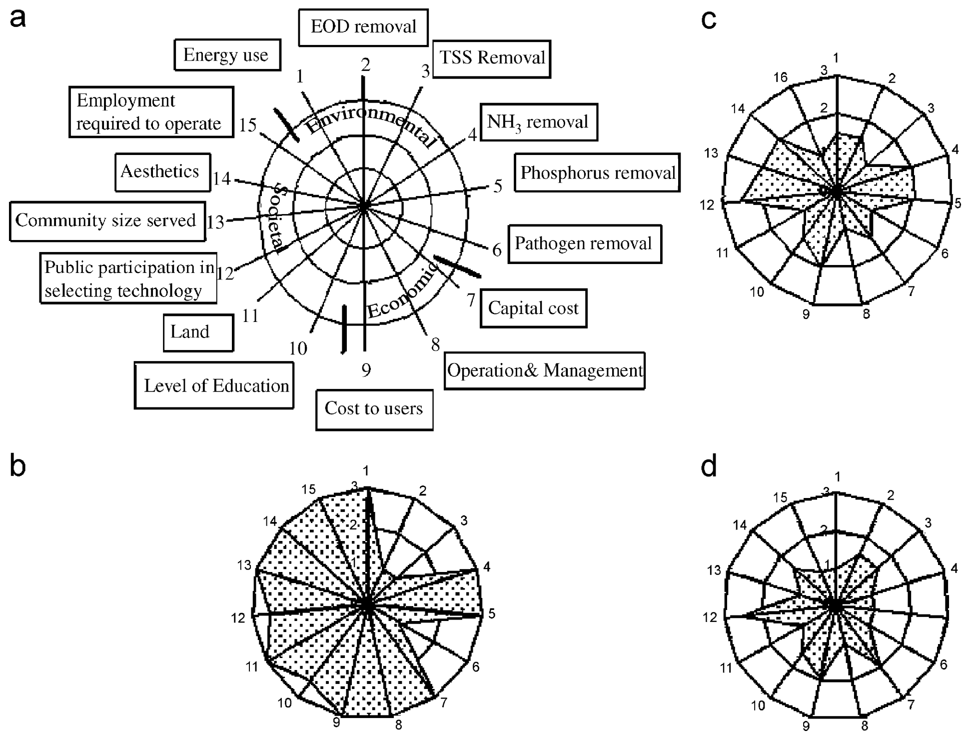

Fig. 3. (a) Target plot showing the three dimensions of wastewater sustainability, the scale of impacts from these three aspects and the sustainability indicators used in the assessment. Impect values closer to the center of the target plot are more preferable. (b) Summary of impacts from a mechanical treatment system. The plot indicates most of the impacts are further from the center. (c) Summary of impacts from a lagoon treatment system. The plot indicates impacts values are close to the center. (d) Summary of impacts from a terrestrial treatment system. The plot indicates that most impact values are more closer to the center.

odor is seasonal; therefore, there is lower odor potential in the winter than summer months. These systems also have low energy use, and provide sufficient removal of biochemical oxygen demand, total suspended solids, and pathogens. Their lower capital and operation and management costs make them ideal systems for small communities. Although these systems are less mechanized, they can contribute more to the economic growth of a community in the long term by employing more staff per plant capacity than larger mechanical systems that employ fewer staff per plant capacity.

Of all three systems, land treatment systems were found to pose the least overall impact as shown by Fig. 3 results. Advantages of land treatment systems include lower capital and resulting user costs and low potential to produce odor. These systems also have low energy use during operation, and high removal of biochemical oxygen demand, total suspended solids, nitrogen, and pathogens. Like lagoon systems, land treatment systems were found to contribute to economic growth by employing more staff per plant capacity than the larger mechanical systems and also provide a community with open space.

The results suggest that using the sustainability indicators developed in this study, wastewater treatment technologies, such as lagoon and land treatment systems were shown to be a more sustainable choice, considering economic, societal, and environmental issues, when selecting a technology to serve communities with wastewater generation rates of less than 5 MGD ($18.9 \times 10^3\, m^3/day$).

4. Conclusions

The sustainability of mechanical, lagoon, and land treatment technologies for wastewater treatment was evaluated, using a set of sustainability indicators developed particularly for this study. The results showed the overall sustainability of a wastewater treatment technology is a function of economic, environmental and social dimensions, and the selection and interpretation of indicators is influenced by an area's geographic and demographic situation. The results of this study are an attempt to look beyond the engineering cost and environmental performance associated with a particular treatment technology in order that selection of a technology associated with the management of wastewater treatment meets triple bottom line expectations for an equal balance of environmental, economic, and societal sustainability. One goal of this paper was to initiate a discussion on how to address a more integrated evaluation of the overall sustainability of wastewater treatment technologies.

While we acknowledge the many sources and range of data that went into this evaluation, and the difficulty in identifying a "best overall option", what is interesting is that this study demonstrated there are varying degrees of sustainability in the way a particular treatment technology is selected and then operated. It is not as easy to design a wastewater treatment system that values education of the workforce, open space, and employment in the community, and minimizes aesthetic nuances associated with odorous air emissions, while also minimizing costs, energy use, and maximizing treatment performance.

If a particular wastewater management strategy is deemed non-sustainable, the impact will extend beyond its immediate operational vicinity and even into future generations. Therefore, traditional sustainability indicators for wastewater systems that have emphasized environmental stressors at the neglect of societal issues need to strive in the future to include current and intergenerational balanced impacts. In addition, the design of wastewater management systems that are better integrated into larger community needs could be considered. For example the reuse of treated wastewater and management of solid residuals could be better integrated with local agriculture activities which would re-distribute and return nutrients back to the surrounding environment, instead of concentrating nutrient fluxes in one receiving water body. Ideally the use of onsite-treatment systems like septic tanks, constructed wetlands, and even composting latrines has potential in contributing to sustainability as they rely on non-energy and chemical intensive processes that return nutrients to the surrounding environment. In either case, the realization of more sustainable wastewater management will require a more balanced approach in evaluating a particular management strategy's overall sustainability.

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