Selecting Wastewater Systems for Sustainability in Developing Countries

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ABSTRACT

This paper presents a methodology for systematically incorporating multi-dimensional sustainability considerations into the selection of wastewater options for developing countries and the evaluation and comparison of these options. Appropriate technologies for developing countries were screened based on their function and their use of operational sustainability features; this list of technologies can then be used to elaborate design options. Sustainability indicators are used to enable a parallel comparison of the options from environmental, economic, and socio-cultural perspectives. For illustration, the indicator approach is applied to a case study of the sanitation options for peri-urban/rural areas of the eThekwini Municipality in South Africa.

KEYWORDS

Sanitation; sustainable development; VIPs; urine diversion toilets

INTRODUCTION

Wastewater management or sanitation is a basic human requirement whose main purpose is to separate human waste from human settlements in order to prevent disease. Developing countries continue to need improved access to sanitation and its benefits, as demonstrated by the findings by the World Health Organization (WHO) that poor sanitary conditions and practices cause 85 to 90% of diarrhoeal diseases in developing countries (Prüss-Üstün et al., 2004). Such diseases subsequently contribute to the deaths of 1.6 million children under the age of five each year (WHO and UNICEF, 2006).

In developing countries, the simplicity and low cost of simple pit latrine construction, operation, and maintenance contribute to its widespread use. Unfortunately, however, pit latrines can contaminate groundwater supplies (Jacks *et al*., 1999), often smell bad and serve as a breeding ground for disease vectors, and are impractical in rocky and sandy places, those with a high groundwater table, and those with insufficient space for burying pit contents or building replacement pit latrines. Experience has shown that replacing pit latrines with waterbourne sewerage connected to centralised treatment plants—the conventional model for developed countries for the past fifty years or so—is not a panacea. For example, Wright (1997) notes that more than 90% of such plants in Mexico are non-functional. Aside from the cost, conventional treatment plants are generally not appropriate in developing countries because they: require complex equipment that often can not be manufactured locally; require expertise to operate and maintain; rely on plentiful water supplies; require a stable supply and a large amount of energy; and, to protect water bodies, are focused on the removal of organic components, which are a secondary concern in developing countries where the removal of pathogens is of paramount importance. Finally, where fertilizers and soil conditioners are unaffordable to the poor, it makes sense to recover organic matter and nutrients from human excreta in a safe manner, and conventional sanitation systems are generally not designed to do this. Clearly, alternatives to pit latrines and conventional sewerage and wastewater treatment plants are needed.

How can the urgent need of developing countries for improved wastewater systems be addressed while striving towards sustainability from environmental, economic, and socio-cultural perspectives? This paper first explores how environmental sustainability principles can be translated into practice specifically within a wastewater management system context, and how they can be used to guide the selection of appropriate technologies in developing countries and to develop alternative sanitation options. A method for the side-by-side multi-dimensional evaluation and comparison of such options is then presented, and, finally, applied to a case study in Durban, South Africa as an illustration.

ENVIRONMENTAL SUSTAINABILITY IN THE CONTEXT OF WASTEWATER SYSTEMS

From an environmental perspective, the following sustainability principles are relevant to wastewater systems: adaptability to local conditions, resource conservation, resource recovery, and waste minimization. These can be translated into the operational features listed in Table 1 in a wastewater management context. While the concept of sustainability has increasingly become mainstream, currently, the considerations in wastewater management in developing countries still focus primarily on just one or two of the features below, namely the use of locally available and affordable resources and water conservation. Table 1 highlights the fact that the list of considerations should be broadened in order to make greater progress towards the sustainability of wastewater systems. Note that Table 1 describes how the features can contribute to sustainability, but some of these features may actually be double-edged—i.e., they can also contribute to unsustainability. For example, decentralisation may mean that there are no benefits from economy of scale, and the system may become economically unsustainable. As discussed later in this paper, these *net* effects can be evaluated from a multi-dimensional perspective using indicators. Using operational sustainability features to screen wastewater management technology options for developing countries, a list of alternative (i.e., non-conventional) systems/components was generated as shown below in Table 2. The table translates *environmental* philosophical principles into physical infrastructure. Note that while many advocates of the "ecological sanitation" or "ecosan" model of sanitation promote the features in Table 1, they have tended to focus only on the application of the first few technologies listed in Table 2. Table 2 is intended to demonstrate that in fact a wide range of technological options exist towards more sustainable wastewater systems, with applications possible in diverse local conditions.

In developing wastewater management system options, incorporating those components or systems from Table 2—especially those with higher numbers of sustainability features—is a first step towards integration of environmental sustainability principles into the wastewater system. Any option developed should of course meet the local technical requirements (e.g., flowrate capacities, minimum treatment standards). The next steps are to evaluate and compare the overall sustainability of the design options in the local context.

Table 1. Operational features of wastewater systems and their potential contribution to environmental sustainability.

Operational Feature	Potential Contribution to Environmental Sustainability
Decentralisation	Facilitates resource recovery at local level, facilitates source stream separation and thus separate treatment and reuse of the waste streams, minimizes material and energy requirements through reduced wastewater infrastructure and transport distances, and allows adaptability to local conditions, including management at the household or community level.
Use of Locally Available and Affordable Resources (land, energy, materials, and labour)	In developing countries, conventional wastewater treatment plants have often failed due to lack of local capacity to meet the required stable energy supply, materials, and human skills. Land availability may also be an issue as wastewater system components that are less technologically and mechanically complex may require more land area.
Waste Flow Stream Separation	Contributes to sustainability by preventing cross-contamination and allowing for treatment appropriate to the wastewater quality, which can lead to reduced chemical and energy consumption and improved treatment. Facilitates recovery of nutrients and organic matter. Separation and upper soil disposal of urine can reduce groundwater pollution.
Water Conservation	If water supply is limited, water conservation (e.g., use of dry toilets) is a critical feature of any sustainable system. Because water extraction, treatment, and delivery consume materials and energy, minimizing water consumption is nevertheless a sensible step towards sustainability regardless of water availability. Low water use also makes pollution less mobile and, if necessary, manual emptying of toilet contents easier.
Nutrient and Organic Matter Recovery	Recovery of nutrients and organic matter from wastewater not only provides a renewable source of these valuable resources, but also reduces their potential negative environmental impacts, such as eutrophication. Use of wastewater-derived nutrients and organic matter can be especially beneficial in developing countries where land has been severely degraded by erosion and over-farming, and where artificial fertilisers may be unaffordable.
Water Recovery	Wastewater is a renewable water source that can ease the demand on limited fresh water supplies. Depending on local regulations, highly treated wastewater can be used directly or indirectly to augment drinking water supplies. More widely-accepted are its uses for mitigation of salinity intrusion, irrigation of agriculture and landscapes, industrial applications, and ecosystem restoration. At the household or community levels, grey water may be reused with or without treatment.
Energy Recovery	Organic matter in wastewater can be used as a renewable short-term cycle carbon energy source, often done through anaerobic digestion of sludge to produce methane for use as fuel; direct incineration of sludge can also be used.
Minimisation of Waste Sludge	Sludge from wastewater treatment is often viewed as a waste, even though it can actually be a valuable source of nutrients, organic matter, and energy. Treating sludge as a resource rather than waste can reduce its environmental impacts and the demand on other non-renewable sources of nutrients, organic matter, and energy, as noted above.

Table 2. Examples of alternative sanitation components and systems and their *potential* operational sustainability features.

SUSTAINABILITY FEATURE	Decentralisation	Waste Flow Stream Separation	Water Conservation	(*Facilitates*) Resource Recovery				Minimisation of Waste Sludge
				Urine Nutrients	Faecal Nutrients & Organics	Water	Energy	
Dehydration (Dry) Toilets	✔	✔	✔		✓		✓	✔
Composting Toilets	✔	✓	✔	✓	✓			✔
Separate Urine Collection		✔		✓				✔
Waterless Urinals and Low-Flush Systems		✔	✔	✓				
Greywater Recycling	✓	✔	✔			✓		
Constructed Wetlands	✓			✓	✓	✓		
Wastewater Land Application				✓	✓			
Sludge (Biosolids) Land Application				✓	✓			✔
Wastewater Application to Aquaculture			✔	✓	✓	✓		
Biogas/Biosolids as an Energy Source					✓		✓	✔
Simplified and Settled Sewerage	✓							

✓ – May or may not be applicable depending on specific design.

EVALUATING THE SUSTAINABILITY OF WASTEWATER SYSTEMS

Literature Review of Tools

This section presents an overview of tools that have been used to assess the sustainability of engineered systems, particularly wastewater systems. They are often used together, with one providing the input to the other, or used in parallel to address the various dimensions of sustainability. Many of the tools are based on a system analysis approach (e.g., Exergy Analysis, Materials Flux Analysis, and Environmental Life Cycle Assessment - LCA); that is, they use a comprehensive approach based on mass and energy balances that include substance/material use, emissions, costs, and required land area (Balkema *et al*., 2002). Table 3 lists and describes the tools, and identifies the sustainability dimension/s they attempt to address.

Table 3. Tools used in the literature to assess the sustainability of engineered systems, particularly wastewater systems.

Tool and Description	Sustainability Dimension/s Addressed		
	Environ-mental	**Economic**	**Socio-Cultural**
Exergy Analysis – Quantifies all exergy (useful fraction of energy that can be used to perform mechanical work [Hellstrom & Karrman, 1997]) inputs & outputs; results then used to compare system efficiencies & quantify consumption of physical resources; gives insight into process efficiency, but does not result in a complete accounting of environmental impacts (Balkema *et al*., 2002).	✓		
Material Flow Analysis (MFA) - system analysis-based quantitative calculation of flows of materials & substances, pollutants, & products (Assefa *et al*., 2005); results allow for estimates of exergy consumption & production, costs, revenues, & environmental impacts associated with each material flow.	✓	✓	
Material Intensity Per Unit Service (MIPS) - material input per total unit of services delivered by product over its lifetime, from resource extraction to final waste disposal (Schmidt-Bleek, 1999); used to calculate “ecological rucksack”: Σmaterial input (kg) of natural material - weight of product, represents stress exerted by goods on the environment, a potential indicator of its sustainability impact.	✓		
Economic Analysis - as a sustainability assessment tool, evaluates whether the system can pay for itself, with costs not exceeding benefits (Balkema *et al*., 2002); all costs & benefits (e.g., financial, socio-cultural, & environmental) ideally included in the analysis, but it is often difficult to objectively quantify non-financial concerns in monetary terms.		✓	
Sustainability Indicators - relies on evaluation of indicators selected according to the specific project goals; indicators are parameters used to define/describe a condition, usually to be measured against a benchmark or a target; for wastewater systems, indicators can be selected to characterize sustainability based on public health, environmental, socio-cultural, economic, & engineering considerations.	✓	✓	✓
Life Cycle Assessment (LCA) - well-established tool for evaluating environmental impacts—from use of land, water, materials such as minerals, energy, & their associated emissions to land, water, & air—over the lifetime of a product/service/process; standardized approach consists of goal & scope definition, life cycle inventory, life cycle impact assessment, & interpretation (ISO, 2006a&b).	✓		
Integrated Model: Organic Waste Research Model (ORWARE/URWARE) – developed for quantifying & comparing the environmental impacts, energy balances, & economics of municipal waste management schemes (Assefa *et al*., 2005); uses MFA to quantify material flows, subsequently used for estimating energy balances, costs, & revenues; LCA guides delineation of system boundaries & assessment of potential environmental impacts; Life Cycle Costing used to valuate financial & environmental costs.	✓	✓	
Ecological Footprint Analysis (EFA) – generally EFA calculates land area (in global acres of biologically productive space) needed to sustain human consumption & absorb its ensuing wastes (Redefining Progress, 2005); can be tailored to evaluate environmental impacts of a specific service/product, such as wastewater management; requires information on material & energy flows, & direct land use requirements.	✓		

Recommended Approach

Once the technology options have been screened and selected (using Table 2 as a guide)—while of course taking into account their ability to meet the local technical requirements—an evaluation of their relative sustainability should be performed. The use of sustainability indicators is recommended for this purpose, as it allows for a comprehensive evaluation of environmental, economic, and socio-cultural dimensions. It will require input from other tools. LCA can be used as the quantitative basis for the environmental indicators. It is a well-established and comprehensive tool with international standards, and recommended by the United Nations Environment Programme (UNEP, 2003). The economic dimension can be evaluated based on both financial and economic analyses, which can take into account factors such as ability to pay and potential business generation effects. The socio-cultural issues can be addressed qualitatively through detailed interviews, focus groups, general surveys, and first-hand observations. Sustainability indicators can be used to evaluate and compare wastewater systems, as a planning or decision-making tool or as an *ex-post* evaluation tool to determine potential improvements to the sustainability of existing systems. Indicators can and should be developed to address the specific goals of a project, taking into account the local context. In developing countries, for example, where high unemployment rates and poverty are common, employment and local business generation effects are important considerations for having a more comprehensive impact on sustainable development. The next section presents a case study to illustrate how sustainability indicators can be used to evaluate and compare two sanitation options.

CASE STUDY: PERI-URBAN/RURAL WASTEWATER SYSTEMS IN THE ETHEKWINI MUNICIPALITY IN DURBAN, SOUTH AFRICA

The eThekwini Municipality (ETM) is responsible for providing water and wastewater services to over 3 million people in the City of Durban on the eastern coast of South Africa, as well as to the surrounding wider metropolitan area consisting of urban, peri-urban, and rural areas. The Durban area has a mild sub-tropical climate with an annual rainfall of 1,009 mm; it is very hilly, with a few flat areas in the Durban downtown and harbour areas.

The evolution of the ETM’s current sanitation program is closely tied to major events in the history of South Africa, particularly its transition from apartheid (DWAF, 2002). During the apartheid era between 1948 and 1994, whites[1], blacks[1], Indians[1], and coloureds[1] lived in segregated areas in the city of Durban, ruled by a white government, as well as the surrounding mainly peri-urban and rural areas. By early 1995, 95% of Durban was sewered (Harrison, 2008)[2]; small urban sections of the surrounding areas were also sewered. Parts of Durban were served by two deep marine outfalls that discharged raw wastewater—with only oils and grit removed—into the sea. The rest of Durban’s wastewater underwent secondary treatment for surface water discharge. Outside of Durban, sanitation consisted mainly of open defecation (rural areas), simple pit latrines, and the “bucket system”, in which containers of human excreta were manually collected 2 to 3 times per week for emptying into designated dump sites connected to the sewage reticulation system. Pre-1995, many of the non-white undeveloped areas outside Durban were managed by a variety of agencies. When apartheid officially ended in 1994, government was restructured to unify the country and correct historic inequalities. Consequently, Durban was incorporated with surrounding areas previously

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[1] Official “racial” designations under apartheid: whites are of European origin (primarily Dutch and British), blacks are of native African descent, coloureds are a mixed race of primarily Malay, white (Caucasian), and/or black backgrounds, and Indians are Asians from India.

[2] Personal communication with John Harrison (Sr. Engineer – Planning, eThekwini Water and Sanitation), March 10, 2008, Durban, South Africa.

overseen by approximately forty local authorities to form the ETM; the area overseen by the unified municipality ultimately expanded by more than ten times to 2,000 km^2 and became a diverse landscape of urban, peri-urban, and rural areas. The ETM inherited a complex patchwork of unconnected water and wastewater systems that were previously managed separately, often with very different levels of service.

Consistent with the national government's goal to provide at least the minimum acceptable level of sanitation to all South Africans by 2010 (DWAF, 2001), the ETM began to plan for providing universal sanitation coverage to its service area. The ETM's efforts focused mainly on the rural and peri-urban areas and the emerging informal settlements in the urban areas, most of which did not meet the minimum acceptable level of service defined as a Ventilated Improved Pit (VIP) latrine or equivalent by the national government (DWAF, 2002). The ETM also recognized that it would have to develop an alternative to VIPs for unserved areas. Emptying VIPs every five years or so is labour-intensive and expensive, and a pit emptying backlog for existing VIPs (inherited from previous agencies) quickly developed. This is because many VIPs were located on steep hillsides with no road access and therefore had to be emptied manually. Furthermore, a significant amount of space (2m x 2m x 1m) is required to make onsite burial of pit contents an option; ground conditions and lack of space often precluded this option. From a construction perspective, the ETM also recognized that VIPs had limited applicability in areas with rocky surfaces and high groundwater tables (they require pit depths of 2 to 3 m). For example, in Umzinyathi, one of the pilot areas targeted by the ETM in the late 1990s/early 2000s, the ETM found that based simply on hydrogeological considerations, only 40% of the households could be served by VIPs. Considering pit emptying access issues, this proportion dropped to 20%[2].

In their search for an alternative, the ETM ultimately decided that a dual pit Urine Diversion Dehydrating (UDD) toilet was the best option for peri-urban/rural areas where there was at least 350 m^2 of land available[3] for the exclusive use of the householder. In addition, the householder would receive a reticulated basic supply of potable water. The ETM's UDD toilet is designed with two ventilated 1 m^3-chambers and a moveable toilet seat. When the active chamber is full, the pedestal is moved above the empty chamber; the filled chamber is then closed and its contents are allowed to dry and undergo hygienization while the other chamber fills (designed for approximately a 12 month period for a household of eight). Once the second chamber is filled, the contents of the first chamber are removed and buried by the household (or a contractor); the freshly emptied chamber is now ready for use again. Theoretically, the UDD toilet can be used indefinitely and completely managed at the household level, presenting significant advantages over the VIP; it can also be constructed where there are hydrogeological conditions unsuitable for VIPs.

The decision to switch from VIPs to UDD toilets was primarily based on maintenance and cost considerations by the ETM—*but how do the two systems compare when one considers a broader and more multi-dimensional sustainability perspective? And how would the results of the selection process change?* For illustration purposes, the indicator approach recommended in this paper is qualitatively applied to ETM's rural/peri-urban sanitation programme to evaluate and compare the two alternatives; the preliminary results are presented in Table 4. For this exercise, the indicators were chosen based on a literature review and a consideration of local issues of concern in the ETM. For example, the indicator "local development, business and income-generation effects" is particularly important in South Africa—and many

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[3] This includes the land required under local weather conditions for the management—via evapotranspiration—of greywater.

developing countries—where poverty alleviation is a key goal of any government-sponsored program. Ideally, the indicators would be selected through a stakeholder consultation process to ensure that the interests all of the stakeholders, particularly the users, are represented. If required, some indicators can be assessed more quantitatively. Note that there is less experience associated with UDD toilets and therefore there is much to learn about their real-life performance; research projects are currently underway (e.g., at the University of KwaZulu- Natal) to evaluate the UDD toilets more systematically and quantitatively.

Table 4. Preliminary evaluation and comparison of the alternative sanitation systems installed in peri-urban/rural areas in the eThekwini Municipality from a sustainability perspective.

INDICATORS[a,b]	**VIPs**	**UDD Toilets**
ENVIRONMENTAL		
Use of natural resources (construction and O&M)		
Land	Medium	Medium
Embodied Energy	Low	Low
O&M Energy	None (unless off-site disposal required)	None
% Renewable Energy (O&M)	None	None
Water Consumption (O&M)	None	None
Water discharges		
BOD/COD discharge to water bodies	None	None
N and P discharge to water bodies	None	None
Hazardous substances: heavy metals (e.g., Cd, Pb, Hg, and Cu) , persistent organic compounds, etc.	None	None
Air emissions		
Contribution to global warming (Construction & O&M)	Low	Low
Air emissions of hazardous substances (e.g., dioxins)	Low	Low
Odour	Medium	Medium (but less than VIPs)
Land discharges		
Hazardous substances: heavy metals (e.g., Cd, Pb, Cu, and Hg), persistent organic compounds, etc.	Medium (excreta are land-applied)	Medium (excreta are land-applied)
Resources recovered		
Nutrients applied to agriculture	None	Household-dependent[4]
Energy	None	None
Organic substances applied to agriculture or other uses	None	Household-dependent[4]
Water	Household-dependent (Greywater only; some water may be used for anal cleansing)	Household-dependent (Greywater only)
ECONOMIC		
Capital Cost/1,000 people/yr (Construction only)	\$2,000-6,200	\$8,000
O&M Cost/1,000 people/yr (Pit emptying only)	\$6,200	\$0 (household) or \$1,900-2,100 (contractor)
User Ability to Pay (Annualized cost as % income)[5]	1.7%	0-0.8%
Financial benefits from reuse	None	None (But with future potential)
Potential for local development, business and income-generation effects	High (Construction and pit emptying service)	High (Construction and pit emptying service)

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[4] ETM currently does not recommend recycling of the UDD chamber contents.

[5] For incomes of 1000 ZAR/household/mo.

INDICATORS[a,b]	**VIPs**	**UDD Toilets**
SOCIO-CULTURAL/INSTITUTIONAL		
User acceptability: compatibility w/ user habits and preferences; convenience; comfort; personal security; attractiveness	Medium	Medium
Adaptability to different age, gender, and income groups	Medium	Medium
Current legal acceptability and institutional compatibility	Low	Medium
Exposure to pathogens and risk of infection related to all system elements including collection, treatment reuse and final destination of products/wastes	Medium	Low
Risk of exposure to hazardous substances: heavy metals, medical residues, organic compounds, etc.	Medium	Low
Health benefits due to improved hygiene, food production, nutrition, status, livelihood	Medium	Medium *(Potentially greater with safe excreta reuse for agriculture)*
Effects of system failure	Medium	Low
Robustness of system	High	Low
Possibility to use local competence for construction and O&M	High	High
Ease of system monitoring	Medium	Medium
Durability/Lifetime	Medium	High
Complexity of construction and O&M	Low	Medium
Compatibility with existing systems	High	High

a. Indicators were developed and modified based on UNESCO-IHP and GTZ (2006), Bracken *et al.* (2005), Balkema *et al.* (2002), and Lundin and Morrison (2002). B. Assumes an average of 4.3 people/household.

DISCUSSION

From an operation and maintenance (O&M) environmental emissions perspective, the main difference between VIP and UDD toilets is the potential for N and P contamination of groundwater by the VIP, as it allows for stormwater and washwater infiltration into the porous pit, which can mobilize contaminants. Otherwise, the two systems function similarly in that urine and faeces are ultimately discharged to land, and not to water bodies, thus preventing the microbial contamination of surface water supplies and minimizing the potential for eutrophication. In the case of the UDDs, faeces are isolated from land for some time (approximately 1 year) before eventually being buried. In the case of VIPs, urine, faeces, anal washwater (and other solid waste discharged into the pits) are in contact with the soil from the start of use. It is important to note that both the VIPs and UDD toilets are only designed for blackwater (mainly urine and faeces) management; they do not provide for greywater management. Greywater disposal is generally done via land disposal, sometimes via irrigation of vegetable gardens. In the ETM, greywater reuse is dependent on the household and at least some reuse often occurs for cleaning or dust control. In both cases, the structures are not material-intensive, and generally require similar amounts of construction materials (primarily brick, blocks, cement mortar, wood for the door, and tin for the roofing).

From an economic perspective, the two systems also perform similarly; however, the O&M costs associated with UDD toilets confer advantages in that they can drop to zero for both the user and the municipality if households do the emptying themselves. Note that the areas currently served by the UDDs are indigent and the full capital cost of the units are therefore subsidized by the ETM. The ease of emptying the UDD toilets is one of their key advantages compared to VIPs. It remains to be seen, however, whether households will be comfortable in the long-term with emptying the chambers themselves; interviews with users reveal that they are generally uncomfortable with the idea of emptying the chambers (e.g., WIN-SA, 2005). More experience and surveys of long-term UD toilet users are needed to determine what proportion will do the emptying themselves and what the ultimate cost will be to the users. Another potential advantage—untapped in the case of ETM—of the UDD toilets is that they create the possibility of deriving economic value from the collected excreta. In other countries (e.g., Burkina Faso and Malawi), dehydrated or composted faeces and separately-collected urine from similarly-designed toilets are used as soil conditioner and fertilizer, leading to increased crop yields and/or reduced artificial soil conditioner/fertilizer costs to the households. Excreta reuse is currently not being promoted by the ETM.

Finally, from a socio-cultural/institutional perspective, the VIPs and UD toilets confer some similar advantages, but also differ in some respects. The UDD toilets perform better from an institutional perspective (both are acceptable by national standards but the UDDs are supported by the ETM because of the perceived greater ease of maintenance, particularly to the ETM), a risk perspective (exposure to pit contents due to flooding is problematic with VIPs and the viability of pathogens in the pits is theoretically higher than in the UD chambers, although more scientific evidence is needed to support this), and a durability/lifetime perspective (because of much lower material volumes and potentially higher degradation rates, space requirements are lower for UDD toilets and they theoretically can operate indefinitely). VIPs perform better from system robustness and ease of monitoring perspectives (less complex to use as urine and faecal separation are not required, and even some water in the VIPs is acceptable), and from a complexity of construction and O&M perspective (UDD toilets have a more sophisticated design due to the two chambers and the urine separation requirements, and operation requires more user discipline). The two systems perform similarly from user acceptability, adaptability, health benefits, and compatibility with existing systems perspectives.

CONCLUSIONS

In this analysis, the two options are not too dissimilar overall. The key differences lie in the *potential* for resource (nutrients and organic matter) recovery in the case of the UDs, which can have environmental, economic, and socio-cultural impacts and the O&M requirements, which have both economic and socio-cultural impacts. As things currently stand, the biggest challenges of the UDD toilets are related to the education/training of the users on their proper operation and maintenance and the potential need for a service provider, which is affordable to users, to empty the chambers for households who do not want to empty the chambers themselves. The ETM is already working on addressing these challenges, which are not insurmountable, and the latter even has the benefit of contributing towards local economic development. It therefore appears that the UDD toilets are a superior alternative to the VIPs.

The methodology presented above presents a systematic and explicit way of incorporating a multi-dimensional sustainability consideration into the development of wastewater options for developing countries and an evaluation and comparison of these options. Appropriate technologies for developing countries were screened based on their function and their use of operational sustainability features; this list of technologies can then be used to develop design options. Indicators are used to enable a parallel comparison of the options from environmental, economic, and socio-cultural perspectives. This is intended to avoid a decision-making process wherein one factor (e.g., O&M cost) and/or one perspective (e.g., a regulator's) end up driving a program that has wide-ranging effects on a variety of stakeholders from public health to the economic viability of municipalities etc. The ultimate selection of the most sustainable option rests on the shoulders of the stakeholders, who will need to decide how to take into account the various indicators based on the local issues of concern. There are formal and informal methods of so-called "multi-criteria decision making" (for examples, see Hurley *et al.*, in press); the approach taken should reflect the local conditions, particularly the local governance structures and culture. While, in practice, limited budget and time for project implementation often pose significant constraints on the decision-making process, to make progress towards sustainability, the process should be as deliberate and stakeholder-inclusive as possible.

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