Evaluating the Sustainability of an Innovative Dry Sanitation (Ecosan) System in China as Compared to a Conventional Waterborne Sanitation System

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ABSTRACT

The use of sustainability indicators for evaluating sanitation systems is applied to the Erdos Eco-Town Project (EETP) in China for illustration. The EETP is the largest urban settlement in the world employing ecological sanitation, which incorporates separation of waste streams, dry toilets, and resource recovery. The EETP's dry sanitation system is compared against the Dongsheng District's conventional sewer and centralised STP. The two systems are compared based on technological, environmental, economic, and societal indicators. Overall, the two systems perform reasonably well from a technological perspective. The conventional system performs significantly better than the dry system with regards to land and energy requirements, and global warming potential; it also performs better based on freshwater aquatic and terrestrial ecotoxicity potentials, but by a smaller margin. The dry system has superior environmental performance based on water consumption, eutrophication potential, and nutrient and organic matter recovery. The dry system is a more costly system as it requires greater infrastructure and higher operational costs, and does not benefit from economies of scale. The waterborne system performs better based on the societal indicators largely because it is a well-established system.

KEYWORDS: Ecological sanitation, wastewater, urine-diversion toilets, indicators.

INTRODUCTION

Sanitation Systems and Sustainable Development

Sanitation is a basic human requirement whose main purpose is to separate human excreta and other household wastes from settlements in order to prevent disease and environmental pollution. This paper specifically focuses on the management of domestic wastewater, which is composed of human excreta (faeces and urine) and greywater (used water from all household drains and appliances excluding the toilet). Where they have been appropriately installed and properly maintained, conventional systems for managing wastewater—such as sewers connected to centralised treatment plants—have contributed to both improved public health and environmental protection. However, what has become increasingly clear over the last few decades is that these systems are also associated with the serious disadvantages of high costs, reliance on increasingly scarce drinking water supply for transport of wastes, minimal resource recovery, high energy requirements, and surface and groundwater pollution, and that alternative forms of sanitation are needed to make progress towards sustainability. What sorts of alternative solutions exist, and how should they be evaluated and the best option selected?

Over the last few decades, there has been a paradigm shift in the way people think about human development and its relation to the environment. It is clear now that addressing such issues needs to be guided by the principles of "sustainable development", which was defined by the World Commission on Environment and Development (1987) as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This is especially relevant in the case of sanitation, a basic and perpetual human requirement with a direct impact on nature. The so-called Brundtland definition above is commonly used but its practical application and quantification remain elusive. From an environmental perspective, the following sustainability principles are relevant to sanitation systems: adaptability to local conditions, resource conservation, resource recovery, and waste minimization. Flores *et al.* (2009, *in press*) discuss how such principles can be translated into physical operational features specifically within a sanitation system context, and how these features can then be used to guide the development of sanitation system options.

Sustainability Evaluation of Sanitation System Options Using Indicators

Many tools have been used to assess the sustainability of engineered systems. For a summary of these tools and their applications to sanitation systems in particular, see Flores *et al.* (2009, *in press*). These tools are often used together, with one providing the input to the other, or used in parallel to address the various dimensions of sustainability. The use of sustainability indicators was found to be the most comprehensive tool, as it allows for a parallel evaluation of the multiple facets of sustainability. This paper explores the use of sustainability indicators as an approach for evaluating sanitation system options, and applies it to the case of the Erdos Eco-Town Project (EETP) in the Dongsheng District of Inner Mongolia, China for illustration. Guided by the principles of sustainability, a group of indicators was selected based on literature reviews (e.g., UNESCO-IHP and GTZ, 2006; Bracken *et al*., 2005; Balkema *et al*., 2002; and Lundin and Morrison, 2002), professional judgement, and relevance to the case study. As can be seen from Table 1, the indicators are categorized according to technological, environmental, economic, and societal concerns.

Ecological Sanitation and the Erdos Eco-Town Project

As noted above, alternatives to conventional sanitation systems are needed. One such alternative that strives for sustainability is ecological sanitation or "ecosan", an innovative type of dry sanitation system. The term "dry" is used to describe sanitation systems that do not require water to operate the toilets and to transport waste, in contrast to waterborne systems. While ecosan has no strict definition, the following are often cited as critical features of an ecosan system (Winblad and Simpson-Hébert, 2004): separation of waste streams (urine, faeces, and greywater), minimal or no water consumption by toilets (e.g., use of "dry toilets"), and resource recovery. Proponents of ecosan promote a paradigm shift to the management of wastewater as a resource rather than as waste, pointing to its nutrient and organic matter contents and their potential values to agriculture (for more information, see the Sustainable Sanitation Alliance website: www.susana.org).

The EETP represents the largest-scale attempt to build an urban settlement using ecosan. The EETP was one of many urban housing projects developed starting in the early 2000s to serve the rapid increase in demand in the Dongsheng District of Erdos, fuelled by the region's rapid economic growth. The main driver for ecosan implementation is the severe and chronic water shortage in Dongsheng and the potential for reducing the demand on fossil groundwater resources currently being consumed; its potential additional local benefits include decreased demand on the local sewer and sewage treatment plant (STP) system, nutrient and organic matter recovery for agricultural use, and groundwater protection. The soils in Dongsheng and the surrounding region are of very poor quality (Chreod Ltd., 2005), and could benefit from the addition of fertilizers and conditioners. The Stockholm Environment Institute provides financial, managerial, and technical support on the ecosan aspects of the EETP. The EETP was completed in 2007 and features 832 modern apartments in multi-storey buildings, a nursery school, and a service centre for approximately 3,000 people. The ecosan system consists of urine-diversion dry (UDD) toilets and urinals, faecal collection in basements, urine storage tanks, an onsite composting station for faeces and potentially other organic solid waste, and an onsite bio-contact oxidation greywater treatment plant (Figures 1a-e). In the UDD toilets, urine and faeces are collected separately without water during normal operation, and sawdust is added to the faecal matter to keep the faecal collection bowl clean and minimize odours and flies.

Using indicators, the sustainability of the ecosan system at EETP is compared against that of the conventional sewerage and secondary sewage treatment plant (STP) system serving the other areas of Dongsheng District (Figures 2a-b). Constructed in 2001 and expanded in 2005, Dongsheng's main STP has a flow capacity of 40,000 m^3/day (10.5 mgd) and uses a two-stage bio-membrane process; however, the STP can not reliably meet recently promulgated N and P standards at its design capacity. A new 10.5 mgd STP is to be completed at the end of 2009. As of 2007, approximately 75% of Dongsheng's area was covered by the sewer system. The existing STP is currently underutilized; in 2008, it processed 26,000 m^3/day on average. Presumably, the new STP is designed to consistently meet discharge standards at its design capacity and to provide additional capacity to handle expected population growth and expanded sewer coverage in Dongsheng. The existing STP is 7 km away from the EETP site.

METHODOLOGY

As noted previously, this paper uses indicators to compare the sustainability of the ecosan system at EETP to that of the conventional sewerage and STP system serving the other areas of Dongsheng District. The evaluation is based on an equivalent EETP-type settlement of 1,000 households, and is *based on the current operations of the two systems as of July 2009*. This is particularly important to note in the case of the EETP dry system, as the technology is new and it has only been operating for less than two years; there is therefore much potential for improving the system operations.

1a 1b 1c (top), 1d (bottom) 1e

Figures 1a-e. The EETP and its dry toilets and urinals. 1a. A schematic of an EETP multi-storey building illustrating how the toilets are connected to the faecal collection bins in the basement and urine storage tanks (from Zhu, 2008). 1b. A UDD toilet. 1c. The sawdust dispenser of the UDD toilet. 1d. The UDD toilet with the faecal hole in the back (left) and the urine hole in the front (right). The metal button in front turns the faecal collection bowl upright when activated by the user's weight; when the user stands up, the bowl turns 180° and releases the bowl contents into the chute. 1e. Waterless urinal.

Using the software GaBi, a Life Cycle Analysis (LCA) is used to quantify the environmental indicators associated with the construction and operation of the two systems over a 20-year period. LCA is a well-established tool for evaluating different environmental impacts over the lifetime of a product, service, or process. It is often referred to as a "cradle-to-grave" approach. For more information about the LCA procedure and international standards, see the documents ISO 14040:2006 (ISO, 2006a) and ISO 14044:2006 (ISO, 2006b). The LCA uses cradle-to-gate life cycle inventory data for the various materials and other resources used in the construction and operation of the two systems (e.g., steel and concrete used in the STP construction, diesel used for transporting compost). The dry system construction material data were derived from detailed audits of the actual construction costs; in the case of the waterborne system, material data were based on literature values for a comparably-sized secondary treatment plant. In both cases, operations data were derived from actual operations as much as possible. The databases in GaBi are primarily derived from North America and Europe, and therefore may differ for materials locally-produced in China. However, by using the same data sources for the two systems being compared, the results should provide a reasonable comparison on a ***relative*** basis. The LCA results presented should therefore not be treated as absolute values. The environment impact methodology used is CML2001 developed by the Institute of Environmental Sciences at the University of Leiden.

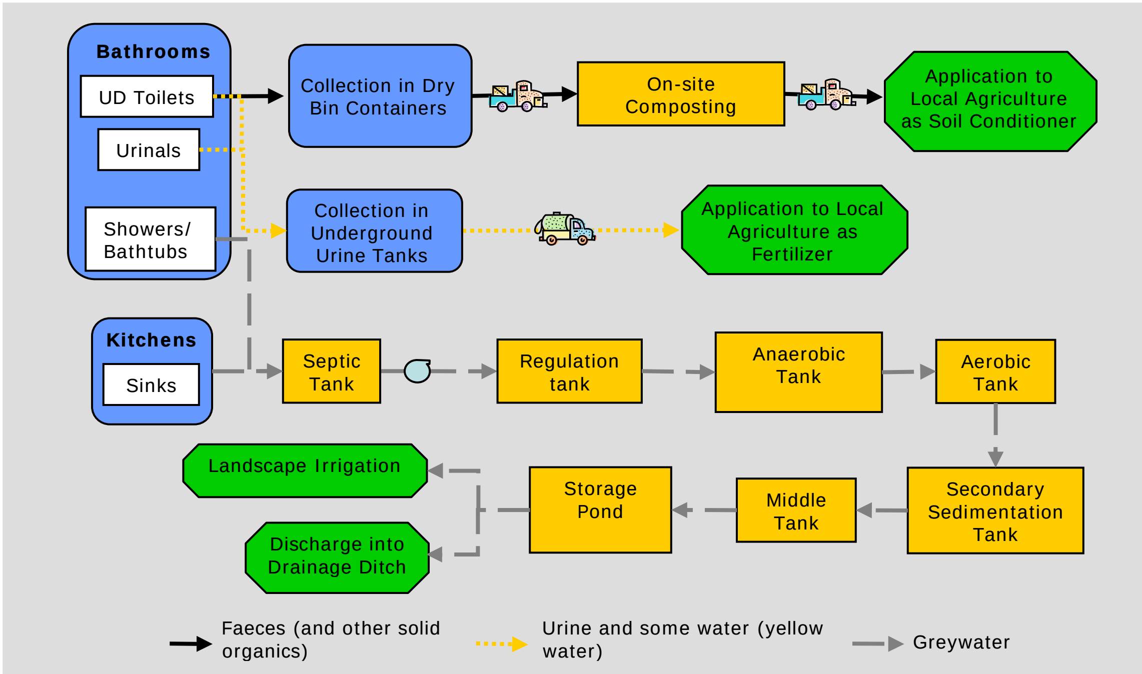

Figure 2a. Scenario 1: Dry sanitation system at EETP with urine-diversion dry toilets, urine collection, faecal composting system, and onsite greywater treatment system.

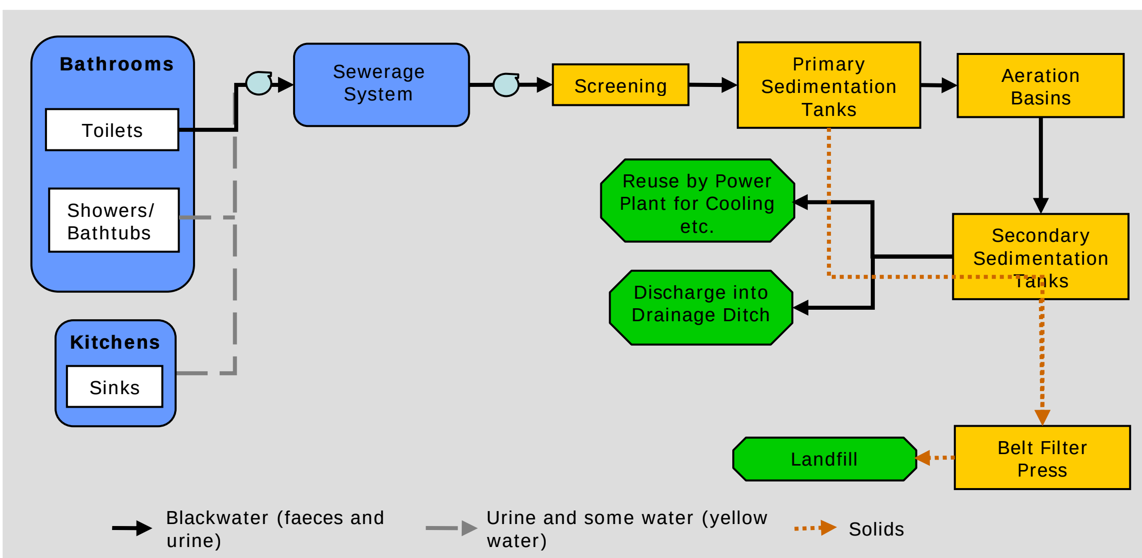

Figure 2b. Scenario 2: Conventional waterborne sewerage and centralised secondary sewage treatment plant.

Generation & Collection   Treatment   Discharge/Utilisation

Figures 2a-b. Schematic diagrams of case study scenarios of dry sanitation and conventional waterborne sanitation systems. The evaluation is based on a settlement of 1,000 households.

Life Cycle Cost Analysis serves as the basis for the economic indicators, which are evaluated largely based on the work of Zhou *et al*. (2007). The societal indicators are evaluated qualitatively through surveys of residents, interviews of stakeholders (residents, government officials, farmers, etc.), and observations. Qualitative indicators can naturally be quite subjective; the results presented here are based on the authors' best judgment based on the evidence. The ratings used are: very poor, poor, neutral, good, and very good.

RESULTS

The results of the evaluation of the sustainability indicators for the two case study scenarios are summarized in Table 1 and discussed in the next section.

Table 1. Summary of the evaluation results of the sustainability indicators for the two case study scenarios based on 1,000 households (HHs) in the Dongsheng District.

INDICATORS	DRY SANITATION SYSTEM	WATERBORNE SANITATION SYSTEM
TECHNOLOGICAL		
Ability to meet treatment standards	Neutral	Poor
Ability to meet capacity requirements	Good	Very good
Ease of system operation and maintenance (O&M)		
Users	Very poor	Very good
O&M Staff	Good	Poor
ENVIRONMENTAL[a,b]		
Use of Natural Resources		
Land – Treatment System[c] (m^2/person)	2.7	0.14
Energy		
Electricity - Operations (kWh/person/year)	139	12.7
Diesel – Operations (L/person-yr)	2.5	0.01
% Renewable Energy – Operations (% of Total Energy)	0	0
Water - Toilet/Urinal Water Operation (L/person-yr)	913	7,665
Water Discharges		
Direct Discharges to Surface Water (kg)		
BOD/COD	0	0
Nitrogen	0	0
Phosphorus	0	0
Hazardous Substances: heavy metals, persistent organic	0	0
compounds, pharmaceutically-active compounds	0	0
Eutrophication Potential (kg Phosphate Equivalent)		
Construction for 1,000 HHs	1,075	127
O&M for 1,000 HHs over 20 yrs	68,263	240,322
Total	*69,338*	*240,449*
Freshwater Aquatic Ecotoxicity Potential (kg DCB-Equivalent)		
Construction for 1,000 HHs	222,574	59,142
O&M for 1,000 HHs over 20 yrs	154,833	143,231
Total	*377,407*	*202,373*
Air Emissions		
Global Warming Potential – 100 years (kg CO_2-Equivalent)		
Construction for 1,000 HHs	4,323,306	447,565
O&M for 1,000 HHs over 20 yrs	15,312,701	1,091,781
Total	*19,636,007*	*1,539,346*
Odour (O&M)	Poor	Good

INDICATORS	DRY SANITATION SYSTEM	WATERBORNE SANITATION SYSTEM
Land Discharges		
Direct Discharges of Hazardous Substances: heavy metals, persistent organic compounds, pharmaceutically-active compounds	app. 100%	app. 100%
Terrestrial Ecotoxicity Potential (kg DCB-Equivalent) Construction for 1,000 HHs O&M for 1,000 HHs over 20 yrs *Total*	 4,555 99,609 *104,164*	 750 86,758 *87,508*
Resources Recovered		
% of Nutrients in Faeces, Urine, and Greywater Applied to Agriculture[g] Nitrogen Phosphorus	 61% 63-80%	 0% 0%
% Energy (Recovered for Electricity Generation, etc.)	0%	0%
% Organic Matter in Faeces, Urine, and Greywater Applied to Agriculture or Other Uses	app. 20%	0
% Water[d] (Reclaimed for Irrigation and Industrial Applications)	0%	17%
ECONOMIC[e]		
Capital Cost Per Capita	$480	$217
Annual O&M Cost Per Capita	$26	$11
User Ability to Pay (Annual O&M Cost as % of Income)[f]	1.3%	0.5%
SOCIETAL		
User Acceptability and Desirability (Compatibility with Habits and Preferences)	Poor	Very good
Accessibility by Different Age, Gender, and Income Groups	Poor	Good
Exposure to Risk (Pathogens, Hazardous Substances, and Physical Injury)	Poor	Neutral
Legal Acceptability and Institutional Compatibility	Neutral	Good

Notes: **a.** *The results for the environmental indicators presented above are based on a preliminary Life Cycle Analysis as of July 2009. For the final results, contact the corresponding author.* **b.** The LCA results presented have not accounted for the *potential* benefits of commercial fertilizer replacement by urine/compost. They also do not include the environmental impacts associated with the precipitation chemicals used at both the Dongsheng STP and the EETP greywater system and the flush water used in both systems. **c.** Agricultural land for compost and urine application are not included. **d.** In theory, the treated greywater produced by the EETP can be recycled for irrigation purposes; however as of May 2009, this has not been practiced. In the case of the Dongsheng STP, it is the government's aim to recycle 100% of the treated effluent via use by power plants for cooling water, landscape irrigation, and construction applications. **e.** Conversion from Chinese currency (RMB) to US dollars (USD) is based on the rate of 6.85 RMB to 1 USD, which is based on October 2008 values. The economic analysis is derived primarily from Zhou *et al*. (2007) – for more details, see this report. **f**. Based on an estimated average annual urban income of 14,000 RMB ($2,044) in the Dongsheng District in 2006. **g**. Dry system: assumes urine and compost are both applied to farms, and pond sludge is recovered for agricultural application as well.

Technological Indicators

Ability to Meet Treatment Standards

China's national wastewater discharge standards are categorized according to the receiving body (Table 2). The most stringent set of standards, Grade IA, applies to important/sensitive water bodies. The Dongsheng District is regulated under Grade II standards, which apply to discharges into water bodies for general industrial water supply, recreational waters in which there is no direct human contact with the water, and water bodies for agricultural water supply and for general landscape requirements. Both the EETP dry sanitation system (specifically the associated greywater treatment plant) and the Dongsheng STP discharge into drainage ditches whose flows mainly consist of wastewater discharges (Figures 3a-b). The ditches essentially function as informal groundwater infiltration and evapotranspiration systems.

Table 2. Summary of China's key national wastewater discharge standards (World Bank, 2007).

Wastewater Effluent Standard	Grade IA	Grade IB	Grade II
COD (mg/L)	50	60	100
BOD_5 (mg/L)	10	20	30
TSS (mg/L)	10	20	30
Total-P (mg/L)	0.5	1.0	3.0
Total-N (mg/L)	15	20	--
NH3-N (mg/L)	8	15	30
Anionic Surfactants (mg/L)	0.5	1	2
pH	6-9	6-9	6-9

The EETP is unable to meet the greywater discharge standards consistently. Testing of the EETP greywater treatment system in 2007 indicated that it generally met Total-P and NH_3-N requirements, but could not meet COD consistently (Zhu, 2008). A review of 2008 monitoring results for the greywater system found exceedances of COD, Total-P, TSS, and anionic surfactants at various times. Much of this can be explained by the exceptionally low use of water by the households and therefore low dilution of the greywater. The Chinese discharge standards, like others around the world, are based on concentrations and not mass loadings. A site visit in April/May 2009 indicated that the greywater discharge outfall is blocked and needs to be repaired.

Figures 3a-b. Discharge outfalls for EETP treated greywater (left) and Dongsheng STP treated wastewater (right).

Wintertime, when temperatures can drop to -25 degrees Celsius, is challenging for the operation of the Dongsheng STP. The cold temperatures inhibit biological activity in the uncovered outdoor membrane bioreactor system (Lifeng, 2007). However, the installation of heaters has apparently improved the STP's wintertime wastewater effluent quality (Lifeng, 2009), allowing the STP to generally meet discharge requirements. According to Lifeng (2009), the new STP to be completed at the end of 2009 is designed to meet the Grade II standards consistently. Operated properly, membrane bio-reactors generally produce very high-quality effluent typical of aerobic systems (Stephenson *et al*., 2000). In reality, however, it is often difficult to have the local expertise able to handle the complex operation of secondary treatment plants, particularly in smaller towns and cities in China (World Bank, 2005).

At the EETP, the urine collected in the storage tanks is treated via storage (one month or longer) while the faeces/sawdust mixture is converted to compost for agricultural applications. Contrary to the original design, residents commonly use water to flush away urine (on average 0.5 L per urination – Harada [2008]). The current composting procedure takes 35 days per cycle. Testing performed by the Erdos Agricultural Center (2007) indicates that the urine solution and the compost mixture generally met standards for agricultural applications, even though their nutrient contents were lower than expected due to excessive amounts of water and sawdust. More recent testing of the compost produced by the new onsite composting system (completed in late 2008) shows that the compost has low N, P, and K contents compared to commercial fertilizers on a mass basis, but comparable to composted garden waste (Mertens, 2009). Agricultural applications of urine and compost are currently not restricted. Note that it is common practice for farmers in China to apply faeces and urine mixtures collected from dry public latrines to agriculture.

Ability to meet capacity requirements

With the exception of the faecal composting system, the dry sanitation system components at the EETP have been designed to meet or exceed the EETP's minimum capacity requirements. The sizing or number of units of the collection system components naturally has an impact on operations (e.g., frequency of bin collection and emptying), and ultimately costs, but the capacity of the collection system is generally not a limiting factor at the scale of the EETP from a technical perspective. The greywater treatment system appears to be over-sized at a capacity of 250 m^3/day or 86 L/person/day, considering that water consumption estimates are only in the range of 33 L/person/day (Harada, 2008) to 48 L/person/day (Zhu, 2008). Recent measurements over a 26-day period in May and June 2009 showed a maximum daily reading of approximately 180 m^3/day at the greywater treatment plant's influent. The composting system is currently significantly undersized, and will require the equivalent of nine additional similar-sized facilities to compost all of the faecal mixtures produced by 1,000 households; while land availability may become a limiting factor, there is no technical performance reason why this can not be achieved. Alternatively, the material collected from the faecal bins can be taken to local farms for outdoor composting.

The EETP's disposal/reuse components are potentially problematic from a capacity point of view. Until the greywater treatment system can meet reuse standards, the treated greywater can only be discharged from the storage pond via a drainage ditch (Figure 3a); a visit to the drainage ditch site in April 2009 indicated blocked drainage and slow percolation into the ground. Redesign of the outfall site to prevent flooding during high flows may be required, especially if the surrounding area is to be developed for housing. Urine disposal via agricultural application depends on the demand by third parties, and their infrastructure. As currently designed, urine is to be transported directly to farmers' tanks. As of 2009, there has not been demand for agricultural application of the collected urine; consequently, urine is being discharged at the local landfill. The disposal of composted faeces via agricultural application faces the similar question of demand reliability. As of May 2009, there was one farmer receiving compost produced by the EETP; however, only a fraction of the faeces is currently being composted onsite. The reliance of the urine and compost disposal systems' capacities on external factors may limit their capacities.

Conventional sewers and sewage treatment plants are used around the world to handle a wide range of flows, and can generally be designed to function well for the case-specific capacity requirements. Under Scenario 2, the hypothetical sewers carrying mixed wastewater from the EETP would be connected to the existing sewerage network and STP serving the much greater population of the Dongsheng District. In fact, other new housing developments in the immediate vicinity of the EETP are already served by conventional sewerage. With a new 40,000 m^3/day (10.5 mgd) STP nearing completion at the end of 2009 to supplement the existing STP's 20,000 m^3/day (5.25 mgd) capacity, it is the government's goal to reuse all of its treated wastewater via irrigation, power plant cooling, and construction applications (Lifeng, 2009); however, it is not clear how this goal can be achieved without a pipeline distribution system for treated wastewater.

Ease of System Operation and Maintenance

The dry sanitation system faces a number of operation and maintenance challenges. In general, it is a more complex system to operate and maintain because of the separate waste streams involved. From a user perspective, the main differences between the dry and wet systems are related to the operation and maintenance of the urine-diversion dry (UDD) toilets and urinals. A survey of 100 households in April and May 2009 (Flores, 2009) found that the average user response to the question "How convenient/easy is the [UDD] toilet to use?" was 2, on a scale of 1 to 9, with 1 being "very inconvenient/difficult". The urinals fared slightly better at an average user rating of 2.8 (Figure 4). The inconvenience of the UDD toilets was primarily associated with the need to separate streams of urine and faeces, the use of sawdust, and the difficulty of maintaining them clean. The urinals are fairly easy to use, although the current installations are too small, resulting in floor splashing and consequently odours. As noted previously, many users (88% in one survey – Harada [2008]) have been adding water to the urinals and urine holes after every use to keep them clean and minimize odours. The ventilation system used for controlling odours from the faecal chutes is still underperforming and the design needs to be improved. The precipitation of struvite on the odour traps in the urine holes and in the urinal S-traps requires regular maintenance by the users or by the EETP staff. Precipitation in the less accessible parts of the urine collection system is a potentially big future maintenance issue (Zhu, 2008); pipe flushing may be required every few years.

From the operations staff perspective, the urine collection and disposal system and the faecal collection, treatment, and disposal system are fairly easy to operate and maintain. The procedures are not technically complex, although they are somewhat labour-intensive and unpleasant in the case of the faecal management system. The operation and maintenance of the greywater treatment plant requires a skilled worker, as in the case of an STP.

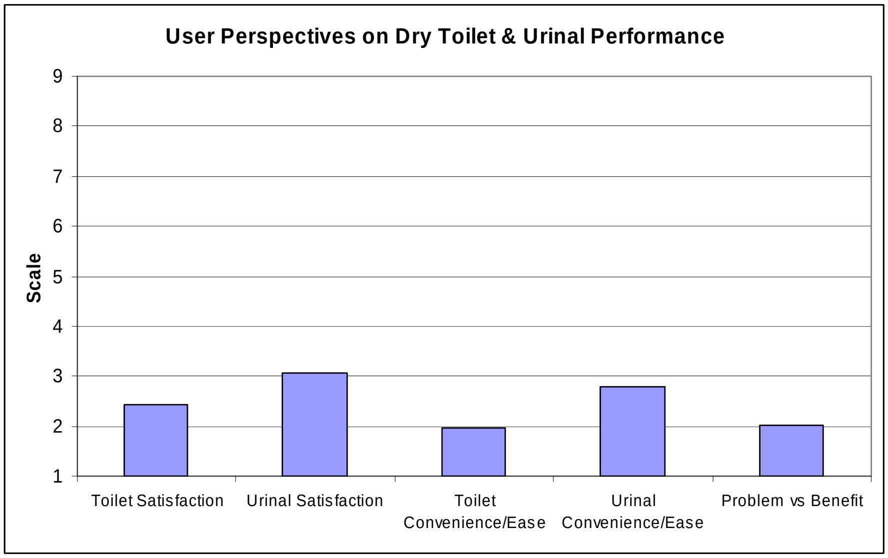

Figure 4. Results from the April/May 2009 survey of 100 households at the EETP (Flores, 2009). Averages of user perspectives on dry toilet and urinal performance (Satisfaction: 1 = Very Unhappy, 9 = Very Happy; Convenience/Ease: 1 = Very Inconvenient/Difficult, 9 = Very Convenient/Easy; Problem vs Benefit: 1 = More of a Problem, 9 = More of a Benefit)

The flush toilets associated with the conventional waterborne sanitation system are generally perceived by users as being easier to operate and maintain (Flores, 2009); naturally this only applies when there is a steady water supply. As noted previously, the operation of a secondary treatment plant like the Dongsheng STP is fairly complex, and requires skilled workers and sophisticated monitoring equipment. Operation of the STP has been found to be particularly difficult in the winter due to the cold temperatures. Preventing blockages in sewer systems that can cause overflows of raw sewage requires regular maintenance of the sewer network.

Environmental Indicators

Use of Natural Resources

Except for water, the dry sanitation system consumes much greater amounts of natural resources compared to the conventional waterborne sanitation system. This is in large part due to the conventional system's centralised and larger-scale design, allowing it to benefit from economies of scale in both construction and operation. In addition, the current design of the faecal collection system at the dry system is quite material-intensive because of the basements required for faecal collection and storage. The dry system's transport requirements are quite energy-intensive as the receiving farms are 40 km away from the EETP; transport of large volumes of urine/water is particularly energy-intensive.

Discharges

The effluent from both the dry and the conventional systems are discharged similarly, *i.e.* via surface soil discharge, and thus neither has direct wastewater discharges into surface water bodies. The total Eutrophication Potential of the conventional system is 3.5 times greater than that of the dry system, in large part due to the latter's recovery of nutrients for agricultural application (note that this assumes that the urine and compost are fully recovered). The dry system's total Freshwater Aquatic Ecotoxicity Potential is approximately twice that of the conventional system, resulting from the use of larger amounts of PVC for the separate collection of waste streams. The total Global Warming Potential (GWP) of the dry system is 13 times greater than that of the conventional one, resulting from the much greater electricity and diesel consumption of the dry system during operations. Additionally, the greater requirements for cement, concrete, and PVC for the construction of the dry system contribute to its greater GWP. Odour is a common complaint for users of the dry toilet, resulting from ammonia emissions from urine and likely sulfide and organic emissions from the faecal chutes. As noted above, the ventilation system at the EETP still requires much improvement. Both the composting station at the EETP and the conventional STP suffer from odours that can be problematic for residents in close proximity. Any hazardous substances found in urine, faeces, and greywater are equally likely to end up in land for both the dry and conventional systems since both the liquid and solid portions of wastewater are discharged to land. Accordingly, the two systems have similar Terrestrial Ecotoxicity Potential (TEP) associated with their operations. Since construction TEP contributes only a small percentage, the total TEPs are similar for the two systems.

Resources Recovered

The dry system has superior resource recovery capabilities in the case of nutrients and organic matter. However, both systems are capable of recovering water for irrigation and other purposes. The EETP's greywater system is expected to be capable of producing higher-quality reclaimed water as it does not receive urban stormwater and the associated high contaminant loads; on the other hand, because of the low dilution rates, the greywater tends to be more concentrated. The collection system of the Dongsheng STP, while designed to receive only wastewater and not stormwater, is more susceptible to illegal/unplanned discharges, and is thus more likely to have lower-quality effluent.

Economic Indicators

Capital Cost Per Capita

According to the results of Zhou *et al.* (2007), the capital cost of the dry system is 2.2x greater than that of the wet system: $480 versus $217 per capita. Capital cost comprises pilot tests and experiments, engineering, environmental assessment, design and construction management, civil works and equipment (including the toilets and all of the indoor plumbing, and the collection, treatment, and disposal systems), land-use fees, and current capital. The difference in capital cost is mainly driven by the high cost of construction of the basement to house the dry system's faecal collection system; it represents 40% of the total dry system cost and 85% of the entire cost of the wet system. The costs of the dry system's small greywater treatment plant and the composting system also contribute significantly, resulting in unit treatment costs six times greater than that of the larger conventional system, even without including the necessary expansion of the dry system's composting facility.

Annual O&M Cost Per Capita

According to the results of Zhou *et al.* (2007), the O&M cost of the dry system is 2.5x greater than that of the wet system: $26 versus $11 per capita per year. These values do not include actual and potential incomes generated from the sales of recovered resources such as urine, compost, and water from the dry system and water from the wet system. Note that the sludge from the wet system's STP is not considered marketable as the STP receives a large proportion of industrial wastewater, which results in the sludge being classified as hazardous waste. The future of urine and compost sales from the dry system is currently uncertain. As of May 2009, there was one farmer receiving the compost and only paying for the transport costs. Urine collected from the EETP is currently not being utilized other than on demonstration agricultural plots and growth trials.

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User Ability to Pay (Annual O&M Cost as % of Income)

The average annual per capita income of urban residents in the Dongsheng District as of 2006 was 14,000 RMB or $2,044 (EcosanRes, 2007). The annual O&M costs as percentages of an average urban resident's income for both the dry and conventional systems are relatively low and within the generally acceptable range of two to three percent (Pickford, 1994).

Societal Indicators

Table 3 summarizes the positive and negative aspects of the dry and waterborne sanitation systems relative to the societal indicators. Because the dry sanitation system is a relatively new urban technology, some key societal issues associated with its implementation are described in more detail below.

The main user interface of the dry sanitation system at EETP—the UDD toilets and urinals—are under continuing development and are therefore still being redesigned for improved acceptability by users. Note that the EETP is occupied primarily by the middle class and higher income level groups. The April/May 2009 survey (Flores, 2009) found high dissatisfaction with the UDD toilets and urinals in this group. The average user response to the question "What is your level of satisfaction with your urine-diverting toilet?" was 2.4, on a scale of 1 to 9, with 1 being "very unhappy" and 9 being "very happy". The urinals fared just slightly better at an average user rating of 3.1. (Figure 4). Only 8% of those interviewed said they would recommend the system. In contrast, 96% of those interviewed expressed that they would prefer a flush toilet to be installed at their household. While dry toilets are quite common in China, they are often associated with lower standards of living. For example, the newer public toilet facilities in Dongsheng have been equipped with water-flushed toilets while the older ones use dry shallow pit-latrine type toilets, seemingly reflecting the local view of what constitutes increased standards of modernity.

The application of human excreta to agriculture has been practiced in China for several millennia (Shiming, 2002); the EETP system's ecological sanitation principle of resource recovery from excreta can therefore be expected to be more accepted there than in many other parts of the world without a similar history. Surprisingly, however, the April/May 2009 survey found that only about 20% of the respondents found untreated urine application to agriculture to be acceptable and about 40% in the case of treated faeces (Flores, 2009). This may simply be a reflection of a subconscious acceptance, rather than a conscious and public one, of human excreta application to agriculture; or perhaps it is a reflection of changing attitudes as people move up the economic ladder in China. Currently, the application of excreta to agriculture is not strictly regulated in China.

Table 3. The positive and negative aspects of the dry and waterborne sanitation system scenarios relative to the societal indicators.

INDICATOR	POSITIVES	NEGATIVES
User acceptability and desirability (compatibility with habits and preferences)		
Dry System	Toilets/urinals: located indoors, can be used even when there is no water supply Indoor private toilets generally preferred by users	Toilets/urinals: new technology - require user familiarization and training, require more rigorous manual user cleaning, operation currently not optimized for user convenience Greater potential for odours in system
Conventional System	Toilets: located indoors, generally considered easy to use, popular symbol of modernity Generally no odours in households	Toilets: susceptible to misuse and malfunction (e.g., blockage and flooding), require periodic manual user cleaning, only usable for defecation when water is available
Accessibility to different age, gender, and income groups		
Dry System	Toilets: possibility to improve design for adaptability to different age and gender groups	Toilets: currently not optimized for all ages and genders, separation of urine and faecal waste streams can be challenging for users particularly women and children Current system design not applicable to low-income groups (costs too high)
Conventional System	Water-flushed toilets adaptable to different age and gender groups	Sewerage and treatment system generally not applicable to low-income and rural groups in China (costs too high)
Minimization of Risk Exposure (Pathogens, Hazardous Substances, and Physical Injury)		
Dry System	Minimal user exposure to wastewater under normal operating conditions Smaller volumes of wastewater being handled means less likelihood of catastrophic event in case of system failure	Manual transport of faeces increases worker exposure to biological hazards and physical injury. Quality control of composting product at EETP needs to be tested – therefore reuse of faeces in agriculture potentially exposes farmers to biological hazards
Conventional System	Minimal user exposure to wastewater under normal operating conditions Automated (non-manual) transport of wastewater to treatment locations	In case of system failure, potential for high levels of adverse exposure
Legal acceptability and institutional compatibility		
Dry System	Reduced discharge to water bodies, for which standards are difficult to meet Greywater treatment technology similar to conventional wastewater treatment systems, therefore familiar to regulators	New regulations required New decentralized management model required Requires close working relationship between system managers and farmers
Conventional System	Existing physical and administrative/management infrastructure Existing regulatory standards	Regulatory standards can be difficult to meet under current conditions

From an income perspective, the EETP dry sanitation system was particularly designed for a middle-class/upper middle-class development, and is therefore not the most basic model of such a system. The greywater treatment system in particular is relatively advanced technologically and generally not applicable at the lower income levels. The general concept of a source-separated dry sanitation system is certainly adaptable to different income groups. In the Guangxi province of China, for example, a project installed UDD toilets in 100,000 rural or low-income households, with two-thirds of the cost covered by the households (GTZ, 2005). These toilets function similarly to the EETP system in that faeces (after dehydration in the Guangxi case) and urine are source-separated and applied to agriculture.

From a risk perspective, one particular area of concern for the EETP dry system is the handling of faecal matter—the most pathogenic portion of domestic sanitation systems—by the maintenance personnel. The current pre-composting procedure is as follows: 1) maintenance personnel collect the filled bins once a month from the basements and load them onto a truck using a winch, 2) the bins are transported to the composting station, where the contents are manually dumped into the top of a sifter, 3) maintenance staff use a rake to remove the screened faeces/sawdust/toilet paper/etc. mixture onto the floor of the composting station, where they further manually remove any garbage/noncompostable materials, 5) the sifted material is then loaded onto a wheelbarrow for transport to the composting chambers. At each step throughout this procedure, the personnel—although covered in protective clothing and masks—are exposed to raw faecal matter, and there is ample opportunity for contaminating surfaces with raw faecal material. Furthermore, improper use of the bins by residents pouring water down the faecal chutes results in heavy water-filled bins that need to be manually cleaned by personnel (see Figure 5a for an example). The faecal handling procedure clearly needs to be improved, possibly with more mechanization.

Figures 5a and 5b. A bin resulting from improper use, *i.e.* user is discharging excessive water into the faecal chute (left). A bin from a properly-used dry toilet (right).

The management of an onsite system such as the EETP dry sanitation system requires a new model different from the prevailing centralized, government-managed model. Currently, the dry system is managed by a site-based team of maintenance personnel. If the EETP model is extended to other neighbourhoods/communities, possible management models include: management of several neighbourhoods by one team (private service provider or a governmental department), one management team for each neighbourhood, or the development of specific service providers serving different communities (e.g., composting, transport of urine or compost to agricultural fields).

CONCLUSIONS

The key findings from the evaluation of the sustainability indicators are as follows:

- Overall, the two systems perform reasonably well from a technological perspective. The dry sanitation technology is less mature than the waterborne system, and therefore requires further improvements particularly with regards to odour control, toilet design, and faecal material handling. The operation of the centralized secondary treatment plant, as well as the onsite greywater treatment plant, is fairly complex and requires skilled workers.
- The waterbourne system performs significantly better than the dry system with regards to treatment system land requirements, energy requirements, and global warming potential; it also performs better based on freshwater aquatic and terrestrial ecotoxicity potentials, but by a smaller margin. The dry system has superior environmental performance based on water consumption, eutrophication potential, and nutrient and organic matter recovery. The differences in environmental performance are primarily driven by the greater material requirements of the dry system, its high energy requirements, and its capacity for resource recovery for agricultural purposes.
- The dry system is a more costly system as it requires greater infrastructure and higher operational costs, and does not benefit from economies of scale. While the potential financial benefits from the sale of urine and compost for agriculture have not been included, the dry system O&M cost is unlikely to drop below that of the waterborne system.
- The waterborne system performs better based on the societal indicators largely because it is a well-established system. Physical infrastructure, management structures, and legal standards have been developed based on the conventional approach to sanitation. Perhaps more importantly, the dry system suffers from low user acceptability due to the more complex design of the UDD toilet, odours, and the prevailing view of the flush toilet as the “gold standard”.

The results above identify the potential of dry systems to contribute to reduced water consumption, the recovery of valuable resources from domestic wastewater, and reduced eutrophication. The first two benefits are particularly relevant in the context of the Dongsheng District, which suffers from water shortage and poor-quality soils. However, as currently designed and operated, the dry system has some serious disadvantages that limit its prospects for sustainability. To improve the sustainability of the dry system, the indicator evaluation highlights the need to reduce the dry system’s material requirements (particularly its large uses of concrete and PVC) and operational energy requirements. Such reductions will improve both the dry system’s environmental and economic performance. Technological improvements of the ventilation system (for odour control), UDD toilet design, and faecal management will also contribute to improved sustainability from a societal perspective. Finally, policy changes are necessary to accommodate dry systems and realize their benefits.

The sustainability impacts of specific improvements to the dry system, in line with those described above, will be investigated in further work. The effects of site-specific factors such as local culture and policies, proximity to agriculture, existing sanitation infrastructure, water supply availability, etc. will also be evaluated.

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