Towards Sustainable Sanitation:
Evaluating the Sustainability of Resource-Oriented Sanitation

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This dissertation is submitted for the degree of Doctor of Philosophy.

DECLARATION OF ORIGINALITY

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text.

and

STATEMENT OF LENGTH

This dissertation does not exceed 65,000 words, including appendices, bibliography, footnotes, tables, and equations and does not to contain more than 150 figures.

I am indebted to the generations who came before and after me.

This work is dedicated to my parents, Engracio and Amparo, and to my son, Benjamin.

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I am incredibly lucky to have been surrounded by dear friends, colleagues, and family on this journey:

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The sewer is the conscience of the city.
- Victor Hugo (Les Miserables)

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SUMMARY

Resource-oriented sanitation systems are designed to recover resources from wastewater while minimizing the demand on other resources, particularly water and energy. This research explores the proposition that such systems offer a more sustainable alternative to conventional waterbourne systems. Its centrepiece is a case study of the world's largest urban dry sanitation system designed for complete resource recovery, located at the Erdos Eco-Town Project (EETP) in the Inner Mongolia Autonomous Region of China. In the case study, the sustainability of the EETP's dry system (DRY system) is compared against that of a conventional waterbourne system (WET system) based on technical, environmental, economic, and societal indicators.

From a technical perspective, the two systems were found to be generally capable of meeting treatment standards and capacity requirements. However, the less technologically mature DRY system requires further improvements particularly with regards to odour control, toilet design, and faecal material handling. The DRY system offers clear environmental advantages such as reduced water consumption, the recovery of valuable resources from domestic wastewater, reduced eutrophication, and reduced toxicity of agricultural soils; however, these benefits come at the cost of higher energy consumption and greater infrastructure requirements. The DRY system is a more costly system as it requires greater infrastructure and therefore higher capital costs, has higher operational costs, and does not benefit from economy of scale. As a novel technology, however, it does offer the potential for local business development. The WET 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. The DRY system suffers from low user acceptability due to the more complex design of the urine diversion dry toilets, odours, and the prevailing view of the flush toilet as the "gold standard". An important concern with the DRY system is the health risk associated with its faecal management system.

The dry collection of faeces was a major challenge with the EETP's sanitation system. A hypothetical analysis revealed that combining urine diversion with minimal flush water for faeces is a good alternative, and can contribute significant progress towards sustainability. Because such a system is a less radical departure from conventional systems, it can be implemented more easily and has a greater chance of user acceptance. Implementation of such alternative sanitation systems generally requires some changes in policy such as how treatment standards are created and how resource-recovery systems are encouraged.

The use of indicators to perform a comparative sustainability evaluation was found to be an effective means of simultaneously examining the technical, environmental, economic, and societal dimensions of sustainability. It facilitated the explicit analysis of specific issues of concern in the context of the case study, and highlighted trade-offs amongst the different facets of the systems. The use of indicators does not necessarily directly point to a clear decision as to which system is more sustainable; however, it does lay the foundation for the decision-making process.

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ACRONYMS AND ABBREVIATIONS

AP	Acidification Potential
BOD	Biochemical Oxygen Demand
CFC	Chlorofluorocarbon
COD	Chemical Oxygen demand
DALY	Disability Adjusted Life Years
DCB	Dichlorobenzene
District	Dongsheng District
EETP	Erdos Eco-Town Project
EF	Ecological Footprint
EFA	Ecological Footprint Analysis
EP	Eutrophication Potential
FAEP	Freshwater Aquatic Ecotoxicity Potential
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit
GWP	Global Warming Potential
HDPE	High density polyethylene
HTP	Human Toxicity Potential
IHP	International Hydrological Programme
LCA	Life Cycle Analysis
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
MAEP	Marine Aquatic Ecotoxicity Potential
MAP	Monoammonium phosphate
MDG	Millennium Development Goals
MFA	Material Flow Analysis
MI	Material Input
MIPS	Material Intensity Per unit Service
N	Nitrogen
NdeN	Nitrification-denitrification
NH_4-N	The nitrogen fraction of ammonia (ammonia-nitrogen)
O&M	Operations and maintenance
OLDP	Ozone Layer Depletion Potential
OECD	Organization for Economic Cooperation and Development
ORWARE	Organic Waste Research Model
P	Phosphorus
Pe	person
pH	power of hydrogen (measure of acidity or alkalinity)
POCP	Photochemical Ozone Creation Potential
PVC	Polyvinyl chloride
RMB	Renminbi (Chinese currency, same as yuan)
RR	Radioactive radiation
SEI	Stockholm Environment Institute
STP	Sewage Treatment Plant (also called Wastewater Treatment Plant)
TEP	Terrestrial Ecotoxicity Potential
TP	Total Phosphorus
TSS	Total Suspended Solids
UAN	Urea- ammonium nitrate
UD	Urine diversion
UDD(T)	Urine diversion dry (toilet)
UK	United Kingdom

UN	United Nations
UNESCO	United Nations Educational, Scientific, and Cultural Organization
URWARE	Urban Water Research Model
USA	United States of America
USEPA	United States Environmental Protection Agency
WHO	World Health Organization
Yr	Year

1 Problem Definition

Where they have been appropriately installed and properly maintained, conventional waterbourne[1] sanitation systems—*i.e.*, mixed wastewater transported by sewers to centralised treatment plants—have contributed to both public health and environmental protection. However, what has become increasingly clear over the last few decades is that such systems also have significant disadvantages, which can make them unsustainable in the long run. There is therefore a need to investigate alternative sanitation options that may be less unsustainable, particularly to serve the rapidly increasing urban populations. One such alternative is a group of sanitation systems and components that embody an alternative philosophy of looking at wastewater, treating it as a resource rather than a waste and being mindful of the need to conserve resources; they are referred to here as "resource-oriented" sanitation systems and are the focus of this research.

The following sections briefly review the function of sanitation systems and the current state of sanitation in different parts of the world; discusses the drivers for making sanitation systems more sustainable; and presents the research's goals, target audience, objectives, and scope. Finally, an overview of the rest of the thesis is provided.

1.1 Sanitation and its Purposes

The term "sanitation" generally refers to the removal or treatment of wastes to create hygienic conditions and prevent disease; in this research, it specifically refers to the management of the liquid waste—wastewater—generated by human settlements. Sanitation is therefore also referred to as "wastewater management" in this document. Wastewater is essentially water that has been fouled by various uses (Metcalf and Eddy Inc., 1991) in households and in public, commercial, and industrial establishments. **Table 1-1** summarises the characteristics of wastewater derived from different sources. This research focuses on the domestic wastewater generated by households, which includes black water, yellow water (sometimes collected separately), and greywater.

The major biological, chemical, and physical constituents of domestic wastewater are listed in **Table 1-2**. Some of these constituents can be considered a contaminant or a resource depending on how the wastewater is managed. Specifically, the nutrients and biodegradable

1 "Waterbourne" refers to the use of water to transport excreta (and other small solids) in wastewater.

organic matter in wastewater can be problematic when discharged to a surface water body in large amounts because they can lead to negative ecological impacts; however, they can instead be recovered from wastewater and used as a resource, as discussed in **Chapter 2**. Wastewater treatment processes to remove contaminant groups of concern are generally classified into three stages: 1) *primary treatment* – physical operations such as screening and sedimentation to remove floating and settleable solids, 2) *secondary treatment* – biological and chemical processes to remove organic compounds, and 3) *tertiary (advanced) treatment* – additional processes to remove other constituents such as nutrients, salts, etc.

Table 1-1. *Characteristics of different forms of wastewater (UNESCO-IHP and GTZ, 2006).*

Wastewater Type and Source/s	Typical Production Rates	Characteristics and Treatment Requirements
Black water - a mixture of faeces and urine (human excreta) with or without flushing water	50 kg per capita per year	Consists of organic matter, nutrients, trace elements, and microorganisms from the intestinal tract; when derived from infected people, highly contaminated with pathogens (e.g. bacteria, worm eggs). Requires treatment to prevent spread of disease and to protect surface waters from decreased oxygen levels.
Yellow water - urine only or mixed with flushing water	500 litres per capita per year	Contains most of nutrients (nitrogen, phosphorus, potassium) found in domestic wastewater; may contain hormones and pharmaceutical residues; generally sterile. Nutrients may need to be removed prior to discharge into surface water.
Greywater - all building wastewater except black water	25 – 100 m^3 per capita per year –	May contain a variety of substances (oils, detergent, etc.) but generally safe from a health perspective. Treatment requirements depend on discharge/reuse process.
Industrial wastewater - effluent from industrial processes	Site-specific	Contaminants depend on industrial process; pre-treatment may be required before discharge into a common sewer system
Stormwater - water that runs off land and impervious surfaces (e.g., paved streets) after precipitation events	Site-specific, depends on climate and infrastructure	Can be contaminated with pathogens from faeces on the ground (e.g., from dogs), chemicals found on ground surfaces (e.g., fertilisers, pesticides), and sediments.

Table 1-2. *Major biological, chemical, and physical constituents of domestic wastewater (Metcalf and Eddy Inc., 1991)*

Constituent	Description	Examples of Sources
Solids	"Total solids" is the matter that remains as a residue upon evaporation at 103 to 105°C; some are organic (e.g., microorganisms bound to suspended solids); solids are settled out through primary sedimentation, filtered, or degraded	Sand and grit, faces, food scraps
Organics	Proteins, fats, and other carbon-containing matter; typically measured as Biochemical Oxygen Demand (BOD) or Chemical Oxygen Demand (COD), which are indicators of how much oxygen is consumed during their degradation and the potential impact on surface water; refractory organics (non-biodegradable) are difficult to remove through conventional treatment methods	Faeces, food scraps, detergents, pesticides, cooking oils
Salts (Total Dissolved Solids)	The fraction of total solids in solution; includes sodium chloride, nitrates, phosphates, etc.	Water supply, urine, salt, chemical products
Nutrients and Trace Elements	Typically present in the form of salts; Nitrogen (N), Phosphorus (P), and Potassium (K) are the key nutrients; trace elements include cadmium, etc.	Urine, faeces, detergents
Microorganisms	Include bacteria, protozoa, and viruses	Faeces, soil, animals
Helminths	Parasitic worms	Faeces

Of those listed above, the constituents with the most direct impact on public health are the pathogenic or disease-causing microorganisms and helminths, such as *Escherichia coli*, *Giardia lamblia*, and hookworm. The most important purpose of sanitation is therefore to protect public health by rendering wastewater biologically safe and/or by isolating it from human contact and from drinking water supplies. Factors that affect the survival of pathogenic organisms in wastewater are: temperature, pH, moisture, ultraviolet (UV) light exposure, presence of other organisms, and nutrient and oxygen levels. These organisms are usually treated through a combination of physical removal (e.g., filtration) and disinfection (e.g., chlorination). In places where intestinal infections are widespread (e.g., rural parts of China [Tang and Luo, 2003]), the treatment and isolation of highly-contaminated human excreta are even more critical to break the cycle of infection. Wastewater's isolation from drinking water sources also addresses other problematic wastewater constituents such as nutrients, particularly in the form of nitrate, which can cause a disease in babies called methaemoglobinaemia when ingested in large amounts (WHO, 2006a).

In addition to protecting public health, wastewater management systems are also intended to protect the environment: excessive loadings of salts, nutrients, organic matter, and suspended solids can overburden surface water bodies and cause adverse ecological impacts such as fish deaths. There are also important—but often overlooked—socio-cultural purposes for sanitation. Properly functioning sanitation systems provide privacy and security, an especially important issue for women and girls, and elevate human dignity (UN, 2004). Perhaps surprisingly, sanitation also has an important role in promoting girls' education as related to privacy and health concerns: LaFraniere (2005) highlighted how the lack of properly functioning sanitation facilities at schools in sub-Saharan Africa is preventing girls—already limited in attendance—from going to school or attending school regularly.

1.2 The Status Quo of Sanitation

In developing countries, the most common form of engineered sanitation is the pit latrine, which is essentially a deep hole dug in the ground that is used as a receptacle for human waste and is either emptied (often manually) or abandoned when full. A toilet or another type of pedestal may be fitted over the hole and a superstructure may be built for privacy. Unfortunately, even a simple functioning covered pit latrine is beyond the reach of many people in the developing countries. As of the year 2004, *only 60% of the world had access to functional sanitation facilities*, with 2.6 billion people either defecating in the open or in unsanitary facilities (WHO and UNICEF, 2006); in developing countries, this percentage was even lower at 50%. "Unimproved" or unsanitary facilities include: toilets that flush to streets, yards, or open sewers; pit latrines without pedestals or open pits; buckets; and hanging toilets or latrines.

The World Health Organization (WHO) estimates that poor sanitary conditions and practices cause 85-90% of diarrhoeal diseases in developing countries (Prüss-Üstün *et al*., 2004), contributing to the deaths of 1.6 million children under the age of five each year (WHO and UNICEF, 2006). In addition, one billion people suffer from soil-transmitted helminth infections (WHO, 2004), which are perpetuated by unsanitary faecal disposal. These two examples highlight the huge impact of the lack of sanitation—coupled with lack of access to clean water—on public health in developing countries. These public health impacts, in turn, impede economic and social development and perpetuate the cycle of poverty. The United Nations (UN) is leading a global effort to improve sanitation coverage in developing countries under the blueprint of the Millennium Development Goals (MDGs); further information on this effort can be found on the UN's website[2]. Given the scale of the problem, the solution clearly requires a fundamental re-thinking of sanitation service provision.

2 http://www.un.org/millenniumgoals/bkgd.shtml

In developed countries, sanitation coverage is >99% (WHO and UNICEF, 2006); unlike the case of developing countries, the provision of services is therefore not the issue. Sanitation in developed countries has achieved public health protection[3] but environmental protection has been increasingly challenging. The Urban Waste Water Directive (91/271/EEC) by the European Union, for example, was specifically developed to address the adverse effects of urban wastewater discharges on the environment[4]. In developed countries, primary and secondary treatment are generally required by regulations, with tertiary treatment for nutrient removal increasingly required for discharges into sensitive water bodies at great economic—and potentially environmental—cost.

The dominant paradigm in developed countries has been the waterbourne collection of excreta along with greywater in sewer systems, which transport the wastewater to centralised sewage treatment plants (STPs). The wastewater is then treated to varying degrees before it is discharged to a surface water body or to land. When such centralised systems are not feasible, decentralised or semi-decentralised septic tank and subsurface disposal systems, which are also waterbourne, are normally the second choice. The Etruscans and Romans were using waterbourne waste collection systems over 2,000 years ago (Stambaugh, 1988). However, the widespread use of modern sewerage systems in urban areas traces its roots to the mid-19th century, with increasing awareness of the connection between wastewater and disease and the consequent need to remove wastewater from human settlements and from contact with drinking water supplies (Burian *et al*., 2000). Fisher and Cotton (2005) provide a good overview of the evoution of—and the drivers for—the provision of sewerage services to poor urban populations in 19th century Britain.

1.3 The Need for Alternatives to Conventional Sanitation

In developed countries, the two main drivers for alternative sanitation are environmental protection and the need for additional capacity. Sewered sanitation systems contribute to the environmental degradation of water bodies through discharges of nutrients, heavy metals, endocrine-disrupting compounds, and other contaminants. They often rely on high-quality drinking water supplies—which are becoming increasingly limited—to dilute and transport waste. Properly-built and operated conventional wastewater systems that provide primary and secondary treatment are very expensive and unaffordable by most developing

3 In a 2007 British Medical Journal survey of 11,300 medical professionals, sanitation was found to be the most important medical advance since 1840 (Ferriman, 2007).
4 http://ec.europa.eu/environment/water/water-urbanwaste/index_en.html. Accessed 9 August 2007.

countries' standards. Advanced or tertiary treatment to remove nutrients is unaffordable even for many regions in industrialized countries. Conventional systems in developed countries are reaching their capacity in densely populated and fast-developing regions with receiving waters becoming less able to assimilate increasingly large volumes of wastewater without serious environmental impacts.

In developing countries, public health protection continues to be the main driver for improvements in sanitation. Pit latrines, the most commonly used form of sanitation, pose problems. They often contaminate groundwater supplies, which are a common source of drinking water in the developing world. They also often smell bad and serve as a breeding ground for flies, mosquitoes, and other disease vectors. Finally, they are impractical in rocky and sandy places, and those with a high groundwater table. History has shown that replacing latrines with centralised treatment plants is not a panacea. Over the last few decades, international organisations such as the World Bank have supported the construction of conventional wastewater treatment plants in developing countries, as exported from the developed countries. Such projects often failed. For example, Wright (1997) notes that more than 90% of plants in Mexico are non-functional. Aside from their high costs, conventional treatment plants are generally not appropriate in developing countries because they require complex equipment that generally can not be manufactured locally; they require expertise to operate and maintain; they rely on plentiful water supplies; they require a stable supply and a large amount of energy; to protect water bodies, they are focused on the removal of organics, which are a secondary concern in developing countries where the removal of pathogens is of paramount importance; and they are not suited to the hot climates of many developing countries.

Finally, conventional models of sanitation often view wastewater as "waste" that requires disposal; in fact, it contains valuable resources, namely organic matter, nutrients, and water. Resource-oriented[5] sanitation systems and components, as defined here, are a group of alternatives that are instead designed to recover these resources while minimizing the demand on other resources. Such technologies have the potential not only to meet disposal requirements, but to avoid pollution and provide income. In light of these potential advantages, this research specifically focuses on investigating these alternatives.

5 The terms ecological sanitation, sustainable sanitation, and reuse-oriented sanitation are also used similarly by practitioners in the field with slightly varying definitions.

1.4 The Urban Challenge

The year 2007 marked the first time in human history when the number of people living in urban areas exceeded those living in rural areas (UN, 2004). The increasing concentration of the global population in urban areas will continue, with most of the increase over the next twenty to thirty years likely to be in Africa, Asia, and Latin America (UN, 2004). In China alone, 268 million people migrated from rural to urban areas between 1980 and 2000; by 2020, 200 million more are expected to follow this trajectory (Yusuf and Saich, 2008). Providing for wastewater management services in urban and peri-urban settings presents special challenges, namely high population density and the associated concentrated demand on resources and concentrated production of wastes; limited space; and the need to work with existing infrastructure. This research specifically explores how the challenges of urban wastewater management can be met through alternative forms of sanitation.

1.5 Sustainable Development

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 widely agreed now that human development needs to be guided by the principles of "sustainable development", which was defined by the World Commission on Environment and Development (1987) as follows:

> *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: the concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs".*

This is especially relevant in the case of sanitation, a basic and perpetual human requirement with a direct impact on nature. Furthermore, the poor have been disproportionately affected by the deficit in sanitation provision. The so-called Brundtland definition above is commonly used but its practical application and quantification remain elusive. This research thus aims to address the need for alternative sanitation options while investigating how the concepts of sustainable development can be translated into practice in a sanitation context.

1.6 Goals, Target Audience, Objectives, and Scope

This research aspires to contribute to the increased sustainability of sanitation systems in urban and peri-urban areas and has set out to achieve the following specific research goals:

1) to evaluate and compare the sustainability performance of a dry sanitation system with complete resource recovery and a conventional waterbourne system in an urban area and

2) to develop engineering and policy-oriented recommendations for the improved sustainability of such systems.

The target audience for this research consists of two main groups: *policy-makers* and *engineers* who are responsible for designing wastewater management systems.

To meet the research goals, this research specifically addresses the following questions:

- How can sustainability principles be translated into operational features in sanitation systems?
- How can the sustainability of sanitation systems be evaluated?
- How does the sustainability of alternative resource-oriented sanitation systems compare with that of conventional sanitation systems? And how can these systems be made more sustainable?

As noted previously, the focus of this research will be urban and peri-urban areas, as driven by their rapid growth and the particular challenges they face. The need for improved sanitation in rural areas, particularly in developing countries, is also urgent; however, due to the need to limit the scope, it has not been included in this research.

1.7 Overview of the Following Chapters

Chapter 2 translates abstract sustainability principles into operational terms in a wastewater management context; it also reviews the work that has been done on sustainability evaluations and their specific application to wastewater systems. **Chapter 3** discusses the methodology undertaken in this research, and describes the case study selected as a tool for exploring the research questions. **Chapters 4 to 7** present the results of the sustainability evaluation performed based on the case study scenarios. **Chapter 8** brings together and summarizes the results, discusses the limitations of the analysis and additional issues to consider, and makes recommendations. **Chapter 9** investigates alternative scenarios for the case study. Finally, **Chapter 10** presents the overall summary, conclusions, and recommendations.

2 *Sanitation Systems and Sustainability*

2.1 Towards Sustainability

The state of sustainability is an ideal; people therefore talk of moving towards the direction of sustainability rather than achieving it[6]. In the context of wastewater management, practitioners agree that to improve the sustainability of sanitation systems, important considerations need to be given to socio-cultural and institutional compatibility, financial and economic viability, health protection, operation and maintenance requirements, and environmental impacts (Panesar, 2009).

The concept of resource-oriented sanitation systems was borne out of the desire to improve the environmental performance, in particular, of sanitation systems. From an environmental perspective, the following principles of sustainability are relevant to sanitation systems: adaptability to local conditions, resource conservation, resource recovery, and waste minimization. These principles can be physically translated into the following operational features: decentralisation, waste flow stream separation, water conservation, nutrient and organic matter recovery, water recovery, energy recovery, and minimisation of waste sludge. Resource-oriented sanitation systems are therefore built upon these features. **Table 2-1** describes how these features can potentially contribute to improved sustainability.

Other terms are similarly used to describe systems that promote the features above such as ecological sanitation (ecosan), sustainable sanitation, and reuse-oriented sanitation; each is used with slightly varying definitions depending on the user. “Ecosan”, in particular, has been promoted widely. While it has no universal definition[7], it has historically been associated only with dry (or non-waterbourne) systems that recover nutrients from excreta for agriculture (Esrey *et al*., 1998). Ecosan is controversial amongst sanitation practitioners; for example, Duncan Mara, professor of civil engineering at the University of Leeds in the UK and a leading figure in sanitation in developing countries, is an outspoken critic, citing cost as a primary limitation of ecosan (McCann, 2005). The term resource-oriented is used here to distinguish it from the much more narrowly-defined ecosan.

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6 See, for example, the discussion of sustainable sanitation by the Sustainable Sanitation Alliance at http://www.susana.org/lang-en/intro/156-intro/53-what-is-sustainable-sanitation. Accessed 27 April 2010.

7 Its definition continues to evolve. The EcoSanRes discussion group, which consists of over 600 members in the field of ecosan, had an online debate about what is considered ecosan as recently as November 2009.

2.2 Resource-Oriented Sanitation Components and Systems

A domestic wastewater management system involves the collection and transport of greywater and human excreta, their treatment, and their disposal or utilisation. A particular component may deal with one or more of these stages of wastewater management. Examples of non-conventional resource-oriented sanitation components and systems that embody one or more of the sustainability features described above are presented on **Figure 2-1**, and are classified based on their function and type of wastewater they handle. In some cases, the component or system is used to treat combined domestic wastewater; the technology is therefore shown to handle faeces, urine, and greywater on **Figure 2-1**. “Dry” toilets refer to toilets that do not require water for operation, unlike flush toilets. Note that while **Figure 2-1** focuses on alternative components or systems, conventional ones (e.g., regular flush toilets) can also play a role in a resource-oriented sanitation systems. For more detailed descriptions of these technologies, see: Crites and Tchobanoglous (1998), Tilley *et al*. (2008), and Winblad and Simpson-Hébert (2004).

Table 2-1. *Operational features of sanitation systems that may lead to improved 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 (Green and Ho, 2005).
Use of Locally Available and Affordable Resources (land, energy, water, materials, and labour)	Makes system adaptable to the local conditions, reduces costs, increases reliability, and reduces the environmental impacts of material transport.
Waste Flow Stream Separation	Prevents cross-contamination and allows for treatment appropriate to the wastewater quality, which can lead to reduced chemical and energy consumption, improved treatment, and lower environmental impacts. Facilitates recovery of nutrients and organic matter (UNESCO-IHP and GTZ, 2006; Larsen and Lienert, 2007).
Water Conservation	Reduces demands on freshwater supplies—which may be severely limited[8]—and the associated chemical, energy, and labour demands of water extraction, treatment, and delivery. Low water use for excreta disposal also makes pollution less mobile and, where necessary, manual emptying of toilet contents easier.

8 It is estimated that 48 countries will be classified as water-scarce or water-stressed by 2025, increasing to 54 countries by 2050 (WHO, 2006b).

Operational Feature	***Potential*** **Contribution to Environmental Sustainability**
Nutrient and Organic Matter Recovery	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	Eases the demand on limited fresh water supplies. Depending on local regulations, examples of uses of treated wastewater are: mitigation of salinity intrusion, irrigation of agriculture and landscapes, industrial applications, ecosystem restoration, and groundwater recharge. At the household or community levels, grey water may be reused with or without treatment.
Energy Recovery	Provides a renewable short-term cycle carbon energy source, often through anaerobic digestion of sludge to produce methane for use as fuel; direct incineration of sludge can also be used. Can be done from the household to municipal levels.
Minimisation of Waste Sludge	Treats sludge as a resource rather than waste, reducing its environmental impacts and the demand on other non-renewable sources of nutrients, organic matter, and energy. Facilitates compliance with increasingly stringent landfill disposal regulations (e.g., EU Directive 99/31 [Lundin *et al*., 2004]).

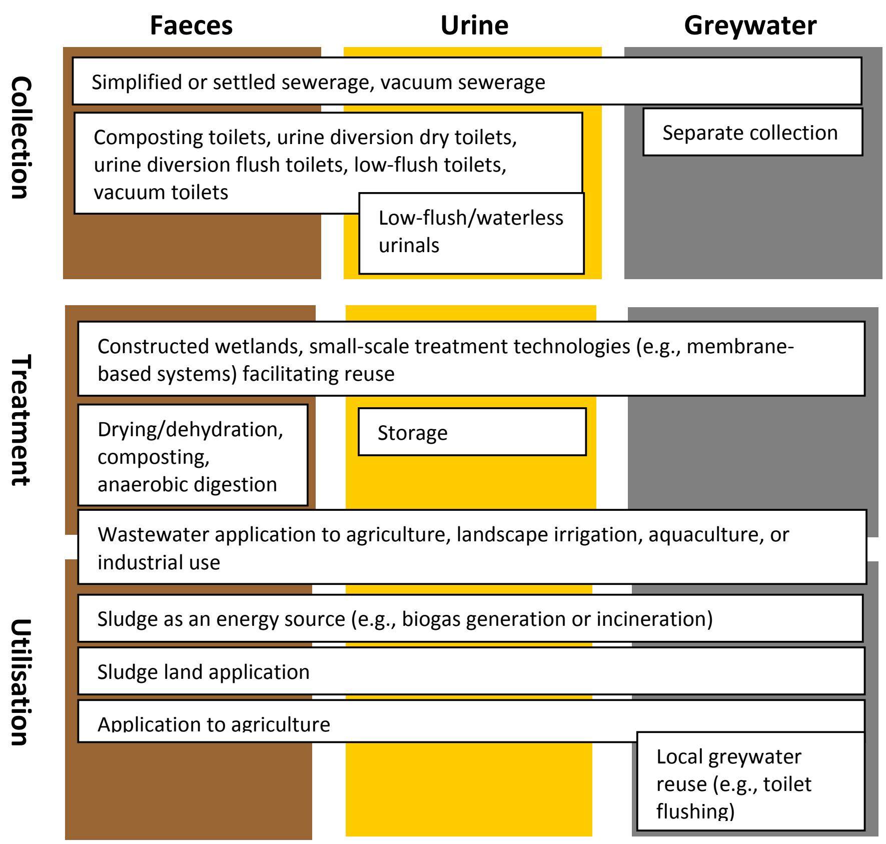

Figure 2-1. *Examples of alternative (non-conventional) resource-oriented sanitation technologies (after UNESCO-IHP and GTZ, 2006).*

As can be seen from **Figure 2-1**, there is a wide range of alternative resource-oriented sanitation technologies. **Table 2-2** identifies the specific sustainability features associated with each technology. These technologies can be applied to a wide range of conditions: rural and urban/peri-urban in both developing and developed countries. They can also be used at different levels: household (decentralised), community (semi-decentralised), and municipality (centralised). The technology may be very simple or quite high-tech, and they can be selected for or adapted to different climates and geologic conditions. Conventional sanitation components and systems continue to have a role where they can meet sanitation objectives and are affordable; however, their sustainability can potentially be improved by combining them with one or more of the alternative sanitation options such as constructed wetlands for tertiary treatment or the use of biogas as an energy source.

Some alternative options represent big shifts in infrastructure and institutional and personal behaviour relative to conventional options, which can make their implementation challenging. For example, toilets that require separation of faeces and urine ("urine diversion" toilets) are still quite unusual in most of the world and will require user adjustment. In almost all urban areas in developed countries, wastewater management is centralised, requiring little participation at the household or community levels; in addition to the changes in physical infrastructure, shifting to decentralised systems would require changes in the roles and responsibilities of households and communities, and of local governments. This underlines the necessity of assessing not just the technical, economic, and environmental issues associated with an alternative sanitation option, but also wider societal issues.

Table 2-2. *Examples of alternative resource-oriented sanitation components and systems and their associated sustainability features.*

SUSTAINABILITY FEATURE	Decentra-lisation	Waste Flow Stream Separation	Water Conservation	(Facilitates) Resource Recovery				Minimisation of Waste Sludge
				Urine Nutrients	Faecal Nutrients/ Organics	Water	Energy	
Simplified/settled sewerage	✓	✓						
Vacuum toilets & sewerage	✓	✓	✓	(✓)	(✓)		(✓)	
Composting toilets	✓	✓	✓	✓	✓			✓
Urine diversion toilets	✓	✓	✓	✓	✓			(✓)
Low-flush/waterless urinals		✓	✓	✓				(✓)
Separate greywater collection	✓	✓		✓	✓	✓	(✓)	(✓)
Constructed wetlands	✓			✓	✓	✓		
Small-scale treatment technologies	✓	(✓)	(✓)	(✓)	(✓)	(✓)	(✓)	(✓)
Drying/dehydration, composting, anaerobic digestion of faeces	✓	✓	(✓)		✓		(✓)	(✓)
Urine storage	✓	✓		✓				
Wastewater application to agriculture or landscapes				✓	✓	✓		
Wastewater application to aquaculture				✓	✓	✓		
Biogas/sludge as an energy source		(✓)			✓		✓	✓
Sludge land application		(✓)			✓			✓
Application of faeces and urine to agriculture	✓	(✓)		✓	✓			✓
Greywater reuse (e.g., toilet flushing)	✓	(✓)				✓		

(✓) Applicability depends on the specific design.

While some resource-oriented sanitation options are in mature stages of development (e.g., constructed wetlands), many continue to require additional research on their technological development, process improvements, socio-cultural acceptability, integration into existing infrastructure, associated risks, public health impacts, cost reductions, and development of different business or government models for their operation and maintenance.

2.3 Literature Review of Sustainability Evaluations

This section presents a literature review of sustainability evaluations of conventional and alternative wastewater management systems. It begins with a description of the various tools that have been used to evaluate the sustainability of engineered systems. Applications of these tools specifically to sanitation systems and their key findings are subsequently discussed. Finally, the research gaps and how this work intends to address some of these gaps will be presented.

2.3.1 Sustainability Evaluation Tools

There has been increasing development of sustainability assessment tools beginning in the late 1980s. 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. For example, the results of an economic analysis and an exergy analysis may serve as inputs to an assessment of sustainability indicators, in which cost and energy consumption are two of the indicators. Similarly, a Life Cycle Analysis (LCA) may provide information on a non-renewable resource consumption indicator. In some cases, a specific tool (e.g., ORWARE) was developed as a product of the integration of various tools. Many of the tools are based on a system analysis approach (e.g., Exergy Analysis, Materials Flux Analysis, and 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). They evaluate whole systems and use multi-dimensional sets of indicators.

Table 2-3 lists and describes the tools, and identifies the sustainability dimension/s they attempt to address. None of the tools, except potentially sustainability indicators, address technical performance (e.g., meeting capacity requirements, ease of operation and maintenance). Also, it is only through the use of sustainability indicators that one can account for societal factors (e.g., user acceptability).

2.3.2 Findings from Sustainability Evaluations of Sanitation Systems

Much of the published sustainability evaluation work on alternative sanitation systems in urban or peri-urban areas has been based in developed countries such as Sweden (e.g., Tidaker *et al*., 2006; Wittgren *et al*., 2003; Tillman *et al*., 1998), Germany (Otterpohl *et al*., 1997; Remy and Ruhland, 2006), the Netherlands (Mels *et al*., 1999), and Australia (Gardner *et al*., 2008; Lundie *et al*., 2004). A notable exception is recent work by Murray (2009), which presents a new evaluation tool using indicators for "reuse-oriented" sanitation systems and applies it to case studies in China. Work is also underway to complete the evaluation of a large-scale pilot project in the city of Ouagadougou in Burkina Faso that provided urine diversion dry toilets to 922 households with intended full recovery of nutrients and organic matter for agriculture (Fall, 2009). In these studies, the number of people served ranged from a household level of 2-10 persons to a large metropolitan area of many millions of people. Many studies looked at an entire wastewater management system (e.g., Tillman *et al*., 1998), while some only considered sludge handling (Lundin *et al*., 2004); a few studies analysed water and wastewater management systems together (e.g., Lundie *et al*., 2004). In a study by Gardner *et al*. (2004), the decentralised water and wastewater management system was part of a broader study looking at decentralised urban development.

The scenarios analysed usually included a comparison of alternative sanitation components and systems to conventional ones (particularly centralised STPs and septic tanks); in some cases, conventional and alternative resource-oriented components are combined. Examples of alternative options analyzed in these studies include: urine-diversion toilets; composting toilets; agricultural application of compost, urine, or sludge; greywater reuse through irrigation; decentralised systems such as sand filters and membrane filtration; co-composting of faeces with organic kitchen waste; vacuum sewerage; and biogas generation for energy use. Hellstrom and Karrman (1997), for example, performed an exergy and material flow analysis of an existing sewer system connected to a regional STP against two hypothetical alternative scenarios: 1) onsite septic tanks and sand filters with septic tank sludge transported to an offsite biogas generation facility and other residuals transported to farmland for use as a soil conditioner and 2) ultra-low-flush urine diversion toilets, with concentrated blackwater collected by a vacuum system then trucked to a biogas production facility, urine transported by trucks for agricultural use as fertilizer, and greywater collected separately and treated onsite via a sand filter bed.

Table 2-3. *Tools used in the literature to assess the sustainability of engineered systems, particularly sanitation systems.*

Tool and Description	Sustainability Dimension Addressed		
	Environmental	**Economic**	**Societal**
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 account for all 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 product lifetime service, from resource extraction to final waste disposal (Schmidt-Bleek, 1999); used to calculate “ecological rucksack” (Σmaterial inputs (kg) of natural material minus weight of product), which represents stress exerted on the environment, an indicator of its sustainability impact.	✓		
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).	✓		
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.	✓		
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.	✓	✓	
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 (e.g., Lundin and Morrison, 2002; Ashley *et al*., 2004).	✓	✓	✓

The example above is typical in that most of the alternative options analyzed in previous studies are hypothetical; this is because the implementation of resource-oriented components and systems in urban areas has been very limited thus far. In developed countries, notable exceptions are land application of sludge for soil conditioning, wastewater reuse for landscape irrigation and industrial purposes, and energy recovery from sludge biogas, which are all increasingly being practised or encouraged[9]. In most cases, however, these practices are viewed simply as a means of disposal or a side benefit of wastewater management. Urban or peri-urban sanitation systems that are specifically designed to maximise resource recovery and/or minimise resource consumption and waste (as described in **Section 2.1**) are currently uncommon. The ones that do exist in Germany, Sweden, Austria, and Australia are at a fairly small scale (100 or fewer residences), and most of them are still working towards achieving resource recovery (specifically agricultural application) due to regulatory restrictions (e.g., solarCity in Linz, Austria [Ulrich, 2009]), negotiations with farmers (e.g., Kullön in Vaxholm, Sweden [Stintzing, 2009]), and delayed construction/operation (e.g., Flintenbreite in Lübeck, Germany [Otter-wasser, 2009]). Two examples of existing facilities are described below:

- The "ecological settlement" in Allermöhe in Hamburg, Germany serves 36 houses or approximately 140 people (Rauschning *et al*., 2009). The sanitation system consists of composting toilets and separate collection of greywater. Faeces, urine, and organic kitchen waste are composted together and applied to gardens onsite. Greywater is treated through a constructed wetland and discharged to a surface water body. It began operation in 1986 and continues to be operational.
- The Gebers collective housing project in Orhem, a suburb of Stockholm in Sweden, consists of 32 apartments housing approximately 80 people (GTZ, 2005a). Its sanitation system consists of urine-diversion toilets with urine collected for use as fertilizer and faeces composted for soil conditioning in agriculture. Greywater is piped to a centralised STP.

The pilot project in Ouagadougou referred to above is at a fairly large scale of nearly 1,000 households; however, it is not a complete wastewater management system as it is only processing excreta.

9 For example, in the USA: 60% of sludge is applied to land as fertilizer or soil conditioner (National Research Council, 2002), an estimated 6.4 million m^3/day of wastewater is reused with reclaimed water use on a volume basis growing at an estimated 15% per year (USEPA, 2004), and 10% of STPs with capacities ≥20,000 m^3/day recover energy from biogas (USEPA, 2007).

As can be seen from **Table 2-3**, many of the sustainability evaluation tools are designed to measure environmental performance. This is consistent with the finding that many of the more rigorous studies on alternative sanitation systems over the last decade have only focused on the environmental dimension of sustainability (see, for example: Mels *et al*., 1999; Wittgren *et al*., 2004; Remy and Ruhland, 2006, Jonsson *et al*., 2008, Foley *et al.,* 2010). One major reason for this is that, in developed countries, the environmental impacts of sanitation systems have been of utmost concern and have been driving the search for alternatives. It is only in the last few years that there has been increasing attention paid to the importance of a more holistic sustainability evaluation that simultaneously examines the technical, environmental, economic, and societal performance of alternative sanitation systems (see, for example: Larsen and Lienert, 2007; Munch and Mels, 2008). Gardner *et al*. (2008) describe several related research projects that are evaluating the various dimensions of sustainability as they relate to an "ecovillage" with a decentralised non-conventional wastewater management system in Queensland, Australia. On its website, the Sustainable Sanitation Alliance, which is a global network of over 100 organisations supporting "sustainable sanitation", publishes case studies that include a basic qualitative sustainability assessment based on the following criteria: health and hygiene, environmental and natural resources, technology and operation, finance and economics, and socio-cultural and institutional (see http://www.susana.org/).

Specific findings from sustainability evaluations in the literature, including those referenced above, will be discussed throughout the following chapters where appropriate, and compared and contrasted with the findings from this research.

2.3.3 Research Gaps Addressed by this Research

A review of the literature indicates that while there has been increasing work done on sustainability evaluations of wastewater management systems starting in the late 1990s, the body of work is still quite limited in scope. The handful of case studies available prior to the initiation of this research involved either conventional systems, or hypothetical and/or small systems. Previous studies have generally focused their detailed analyses on the environmental dimension of sustainability. The literature review did not reveal a holistic sustainability evaluation of alternative sanitation systems that simultaneously examines technical, environmental, economic, and socio-cultural issues in detail, as is done in this research. The economics of alternative sanitation systems—particularly those most commonly considered ecosan by advocates (e.g., composting toilets)—has been hotly debated by wastewater professionals especially in the context of developing countries

(McCann, 2005). In the midst of this debate in 2005, Professor Peter Wilderer, the recipient of the 2003 Stockholm Water Prize, stated that “a rigorous economic study is long overdue” (McCann, 2005).

Finally, the field would benefit from additional case studies evaluating settings that differ from those already examined (climatologically, hydrologically, culturally, etc.). The previous works—many of which are based on hypothetical scenarios—have highlighted the critical relevance of: population density, system size, the relationship between the location of the wastewater facility and agricultural land, agricultural practices related to wastewater by-product application, energy sources for wastewater system operation and fertilizer production, sources of and demand for fertilizers, and peoples’ perceptions and levels of participation. These are all-site-specific issues, indicating that the limited number of studies currently can not be used to arrive at more global conclusions about the sustainability of ecosan options. This research would contribute to a growing body of data on the performance and applicability of alternative sanitation systems.

The review of sustainability evaluation tools indicates that the simultaneous examination of the technical, environmental, economic, and societal dimensions of sustainability can be done through the use of carefully-selected indicators, which will require input from other tools such as Life Cycle Analysis. Other researchers have noted such value of using indicators for sustainability assessments in the water and sanitation industry (e.g., Ashley *et al*., 2004)

The research methodology used to address the research gaps identified above is described in the following chapter.

3 Methodology and Case Study Description

This chapter describes the case study approach used in the research, the selection of the case study and its features, and the methodology used to perform a sustainability evaluation.

3.1 Case Study Approach

The centrepiece of this work is a case study of a unique project in China, which will be described in detail in the following section. The case study approach was selected for this study because it is especially appropriate for investigating relatively new areas of research (Eisenhardt, 1989); as noted in **Chapter 2**, resource-oriented sanitation systems still represent a sort of new frontier. Alternative sanitation systems in urban and peri-urban areas designed with sustainability in mind are currently very few; therefore, an intensive study of a case study is more appropriate than a survey- or statistical sampling-based methodology. Furthermore, the implementation of sustainable sanitation systems involves a complex set of environmental, economic and socio-cultural variables that are generally site-specific. Of these three sets of variables, the socio-cultural ones are particularly difficult to quantify. Yin (2003) states the value of case study research in such situations as follows:

> *"The distinctive need for case studies arises out of the desire to understand complex social phenomena. In brief, the case study method allows for investigators to retain the holistic and meaningful characteristics of real-life events…"*.

Yin (2003) further notes that case studies are a good tool for researchers who believe that contextual conditions are highly relevant to the phenomenon being studied. In the case of sanitation systems, a common cause identified for system failures—particularly those implemented by international organizations in developing countries—is the inappropriateness of the technology to local conditions such as the environment/climate, affordability, user preferences, government institutions, etc.

One often-noted criticism of the case study approach is that of not knowing whether the results from one case study can be generalized to another case, a question of "external validity". Yin (2003), however, notes that this perceived problem often results from confusing case study research with survey research. While the latter is designed to lead to a *statistical generalization*, case study research is designed to lead to an *analytic generalization*. Findings from one case study are not to be generalized to other case studies;

rather, a particular set of results is generalized to a broader theory. In this research, for example, the findings from a single case study of a sanitation system in one location can reveal what types of problems can occur and why, what treatment performance levels and costs are within the range of possibility, what variables significantly affect these performance levels and costs, etc. Such evidence-based information, culled from various sources (interviews, observations, literature reviews, etc.), can then be used to test or build a theoretical framework on the sustainability of resource-oriented sanitation systems. This theory can then further be tested in and/or applied to future case studies or projects.

The original intent of this research was to identify full-scale implementations of resource-oriented sanitation systems in urban or peri-urban areas and to select a subset for use as case studies. Based on the literature review, however, it became apparent that there are currently very few such systems in existence. Many of the components and systems shown on **Figure 2-1** can be found in use but were generally not implelented under a system-wide and multi-dimensional view of sustainability. Reflecting the current state of the art, the "sustainability evaluation" in this research will thus be more similar to an assessment, rather than an audit; the terms *ex ante* and *ex post* assessment can also be used, respectively (EDIAIS, 2001). An *ex ante* assessment forecasts potential impacts based on the available—but likely limited—evidence or data (Horlings and Scoggins, 2006). It is used for planning or design purposes or for initial policy development, which is consistent with the research objectives. In contrast, an audit or *ex post* assessment looks at actual impacts based on historical data. At this time, it is not possible to perform a rigorous *ex post* assessment; reliable evidence for the sustainability—or lack thereof—of resource-oriented sanitation systems will take many years, likely decades, to fully emerge. After all, by definition, sustainability involves long-term impacts.

3.2 Description of Case Study: The Erdos Eco-Town Project in the Dongsheng District of Inner Mongolia, China

3.2.1 Selection of the Case Study – Why China?

China has been experiencing massive migrations from rural to urban areas since the mid-1980s (Zhao, 2005). In fact, the Chinese government is encouraging the migration of 300 to 500 million people from rural areas to towns and cities by 2020, with the country's urban population expected to rise to about 800 million at that time, up from 500 million as of 2002. This urbanization requires new infrastructure to serve the more dense populations found in towns and cities as compared to rural areas. Wastewater production, for example, is more concentrated geographically, requiring more local environmental capacity to assimilate the resulting wastewater and sludge.

According to the World Bank (2001), in 1998, only about ten percent of municipal wastewater discharges in China received secondary treatment. Additionally, existing wastewater treatment capacity is only being utilized at about 70% because sewer systems have been unable to keep in pace with treatment capacity. The World Bank (2001) notes that:

> *"The combination of a rapidly increasing urban population, increasing urban water supply service levels, and increasing per capita urban consumption are producing compounded increases in municipal wastewater flows and pollutant loads."*

The Organisation for Economic Co-operation and Development (OECD) (2001) lists municipal wastewater treatment as one of the priority environmental issues in China's urban areas.

Many parts of northern China, including Inner Mongolia, suffers from severe and chronic water shortages; water conservation is therefore a critical part of any water supply strategy in these areas. In the Dongsheng District, lack of water is a key obstacle to development (Chreod Ltd., 2005). Furthermore, the application of human excreta to agriculture has been practised in China for several millennia; resource recovery from excreta can therefore be expected to be more accepted there than in other parts of the world. Compared to other countries, there has been a relatively rapid uptake of resource-oriented sanitation systems in China. Panesar and Werner (2006) note that more than one million urine-diverting toilets have been installed in seventeen provinces in China since 1997. These toilets, however, have been mainly installed in rural areas; its application to urban areas remains to be tested. Finally, Erdos, which suffers from poor soils, as discussed further below, can benefit greatly from the soil conditioning and fertilizing properties of human excreta.

The current weak sanitation infrastructure combined with the rapid urbanization means that the sanitation situation in China will only get worse unless major shifts are made in addressing wastewater management. Resource-oriented sanitation appears to offer significant benefits, and should therefore be considered as an option.

3.2.2 The Erdos Eco-Town Project

In 2003, the Stockholm Environment Institute (SEI), based in Sweden, and the Dongsheng District (District) in the Republic of China agreed to support a project to test the concept of a dry sanitation system with complete resource recovery in an urban setting. The District is in the Erdos Prefecture-Level City (Erdos) of the Inner Mongolia Autonomous Region (**Figure 3-1**).

The District, with its water shortage problems and sanitation challenges, appeared to be a good candidate for testing such a system in peri-urban/urban settings. SEI, through its EcoSanRes Programme, has been a key player in promoting the concept of ecological sanitation for many years. Its role in the project was related to "*technical solutions, management aspects, institutional dimensions, community sensitization, policy promotion, cost-benefit analyses and monitoring*" (EcoSanRes, 2006). The District was responsible for coordination with the developer; promotion of the project; infrastructure such as roads, green areas, and lightning; education for households; and sanitation system operation (Sun, 2009).

The original plan called for a project to provide peri-urban housing to farmers who had been displaced from their herding/grazing areas in order to reduce erosion and desertification. The houses would consist of one to two-storey buildings with small courtyards using dry toilets and on-site greywater treatment system. Plans changed in 2004, however, as the District experienced rapid economic growth accompanied by rapid urbanisation. With the increased standard of living, there was a high demand for urban housing. In response, the District decided to change the project to a mainstream market-based urban building project called the Erdos Eco-Town Project (EETP)[10] (Rosemarin, 2009b). In its first phase, completed in 2007, 43 modern urban buildings were constructed by a private developer, the Daxing Estates Company: 42 buildings are four to five storeys high and one building is two storeys high. This phase covers one-third of the planned land area and represents approximately 40% of the planned total population of 7,000 residents. Residents began moving into the apartments at the end of 2006 even before construction was entirely completed. There are a total of 832 apartments, as well as a nursery school and a service centre with restaurants and shops. The EETP's sanitation system was designed as the world's largest urban implementation of dry sanitation with complete resource recovery in multi-storey housing. As a case study, the EETP presented a unique opportunity to evaluate the feasibility and sustainability of dry resource-oriented sanitation systems in urban settings.

By mid-2009, however, a decision was made to convert the dry sanitation system to a waterbourne system with flush toilets. There were a number of reasons for this decision, and they are discussed in the following chapters. Ultimately, the decision was driven by the

10 Known locally as the Haozhaokui Village.

dissatisfaction of the EETP residents. While the EETP was never able to fully achieve its goals of complete resource recovery by 2009, it nevertheless represents a major step towards the exploration of the feasibility of full resource-oriented sanitation systems in urban areas. There are therefore many important lessons to be gleaned from it, and this research is an attempt to capture these lessons to help inform future efforts.

3.2.3 The Dongsheng District

3.2.3.1 Location

The Dongsheng District is the political seat of Erdos, located in the southwestern part of the Inner Mongolia Autonomous Region of the People's Republic of China. Autonomous Regions in China are an administrative unit equivalent to provinces except that they have more authority for self-rule (Chreod Ltd., 2005). The District is found in the northeastern area of Erdos, and is 100 km south of Baotou and 600 km west of Beijing. It lies at 1,400 to 1,600 m above sea level with the following coordinates: 39° to 39°58' north and 109°08' to 110°23' east (Zhu, 2008).

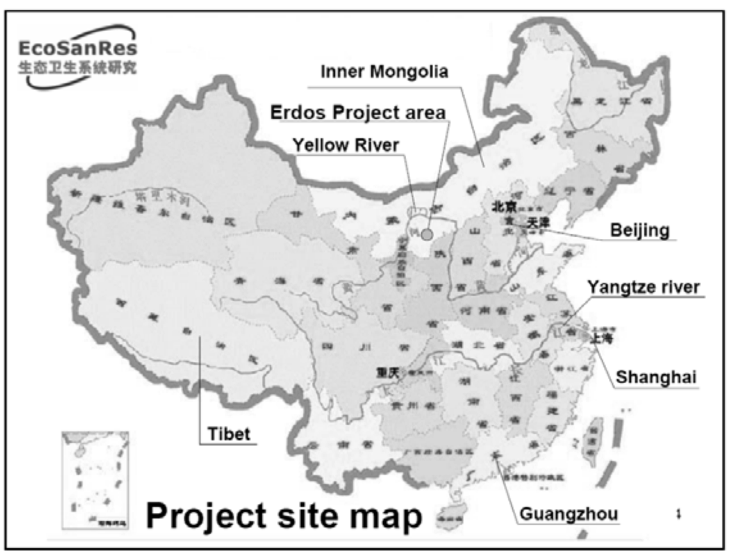

Figure 3-1. *A map showing the location of the Erdos Eco-Town Project (referred to as "Erdos Project area"). [From Rosemarin, 2009a].*

Geographically, Erdos covers the Erdos Plateau, which sits atop China's largest coalfield (seventh largest in the world) and a major natural gas deposit (Chreod Ltd, 2005). It is therefore a major coal and natural gas mining region. Between 2001 and 2005, its coal production more than tripled from 80 to 260 million tons, and, as of 2005, there were plans to double its coal production to 500 million tons by 2010[11]. Dongsheng District has significantly benefited from a surge in coal production and rising coal prices, and began undergoing massive and rapid economic expansion as a result in the mid-2000's (EcoSanRes, 2006). Between 2004 and 2005, Dongsheng District's Gross Domestic Product grew by 31% (Zhou *et al*., 2007). Aside from coal and natural gas production, the manufacture of cashmere wool garments is another major industry in this region (Zhu, 2008).

Erdos not only benefits from its rich natural resources of coal and natural gas, but also its proximity to Huang He (Yellow River), China's second largest river. The land around the river is enriched by the river's alluvial deposits, supporting agriculture; however, this rich agricultural land only represents a small fraction (4%) of the Dongsheng District. Beyond the alluvial plains of the northern area are dry grasslands, deserts, and loess landscapes. There are two deserts in the center of the District, Maowusu and Kubuqi, representing 48% of the total District area (Chreod Ltd., 2005). The extensive agriculture practised in the alluvial plains forms a sharp contrast to the desert environments where plant life is sparse.

A combination of natural and manmade (e.g., overgrazing, historic burning of ground cover, industry) conditions has resulted in the Erdos Plateau being part of one of the most fragile ecosystems in the world, suffering from aridity, desertification, soil salinization and alkalinization, dust-storms, and high pollution levels. These environmental problems, particularly the arid climate and poor soils, seriously impact the District's development.

The planned area of Dongsheng totals 47 km^2, with the western region undergoing rapid development since the early 2000s. The Erdos Eco-Town Project was originally located in the relatively undeveloped northwestern outskirts of Dongsheng but is now surrounded by other new multi-storey apartment complexes and some commercial buildings.

A collage of images from the Dongsheng District is presented on **Figure 3-2**.

11 http://english.peopledaily.com.cn/200512/27/eng20051227_231175.html. Accessed April 27, 2009.

Figure 3-2. *A collage of images from the Dongsheng District. [A. Flores, taken in August and September 2007.]*

3.2.3.2 Climate and Hydrology

Dongsheng District is located in an area with a temperate continental climate. The area is semi-arid with an average annual precipitation of 385 mm (1957 to 2006) and evapotranspiration of 2,043 mm (1981-2006) (EcoSanRes, 2006). Precipitation is mostly concentrated in June, July, and August. Summertime temperatures go up to 28°C while wintertime temperatures drop down to -25^{o}C. Strong winds occur in the area more than 40 days per year, resulting in dust-storms which affects areas as far away as Beijing (Chreod Ltd., 2005).

Aside from the Yellow River which borders it, surface water is scarce in the Erdos Plateau, and the 70 small lakes that exist there are salty or alkalized (Chreod Ltd., 2005). To the author’s knowledge, there is no natural surface water body in the immediate vicinity of the urban areas of Dongsheng District. Groundwater is unevenly distributed. Northwest of the Dongsheng District, in the Mu Us sandy area and the northern Hobq desert along the Yellow River, groundwater is abundant and can be found within 10 metres of the ground surface

(Chreod Ltd., 2005). At the EETP site, however, groundwater is found in limited quantities only between depths of 10.8 and 19.6 m; it was deemed unsuitable as a local water supply (Zhu, 2008).

3.2.3.3 Demographics

Like many urban parts of China, Dongsheng District is receiving large populations of migrants from rural areas. Dongsheng District has a total population of approximately 430,000 and is the largest district of Erdos, which has a total population of 1.4 million . The EETP is located a few kilometres from the downtown area of Dongsheng, which, as of early 2000, had 15,000 households living in multi-storey buildings and 45,000 in single-storey houses (EcoSanRes, 2006).

Many of Dongsheng's industrial workers are employed by the textile and coal industry. The Erdos does not have a sufficient trained work force and workers often have to be brought in from other places to work in the coal mines, etc. (Chreod Ltd, 2005). There is a wide discrepancy in incomes between urban and rural residents. In 2007, the average per capita disposable income of urban residents was RMB 14,091, while that of rural residents was RMB 5,430.

At the EETP, a survey of 99 households (described in **Section 3.3.2**) revealed an average household size of 2.8 people and a median size of 3.0 people. Of the respondents, at least[12] 25% had university-level education. Adult residents at the EETP come from diverse working backgrounds (retired and active): farmers, housewives, business people, teachers, technicians, government clerks and officials, engineers, doctors, and others. Prior to moving in to the EETP, 75% of respondents had access to private flush toilets, indicating their previous residence in primarily urban areas.

3.2.3.4 Existing Water and Sanitation Systems in the Dongsheng District

The District is located in a water-stressed region that relies on groundwater and imported surface water for its water supply. According to Zhou *et al*. (2007), the per capita water supply in the District is only 300 cubic meters, which is approximately 1/7 of the national average and is indicative of water-scarcity (Gleick, 2002). Its groundwater supply is derived from the East Wulanmulun to the south; Hantaichuan to the north; and the Haojiagebo well in the urban area. Together, these sources can produce 25,000 m^3/day (Zhou *et al*., 2007). Starting in 2005, surface water was introduced to the District via a 100-km pipeline from the

12 Only 35 of the 99 respondents answered the question regarding their educational backgrounds.

Yellow River; using five booster stations, water is lifted 486 metres. The first phase of the pipeline delivered water at a rate of 50,000 m^3/day, while the second phase (scheduled for 2010), is expected to deliver an additional 50,000 m^3/day. Even with the additional supply, a daily water shortage of 3,000 m^3 is expected in 2010.

In 2003, the per capita domestic water consumption in the District was 80L/day; this number is relatively low and is expected to go up significantly as more urbanization takes place. Nationally, urban water consumption was as high as 326 L per capita per day in 2003 in China (Amarasinghe *et al*., 2005).

EcoSanRes (2006) described the sanitation system in the District as of early 2000 as follows:

> *"…about 20,000 households have flush toilets while the rest of the population use 280 public toilets, among which 17 are flushing, 156 are deep pit latrines, and the balance shallow pit latrines. In the peri-urban and rural areas most households have their own shallow pit latrines but these are in bad condition. Open defecation is common. The pit latrines vary in quality but in general are very poor risking both health and the environment…Prior to 1985, sewage from the flush toilets was mixed with rainwater in ditches and directly discharged without treatment. The city began to construct its sewage system with collector pipes in 1985. This system covered 64% of the city area in 2002, and rainwater was collected in a separate system of 31 kilometres of pipeline and covered/lined ditches in 2000…The groundwater beneath the city is polluted with sewage. There is an obvious need for a wiser use of water and transformation over to a sustainable sanitation system that is using little or no water…"*

Figures 7-5, 7-6, and 7-7 show images of the types of toilets that can be found in and around the District.

In 2001, the District constructed a large centralised sewage treatment plant (STP) that employs an aerobic attached-growth secondary treatment process; a schematic is shown on **Figure 3-3a**. Upon expansion in 2005, the STP reached a flow capacity of 40,000 m^3/day; however, the STP can not reliably meet treatment standards[13] at its design capacity (Wang, 2007). A second STP is to be completed by 2010, with the capacity to treat 60,000 m^3/day. This second STP is designed to consistently meet reclaimed water standards[13]. According to Wang (2007), the plan is to continue to use the original plant to treat 20,000 m^3/day under the less stringent Grade II[13] standards and to divert the other 20,000 m^3/day to the new STP for additional treatment.

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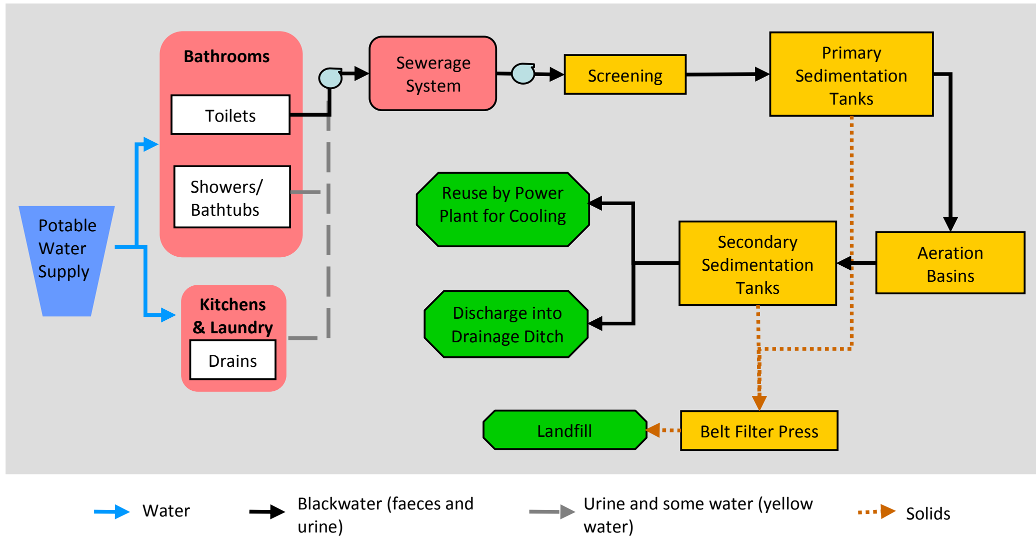
13 See **Chapter 4** for more details, including a list of standards in **Table 4-1.**

By 2007, approximately 75% of the District's area was covered by the sewer system. With the new STP, the District is preparing to meet increased wastewater collection rates and future population growth. As of 2008, the existing STP was underutilized: it processed only 26,000 m^3/day on average. The existing STP is 7 km away from the EETP site.

3.2.4 EETP Dry Sanitation System

The EETP apartments are provided with a sanitation system consisting of urine-diversion dry[14] (UDD) toilets and urinals, urine pipelines and storage tanks, a faecal collection system, a composting station for faeces and organic solid waste, greywater pipelines, and a greywater treatment plant. The system was originally envisioned to achieve full resource recovery from human excreta, greywater, and organic kitchen waste. Urine was to be collected separately and pplied to agriculture as fertilizer. Faeces was to be collected in dry form and composted with sawdust and organic kicthen waste, with the compost applied to agriculture as soil conditioner. Finally, greywater was to be collected separately, treated onsite, and used for landscape irrigation and perhaps other applications. This original vision is shown in the process schematic on **Figure 3-3b**. Features that were not fully implemented by the time the dry system had been converted to a waterbourne system in 2009 are shown in dashed boxes. An overview of the various components of the system is provided in the following sections.

14 "Dry" refers to the fact that water is not required to operate the toilet.



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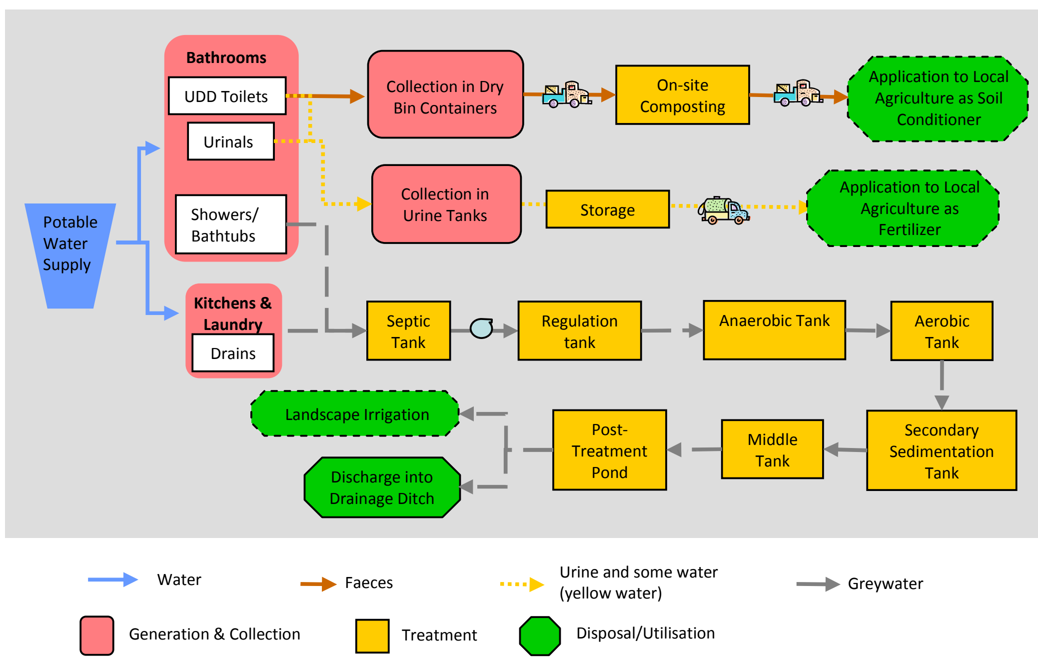


(b)

Figures 3-3a and 3b*. Process schematics of the (a) conventional sewer and centralised Dongsheng STP and (b) EETP dry sanitation system as envisioned (features shown in dashed boxes had not been fully implemented as of 2009).*

3.2.4.1 Urine-Diversion Dry Toilets

The urine-diversion dry (UDD) toilet for the EETP is designed to separate urine from faeces and to require no water (hence "dry") for transporting both types of waste. Urine is collected in a hole at the front of the toilet and faeces is collected in a hole at the back. UDD toilet technology remains under development, although there are a number of products that have been commercially available for a few decades (e.g., Separett toilets). At the EETP, three major toilet prototypes were developed (Zhu, 2008). The first prototype was installed in all 832 flats by the end of 2006. This toilet had two innovative features: a Teflon®-coated turning bowl to collect the faeces and a sawdust dispenser. The bowl is upside down when the toilet is not in use; when the user sits on the lid, a lever is activated by the user's weight, which rotates the bowl by 180 degrees so the bowl can serve as a receptacle for faeces. When the user takes his weight off the lid, the bowl rotates back to its standby position, and deposits the faeces down the faecal chute. The sawdust dispenser allows the user to add sawdust to the bowl to aid in drying the faecal matter and to increase the carbon: nitrogen (C:N) ratio of the resulting compost. Sawdust can also be added to the bowl before defecation to further minimize any sticking to the bowl's surface.

The experience of the users at EETP revealed several problems with the first prototype: 1) the bowl did not consistently turn 180 degrees so faecal matter could be deposited on the outside of the bowl, 2) some users, especially women and children, were not heavy enough to activate the bowl, 3) to keep the lid open for cleaning, one hand needs to press down on the lid, leaving only one hand free to clean the bowl, 4) the bowl is difficult to clean, especially with minimal water, and 5) the use of sawdust was problematic (Zhu, 2008). Sawdust was re-suspended from the toilet bowl and stuck to users during toilet use raising health concerns from users (Zhu, 2008) and, as observed during site visits, sawdust made it hard to keep the toilet room neat.

To address items 1 to 3 above, a second prototype was developed: the design was modified so that the bowl turned 180 degrees when the toilet cover is opened. This model was installed in one household, where it performed satisfactorily (Zhu, 2008). A third prototype was also developed that replaces the bowl with a sliding plate. In this model, the plate covers the faecal hole and chute when the toilet is not in use and is moved back when the toilet is in use; similar to the second prototype, the lid is used to slide the plate in and out. This third prototype is mechanically simpler than the bowl design, requires less material for the toilet, renders the addition of sawdust by the user unnecessary, and makes cleaning easier (Zhu, 2008). It was also designed to provide for a better seal against odours. An aesthetic benefit is that faeces is discharged directly into the chute without sitting in a bowl underneath the user. This prototype had been tested in one household and received a favorable review.

Images of the toilet designs are presented on **Figures 3-4a to 3-4d**.

***Figures 3-4a to 3-4d**. The urine-diversion dry (UDD) toilets at EETP. (a) The toilet with the urine hole at the bottom of the picture and the faecal hole in the middle. (b) The turning bowl mechanism. (c) The sawdust dispenser. (d) An EETP model showing the faecal chute connected to the toilet. (e) The third toilet prototype with a sliding plate. [A. Flores, taken in September 2007.]*

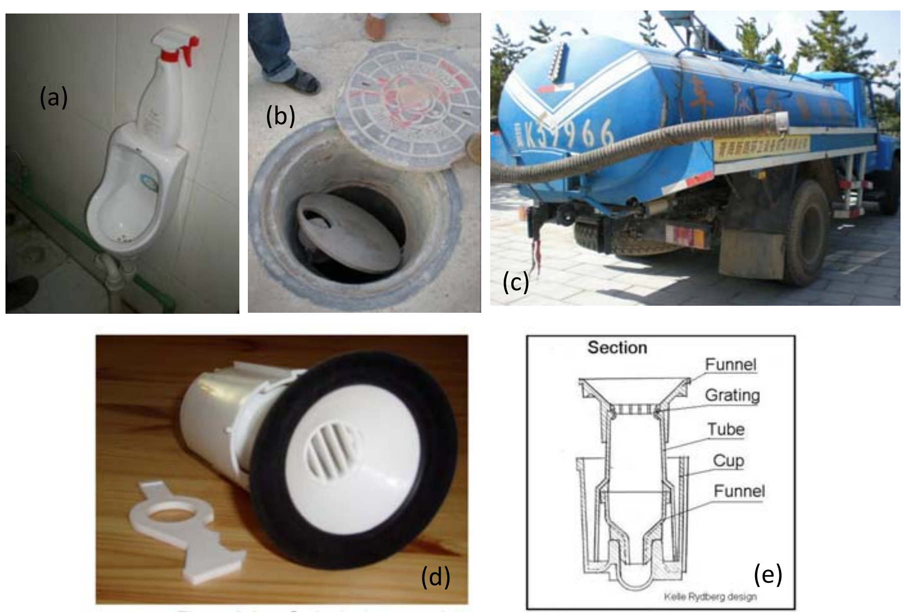
3.2.4.2 Urinals and Urine Collection System

Urine is collected from the urine holes in the UDD toilets and the urinals. Odour control is a key challenge for these components because of the ammonia released from urine. In flush systems, water rinses the surface of the toilet or urinal and removes any urine residual, and the water trap prevents odours from escaping. The original design for the urine holes included a porcelain circular plate to cover the hole, but this was found to be insufficient for controlling odours. A new odour trap design involved the use of a paraffin oil layer sitting atop the urine/water mixture captured in the trap, thereby preventing the escape of odour-causing gases (specifically ammonia) from the urine hole. For the urinals, S-traps were installed to mitigate problems with odour coming up from the urinal pipelines but they did not function very well. Because, by design, minimal water is used in the urinals, the trap is often filled with urine or a mixture of urine and water, continuing to result in odours. Additionally, the original urinals were found to be too small, causing splashing of urine on the toilet floor and exacerbating odour problems (Zhu, 2008).

An additional problem with the urinals and urine holes is the precipitation of struvite ($MgNH_3PO_4$) on the odour trap and the S-trap, causing blockages (Zhu, 2008). Struvite precipitation occurs in concentrated urine solutions because the pH of the solution increases as urease degrades to ammonia, and the high pH renders previously soluble ions insoluble (Jonsson *et al*., 2004). Struvite precipitation in the pipelines is also an issue. The associated maintenance requirements are discussed in **Section 4.3.1**.

The urine collection system (pipelines and tanks) is semi-centralized, with one tank serving 2-3 buildings. Pipeline segments were kept below 200 metres in length to minimize precipitation on the pipe walls and ultimately blockages. To prevent ammonia from escaping from the tanks, through the pipelines, and into the toilet rooms, the tanks' inlet pipelines were submerged below the liquid level. Buckets were placed under each tank inlet pipeline to ensure that even with minimal flow into the tank, the pipeline would remain submerged. A hole drilled into the inlet pipeline provided pressure equalization. To minimize the loss of nitrogen from the stored urine, the tanks were covered. To empty the tanks, a vacuum truck accesses the tanks via quick-coupling valves set into the covers; this was done to prevent urine spills—and odours—in the vicinity of the tanks.

While urine was originally intended to be used as fertilizer in local agriculture, there was no established market as of 2009. The urine was therefore being discharged at the local landfill. Urine reuse and the associated technical, economic, and health issues are discussed in the sustainability evaluation.



***Figures 3-5a to 3-5e**. The urinal and urine collection system at EETP. (a) The urinal with an S-trap. (b) Access to a urine storage tank. (c) The vacuum truck that collects and transports urine. (d) The paraffin-oil odour trap. The key on the left is to be used for disassembling the trap for cleaning. (e) A cross-section drawing of the odour trap. [(a-c) A. Flores, taken in September 2007 and (d-e) from Zhu, 2008.]*

3.2.4.3 Faecal Collection System

Under each household toilet the faecal matter drops down a dedicated chute and into a dedicated collection bin located in the basement. As can be seen on **Figure 3-6a**, this design results in the lower floors having a smaller bathroom area as space is consumed by the faecal chutes descending from the upper floors.

When full, the wheeled collection bins are designed to be emptied by EETP operation and maintenance staff and replaced with clean ones. To prevent bad odour in the basement, the bins needed to be covered with a good seal between the bin covers and the faecal chutes. There were two main prototypes for the covers: a movable cover that could be lifted off the bin when it was being moved for emptying and a sealed cabinet for housing the bin. The movable bin covers consisted of PVC lids connected by steel lifting mechanisms to the chutes (originally connected to the wall but this design was more difficult to construct properly and also heavier). The seals between the lids and bins were made of plastic foam, after rubber was found to provide poor sealing performance. After one year, the foam seals had deteriorated, along with the steel mechanisms (Zhu, 2008). The bins were then encased in sealed cabinets, which cost more and required greater space. **Figures 3-6b and 3-6c** show the two bin cover prototypes.

Figures 3-6a to 3-6d. *The EETP faecal collection system. (a) The layout of UDD toilets, faecal chutes, and bins in the basement. (b) The movable bin covers attached to the faecal chutes. (c) The sealed cabinets housing the bins. (d). The covered pit access to the basements. [(a) from Zhu, 2008 and (b-d) A. Flores, taken in August 2007.]*

The maintenance of the bins is an important consideration. They have to be taken out of the basements regularly and replaced. Multiple basements in each building were originally designed to be connected by corridors with ramps leading to the outside of the building. This design was found to be too material-intensive and expensive, aesthetically-displeasing, and consumed too much space (Zhu, 2008). The compromise involved removing the corridors and providing separate access to each basement via a covered pit (**Figure 3-6d**).

Mitigating odours in the toilet rooms as they come up from the bins in the basements and through the UDD toilets was a challenge. A ventilation system was installed but it was difficult to achieve the required air flow rates and their uniform distribution within the pipeline network. Other factors contributed to the poor performance of the original ventilation system—and the resulting odour complaints—as described below (Zhu, 2008):

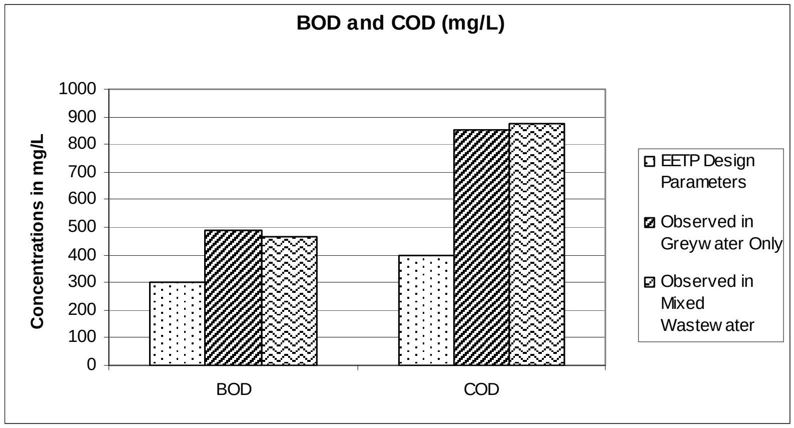
- When the main branch pipe was connected directly to the faecal chutes, materials (sawdust, toilet paper, garbage thrown down the toilet) would get sucked into the pipe and block it, thus contributing to reduced air flow rates. This was addressed by connecting the branch pipe to the bin covers instead, and later, to the sealed cabinets.
- Rearrangement of the fan and pipeline configurations and the installation of regulation valves were necessary to improve the distribution of air flows within the system.
- The original movable bin covers did not seal well. In addition, the flexible branch pipelines used to connect them to the trunk pipelines of the ventilation system provided high resistance and reduced air flow rates. Both problems were addressed by the installation of cabinets.

Compounding the design issues noted above is the poor installation of the ventilation system. Construction-related problems included: misaligned fans and pipelines and high resistance in the pipelines due to excessive bends and turns. As Zhu (2008) notes, better planning of the layout of the complex pipeline network (including urine, greywater, and ventilation pipelines and the faecal chutes) in the basement could help improve the ventilation system installation and performance.

3.2.4.4 Greywater Treatment System

Greywater was collected separately at the EETP and treated onsite using a septic tank, and anaerobic and aerobic treatment followed by sedimentation. The treatment plant was designed for 250 m^3/day. The treatment system, as shown on **Figure 3-3**, was selected based on economic and technical considerations (ability to meet treatment standards and operation and maintenance requirements) after the review of two other alternatives: 1) a septic tank and spray filtration system pioneered in Norway and 2) a septic tank, anaerobic contact tank, and anaerobic bio-filter system developed in China and known as the "underground non-powered domestic waste water treatment" (Zhu, 2008). Greywater was originally envisioned to be reused, with the pond designed to store the reclaimed water for landscape irrigation and to provide aquatic scenery. The plant was built to meet Grade II discharge standards, although there were plans to enhance the treatment process to meet the more stringent Grade IB standards for reuse (see **Section 4.1** for a discussion of standards). These enhancements included the addition of coagulation/flocculation, filtration, and disinfection.

Figures 3-7a and 3-7b compare the design and observed greywater influent values at the EETP in April-June 2007, and observed mixed wastewater values at another multi-storey residence in the Dongsheng District (Minsheng Residential Area) in June 2007. Since no greywater data was available in China, design parameters were based on values from the USA and Sweden (Zhu, 2008). When the treatment system began operation in 2007, monitoring of the greywater quality revealed that the influent had significantly higher levels of Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) than expected. EETP greywater ammonia-nitrogen (NH_4-N) was much lower than the design influent value while Total Phosphorus (TP) was approximately the same as the design influent value. EETP greywater was also found to be similar in BOD, COD, and TP levels to mixed wastewater, but had a much lower NH_4-N content due to urine diversion. Zhu (2008) notes that the average water consumption had been lower than expected, contributing to the more concentrated BOD and COD levels. A large fraction of greywater was also presumed to be originating from kitchen sinks, resulting in high organic matter content.



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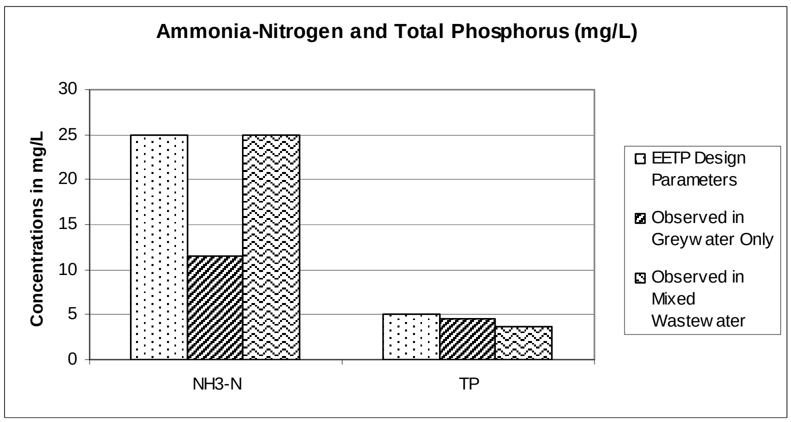

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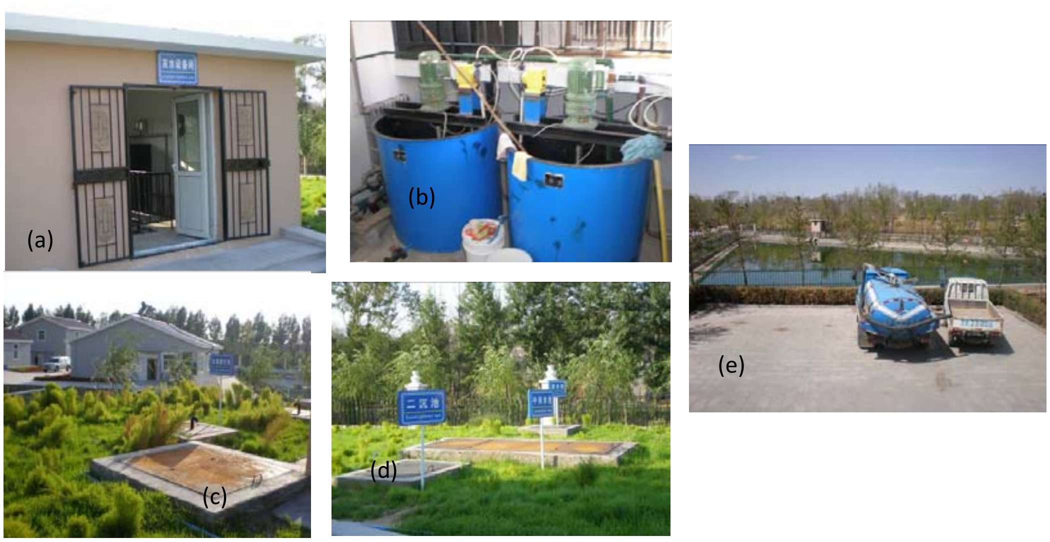
Figures 3-7a and 3-7b. *Greywater treatment system: comparison of design and observed influent values for constituents. (a) Biochemical oxygen demand (BOD) and chemical oxygen demand (COD). (b) Ammonia-nitrogen (NH_3-N) and total phosphorus (TP). Greywater data are from the EETP treatment plant influent in April-June 2007 and mixed wastewater data are from another multi-storey residence in the District in June 2007.*

Starting in August 2007, the greywater treatment plant (**Figures 3-8a to 3-8e**) began producing water that on average met discharge standards for disposal (Grade II) but not general reuse (Grade IB). **Table 3-1** lists the results of monitoring conducted from August through December 2007 (Zhu, 2008). As of 2009, treated greywater was being stored at the pond and discharged via a drainage ditch to the northwest of the EETP site as shown on **Figure 4-1a** in **Chapter 4**.

Table 3-1. *Summary of monitoring results for the EETP greywater treatment plant effluent from August through December 2007.*

PARAMETER (mg/L)	MIN	MAX	AVERAGE	STANDARDS	
				Grade II	Grade IB
Chemical Oxygen Demand	32	176	81	100	60
Ammonia-nitrogen (NH_3-N)	1.0	14	4.0	25	8
Total Phosphorus (TP)	0.8	3.1	1.8	3	1



Figures 3-8a to 3-8e. *The greywater treatment plant at the EETP. (a) The greywater treatment plant building containing chemical storage tanks, pumps, etc. (b) The chemical storage tanks. (c). Underground septic tank in the foreground, anaerobic tank in the middle, and treatment plant building in the back (building closer to the foreground). (d). The rest of the treatment train located underground, on the other side of the treatment building. (e) The storage pond. [A. Flores, (a-d) taken in September 2007 and (e) in April 2009.]*

3.2.4.5 Composting System

The original experimental composting system involved indoor processing of the faecal matter from the collection bins. The first delivery of faecal matter occurred in January 2007. The presence of garbage (particularly plastic bags) and a high percentage of water made the faecal matter difficult to mix. Additionally, the odours were so strong—even with a forced air system that scrubbed the air with HCl and NaOH—that the workers refused to work inside the building. These findings led to the procurement of a sealed indoor composting machine (**Figures 3-9a and 9b**) that was under patent application by Beijing Agriculture University as of 2007. The machine prototype was reported to process organic waste, animal manure, and human waste within 15 days.

This composting machine was found to be ineffective and, in late 2008, a new composting system was installed. The composting machine was converted to a sifter for screening out large inorganic materials, and three sets of dual concrete aerated composting chambers were constructed (**Figures 3-9c and 9d**). As of May 2009, the composting cycle lasted 35 days: sifted materials were placed in the first chamber for 18 days then transferred to the second chamber for an additional 17 days of processing before the compost was bagged (Zhang, 2009) (**Figures 3-9e and 9f**). Each chamber measured 6 m^3. A 3000-watt heater was used for heating from Days 4 through 25 (22 days) and a 550-watt compressor was used to aerate the piles from Days 1 through 25 (25 days) based on the process optimization investigation undertaken by Mertens (2009). Weekly manual turnover of the compost materials was also used to maintain aerobic conditions. The last ten days of the cycle were considered a resting period, allowing the compost to become stabilized. In the Life Cycle Analysis (see **Chapter 5**), 24-hour heating was assumed to be required for only half of the year and aeration throughout the year, but half on and half off during each cycle. Exhaust air collected from the compost piles was processed through an aqueous filter. Effective microorganism (EM) product, a mixture of microorganisms marketed to enhance the composting process, was originally added to the compost piles; Mertens (2009) found that mixing some old compost with the fresh compost materials could be just as effective. The target moisture level was 40%, adjusted through the addition of sawdust or water.

A properly functioning thermophilic composting system requires not only moisture and aeration, but also a good carbon-to-nitrogen ratio in the compost materials. As the microorganisms digest and transform the organic matter in the compost materials, they grow and multiply using the carbon and nitrogen as building blocks for their cells at a ratio of 30 parts carbon to 1 part nitrogen. Excess nitrogen gets converted to ammonia, causing odours (Jenkins, 2005). Esrey *et al*. (1998) therefore recommends a ratio between 15:1 and 30:1, while Jenkins (2005) recommends a ratio between 20:1 and 35:1. Human faeces has a C:N ratio of 5-10 (Jenkins, 2005), and will therefore not compost properly by itself. At the EETP, sawdust was added to absorb moisture and increase the carbon content of the compost materials. Raw sawdust contains very little nitrogen relative to faeces (a C:N ratio of 100-500), and is approximately 50% carbon (Jenkins, 2005). Kitchen organic matter was originally intended to be composted with faeces, but this had not been implemented by the time the dry system was converted to a wet system in mid-2009. Kitchen waste is a good compost material as it has a good C:N ratio; composting it would have reduced the amount of sawdust that needed to be transported and processed and it would have provided a good reuse/disposal mechanism for part of the solid waste generated at the EETP.

Figures 3-9a to 3-9f. *The composting system at the EETP as of May 2009. (a) The composting machine. (b) Inside the composting machine showing the screen used for sifting the material from the faecal bins. (c) The concrete composting chambers. (d) Aerated floor of a composting chamber. (e) and (f) Bagging the compost after 35 days of processing. [(a-b) S. Rued, taken in August 2007 and available at http://www.flickr.com/photos/gtzecosan/, (c-d) from Rosemarin (2009a), and (e-f) A. Flores, taken on 28 April 2009.]*

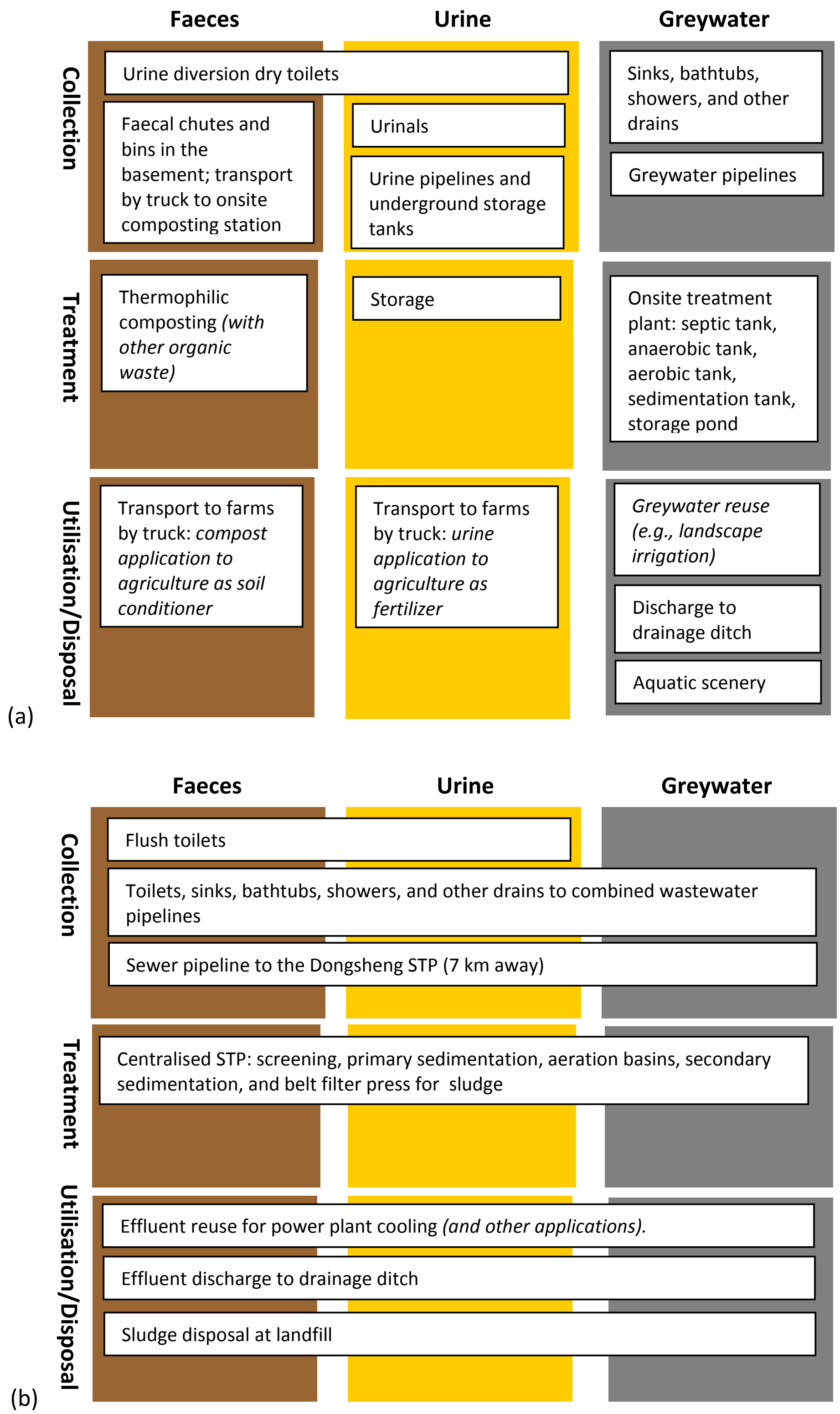
3.2.5 Case Study Scenarios

In this research, two scenarios—DRY and WET systems—are analysed based on wastewater management provision to 1,000 households. While the EETP was designed for 832 households, 1,000 is sufficiently similar in magnitude to allow for similar designs without needing to account for economies of scale. **Figures 3-10a and 3-10b** show the collection, treatment, and disposal/reuse processes associated with the two system scenarios.

The DRY system scenario was based as closely as possible on the actual system in place at the EETP as of Spring 2009 as described in the previous section. One major difference is that complete recovery of the nutrients and organic matter for agricultural purposes was assumed in the environmental Life Cycle Analysis (**Chapter 5**) to reflect the original vision for the site; greywater is discharged to land either for landscape (non-agricultural) irrigation or disposal. Finally, the infrastructure was expanded to allow for all urine and compost to be processed onsite. These modifications were made in order to evaluate the sustainability of a full resource-recovery system—representing a best-case scenario—in an urban setting. While the EETP was unable to achieve this by 2009, it nevertheless was the closest effort to date in realizing this type of system at a large scale.

The WET system scenario is a conventional waterbourne system with effluent reuse. Service for 1,000 households was similarly modeled. Flush toilets and other household drains are connected to a centralized STP similar to the existing Dongsheng STP via a 7-km pipeline. This scenario represents what is being done for other housing developments in the District. Wastewater is partially reused for cooling at a power station and other applications, with the rest discharged to land for disposal.

More details about the two scenarios can be found in the discussion of the sustainability evaluation results in C**hapters 4 to 7**.



Figures 3-10a and 3-10b. *The (a) DRY and (b) WET system scenarios and the associated collection, treatment, and utilization/disposal processes. Items in italics had not been fully implemented as of 2009.*

3.3 Sustainability Evaluation

3.3.1 Sustainability Indicators

A sustainability evaluation is ultimately based on an evaluation of indicators, whether it is stated explicitly or not. An indicator is a parameter that is used to describe a condition, usually to be compared against a benchmark (a baseline condition) or a target (a goal). Indicators are especially useful for defining an abstract concept—such as sustainability, health, or wealth—by breaking it down into more discrete and measurable parameters. More than one indicator is usually needed to define an abstract concept, reflecting its multi-dimensional and complex nature and the potential trade-offs involved.

A review of the literature reveals that indicators for sanitation system sustainability evaluations can generally be grouped into the following categories: public health, environmental, socio-cultural, economic, and engineering performance (Balkema *et al*., 2002; Lundin and Morrison, 2002; Kvarnstrom *et al*., 2004; Bracken *et al*., 2005; UNESCO-IHP and GTZ, 2006). These categories reflect both the "triple bottom line" approach to sustainable development (Elkington, 1994)—integrating people, the economy, and the environment—and the service provided by sanitation systems as engineered systems designed to protect public health and the environment. From their literature review of sustainability evaluations of wastewater systems, Balkema *et al*. (2002) catalogue the following indicator categories as decisive, or having the most significant impact on sustainability: organic matter recovery, nutrient recovery, costs, heavy metal emissions, and land consumption. A review of LCAs of wastewater sludge handling systems by Lundin *et al*. (2004) showed that energy consumption and emissions of nutrients and heavy metals are the indicators most generally associated with the greatest environmental impacts.

Bracken *et al*. (2005) note that "the requirements of sustainability are dictated by context, and can change with time", indicating the importance of considering site-specific conditions for selecting indicators for a given application and a given timeframe. Understanding the objectives of the process is also critical. For example, a company may use sustainability indicators for "reporting, planning, control, benchmarking, formulation of targets [or] as support for decision-making" Palme *et al*. (2005). In this work, the process is intended to operationalize the concept of sustainable development in a wastewater context, to inform the selection and design process, and to identify issues important to the development of sustainability-oriented sanitation policies. While it is based on a specific case study, the goal is to arrive at some general conclusions on the future of resource-oriented sanitation systems. To this end, a broad group of indicators was selected from the literature that integrates the triple bottom line with the engineering or technical dimension (**Table 3-2**). Ideally, for a project such as the EETP, the indicators should be selected in consultation with stakeholders (e.g., the users, the regulators, the environmentalists, local business people, farmers, etc.) evaluated for the options under consideration, and used as the basis for the system selection. For the purposes of this work, the indicators were selected to be as broad as possible, attempting to capture the potential concerns of the various stakeholders. Because the search for alternative sanitation systems has been primarily driven by environmental concerns, a large number of quantitative environmental indicators was included to ensure that trade-offs amongst the different impacts are captured.

Table 3-2. *Summary of indicators, data sources, and tools used in the sustainability evaluation. The indicators were selected to be comprehensive, reflecting the various issues of concern to different stakeholders.*

INDICATORS[(a)]	PRIMARY AND SECONDARY DATA SOURCES AND TOOLS[(b)]
TECHNICAL	
Ability to meet treatment standards	Observations, performance records, literature
Ability to meet capacity requirements	Observations, performance records, literature
Ease of system operation and maintenance (O&M) Users O&M Staff	Observations, surveys, interviews
ENVIRONMENTAL	
Resource Consumption	
Land – Treatment System (m^2/pe)	Construction documents, literature
Energy	Consumption records, GaBi database
Water	Consumption records
Emissions to Water	
% of BOD/COD, Nutrients, and Heavy Metals in Excreta and Greywater Discharged to Surface Water	Literature
Eutrophication Potential (kg Phosphate Equivalent/pe-yr)	Literature; Life Cycle Analysis
Freshwater Aquatic Ecotoxicity Potential (kg DCB-Equivalent/pe-yr)	Literature; Life Cycle Analysis
Marine Aquatic Ecotoxicity Potential (kg DCB-Equivalent/pe-yr)	Literature; Life Cycle Analysis
Emissions to Air	
Acidification Potential (kg SO_2-Equivalent/pe-yr)	Literature; Life Cycle Analysis
Global Warming Potential – 100 yrs (kg CO_2-Equivalent/pe-yr)	Literature; Life Cycle Analysis
Photochemical Ozone Creation Potential (kg Ethene-Equivalent/pe-yr)	Literature; Life Cycle Analysis
Odour (O&M)	Observations, surveys, interviews
Emissions to Land	
% of Heavy Metals in Excreta and Greywater	Literature

INDICATORS[a]	PRIMARY AND SECONDARY DATA SOURCES AND TOOLS[b]
Discharged to Land	
Terrestrial Ecotoxicity Potential (kg DCB-Equivalent/pe-yr)	Literature; Life Cycle Analysis
Resource Recovery	
% of Nutrients in Excreta and Greywater Applied to Agriculture Nitrogen Phosphorus	Literature
% of Energy (from Organic Matter) Recovered for Electricity Generation, etc.	Literature
% of Water Reclaimed for Irrigation and Other Applications	Literature
ECONOMIC	
Capital Cost Per Household – Sanitation	Cost records and literature; Financial analysis
Annual O&M Cost Per Household – Sanitation	Cost records and literature; Financial analysis
User Ability to Pay (Annual O&M Cost of Water and Sanitation as % of Income)	Cost records and literature; Financial analysis
Potential for Local Business Development and Household Income Generation	Observations and literature
SOCIETAL	
User Acceptability and Desirability (Compatibility with Habits and Preferences)	Observations, surveys, interviews
Accessibility to Different Age, Gender, and Income Groups	Observations, surveys, interviews
Minimization of Public Health Risk	Observations, surveys, interviews, literature, bacterial measurements; Qualitative risk assessment
Legal Acceptability and Institutional Compatibility	Observations and literature

(a) References: Balkema *et al*., 2002; Lundin and Morrison, 2002; Kvarnstrom *et al*., 2004; Bracken *et al*., 2005; UNESCO-IHP and GTZ, 2006

(b) A cradle-to-gate database for various materials and processes is embedded in the GaBi Life Cycle Analysis software. This database was derived from the literature, patent information, and other technical sources.

The use of indicators was pilot-tested in a field investigation in Durban, South Africa, where urine-diversion toilets have been installed in large numbers by the eThekwini Municipality. While the investigation revealed that this particular case study did not meet the goals of the research—the sanitation system turned out to be largely based in a peri-urban/rural setting and resource-recovery was not a major component of the project—it helped to refine the indicators and identify the potential challenges and benefits of the methodology. The investigation confirmed the value of indicators to the systematic and explicit incorporation of multi-dimensional sustainability consideration into the development, evaluation, and comparison of wastewater management options. More details about this work can be found in Flores *et al*. (2009).

3.3.2 Tools

As noted in **Section 2.3.1**, various tools are used to arrive at a rating or value for each indicator. **Table 3-2** lists the data sources and tools that were employed for the indicators selected in this work. Most of the indicators required engineering judgment and analysis to develop the ratings; other tools employed are noted in **Table 3-2**, and are described briefly below and in more detail in the relevant sections of **Chapters 4 to 7**. The data used to support the analyses were derived through a variety of data collection techniques, including reviews of literature and project documents, engineering estimates, interviews, surveys, and field observations. The information collected include both qualitative and quantitative data. For the indicators that were qualitatively evaluated, multiple sources of data were used to arrive at a rating whenever possible. The qualitative ratings were as follows: very poor, poor, neutral, good, and very good.

Visits to the case study site in August/September 2007, soon after major construction of the EETP was completed, and nearly two years later in April/May 2009 provided two opportunities for field observations and interviews with stakeholder groups.

A cross-sectional survey of approximately 100 households was also conducted during the second visit ("Spring 2009 Survey") to elicit information about household backgrounds, the users' experiences over the last two years with the operation and maintenance of the dry sanitation system, user training, and perceptions of agricultural application of excreta. A copy of the survey is included in **Appendix A**. It was developed in collaboration with SEI and after review of previous surveys, and translated into Chinese by a translator. With the translator, it was pilot-tested with the first ten households then revised to improve clarity. Participant selection included several approaches: visiting apartments (numbers generated randomly) and approaching people in EETP common areas (playgrounds, supermarket, bus stop, restaurants). A translator was hired and trained to conduct the surveys.

The survey respondents were half female and half male. Not all of the respondents chose to answer the question regarding their educational background, but at least 25% of respondents indicated that hey had university-level education. About 20% of the households surveyed were occupied by one person, while the rest were occupied by couples, couples with children, and extended families (particularly one or more grandparents living with a family). One flat was being used as an office. Approximately 75% of the respondents had used private flush toilets before moving in to the EETP, indicating an urban background or exposure. The demographics at the EETP, as deduced from the Spring 2009 Survey, is also described in **Section 3.2.3.3**.

Interviews were conducted with households, EETP operations and maintenance and other support staff, government officials, and managers of the Dongsheng STP. Agricultural sites in Dongsheng District were also visited. Attempts were made to interview more representatives of the Dongsheng District government and other stakeholders in 2009 but partly due to the politically sensitive nature of the project at that time, the meetings could not be arranged.

3.3.2.1 Life Cycle Analysis

As noted in **Section 2.3.1**, Life Cycle Analysis (LCA) is based on a system analysis approach. It is a well-established tool for evaluating various environmental impacts over the lifetime of a product, service, or process. The general principles and methodology of LCA, and its specific application in this work, is discussed in detail in **Chapter 5**. The LCA is conducted for the construction phase and a 20-year operation phase for the DRY and WET system scenarios. The software GaBi was used to conduct the LCA.

3.3.2.2 Financial Analysis

The financial analysis is mainly based on an accounting of the construction and annual operation and maintenance costs of the two scenarios. Much of the economic analysis results presented here is based on work done by Zhou *et al*. (2007); original estimates were corrected for errors and reconciled with actual costs. Cost projections were also made to account for modifications to the EETP, as described in the descriptions of the case study scenarios in **Section 3.2.4**.

3.3.2.3 Qualitative Risk Assessment

Risk assessment is widely practised for informing policy decisions related to public health. Since the primary purpose of sanitation is to protect public health, it is critical to address the issue of risk when evaluating sanitation systems. The indicator "Minimization of Public Health Risk" (discussed in **Section 7.3**) evaluates how well each sanitation system minimizes public health risk from hazards—namely pathogenic organisms and chemical substances—found in domestic wastewater. Risk is a product of both the nature of the hazard and the exposure. The potential public health risk to users and sanitation system workers, as well as to people in contact with wastewater by-products during reuse applications and/or disposal, are considered in the evaluation. The latter group would include, for example, farmers, consumers of food produced using products recovered from wastewater, landscape maintenance workers, and others. Depending on the health of the population, pathogenic organisms that can be found in wastewater consist of nematodes, bacteria and viruses, and protozoa (WHO, 2006b). Exposure to these organisms can result in health impacts such as intestinal worm infections, malnutrition, diarrheal diseases, and skin infections. Chemical substances in wastewater consist of inorganic and organic compounds, both naturally-occurring and synthetic. Depending on the nature of exposure, certain chemicals in wastewater can lead to health impacts such as methaemoglobinaemia in babies (in the case of nitrate when ingested in large amounts [WHO, 2006c]), heavy metal poisoning (e.g., arsenic and lead), cancer, skin irritations, and endocrine system disruption.

The WHO (2006a) lists three sources of information for quantitatively assessing risk: microbial and chemical laboratory analysis, epidemiological studies, and quantitative microbial and chemical risk assessment. While there is some microbial and chemical laboratory analysis available for the EETP, there is generally very limited quantitative risk assessment information available for the case study. Therefore, the risk assessment is mainly qualitative in nature.

The risk assessment consists of a step-by-step analysis of each sanitation system's collection, treatment, and disposal/reuse processes to identify and characterize hazards, assess potential exposure, and characterize the risks. It draws upon the available microbial and chemical laboratory analysis data; observations of, and interviews related to, behavior and system operation and maintenance; and information available in the literature. The risk characterization considers health protection measures that are being implemented—or can feasibly be implemented—to reduce the probability of adverse effects from the hazards identified. This methodology is in keeping with the approach taken by WHO (2006b) in the development of the four-volume Guidelines for the Safe Use of Wastewater, Excreta and Greywater, in which assessments of environmental exposure and health risks are performed to develop health-based targets and risk management strategies. Health protection measures are a key component of any strategy, helping to provide a multi-barrier protection against hazards and reducing risk. The Guidelines represent the United Nations' position on issues of wastewater, excreta, and greywater use, and is intended to provide policy guidance to national governments. It is one of the key sources of quantitative risk data used in this analysis, and is used to guide the assessment of the health risks.

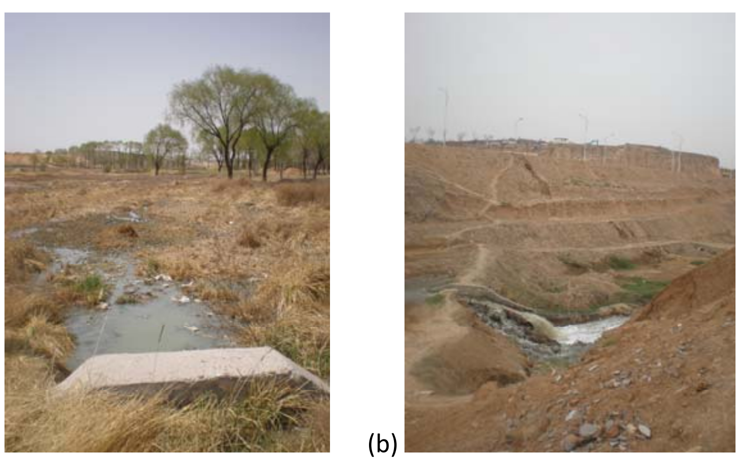
4 Case Study Results: Technical Indicators

This chapter presents the comparative analysis of the technical indicators for the DRY and WET system scenarios as described in **Section 3.2.5**. Because the WET system is well-established and has a long history, the DRY system is discussed in significantly more detail below. The evaluation of the technical indicators uses the following descriptors: very poor, poor, neutral, good, and very good; the results are presented at the end of this chapter.

4.1 Ability to meet treatment standards

China's national wastewater discharge standards are categorized according to the receiving body and/or application (**Table 4-1**). The most stringent set of standards, Grade IA, applies to discharges to important or sensitive water bodies. Grade II standards apply to discharges into water bodies used for industry, agriculture, or landscaping; and into recreational waters in which there is no direct human contact with the water. Grade IB allows for wider reuse applications and has been increasingly applied as the recommended standard for cities and towns (World Bank, 2007). Both the DRY and WET systems discharge effluent into drainage ditches whose flows mainly consist of effluent (**Figures 4-1a and 1b**), and essentially function as informal groundwater infiltration/evapotranspiration systems. Grade II standards apply; however, Grade IB standards are required for the systems' planned reuse applications. Additionally, the District is increasingly pressured to meet Grade IB standards.

(a) (b)



Figures 4-1a and 1b. *Discharge outfalls for (a) EETP treated greywater and (b) Dongsheng STP treated wastewater.*

Table 4-1. *Summary of China's key national wastewater discharge standards (Murray, 2009).*

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) (systems built before Dec. 2005) Total-P (mg/L) (systems built after Dec. 2005)	1.0 0.5	1.5 1.0	3.0 3.0
Total-N (mg/L)	15	20	--
NH_3-N (mg/L) (STPs built before Dec. 2005) NH_3-N (mg/L) (STPs built after Dec. 2005)	8 5	15 8	30 25
Anionic Surfactants (mg/L)	0.5	1	2
pH	6-9	6-9	6-9

4.1.1 DRY System

According to the Erdos Agricultural Center, the application of the DRY system's composted faecal matter to agriculture is allowable and regulated under GB8172-87, which covers *"urban domestic wastes and products from urban compost plants for agricultural use"* and wastes that are not mixed with industrial and other wastes (Liu, 2007). This regulation sets standards for physical, chemical, and biological characteristics of the compost (**Table 4-2**), and its application (e.g., maximum allowable amounts per hectare applied per year, monitoring of effects on the soil, etc.). For agricultural application to be permitted, the compost has to comply with the first nine parameters, but exceptions can be made for the last six parameters on a case-specific basis. An analysis of earlier composting products from the EETP in 2007 indicated that the compost was able to meet the first ten items in **Table 4-2**, but the nutrient levels (item numbers 11-13) were below the recommended values at that time (Liu, 2007).

Table 4-2. *Standards included in GB8172-87 for the application of domestic urban waste to agriculture (Reproduced from Liu, 2007).*

ITEM	PARAMETER[a]	STANDARD
1	Impurities[b]， %	≤3
2	Granularity, mm	≤12
3	Death rate of *Ascaris* eggs, %	95-100
4	Coliform level (number per gram)	10^{-1}-10^{-2}
5	Total Cd, mg/kg	≤3
6	Total Hg, mg/kg	≤5
7	Total Pb, mg/kg	≤100
8	Total Cr, mg/kg	≤300
9	Total As, mg/kg	≤30
10	Organic matter (C), %	≥10
11	Total nitrogen (N), %	≥0.5
12	Total phosphorus (as P_2O_5), %	≥0.3
13	Total potassium (as K_2O), %	≥1.0
14	pH	6.5-8.5
15	Moisture content, %	25-35

NOTES:
a) Except for Items 2, 3 and 4, all other items are calculated on a dry basis.
b) Impurities refer to plastic, glass, metal, rubber etc.

In late 2008, the composting process at the EETP was modified; the original composter was converted to a sifter and three sets of dual composting chambers were constructed. Working with the O&M staff, Mertens (2009) helped to test and optimize the new composting procedure. Testing of the compost produced by the new onsite composting system showed that the compost had low nitrogen, phosphorus, and potassium contents compared to commercial fertilizers on a mass basis, but comparable to composted garden waste (Mertens, 2009). The low nutrient content was likely a result of the sawdust added to the urine diversion dry (UDD) toilets [Liu (2007) and Mertens (2009)]; while legally acceptable, it did make the compost less valuable on a mass basis.

For monitoring the treatment performance of the compost system, temperature profiles are a good measure of hygienizing conditions, as most microorganisms rapidly die off at high temperatures above 40-50°C (Schonning and Stenstrom, 2004). Temperature data for the compost piles were therefore reviewed for the fourth through the sixteenth compost cycles[15], covering a period between December 2008 and July 2009 in which the lowest to the highest ambient temperatures in the District are typically observed; the even-numbered cycles were analyzed to evaluate how the temperature profiles varied under different

15 Records for the first three cycles were not reviewed as they were part of the start-up and testing stage.

ambient temperatures. The data (**Appendix B**) indicate that achieving high temperatures in the 50-60°C range for 14-day periods or longer (as recommended by WHO [2006b]) is achievable both in the winter and summer; however, the composting procedure, as practised, was not consistently able to maintain elevated temperatures. Starting in early April, during the 10th composting cycle, the cycle period was reduced to approximately 35 days by the O&M staff. During cycles 10, 12, 14, and 16, the longest continuous periods when average temperatures stayed between 50 to 60°C were 15, 24, 18, and 6 days, respectively. The inconsistent temperature profiles may have resulted from non-optimal carbon to nitrogen (C:N) ratios (discussed in **Chapter 3**), insufficient volume of raw material to generate enough heat, and insufficient aeration.

Measures that could be taken to maintain high temperatures include: adding organic kitchen waste to optimize the C:N ratio and provide better structure for ventilation (Mertens, 2009); filling the bins for each composting cycle to ensure sufficient volume of raw materials (Mertens, 2009); and using a more powerful blower and more rigorous or frequent manual aeration to maintain aerobic conditions. Jonsson (2009)[16] also suggested the removal of non-compostable solid waste after the completion of the composting process—as opposed to during the preparation for composting—to make use of the solid waste as bulking material and to improve aeration of the pile. Jonsson's suggestion has the added benefit of eliminating the potential additional health risk from workers sifting through raw faecal material. Insulation of the chambers can also assist in maintaining high temperatures. In summary, with some adjustments, the composting procedure should be able to meet treatment standards.

The urine collected in the tanks onsite is treated via storage. There is no specific regulatory standard for urine in China; however, the WHO (2006b) provides some guidelines to render urine safe for agricultural application (see **Section 7.3.1**). Contrary to the original design, residents commonly use water to flush urine, making a more dilute urine solution; dilution results in a less harsh environment for pathogens, leading to a longer required storage time for treatment. The urine storage capacity of the DRY system was therefore expanded in the scenario analyzed under the LCA (**Chapter 5**) to allow for 3 months of storage.

Testing of the EETP greywater treatment plant in 2007 indicated that it generally met Total-P and NH_3-N requirements, but could not meet the COD requirement consistently (Zhu, 2008). A review of 2008 monitoring results found exceedances of COD, Total-P, TSS, and anionic

16 During a site visit to the EETP compost station on 2 May 2009 by Professor Hakan Jonsson, consultant to EcoSanRes, Stockholm Environment Institute.

surfactants at various times. Much of this can be explained by the 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. In reality, the EETP discharges significantly less nutrients and COD per capita than the WET system as a result of waste stream separation and resource recovery; it therefore meets the intent of the discharge standards. To meet the more stringent Grade IB standards, the treatment plant operation will need to be improved with additional processes (e.g., filtration).

Given the DRY system's current deficiencies but the potential for improvement, it was considered to have a "neutral" ability to meet treatment standards.

4.1.2 WET System

According to the District's Environmental Monitoring Director, winter is a particularly challenging time for the operation of the Dongsheng Sewage Treatment Plant (STP), with the low temperatures (down to -25°C) inhibiting biological activity in the uncovered outdoor secondary treatment process (Li, 2009). The STP Director stated that the NH_3-N and P standards were particularly difficult to meet (Wang, 2007). Data provided for August to October 2008 indicate that the existing STP has difficulty meeting other standards consistently even in the warmer months (**Table 4-3**). According to Wang (2007), the new STP planned for completion by 2010 was designed to meet Grade IB standards consistently. Heaters were to be installed at the new STP to improve treatment performance in the winter (Li, 2009). With the new STP taking some of the load off the existing STP, both STPs are expected to have improved performance and more consistent regulatory compliance. In reality, it is often difficult to have the local expertise able to handle the complex operation of secondary treatment plants in China, particularly in smaller towns and cities (World Bank, 2005). However, as discussed in **Chapter 3**, the Erdos is highly-developed and economically prosperous; therefore, with commitment from the District, workers can be properly trained in the STP operation.

Like the DRY system, the WET system has not been optimized but appears capable of meeting treatment standards with some improvements. It was therefore also given a "neutral" rating.

Table 4-3. *Dongsheng STP effluent monitoring results for August to October 2008 (Li, 2009). Items highlighted in bold do not meet the applicable standards.*

Parameter	Grade II Standard	August 2008	September 2008	October 2008
COD (mg/L)	100	**1824***	32	96
TSS (mg/L)	30	**198**	**143**	8
Total-P (mg/L)	3.0	1.8	0.85	--
NH_3-N (mg/L)	30	29.2	18.9	**34.0**
Anionic Surfactants (mg/L)	2	**3.13**	**5.63**	0.05
pH	6-9	7.8	7.8	7.6

* Possibly a sampling error.

4.2 Ability to meet capacity requirements

4.2.1 DRY System

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 EETP's collection system is generally not a technical limiting factor at the scale of 1,000 households.

For the DRY system, modifications were made to the existing system to allow it to meet treatment standards or goals while processing all waste streams onsite; specifically, the total urine storage tank volume and faecal composting facility were expanded as described in **Chapter 5**. There appears to be sufficient land at the site to handle the expansion. The greywater treatment system was over-sized at a capacity of 250 m^3/day or 86 L/person/day for the 832 households at the EETP, considering that water consumption measurements were only in the range of 33-48 L/person/day (Harada, 2008 and Zhu, 2008). Additionally, measurements over a 26-day period in May and June 2009 showed a maximum daily reading of 180 m^3/day at its influent[17]. Thus, the installed greywater treatment system installed could handle the estimated average production rate of 183 m^3/day[18] for 1,000 households.

The DRY system's disposal and reuse components are potentially problematic from a capacity point of view. As discussed in **Chapter 3**, the DRY system scenario assumes complete recovery of nutrients and organic matter (from urine and compost) and recovery

17 As recorded by the treatment plant operator.
18 Based on 62 L/person/day water consumption and 85% recovery rate.

of greywater[19], this had not been achieved in 2009. Urine disposal via agricultural application depends on the demand by third parties, and their infrastructure. As of 2009, there had not been demand for agricultural application of the collected urine; consequently, urine was being discharged at the local landfill. Agricultural application of compost faces the same question of demand reliability. The reliance of the urine and compost disposal systems' capacities on external factors may be limiting for operations. The treated greywater had not been approved for reuse by the District, therefore it could only be discharged from the storage pond via the drainage ditch shown on **Figure 4-1a**. 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 would have been required, especially if the surrounding area were to be developed for housing.

In summary, the DRY system has a good ability to meet the capacity requirements; however, some additional improvements are required, including improved coordination with third parties.

4.2.2 WET System

Conventional sewers and STPs are used around the world to handle a wide range of flows, and can generally be designed to function well for the site-specific capacity requirements. Under the WET system scenario, sewers carrying mixed wastewater from the EETP would be connected to the existing sewerage network and STP serving the much greater population of the District. In fact, other new housing developments in the immediate vicinity of the EETP are already served by conventional sewerage. With a new 60,000 m^3/day STP planned for completion at the end of 2009 to supplement the existing STP's 20,000 m^3/day capacity, it is the government's goal to reuse all of its treated wastewater via irrigation, power plant cooling, and construction applications (Li, 2009); however, it is not clear how this goal can be achieved without a pipeline distribution system for reclaimed wastewater. In any case, any excess treated wastewater would continue to be discharged via drainage ditches such as the one shown on **Figure 4-1b**. Some general limiting factors for STP capacity expansion are the ability of the receiving surface water body to assimilate the contaminants (e.g., nutrients) in the treated wastewater and the availability of land; both factors do not appear to pose problems for the District.

19 This was done to reflect the aspirations for the EETP system, and other potential systems designed for resource recovery.

A conventional sewer system, including the pipelines and pumping stations, is sized to handle the projected maximum hour flow rates to avoid overflows. The pipeline gradients are adjusted to ensure that minimum self-cleansing velocity[20], typically 0.6 m/s (Crites and Tchobanoglous, 1998), is met during times of low flow. The rated capacity of an STP is typically based on the average annual daily flow rate at the design year; however, peak conditions need to be taken into consideration in the design process. Pipelines, tanks, etc. need to be designed to handle the peak hydraulic flow rates to avoid overflows; process units and their support systems should be able to process the peak mass loading rate without violating performance standards (Metcalf and Eddy, Inc., 1991). Similar requirements apply to the EETP's greywater treatment system, which uses processes similar to conventional STPs. Generally, the use of multiple process units in parallel allows a treatment plant to handle the maximum capacity required, as well as the minimum flow rate and mass loading.

In summary, the WET system has a very good ability to meet the required capacity in the District.

4.3 Ease of System Operation and Maintenance

4.3.1 DRY System

The DRY system faces a number of operation and maintenance (O&M) challenges. In general, it is a more complex system because of the separate waste stream processing involved.

From a user perspective, the main differences between the DRY and WET systems are related to the O&M of the UDD toilets and urinals. The Spring 2009 Survey (described in **Section 3.3.2**) 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" and 9 being "very convenient/easy". The urinals fared slightly better at an average user rating of 2.8 (**Figure 4-2**). According to the households, the inconvenience of the UDD toilets was primarily associated with the requirement to separate streams of urine and faeces, the use of sawdust, and the difficulty of maintaining them clean (**Figures 4-3a and 3b**). The urinals are fairly easy to use, although the current installations are too small, resulting in splashing of the surrounding floor with urine and consequently odours;

20 Solids in mixed wastewater may settle out during times of low flow velocities; therefore, the minimum self-cleansing velocity needs to be achieved at least once a day to ensure that the sewer lines do not get blocked.

this can be easily corrected with the installation of larger urinals. As noted previously, many users (88% in one survey [Harada, 2008]) were adding water to the urinals and urine holes in the UDD toilets after every use to keep them clean and minimize odours. The cleaning of the UDD toilets for aesthetic and hygiene purposes is more demanding than that of water-flushed toilets. The use of water and chemicals for cleaning needs to be minimal to limit the amount of fluids entering the faecal bins. Much of the cleaning needs to be done manually as there is no water-flushing action to aid the cleaning of the toilet surfaces; any faeces left stuck to surfaces can contribute to odours. In the Spring 2009 Survey, 60% of the households reported cleaning the toilets after every use or every day.

The maintenance of the toilets and urinals was supported by the onsite O&M team and a 24-hour hotline was established in 2008 so that user complaints could be addressed quickly. McConville (2010) analyzed the types of complaints received between April 2008 and July 2009 and found that most of them were associated with mechanical problems with the toilet, odour, flies, fans, and blockages of the urine pipes. The frequency of calls averaged 66 per month over the 16 months of monitoring. The mechanical problems were related to failures of the springs, chains, and levers of the turning-bowl mechanism, often requiring replacement. Odours could be derived from faeces, urine, or greywater, and were due to a number of things: blocked faecal chutes, malfunctioning blower fans, broken seals on the cabinets (where the bins are stored), open cabinets (which interfered with ventilation system), leaking connection between the urine hole and the urine pipe due to poor construction, blocked odour trap, low/no paraffin oil in the odour trap, blocked S-traps, and dried or inexistent water traps for the greywater pipelines allowing sewer gases to escape into the flats. Flies were a problem in the summertime; with the sealed cabinets, flies could only enter through the toilets. Their presence likely indicated misuse of the toilets, with the flies entering the bins along with food discarded down the faecal chutes (McConville, 2010). The fans' noise bothered some residents, causing some complaints. Finally, precipitation of struvite ($MgNH_3PO_4$)[21] caused blockages of odour traps and S-traps, which occurred as often as once a month.

21 When urea gets converted to ammonia in concentrated urine, the resulting high pH causes precipitation of previously soluble ions (Jonsson *et al*., 2004).

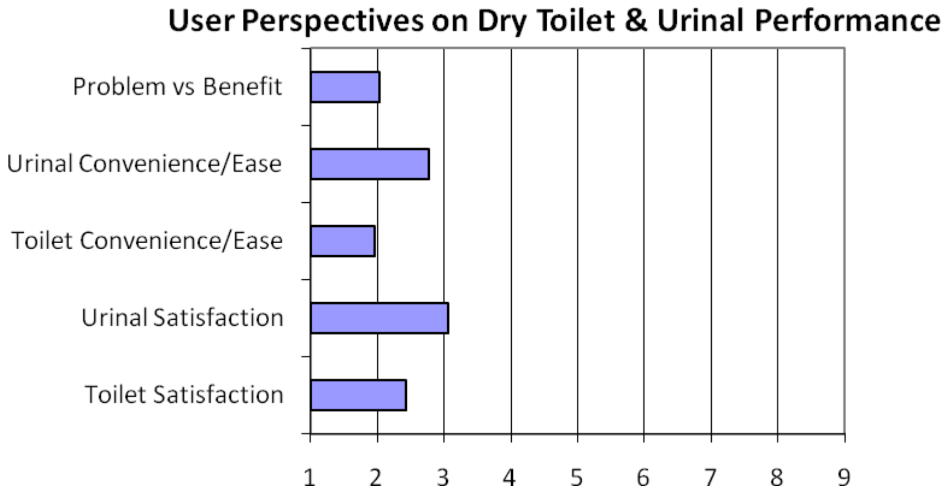


Figure 4-2. *Results from the Spring 2009 Survey of households at the EETP: Averages of user perspectives on dry toilet and urinal performance. Satisfaction: 1 = Very Unhappy, 9 = Very Happy; Convenience/Ease: 1 = Very Inconvenient/Difficult, 9 = Very Convenient/Easy; Problem vs. Benefit: 1 = More of a Problem, 9 = More of a Benefit.*

(a)  (b) 

Figures 4-3a and 3b. *Sawdust use in the UDD toilets. (a) Example of a well-maintained UDD toilet with a sliding plate mechanism. Note that the household is using a box instead of the dispenser. (b) Example of the mess that can be caused by sawdust. [A. Flores, taken September 2007.]*

The maintenance problems listed above were caused by a combination of poor design, poor construction or materials, human error (users not using the toilets properly or workers leaving the cabinet doors open), and some reasonable wear and tear. Poor construction and materials are the easiest to correct in future installations. Improved design of the toilets and ventilation system requires continuing effort from designers and engineers, and optimal solutions have not been found. Human errors can be minimized through better training of users and workers, and, perhaps more effectively, improved design; McConville (2010) reports that workers often found that the households were unresponsive to training or advice on maintaining the toilets and urinals properly.

Preventing blockages due to struvite precipitation can be done at the household level or by maintenance staff. For the former, a vinegar application overnight needed to be done every 10-15 days, while the latter required removal of the traps for soaking in 15% hydrochloride acid (HCl) solution once a month. Precipitation in the less accessible parts of the urine collection system is a potentially big future maintenance issue (Zhu, 2008), exacerbated by the low-or no-gradient installation of the urine pipelines in some parts. An expert who inspected the EETP system (Selke, 2008) noted that flushing the urine collection system to prevent blockages is not a straightforward task, and would require specially-trained team and equipment, re-plumbing of the system to install isolation valves and discharge valves, removal of suspended ceilings during each cleaning, and safe disposal of chemicals.

From the O&M 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, unpleasant, and potentially risky to public health (see **Section 7.3.1**). Access to and processing of the faecal bins need to be improved (**Figures 4-4a and 4b**). The O&M of the greywater treatment plant requires a skilled worker, as in the case of a conventional STP.

Figures 4-4a and 4b. *Views of the covered pit access to the basements at the EETP. Bins are moved in and out of the basements using a hoist attached to the bin collection truck. [A. Flores, taken 5 September 2007.]*

Based on the above, the ease of the O&M of the system was considered very poor for users and neutral for O&M staff.

4.3.2 WET System

The flush toilets associated with the WET system are generally perceived by users as being easier to operate and maintain as indicated by the Spring 2009 Survey; naturally, this only applies when there is a steady water supply. As previously noted, 75% of the respondents to the Spring 2009 Survey had prior experience with flush toilets, so the ease of operation and maintenance can at least partly be attributed to familiarity. The District periodically experiences water supply cut-offs; households prepare by storing water in bathtubs etc. As noted previously, the operation of 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. As discussed further in **Section 7.3.1**, even in societies that have been using flush toilets for many decades, users still need to be reminded to use them properly to prevent blockages. In summary, the WET system was considered very good from a user O&M perspective and neutral for O&M staff.

4.4 Summary of Results

The results of the technical indicator evaluation are summarized in the table below.

Table 4-4. *Summary of the results of the technical indicator evaluation.*

TECHNICAL INDICATORS	DRY SYSTEM	WET SYSTEM
Ability to meet treatment standards	Neutral	Neutral
Ability to meet capacity requirements	Good	Very good
Ease of system operation and maintenance (O&M)		
Users	Very poor	Very good
O&M Staff	Neutral	Neutral

5 Case Study Results: Environmental Indicators

This chapter discusses the evaluation of the environmental performance of the Erdos Eco-Town Project (EETP) dry sanitation system (DRY) and an equivalent conventional waterbourne system (WET). Life Cycle Analysis (LCA) methodology was employed as a major tool for the environmental evaluation, and the details thereof are presented first in **Section 5.1**. Rigorous analysis has been devoted to the environmental dimension of sustainability as the primary drivers for considering alternative resource-oriented sanitation systems are related to the minimization of environmental impacts. As further discussed below, one of the key benefits of LCA is its ability to provide a holistic assessment of environmental issues and to identify environmental trade-offs that may occur. **Section 5.2 discusses t**he evaluation of the environmental indicators.

5.1 Life Cycle Analysis

5.1.1 Overview of LCA and GaBi Software

LCA is a well-established tool for evaluating different environmental impacts over the lifetime of the subject of interest, be it a product, service, or process. It is often referred to as a “cradle-to-grave” approach because a complete LCA examines all of the subject’s life cycle phases from construction through operation and maintenance, and ultimately to disposal or reuse. LCA considers environmental impacts from the extraction, processing, and use of natural resources and the associated emissions of substances to land, water, and air. Recognizing the value of LCA, the United Nations Environment Programme (2003) promotes its use for documenting and analyzing environmental considerations and working towards sustainability.

LCA is useful for identifying specific life cycle phases, materials, or (sub-)processes that contribute significantly to the environmental impacts of the product, service, or process under investigation. Such knowledge can point to design improvements towards environmental sustainability. In an iterative process, LCA models reflecting such design improvements can then be evaluated to see how the various environmental impacts are affected, helping to avoid a mere shifting of the environmental burdens. LCA can also be useful for comparing the impacts of different alternatives—as is done in this research—and providing guidance to decision-making based on specific impacts of concern.

Like any tool, however, LCA has some drawbacks and limitations. Perhaps the most challenging aspect of conducting an LCA is the large quantity of data generally required. The quality of this data is of course important, as it ultimately determines the quality of the results and conclusions. Additionally, LCA aggregates environmental impacts into standard general categories that may mask issues of special interest (Balkema *et al*., 2002). From a sustainability evaluation perspective, LCA is limited in that it only addresses environmental concerns, and therefore needs to be combined with other tools.

In the 1990s, the International Standards Organization (ISO) began developing a standardized technical framework for the LCA methodology as the benefits of LCA across disciplines and industries became apparent. In its 14040 standards series, the ISO (2006a) describes a four-step LCA methodology consisting of:

- <u>goal and scope definition</u> – identification of the purpose of the study, the system boundaries, and the functional unit, and the mapping of a material and energy flow chart,
- <u>Life Cycle Inventory (LCI)</u> – collection of information on consumed resources and emissions within the system boundaries,
- <u>Life Cycle Impact Assessment (LCIA)</u> – assessment and aggregation of environmental impacts accompanied by sensitivity analysis, and
- <u>interpretation</u> – normalization of results, weighting, and/or additional aggregation.

As of 2007, the standards ISO 14040:2006 (ISO, 2006a) and ISO 14044:2006 (ISO, 2006b) together provided the latest official international standards for LCAs, covering LCA principles and framework, and requirements and guidelines, respectively. The guidelines were purposely made broad enough to make the LCA adaptable to system-specific conditions and to reflect its goal/s. **Section 5.1.2** describes the characteristics of the LCA executed in this research within the context of the research goals. The software GaBi Version 4.2 was used to support the LCA. This software was originally developed at the University of Stuttgart in 1992; a spin-off company, PE International GmbH, is currently distributing, enhancing, and updating GaBi, as well as providing consulting services.

In GaBi, the user breaks down the product, process, or system of interest into processes/sub-processes, with their associated material and energy flows and environmental emissions (collectively called the LCI). Data for the LCI may be derived from the user’s personal knowledge of the system, design parameters, experiments and actual measurements, literature reviews, existing LCI databases, or, most likely, a combination thereof. One of the key benefits of GaBi is that it includes an extensive LCI database collection derived from patent, technical, and scientific literature. The databases include cradle-to-gate (from raw material extraction to the factory “gate”) resource flow and environmental emission data for materials (e.g., steel), energy supplies (e.g., power grid mixes), and processes such as transport and disposal. LCI databases are continuing to be developed for research and commercial purposes, particularly in developed countries (e.g., Switzerland, Australia), where much of the LCA work is being done. Curran and Notten (2006) provide a comprehensive review of the various LCI databases available all over the world. GaBi facilitates the LCIA by automatically applying a variety of impact assessment methods to the completed system LCI. The user can therefore select the LCIA method/s most relevant to the goal of the LCA. Finally, GaBi provides a number of tools that can aid in assessing and interpreting the results, including sensitivity analysis, normalization, and weighting.

5.1.2 Goal and Scope

5.1.2.1 Goal and Target Audiences

As noted in **Section 1.6**, the overall goal of this research is to contribute to the increased sustainability of sanitation systems in urban and peri-urban areas. An in-depth case study of the EETP dry sanitation system serves as a lens for closely examining the sustainability issues associated with a large urban resource-oriented sanitation system relative to a conventional waterbourne sanitation system. The LCA is performed to examine the environmental dimension of sustainability, particularly the use of natural resources, emissions to the environment, and the recovery of natural resources. ***The specific goal of the LCA is: to quantify the environmental flows, emissions, and impacts of the EETP dry sanitation system in order to allow for 1) a comparison with those of a conventional waterbourne system and 2) the identification of components—both physical and operational—that can be modified to improve the dry system’s environmental sustainability.***

The inclusion of the dry system’s resource recovery components in the LCA is important as they are considered one of the key drivers for the implementation of dry sanitation systems. The environmental performance of the DRY system is compared against that of a WET system to determine whether such an alternative represents a movement in the direction of improved sustainability.

The target audiences for the LCA are engineers, planners, and policymakers. For engineers and planners, the LCA is intended to elucidate how the environmental performance of resource-oriented sanitation systems can be enhanced, thus pointing the way to technical and operational improvements that can be integrated into future designs of such systems. For policymakers, the LCA is intended to provide a systematic and quantitative evidence base for evaluating the potential environmental benefits of resource-oriented systems so that this information can be considered in the development of sanitation-related policies.

5.1.2.2 Functional Unit

LCA requires the selection of a *functional unit*, which defines on what basis the product or service output is being evaluated; consequently, the LCI data are all quantified based on the functional unit. ***This study's functional unit is the management (collection, treatment, and disposal/reuse) of the excreta and greywater generated by 1,000 urban households in the Dongsheng District over a 20-year period*.** While the existing EETP is designed for 832 households, the LCA is based on a system serving 1,000 households; process units were therefore expanded *where necessary* to reflect the greater population served. The two numbers are sufficiently similar in magnitude to allow for similar designs without needing to account for economies of scale, but the use of the latter number allows the reader to quickly get a sense of the values on a per household basis.

5.1.2.3 System Boundary

An LCA's *system boundary*, which defines the set of unit processes included in the analysis (ISO, 2006a), should generally begin from the extraction of raw materials and end in the reuse or disposal of the finished product (or physical infrastructure required by a service or process) to encompass a complete life cycle. It would therefore include the construction, operation, maintenance, and reuse or disposal phases. However, it may not be necessary to include all of these life cycle phases depending on the specific goals and objectives, and what is known about the relevance of the different phases. Based on studies by Emmerson *et al*. (1995), Barrett (1998), and Gay (1999), Gaterell and Lester (2000) argue that focusing on a few key system inputs and outputs may be sufficient for evaluating the environmental sustainability of wastewater systems.

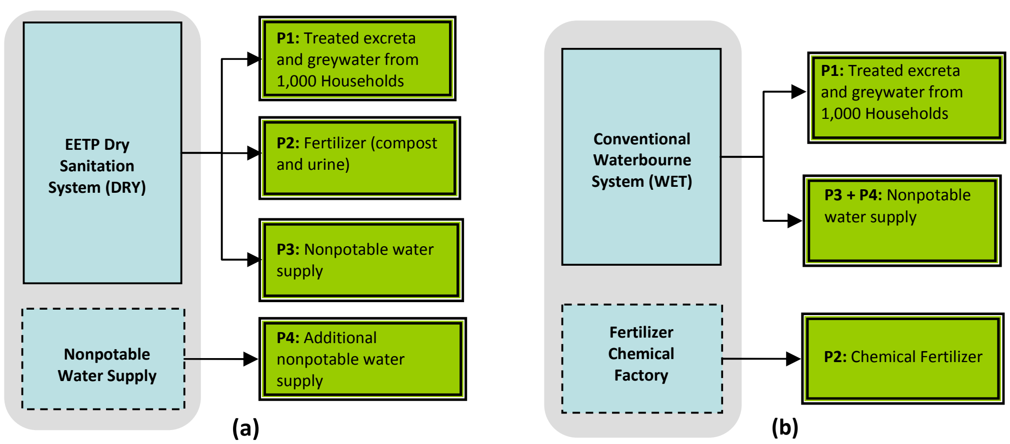
Many studies evaluating sanitation systems have found that the operation phase dominates their life cycle environmental impacts (e.g., Lundie *et al.* [2004], Vlasopoulos *et al*. [2006], Pillay [2006], and Remy and Ruhland [2006]). However, a handful of studies have also shown that the relative impact of the construction phase can vary according to the type of technology employed. Dixon *et al.* (2003) compares small-scale reedbed systems with the more conventional aerated biological filter based on both material and energy flows during construction and energy flows during operation. Consistent with findings by Gaterell and Lester (2000), from energy use and CO_2 emissions perspectives, the authors found that operation dominated the life cycle impacts. From a solids emission perspective, however, the excavation of soil to create the reedbed system resulted in high environmental impact during construction. Similarly, Machado *et al.* (2006) examined a small-scale reedbed system along with slow rate infiltration and the more conventional activated sludge. In this case, an LCA was performed from construction to disposal. In the case of the low-energy systems, construction and disposal represented higher impacts as a percentage of the total impacts as compared to activated sludge, for which operation and maintenance were found to contribute 80% or more to the environmental impacts considered.

In summary, while previous studies show that operation generally dominates the life cycle environmental impacts of sanitation systems, construction can make a significant contribution. Since the EETP dry sanitation system was the first and only large-scale urban dry sanitation system in the world, a more comprehensive assessment was warranted to characterize its environmental performance. Therefore, this study's ***system boundary includes the construction phase and a 20-year operation phase, beginning with the completion of the EETP system in 2007***. The modeling of the construction phase takes into account material lifetimes and any replacements necessary during this time period. The environmental impacts from construction are assumed to be broadly representative of disposal impacts, as they are both related to material intensity and the type of materials used. Exclusion of disposal from the LCA is consistent with much of the recent work done on sanitation systems (e.g., Lundie *et al*. [2004], Gallego *et al*. [2008], and Foley *et al.* [2010]), primarily due to findings from previous studies showing disposal to be of minor significance as compared to the construction and operation of sanitation systems (e.g., Emmerson *et al*. [1995] and Zhang and Wilson [2000]). The limited data available on disposal processes has also prevented its inclusion. Furthermore, it is quite uncommon to demolish entire sanitation systems for disposal.

Some sanitation systems serve multiple functions. The primary function is of course the collection, treatment, and disposal of human excreta and greywater to protect public health and the environment. Many sanitation systems also include the management of stormwater and industrial wastewater in their primary function. Secondary functions can include the production of useful products such as fertilizers, reclaimed water, and energy. Both the DRY and WET systems serve such secondary functions. To make the LCA results of the two systems comparable, the secondary functions are accounted for in a procedure called *system expansion* as described by ISO (2006a) and Tillman (2000) and as visually illustrated on **Figures 5-1a and 1b**. The WET system boundary is expanded to include chemical fertilizer production equivalent to the DRY system's compost and urine. The DRY system boundary is expanded so that it produces the same amount of reclaimed water as the WET system.

In summary, the system boundary starts at the point of excreta and greywater (or combined wastewater) collection and includes treatment and disposal. Reuse via agriculture is also included. It ends where the products are released into the environment and go beyond the authority of those in charge of the sanitation system. The production of potable water is included also as an input to the toilets and urinals, to account for the different water consumptions by the systems' excreta collection. **Figures 5-2 and 5-3** show the system boundaries for the DRY and WET systems investigated.

The GaBi LCA model plans are provided in **Appendix C**.



Figures 5-1a and 1b. *System expansion of the (a) DRY and (b) WET systems as modeled in the LCA.*

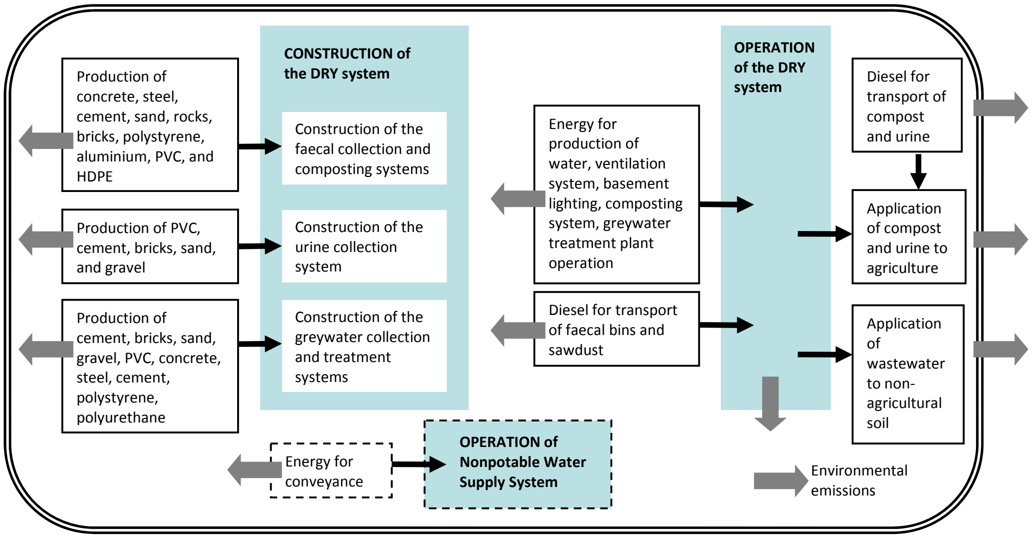


Figure 5-2. *System boundary for the DRY system LCA model. Environmental emissions for the processes shown were included in the LCA. The dashed boxes represent system expansion.*

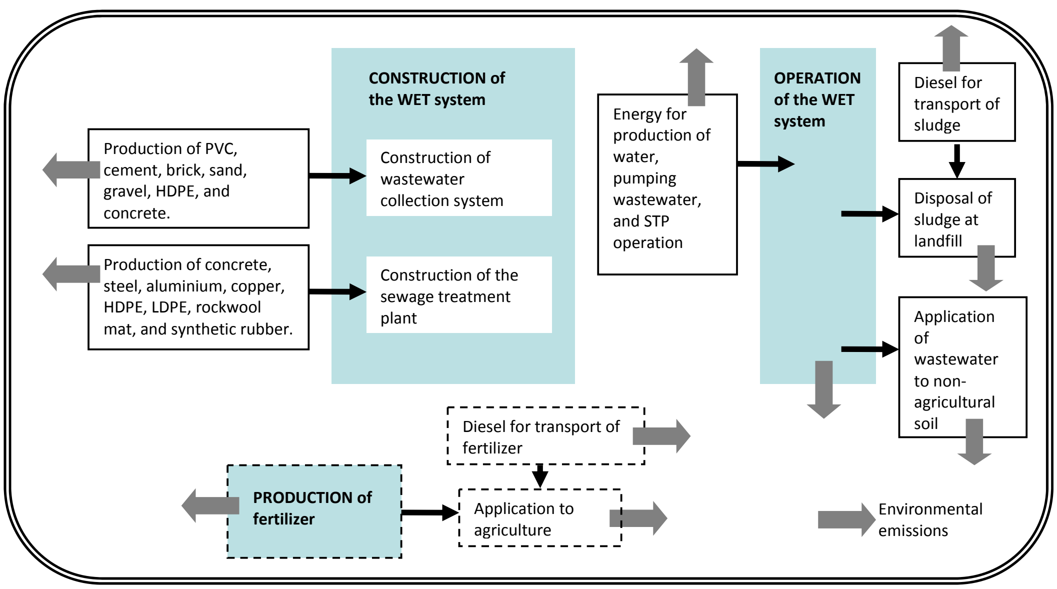


Figure 5-3. *System boundary for the WET system LCA model. The dashed boxes represent system expansion.*

5.1.3 Life Cycle Inventory (LCI)

The *Life Cycle Inventory* is the quantification of the resource consumption and environmental emissions within the system boundary based on the functional unit. For the construction phase, only the materials embodied in the wastewater system components were included in the analysis. For simplification, equipment and other resources (e.g., energy) used for the construction processes were not included as they were assumed to be insignificant. This approach is consistent with work done by others (e.g., Pillay [2006]). Energy use during construction was also not included as it was considered insignificant relative to the entire life cycle of the system (Tillman *et al*., 1998; Lundin and Morrison, 2002). Other items similarly considered insignificant are noted in the following sections. Where site-specific data was not available for a significant item, data was used from other sources and modified as necessary based on engineering experience and the literature. Material amounts were based on a 20-year operating life.

The LCA models use GaBi software's cradle-to-gate LCI databases for the various resources and processes used in the construction and operation of the two modeled systems (e.g., steel and concrete, diesel, and electricity). The databases in GaBi are primarily derived from North America and Europe. Lu *et al*. (2009) note that China's experience with LCA studies is still under development, resulting in very limited China-specific LCI data. The geographic-specificity of data is an important consideration. For globally-traded commodities, this is not a big issue; it is however an important consideration for materials like cement, which are generally locally produced, and for energy sources. However, by using the same database 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.*

A sensitivity analysis is employed to determine the relevance of the assumptions behind the LCI to the overall conclusions, as described in **Section 5.1.6**.

The components of the LCI that were entered into the LCA models, and their associated data sources and assumptions, are presented in the following sections. Note that data used directly from the built-in databases in GaBi are not described in detail here.

5.1.3.1 Inputs to GaBi: Construction

The components included in the construction phases of the WET and the DRY systems are presented in **Tables 5-1 and 5-2**. Much of the DRY system data was derived from detailed construction audits of the actual system; any missing information was estimated based on other EETP data and literature values. The facilities were expanded to allow for complete processing of all excreta at the EETP; specifically, the total urine storage volume was increased to allow for 3-month storage (see **Section 7.3.1** for more details) and the composting facility was also expanded to completely process all faecal materials on-site. The expansion of the composting facility and urine storage only represented 5% of the total original eco-station area and could therefore be incorporated within the original footprint.

Calculations showed that the existing greywater treatment plant and pond could serve 1,000 households.

The WET system was modeled after the existing STP in the Dongsheng District; consumption and emission values were calculated for the proportions represented by 1,000 households. Material data for the Dongsheng sewer system and the STP were not available; a hypothetical design for the sewer line was therefore developed and material data for a comparably-sized secondary treatment plant in Switzerland provided by Doka (2007) was used. Because the system design can vary significantly based on local conditions (e.g., topography, treatment processes), the use of literature values and its impacts on the results are discussed in the sensitivity analysis section. Construction materials associated with the landfill and fertilizer factory have not been included.

Table 5-1. *Components included[a] in the LCA: construction of the DRY system for 1,000 households.*

MATERIALS	MASS (kg)	KEY ASSUMPTIONS[b]
FAECAL COLLECTION SYSTEM Chutes, ventilation system (pipelines and fans), basement structure, cabinets and collection bins		
Concrete	3,685,000	Basement based on improved design of Building 22.
Steel	45,875	
Cement	222,875	
Sand	750,096	
Rocks	5,647,050	
Bricks	8,341,970	
Polystyrene	2,300	
Aluminium	3,546	
PVC	104,375	
HDPE	21,882	
FAECAL TREATMENT SYSTEM Composting building, sifter, composting chambers		
Concrete	715,272	For composting, 54 additional composting chambers were added (only 6 built) plus 1 more sifter, with a corresponding expansion of the building at 5.5x the original size.
Steel	34,278	
Cement	34,398	
Bricks	375,691	
URINE COLLECTION SYSTEM Urine storage tanks, inspection wells, indoor and outdoor pipelines		
PVC	33,795	The total urine storage tank volume was increased by 461 m^3, a factor of 4 increase, to allow for 3-month storage to meet treatment requirements.
Cement	139,163	
Bricks	1,028,846	
Sand	711,010	
Gravel	168,962	
GREYWATER COLLECTION SYSTEM Indoor and outdoor pipelines, inspection wells		
Cement	171,041	Indoor pipelines estimated based on urine collection system.
Brick	503,365	
Sand	642,549	
Gravel	482,752	

MATERIALS	MASS (kg)	KEY ASSUMPTIONS[b]
PVC	45,939	
GREYWATER TREATMENT SYSTEM Treatment train (septic tank, regulating tank, anaerobic and aerobic tanks, sedimentation tank, treated water tank, blowers, pumps), pipelines, operations building, and storage pond		
Concrete	2,931,357	Built system calculated to be sufficient for 1,000 households.
Steel	69,073	
Cement	10,889	
Sand	36,649	
Gravel	1,819	
Polystyrene	2,817	
Bricks	95,669	
PVC membranes	2,330	
PVC pipelines	2,186	
Polyurethane	176	

NOTES:

a. The construction of the following items was not included: water extraction, treatment, and distribution system (wells, pipelines, treatment facility) for both potable and nonpotable water; toilets, urinals, sinks, etc.; treated greywater pipelines; and equipment used in construction.

b. Material amounts were either taken from construction audits or estimated.

Table 5-2. *Components included[a] in the LCA: construction of the WET System with a 40 ML/day STP – portion represented by 1,000 households.*

MATERIALS	MASS (kg)	KEY ASSUMPTIONS
WASTEWATER COLLECTION SYSTEM Local collection system (indoor and outdoor pipelines) and 7-km pipeline to the STP.		
PVC	49,961	Average manhole spacing assumed to be 100 m. Pump stations along the 7-km sewer line not included. Lengths and diameters of local collection system based on EETP greywater system (with slightly larger-diameter outdoor pipeline). Local pipelines made of PVC (as in the DRY system) while 7-km sewer line is made of HDPE as is done at the District.
Cement	171,041	
Brick	503,365	
Sand	642,549	
Gravel	482,752	
HDPE	10,073	
Concrete	151,072	
SEWAGE TREATMENT PLANT (STP) Typical activated sludge plant in Switzerland		
Concrete	1,511,815	Values based on data for a 39.4 ML/day STP in Switzerland (Doka, 2007); Dongsheng STP is 40 ML/day. Landfill for sludge disposal not included, nor the pipeline to the power plants for reuse.
Steel	52,825	
Aluminium	547	
Copper	581	
HDPE	1,540	
LDPE	10	
Rockwool Mat	550	
Synthetic Rubber	556	

NOTE:

a. The construction of the following items was not included: equipment used in construction; water extraction, treatment, and distribution system (wells, pipelines, treatment facility); sanitary wares (toilets and sinks, etc.); pump stations; treated wastewater distribution pipelines; landfill (receiving domestic solid waste and sludge); and fertilizer factory.

5.1.3.2 Inputs to GaBi: Operation

The components included in the operation phases of the DRY and the WET systems, and their system expansions, are presented in **Tables 5-3 and 5-4**. In both cases, operations data were derived from actual operations as much as possible. Other key sources of material and energy flow data, as well as land requirements, were: project reports, construction blueprints, government documents, interviews, and observations during site visits.

Resources used for water recycling after treatment (e.g., pumping) and chemical consumption were not included in either model. A small amount of coagulant is used at the EETP periodically for greywater treatment but it is not tracked (Zhang, 2009) while polymer is used at the Dongsheng STP for thickening. The environmental impacts of these chemicals are assumed to be insignificant relative to the other impacts.

Table 5-3. *Components included[a] in the LCA: operation of the DRY System for 1,000 households over 20 Years.*

PARAMETER[b]	TOTAL AMOUNT	NOTES [References][c]
GENERAL ASSUMPTIONS		
Sulfur in diesel	2,000 ppm	[h]
Truck diesel consumption	10 L/100 km	
Fuel source for power plant	Coal	
FAECAL MANAGEMENT SYSTEM		
Transport of sawdust		
Sawdust amount (kg)	875,000	Based on 50 L sawdust/person/yr [c]
Average R/T distance to sawdust supplier (km)	40	[d]
Mass of diesel for transport (kg)	1,360	
Electricity – Basement Ventilation and Lighting (kWh)	3,326,082	Estimated based on electricity bills for January to May 2009. Equivalent to 166 kWh/household/year.
Transport of faecal bins to eco-station		
Average R/T distance between buildings and eco-station (km)	0.4	
Mass of diesel for transport (kg)	480	Bin emptying 1x/month, 17 bins per truckload [d]
Electricity – Composting (kWh)	2,586,960	24-hour heating half of the year, ventilation on year-round, but half on half off during each cycle. Equivalent to 129 kWh/household/year.
Transport of compost to farms		
Compost amount (kg)	4,025,588	Includes faeces, toilet paper, and sawdust, with total mass reduced by 20% during composting [e].
Average R/T distance between EETP and farms (km)	60	Assumed same distance to the farm that agreed to use compost in 2009.
Mass of diesel for transport (kg)	7,332	Assumed truck payload of 2,800 kg.
URINE MANAGEMENT SYSTEM		
Potable water for flushing (m^3)	63,875	2.5 L/person/day: 0.5 L per urination [a] at 5x/day.
Energy consumption for water supply (kWh)	31,938	Based on 0.500 kWh/m^3 under German conditions [b]. Equivalent to 1.6 kWh/household/year.
Urine capture efficiency (%)	75	Fraction of urine collected via urinals and UDDTs [b].

PARAMETER[b]	TOTAL AMOUNT	NOTES [References][c]
Transport of urine to farms Total amount of urine and water (kg) Average R/T distance between EETP and farms (km) Mass of diesel for transport (kg)	 76,650,000 60 97,729	 1.5 kg urine/person/day [f] and 0.5 L water per urination [a] 5x/day. Distance to the farm that agreed to use compost in 2009. Assumed tanker capacity of 4 m^3
GREYWATER MANAGEMENT SYSTEM		
Electricity – Treatment (kWh)	1,160,700	1.5 kW pump at 18 hrs/day and 5.5 kW blower at 24 hrs/day [g]. Equivalent to 58 kWh/household/year.
SYSTEM EXPANSION: NONPOTABLE WATER SUPPLY		
Additional nonpotable water supply (m^3)	401,774	Difference between DRY and WET system recovered water production.
Electricity – Conveyance (kWh)	100,443	0.25 kWh/m^3 (assumed to be 50% of treated water)

NOTES:
a. Chemical consumption and additional resources used for water reclamation (pumping etc.) were not included.
b. R/T = round-trip
c. References: [a] Harada (2008), [b] Remy and Ruhland (2006), [c] Zhou *et al.* (2007) [d] Zhang (2009) [e] Breitenbeck and Schellinger (2004) in Remy and Ruhland (2006) [f] Jonsson *et al*. (2005) [g] Zhu (2008) [h] International Council on Clean Transportation (2004)

Table 5-4. *Components included[a] in the LCA: operation of the WET System for 1,000 households over 20 Years.*

PARAMETER[a]	TOTAL AMOUNT	NOTES [References][b]
WASTEWATER COLLECTION SYSTEM		
Potable water used for flushing (m^3)	536,550	Based on 21 L/person per day: 3 L per urination, 5x per day, and 6 L/defecation once per day.
Energy consumption for water supply (kWh)	268,275	Based on 0.500 kWh/m^3 under German conditions [a]. Equivalent to 13 kWh/household/year.
Electricity - Pumping (kWh)	132,968	Assumed to be approximately 15% [b] of Dongsheng STP electrical consumption. Equivalent to 6.7 kWh/household/year.
WASTEWATER TREATMENT AND DISPOSAL SYSTEM		
Electricity - Treatment (kWh)	886,457	Based on monthly electricity bills for the Dongsheng STP in 2008. Equivalent to 44 kWh/household/year.
Transport of sludge to landfill Sludge amount (kg) R/T distance between Dongsheng STP and landfill (km) Mass of diesel for transport (kg)	 2,419,388 10 353	 Based on monthly sludge production records for the Dongsheng STP in 2008. Equivalent to 1,936 m^3. [c] Based on truck mileage of 15 L/100 km and 7 m^3 truck capacity [c].
SYSTEM EXPANSION: FERTILIZER SUPPLY		
Urea-ammonium nitrate (UAN) (kg) Monoammonium phosphate (MAP) (kg)	601,325 185,022	Estimated equivalent amounts of chemical fertilizers replaced by urine and compost. N assumed 100% available in urine and 50% available in compost. P assumed 100% available

PARAMETER[a]	TOTAL AMOUNT	NOTES [References][b]
R/T distance between fertilizer factory and Dongsheng	200 km	in both urine and compost. Fertilizers assumed to be produced in the city of Baotou, where a factory exists.

NOTES:
a. Chemical consumption and additional resources used for water reclamation (pumping etc.) were not included. Polyacrylamide is used as a coagulant but is assumed to have minimal impact.
b. References: [a] Remy and Ruhland (2006), [b] Ong-Carrillo (2006) – based on generic activated sludge wastewater treatment plant in the USA, [c] Wang (2009).

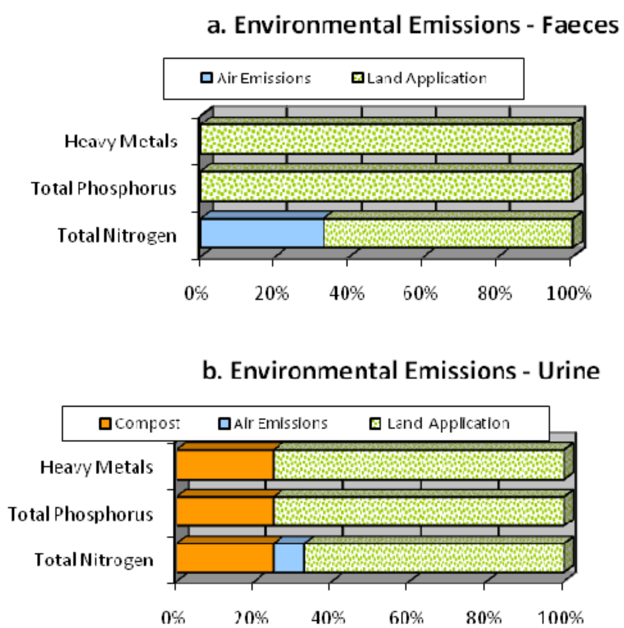
5.1.3.3 Inputs to GaBi: Excreta, Greywater, and Wastewater Constituents and their Environmental Fates

Tables 5-5 and 5-6 below list the excreta, greywater, and combined wastewater characteristics used in the LCA models. Only heavy metal and nutrient flows were included in the models as GaBi software is not able to account for impacts from organic matter; in any case, effluents from both the DRY and WET systems are not discharged to surface water, where organic matter can be problematic. Methane and carbon dioxide emissions to air have not been included; consistent with guidelines from the Intergovernmental Panel on Climate Change (2006), the carbon from domestic wastewater is assumed to be of biogenic origin, and is thus not included in global warming potential accounting. (Note, however, that a recent study by Griffith *et al*. [2009] found fossil-derived carbon representing 25% of the dissolved organic carbon in samples of wastewater effluent . The authors surmise that this carbon originated from petroleum-based household products such as detergents and pharmaceuticals.) Heavy metals and nutrients in greywater/wastewater were assumed to be discharged to “industrial” soil, as opposed to agricultural soil. One of the main differences between the two disposal routes is that the impact methodology used assumes that nutrient discharges to agricultural soil are completely taken up by vegetation; in the case of heavy metals, discharges to agriculture assume a much greater human toxicity potential. **Figures 5-4a, 5-4b, and 5-5** show the breakdown of nutrient and heavy metal emissions by media.

Table 5-5. *Components included in the LCA: DRY System - excreta and greywater characteristics.*

PARAMETER	FAECES	URINE	GREYWATER	NOTES
Organic Matter	**g/person-day**			
Nutrients	**g/person-day**			
N_{tot}	1.37	9.6	1.53	Estimate for China [a]
P_{tot}	0.55	1.1	0.68	Estimate for China [a]
Water		1487		Swedish data [b]
Heavy Metals	**mg/person-day**			
Pb	0.038	0.012	0.26	Swedish data [b]
Cd	0.01	0.0005	0.013	
Hg	0.009	0.00082	0.0013	
Cu	1	0.1	5.2	
Cr	0.124	0.01	0.2	
Ni	0.188	0.011	0.52	
Zn	10.7	0.3	5.2	
	kg/person-day[a]			
Mass - wet faecal matter (inc. water)	0.140			Swedish data [b]
Mass - Toilet paper	0.023			

References: [a] Jonsson *et al.*, 2004 [b] Jonsson *et al.*, 2005



Figures 5-4a and 4b. *Components Included in the LCA: DRY System - Environmental emissions of nutrients (total nitrogen and total phosphorus) and heavy metals from (a) faeces and (b) urine. All greywater constituents are discharged to land.*

Table 5-6. *Components included in the LCA: WET System – wastewater characteristics (domestic only).*

PARAMETER	Wastewater Content	NOTES
Nutrients	**g/person-day**	
N_{tot}	12.5	Estimate for China [a]
P_{tot}	2.33	Estimate for China [a]
Heavy Metals	**mg/person-day**	
Pb	0.038	Swedish data [b]
Cd	0.024	
Hg	0.011	
Cu	6.3	
Cr	0.334	
Ni	0.719	
Zn	16.2	

References: [a] Jonsson *et al.*, 2004 [b] Jonsson *et al.*, 2005

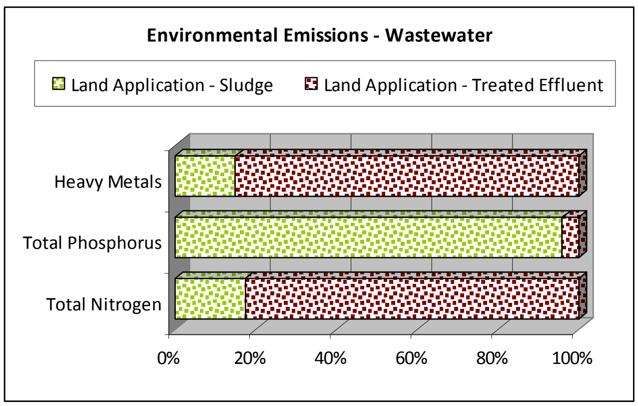


Figure 5-5. *Components Included in the LCA: WET System - Environmental emissions of nutrients and heavy metals from domestic wastewater. All emissions are assumed to be discharged to industrial (i.e., non-agricultural) soil.*

5.1.3.4 Inputs to GaBi: Fertilizer Values and Emissions

As noted previously, the WET system was expanded to include fertilizer production equivalent to the nutrients available in the urine and compost produced by the DRY system.

In 2007, the Test Lab of the Erdos Agricultural Centre performed field testing of the compost and urine collected from the EETP. Tests were conducted on the effects of compost on potato crop yields and of compost and urine on corn crop yields in plots located in the Dongsheng District. Details of the study can be found in Liu (2007). The objectives included finding the optimum dosages and application methods and determining the yield increase effects of compost and urine using controlled field experiments. In the case of potatoes, the applications of varying amounts of compost (30,000-90,000 kg/hectare) were compared against the combined use of manure and ammonium bicarbonate as practised by local farmers (22,500 kg manure and 1,500 kg ammonium bicarbonate per hectare), and no fertilizer application. With the corn tests, various combinations of urine and compost applications (30,000-60,000 kg compost/hectare and 0-27,000 kg urine/hectare) were compared against no fertilizer application, as well as urine application only (9,000 and 18,000 kg per hectare). Compost was found to have a significant fertilizing value on potatoes: yields increased from 20% to 78% compared to unfertilized conditions; however, the maximum tested application of 90,000 kg per hectare yielded 74% less than the local practice. Compost and urine were also found to have a positive impact on corn growth; urine by itself increased corn crop yields by 40% to 57% at 9,000 and 18,000 kg per hectare, respectively, compared to unfertilized conditions.

The tests above are useful for providing solid evidence of the fertilizing value of excreta collected from the EETP. However, the compost used in the study is unlikely to be representative of the compost product in 2009 as the tests were conducted in 2007, when the final composting system had not been installed. In addition, at that time the EETP residents were fairly new to the system and continuing to be trained in the proper use of the DRY system (e.g., minimisation of sawdust and water addition), which could impact the quality of the compost and urine. Therefore, for the purposes of this research, the nutrient values of the compost and urine were calculated based on estimated excreta emissions, losses along the collection and treatment processes, and nutrient availability using data available in the literature.

The estimated fertilizer values from the EETP are equivalent to 2.9 kg and 0.6 kg per person per year available nitrogen (N) and available (P), respectively. These values are similar to those calculated by Remy and Ruhland (2006) in their analysis: 2.6 and 0.54, respectively; as was done by these authors, the soil conditioning value of the organic matter content contained in composted faeces was not included as its impact is difficult to quantify. The benefits of organic matter include improvement of the soil structure, increase of the water-holding capacity, and support of soil microorganisms by serving as food supply (Jonsson *et al.*, 2004). The heavy metal content of fertilizers was based on data from Remy and Ruhland (2006). **Figure 5-6** illustrates the calculation of fertilizer equivalents in the expansion of the WET system scenario over a 20-year period and **Table 5-7** lists the associated emissions of heavy metals and nutrients from chemical fertilizer application.

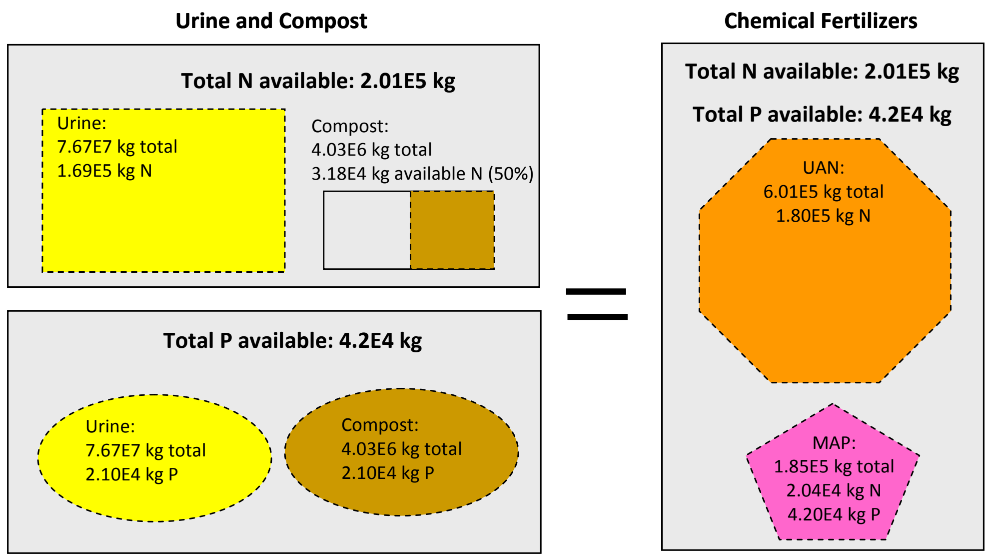


Figure 5-6. *Components Included in the LCA: WET System – Fertilizer equivalents of urine and compost under system expansion (UAN: Urea- ammonium nitrate and MAP: monoammonium phosphate).*

Table 5-7. *Components included in the LCA: WET System – direct emissions of heavy metals and nutrients* to the environment over a 20-Year period from the application of chemical fertilizers to agriculture.*

PARAMETER[a]	EMISSIONS TO LAND (kg)	EMISSIONS TO AIR (kg)	NOTES
As	3.1		Calculated based on average concentrations in N and P chemical fertilizers in Remy and Ruhland (2006)
Cd	4.9		
Cr	66.3		
Cu	13.4		
Ni	12.3		
Hg	0.04		
Pb	16.3		
Zn	117.3		
NH_3		12,188	Calculated based on average emission factors for chemical fertilizers in Remy and Ruhland (2006)
N_2O		7,887	
NO_x		3,011	
N	177,644		

*Emissions from the fertilizer production process itself are not listed here but are included in the model using GaBi LCI cradle-to-gate data.

5.1.4 Life Cycle Impact Assessment

5.1.4.1 Method Overview

The life cycle impact assessment associates inventory data with specific environmental impact categories and category indicators (ISO, 2006a). In GaBi, once an LCI has been generated, environmental impacts are automatically calculated using a variety of impact assessment methods, including: CML, EDIP, Impact 2002+, and TRACI. These methods were developed by different organisations for various applications and objectives; thus, they differ in their approach and focus. Note that the user can also define a new method. One of the philosophical differences amongst the methods is the use of midpoint versus endpoint modeling. According to Bare *et al.* (2003): *"midpoint impact assessment models reflect the relative potency of the stressors at a common midpoint within the cause-effect chain*." Ozone depleting potential and eutrophication are two examples of midpoint impact categories. In endpoint modeling, the ultimate environmental and/or human impact is characterized; examples of endpoints are skin cancer and damage to aquatic life. Key advantages of midpoint modeling are reduced model complexity and fewer assumptions. For example, the contribution of nutrients to eutrophication in surface water is well-characterized; the ultimate damage inflicted upon aquatic life is more difficult to quantify. As such, many models use a midpoint approach (Bare and Gloria, 2008).

Every impact assessment involves *classification* and *characterisation* steps. In classification, LCI data for chemical emissions is assigned to an impact category (e.g., methane emissions to global warming). In characterization, the contributions of various chemical emissions to impact category indicators are quantified using scientifically-developed characterization factors; these factors essentially serve as weighting factors, proportionally reflecting the intensity of the effect of a particular chemical. For each impact category, the category indicator value is calculated as follows (c = chemical) (Pennington *et al*., 2004):

$$\textit{Category Indicator Value} = \sum_{c1,\,c2,\,c3\ldots} [\textit{Characterisation Factor}_c \times \textit{Emission}_c]$$

The environmental impact method selected for this research is CML 2001 developed by the Institute of Environmental Sciences (CML) at the University of Leiden in the Netherlands. This method has been used by other researchers in the past (e.g., Remy and Ruhland [2006] and Pillay [2006]) as it covers the environmental impacts of concern to sanitation systems. Machado *et al*. (2006) note that it is one of the few methods to provide characterization factors for the emissions of nutrients, a key emission of sanitation systems. The choice of the method itself is not as important as choosing a consistent method to make the results comparable between the two systems.

The CML 2001 impact categories included in the analysis are presented in **Table 5-8**, along with information on their scale of impact, associated chemical emissions, and characterization factors. Embodied energy under construction and cumulative energy demand under operation were added as gross indicators of energy consumption. The impact categories include those associated with sanitation systems as identified by previous studies (e.g., Pillay, 2006; Emmerson *et al*., 1995; Remy and Ruhland, 2006; Wittgren *et al*., 2003). Given the novelty of analyzing a large full-scale dry sanitation system, the list of categories was kept broad.

The results of the Life Cycle Impact Assessment for the DRY and WET system scenarios are presented in the following sections. The indicator values for each impact category, broken down by construction and operation and system expansion for each system, are summarized in **Table 5-9**.

5.1.4.2 Results: Construction vs. Operation vs. System Expansion

Figures 5-7a and 7b show the percentage breakdowns of construction (CONS), operation (OPS), and system expansion (OPS-EXP) for the DRY and WET systems, respectively. For the DRY system, system expansion with nonpotable water supply was found to have an insignificant environmental impact relative to the construction and operation phases, with an average contribution of less than one percent. On average, construction and operation have similar percentage contributions at 47% and 53%, respectively; however, except for freshwater aquatic ecotoxicity, one phase generally dominated each impact category. These results differ from other studies noted in **Section 5.1.2.3** that have concluded that the operation phase generally dominates the environmental impacts of sanitation systems; the infrastructure-intensive nature of the EETP design makes the construction phase a significant contributor relative to the 20-year operational phase.

The WET system results differed dramatically. System expansion with fertilizer supply dominated six of the ten impact categories, reflecting the intensive environmental impacts of the fertilizer production process, and underlining the potential for significant gains towards environmental sustainability through the recovery of nutrients. Operation's impacts dominated eutrophication, freshwater aquatic ecotoxicity, and photochemical oxidant creation potential. Construction, on average, had the lowest impacts; its greatest contribution is to marine aquatic ecotoxicity at 41%. Remy and Ruhland (2006) have similarly found that fertilizer supply makes a large contribution to a conventional system's environmental impacts.

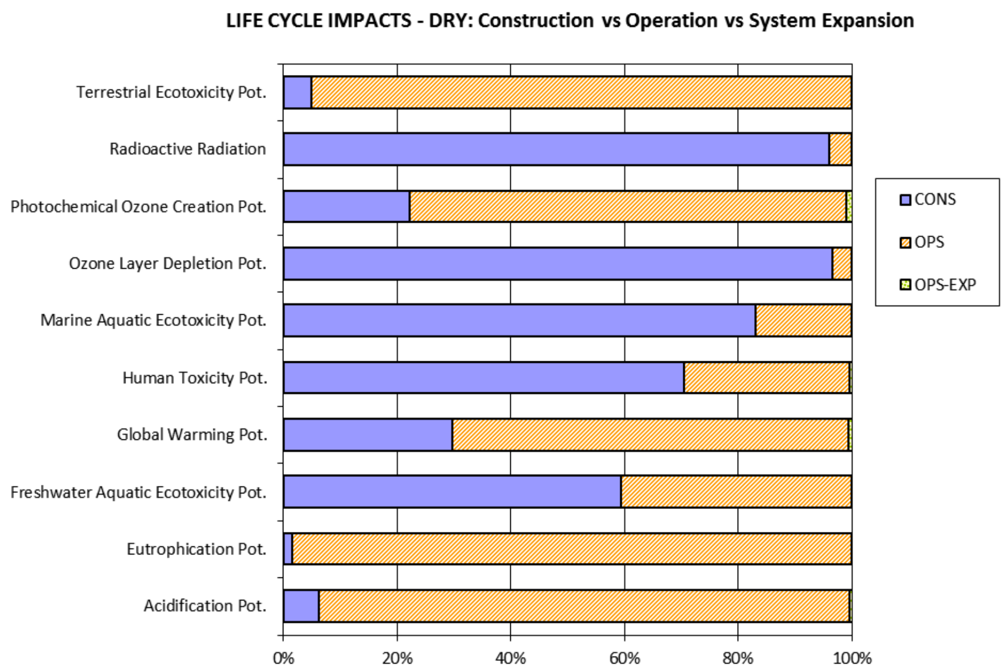
Table 5-8. *Life Cycle Impact Categories included in the study (after SAIC, 2006; Guinee et al., 2001).*

IMPACT CATEGORY	SCALE	EXAMPLES OF ASSOCIATED LCI DATA	CATEGORY INDICATOR	DESCRIPTION OF CHARACTERIZATION FACTOR
Acidification – increased pH of depositions from the air	Regional Local	Sulfur oxides, nitrogen oxides	Acidification Potential	Converts LCI data to hydrogen (H^+) ion equivalents.
Aquatic Ecotoxicity – impacts on the aquatic ecosystem of toxics present in the environment	Local	Toxic chemicals with a reported lethal concentration in fish	Marine Aquatic Ecotoxicity Potential, Freshwater Aquatic Ecotoxicity Potential	Converts LCI data to 1,4-dicholorobenzene (DCB) equivalents[b]
Eutrophication – excessive nutrient enrichment (usually of surface water)	Local	Phosphate, nitrogen dioxide, nitrate	Eutrophication Potential	Converts LCI data to phosphate (PO_4^{3-}) equivalents.
Global Warming – impact of anthropogenic emissions on the increased heat radiation absorption of the atmosphere.	Global	Carbon dioxide, nitrogen dioxide	Global Warming Potential (quantified over 100 years)[a]	Converts LCI data to carbon dioxide (CO_2) equivalents
Human Health – impacts on human health of toxics present in the environment.	Global Regional Local	Total releases to air, water, and soil of chemicals with associated human toxicity.	Human Toxicity Potential	Converts LCI data to 1,4-DCB equivalents[b]
Photochemical Smog – formation of reactive chemical compounds in the atmosphere that may be harmful to human health and ecosystems	Local	Non-methane hydrocarbons (NMHC)	Photochemical Oxidant Creation Potential	Converts LCI data to ethene (C_2H_4) equivalents.
Radioactive Radiation) – impacts on human health of exposure to radioactive materials	Global Regional Local	Krypton-85, carbon-14	Radioactive Radiation	Converts LCI data to Disability Adjusted Life Years (DALY).
Stratospheric Ozone Depletion – thinning of ozone layer due to anthropogenic emissions	Global	Chlorofluorocarbons (CFCs)	Ozone Layer Depleting Potential	Converts LCI data to CFC-11 equivalents.
Terrestrial Toxicity - impacts of toxics in the environment on the aquatic ecosystem	Local	Toxic chemicals with a reported lethal concentration in rodents	Terrestrial Ecotoxicity Potential	Converts LCI data to 1,4-DCB equivalents[b]

NOTES: a. Models commonly quantify over 50, 100, or 500 year periods. b. Uses multi-media exposure pathway modeling.

Table 5-9. *Results of the Life Cycle Impact Assessment for the construction and operation over 20 years of the DRY and WET systems. The values are for 1,000 households.*

IMPACT CATEGORIES	CONSTRUCTION (Sanitation System)		OPERATION (Sanitation System)		OPERATION (System Expansion)	
	DRY	WET	DRY	WET	DRY	WET
Acidification Potential (AP) [kg SO_2-Equivalent]	10,567	1,775	158,821	10,764	839	28,876
Eutrophication Potential (EP) [kg Phosphate-Equivalent]	1,135	187	71,702	240,398	29	5,144
Freshwater Aquatic Ecotoxicity Potential (FAEP) [kg DCB-Equivalent]	222,741	59,705	152,000	143,386	58	40,673
Global Warming Potential (GWP, 100 years) [kg CO_2-Equivalent]	4,592,614	676,259	10,751,012	1,378,771	107,448	3,608,381
Human Toxicity Potential (HTP) [kg DCB-Equivalent.]	1,365,259	344,230	566,220	95,136	6,737	660,872
Marine Aquatic Ecotoxicity Potential (MAEP) [kg DCB-Equivalent]	1,476,587,476	105,505,466	299,134,557	85,707,083	3,509,727	64,398,314
Ozone Layer Depletion Potential (OLDP) [kg R11-Equivalent]	0.0958	0.0127	0.0034	0.0005	0.0000	0.0539
Photochemical Ozone Creation Potential (POCP) [kg Ethene-Equivalent]	1,016	171	3,506	586	46	338
Radioactive Radiation (RR) [Disability Adjusted Life Years or DALY]	0.0023	0.0003	0.0001	0.0000	0.0000	0.0014
Terrestrial Ecotoxicity Potential (TEP) [kg DCB-Equivalent]	4,749	1,089	91,411	86,920	61	438,151
Cumulative Energy Demand [Megajoules]	60,186,489	8,655,837	89,523,447	15,187,352	1,183,147	18,612,576



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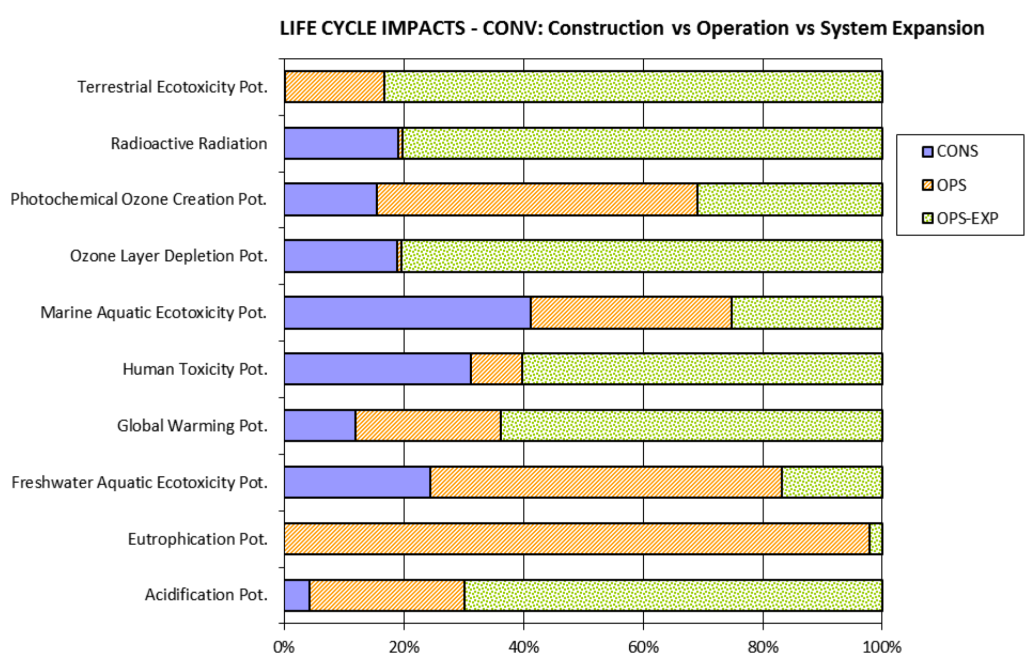
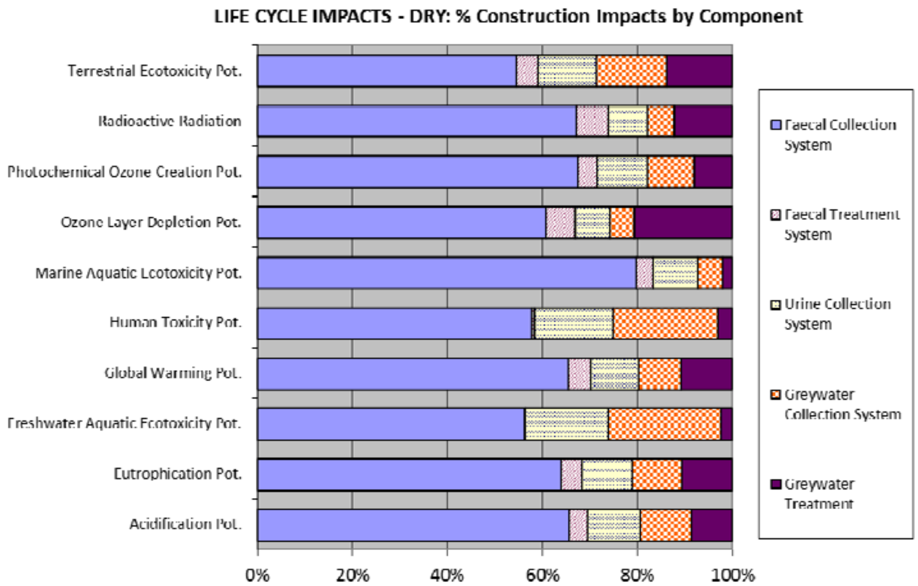


(b)

Figures 5-7a and 7b. *Life Cycle Impacts of the a) DRY and b) WET systems broken down by percentage contributions from construction (CONS), operation (OPS) and system expansion (OPS-EXP).*

5.1.4.3 Results: Impacts by System Component

Figures 5-8a and 8b present the sanitation system construction and operation phase results broken down by system component. The faecal collection system strongly dominates construction impacts, contributing over 50% to all categories. This results from its high material requirements, specifically concrete. The urine and greywater collection systems contribute similar amounts at 11-12% on average. During operation, the faecal collection, the faecal treatment, and the greywater treatment systems similarly contribute 25% and 29%. For the greywater treatment system, the impacts are largely associated with its direct emissions of nutrients and heavy metals to the environment. Overall, power supply is the biggest contributor, representing 71-92% of global warming, human toxicity, marine aquatic ecotoxicity, ozone layer depletion, photochemical ozone creation, and radioactive radiation potential impacts. **Figure 5-9** shows a breakdown of the DRY system electrical consumption. As in the case of construction, the faecal collection system is a major contributor, consuming nearly 50% of the DRY system's energy demands.



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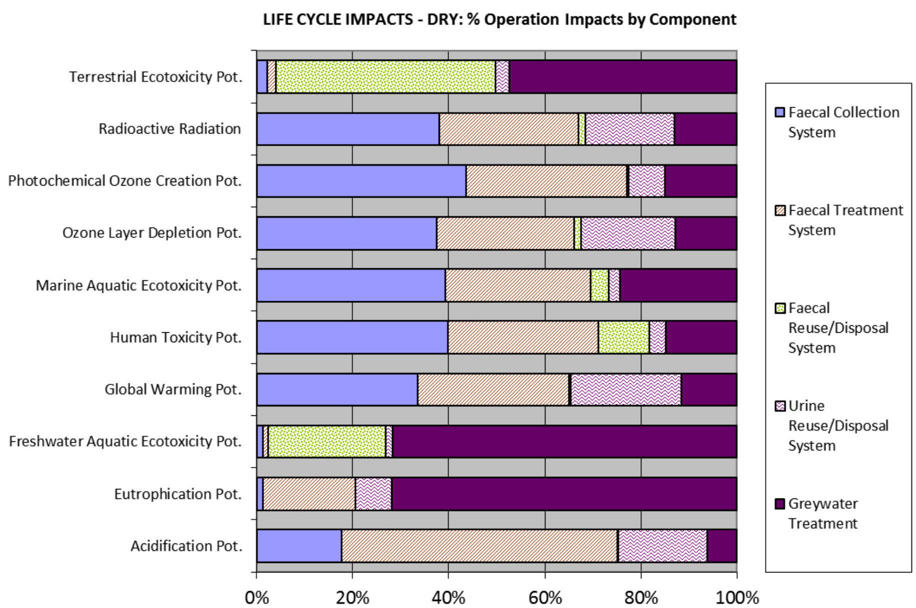
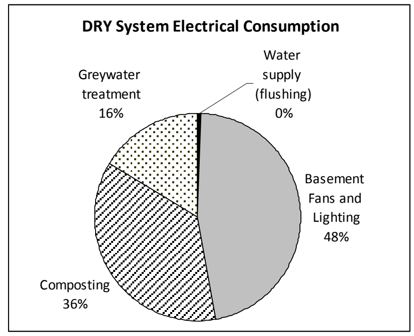


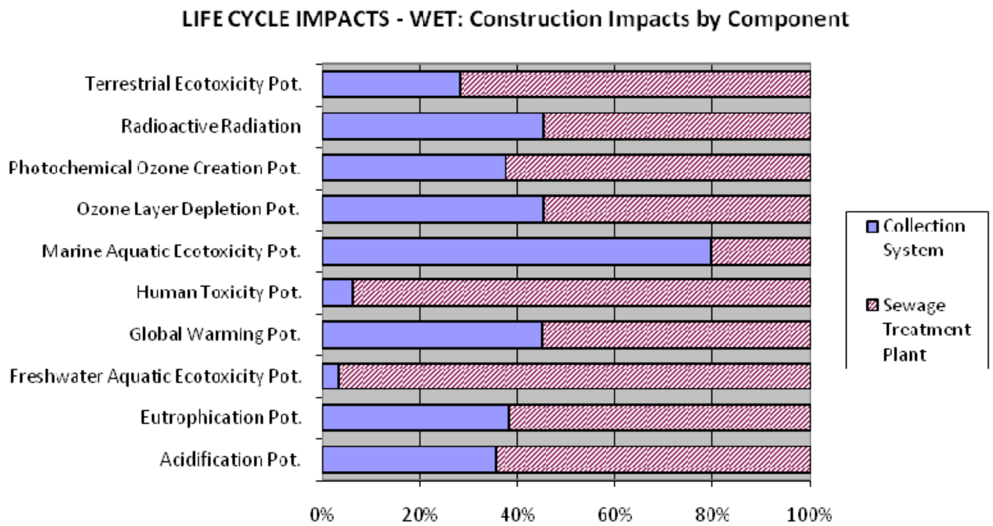
(b)

Figures 5-8a and 8b. *Life Cycle Impacts of the DRY system during a) construction and b) operation over a 20-year period broken down by percentage contributions of the processes. Note that system expansion with nonpotable water supply is not included in these graphs.*

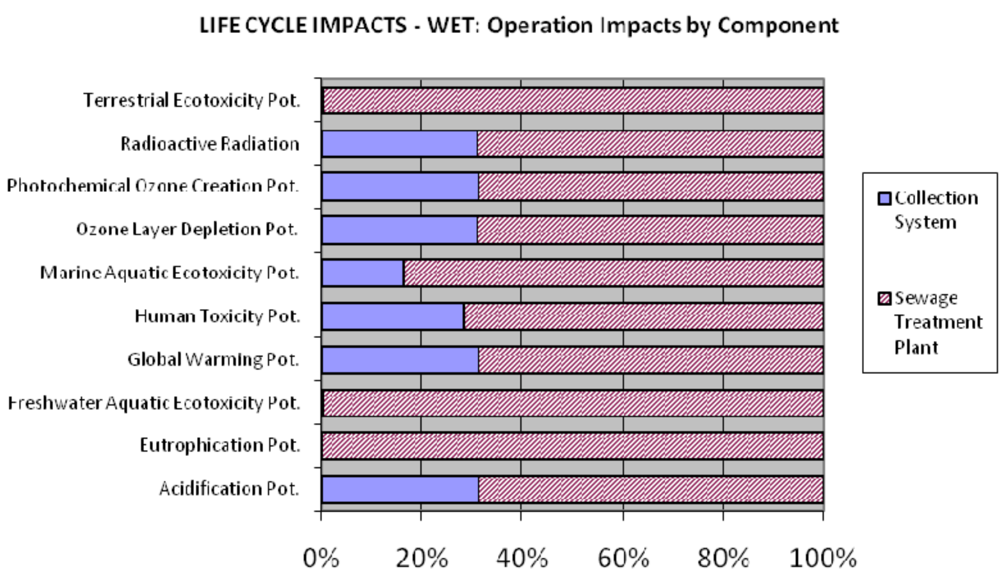
Figure 5-9. *Percentage breakdown of the DRY system electrical consumption.*



Figures 5-10a and 10b present the WET system life cycle impacts for construction and operation, respectively, broken down by system component. During construction, the collection system represents 3-80% of environmental impacts, averaging 36%. The PVC used for the local collection system is a key contributor—particularly from toxicity and ecotoxicity perspectives—accounting for 37% of the total impacts on average. Concrete, bricks, and cement are the next largest contributors. Under the operation phase, the Dongsheng STP dominates, representing 69-100% of impacts. This is because environmental emissions and most of the resource consumption are associated with treatment process.



(a)



(b)

Figures 5-10a and 10b. *Life Cycle Impacts of the WET system during a) construction and b) operation over a 20-year period broken down by percentage contributions of the system components. Note that system expansion with fertilizer production is not included in these graphs.*

5.1.4.4 Results: Cumulative Energy Demand

Cumulative Energy Demand (CED) is a comprehensive indicator, accounting for all of the system energy demands from both renewable and nonrenewable sources. The gross calorific values, as opposed to the net calorific values which include losses associated with water vaporization, were selected for the comparison. As **Figure 11** shows, the DRY system has 3.6x greater CED than the WET system, with 60% of it associated with the operation of the DRY system. In the case of the WET system, the system expansion with fertilizer production and transport represents a large fraction of the total CED at 44%, comparable to that of the wastewater system operation; this finding is very similar to that of Remy and Ruhland (2006).

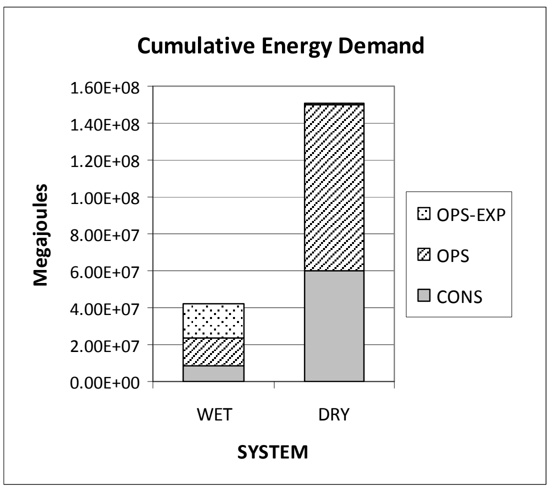


Figure 5-11. Cumulative energy demand of the DRY and WET systems broken down by construction, operation, and system expansion.

5.1.5 Interpretation: Normalization

Normalization is a process by which disparate data can be compared. For example, the impact categories use different units and thus can not be compared directly; by dividing each impact category result by a reference value in the same unit, a dimensionless number can be calculated and used to compare the impact category indicator value results for each system. Examples of reference values commonly used in LCAs are (SAIC, 2006): the total resource use or emissions data for a given area (e.g., global, national, local levels), the total resource use or emissions data for a given area on a per capita basis, the results for a baseline scenario, and the highest values amongst the options being compared.

In this study, several normalization procedures were performed. First, the indicator results for the two systems were individually compared against available national data for China, Germany, and South Korea (**Table 5-10**). These values include environmental impacts from all sources. Because Chinese data was not found for all indicator values, the German and South Korean data were used to get a sense of how the systems performed on a national level in two geographically-different settings. The DRY system indicator values were also normalized against the WET system values to compare their performance amongst the impact categories. These normalization procedures helped to identify the impact categories of most concern, while keeping in mind the local context of the Dongsheng District. Combined with the results presented in **Section 5.1.4**, the components of the DRY and WET systems that contribute the greatest environmental impacts were identified. Such information was then used to guide the improved designs of the sanitations systems towards enhanced environmental sustainability as discussed in **Chapter 8**.

Table 5-10. *Reference values used in normalization. These values represent the total indicator values accounting for environmental impacts from all sources.*

IMPACT CATEGORY	**REFERENCE VALUES (Per Capita Per Year)**		
	China (year unknown)[a]	**Germany (2001)**[b]	**South Korea (2001)**[b]
Acidification Potential [kg SO_2-Equiv.]	36	60	84
Eutrophication Potential [kg Phosphate-Equiv.]		34	37
Freshwater Aquatic Ecotoxicity Potential [kg DCB-Equiv.]		957	879
Global Warming Potential (100 years) [kg CO_2-Equiv.]	8700	14,671	13,097
Human Toxicity Potential [kg DCB-Equiv.]		16,737	16,867
Marine Aquatic Ecotoxicity Potential [kg DCB-Equiv.]		296,437	208,214
Ozone Layer Depletion Potential [kg R11-Equiv.]		0.15	0.18
Photochem. Ozone Creation Potential [kg Ethene-Equiv.]	0.65	18	17
Radioactive Radiation [DALY]		0.000074	0.000073
Terrestrial Ecotoxicity Potential [kg DCB-Equiv.]		98	97

References: a. Li *et al*. (2007) as referenced in Zhao *et al*. (2009) and b. CML 2001 in the GaBi database

Normalization against the German and South Korean national data yielded very similar results. **Figure 5-12** shows the results for Germany. The DRY system made the largest contribution (8.6%) to marine aquatic ecotoxicity as a percentage of total national German values, due to brick and power consumption. The next two highest percentages were acidification potential (4.0%) and eutrophication potential (3.1%). For the WET system, eutrophication (10.4%) and terrestrial ecotoxicity (7.7%) were the two major impact areas; this is consistent with findings by Karrman and Jonsson (2001) for Swedish national data.

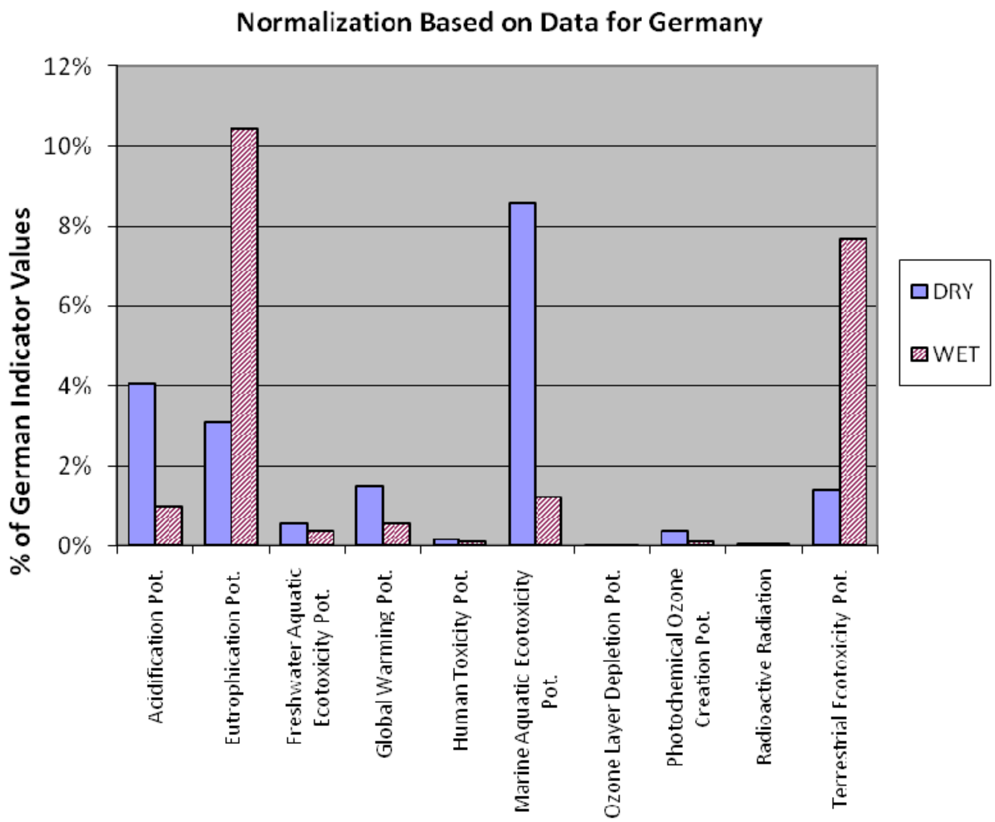


Figure 5-12. *Normalization results: DRY and WET system total indicator values as a percentage of indicator values for Germany in 2001 (on a per capita per year basis).*

The results of normalizing the DRY system impacts against the WET system impacts are presented on **Figure 5-13**. The ratios plotted on the graphs were calculated by dividing the DRY system indicator value by the corresponding WET system indicator value; "total" refers to the sum of construction and operation (including system expansion). The DRY system construction impacts ranged from 4 to 14x those of the WET system while the operation impacts ranged from 0.1 to 4x. The construction of the DRY system clearly offers environmental disadvantages over the WET system, due to its high material intensity. During operation, however, the DRY system offers superior performance based on eutrophication, ozone layer depletion, radioactive radiation, and terrestrial ecotoxicity. It had similar environmental impacts to the WET system based on freshwater aquatic ecotoxicity and human toxicity potential. When the total impacts were calculated, the ratios narrowed down to 0.2 to 7, reflecting the relative contributions of the two phases. Overall, the DRY system performed better under eutrophication and terrestrial ecotoxicity, and performed similarly to the WET system under freshwater aquatic ecotoxicity, human toxicity, ozone layer depletion, and radioactive radiation; it performed worse in the rest of the categories.

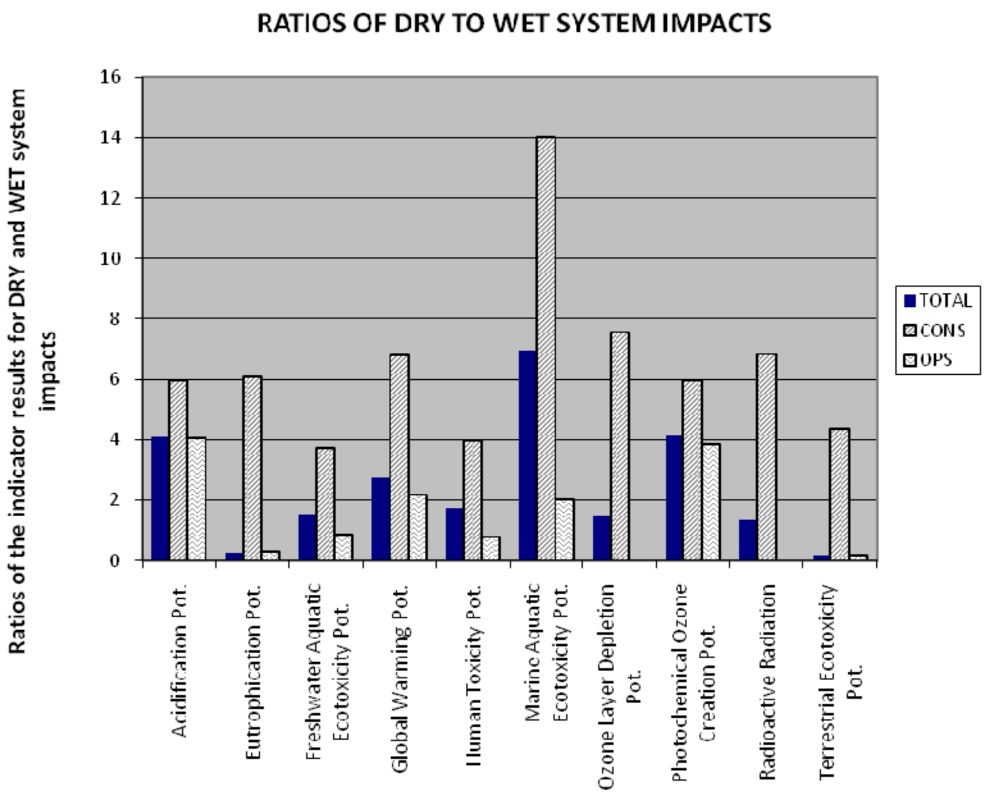


Figure 5-13. *Normalisation of DRY system against WET system indicator values for construction, operation (including system expansion), and total (construction plus operation) impacts. Ratios greater than 1 indicate poorer DRY system environmental performance.*

5.1.6 Interpretation: Sensitivity Analysis

A sensitivity analysis was performed to examine how the assumptions affected the results and the associated conclusions. A number of key parameters was selected for sensitivity analysis based on the key impacts of concern as revealed by the normalization processes described in the previous section.

Table 5-11 below shows the percentage contributions of the key processes and inventory items to the impacts of the DRY system. The specific inventory items that made the three highest contributions were investigated; in general the sensitivity analysis focused on adjusting the parameter values to determine 1) how optimization may decrease the DRY system environmental impacts and 2) to what extent errors in the estimated values may affect the relative performance of the DRY versus the WET systems. Seven sensitivity analysis scenarios (SA-1 to SA-7) affect the DRY system, one (SA-8) affects both systems, and two (SA-9 and SA-10) affect the WET system. These scenarios are briefly described below, and are summarized in **Table 5-12**.

- *SA-1 Urine flush water volume* - The volume of water addition to urine affects not only the size of the storage tanks (and consequently the mass of bricks required), but also the energy required to supply water to the DRY system and the diesel required for transporting urine. This parameter was reduced from 2.5 to 0.5 litres per capita per day—a highly conservative scenario that assumes the full cooperation of users to minimize water addition to the urinals and urine holes—and the storage time was reduced to two months to account for the greater sterilization capability of the more concentrated urine solution.
- *SA-2 Bricks for the construction of the basements* - The mass of bricks used for the construction of the basements was based on the actual materials used during construction as detailed in the accounting audits. For the sensitivity analysis, the mass of bricks was reduced by 30% to reflect any potential improvements in the design or errors in the mass estimate.
- *SA-3 Power for the faecal collection system* - The power for the faecal collection system was estimated based on actual electricity bills for the basements from January to May 2009. The power consumption used in the LCA is 82% greater than the original estimate by Zhu (2008); the difference may be due to inefficiencies in the electrical consumption of the appliances and illegal connections to the basement power supply for other purposes. The power consumption used in the LCA model was equivalent to approximately 19 Watts per household operating continuously. To analyze the effects of overestimating the faecal collection system electrical consumption, it was reduced to 63% of its value, equivalent to 12 Watts per household. This is comparable to the electrical consumption of the Separett toilet, which is equipped with its own fan, and was successfully tested at the EETP as a possible alternative.
- *SA-4 Power for the composting process* - This scenario evaluated the effects of optimizing the DRY system's composting system, with decreases in power consumption by 50% and 90%. The 90% reduction reflects the possibility of greatly

reduced energy consumption based on estimates of the energy demand of biowaste composting presented in Remy and Ruhland (2006). The authors quote work done by Vogt *et al.* (2002) that listed electrical demands of 8.1 kWh, 3 kWh, and 10 kWh per megagram of biowaste for exhaust air treatment during pre-treatment, screening, and intensive composting in insulated boxes, respectively. Using these values, the calculated theoretical energy consumption for composting was much less than that estimated for the DRY system, at only 4%; however, this value may be more representative of composting in a milder climate than that of the Dongsheng District.

- *SA-5 Air emissions from the composting process* - The emissions during composting were estimated based on the data from Vogt *et al*. (2002) for open pile composting as quoted by Remy and Ruhland (2006). The air inside the EETP composting room did get processed through an aqueous scrubber so the nitrogen air emissions may have been lower than assumed, although it was difficult to quantify. Also, the net reduction of nitrogenous air emissions is related to how the aqueous scrubber solution is handled. For this sensitivity analysis, a 90% capture of nitrogen by the compost was assumed. This resulted in a 70% reduction of nitrogenous air emissions.
- *SA-6 Air emissions from urine application to agriculture* - In the DRY system model, nitrogen loss to air from urine was estimated at 8%. In reality, losses of nitrogen can be greater or smaller than 8% depending on the field application technique and other factors. Remy and Ruhland (2006) cite the work of Palm *et al*. (2002), which estimates nitrogen losses between 1 to 10% due to ammonia evaporation, and pilot tests where nitrogen losses of 6 to 14% were observed. Assuming again an optimization scenario, nitrogen loss was reduced to 4% in this scenario.
- *SA-7 Land emissions of nutrients from greywater* - The nutrients in greywater were assumed to be discharged to industrial soil, ultimately contributing to eutrophication through their transport to surface water bodies. To reflect improved reuse conditions, this scenario instead reused the nutrients through landscape irrigation (assumed as disposal to “agricultural” soil in GaBi) and the application of sludge to agriculture. As a consequence, heavy metals in greywater were also assumed to be emitted to agricultural soil. This scenario assumed that the nutrients are used by vegetation.

- *SA-8 Power consumption of water supply* - The power consumption of the water supply did not have a big impact in the original DRY system LCA model. However, this parameter may have been significantly underestimated at 0.50 kWh/m^3, given the fact that additional water supplies to the District have to be transported over a 100-km distance from the Yellow River with a 100-meter lift. As a point of reference, the conveyance of water from northern California to southern California in the USA—using one of the most extensive water conveyance systems in the world—consumes 2.35 kWh/m^3 on average (Ong-Carrillo, 2006); this transfer occurs over hundreds of kilometers in some parts, with the highest pump lift at 587 meters[22]. Including treatment and distribution, the water supply in southern California consumes 2.7 kWh/m^3. In this sensitivity analysis, the power consumption of water is tripled to 1.5 kWh/m^3 in both the DRY and WET system scenarios.
- *SA-9 Concrete and Steel for the STP* - The material inventory for the STP was based on a generic activated sludge treatment plant in Switzerland (Doka, 2007); as in the DRY system inventory, only the materials used in significant volumes/masses were included. The inventory was based on a detailed audit of three-stage activated sludge plants, including phosphate precipitation and biogas recovery. This inventory comes from one of the most definitive sources of Life Cycle Inventory data, the ecoinvent database produced by the Swiss Centre for Life Cycle Inventories. Material inventories for STPs can of course be expected to vary based on site-specific conditions, and material intensities vary also based on the plant size. The values used in the original analysis were compared against other values in the literature[23] and were found to be generally higher than average values[24], indicating that the construction-related environmental impacts are more likely overestimated than underestimated. Nonetheless, an increase in material consumption by the WET system was investigated to see to what extent the differences between the DRY and WET systems were narrowed. In particular, the two main components of STP construction, concrete and steel, were increased by 50%.
- *SA-10 Nitrogen emissions to air from the STP* - All nutrients (and heavy metals) were originally assumed to be discharged to industrial soil in the form of either

22 http://www.water.ca.gov/swp/swptoday.cfm. Accessed 26 March 2010.
23 Pillay (2006), Schneidmadl (1999) as cited in Remy and Ruhland (2006), Remy and Ruhland (2006), Zhang and Wilson (2000), Doka (2007).
24 One obvious contributing factor is that the Swiss STP has more treatment processes than a typical conventional STP.

sludge or wastewater effluent. In reality, some nitrogen is likely to be released to the air in the form of nitrous oxide from the wastewater. While Foley *et al*. (2010) recognize that there is considerable uncertainly in estimates of these nitrous oxide emissions, and considerable variability depending on the treatment configuration, they note a mid-range value of 1%. There is also likely to be nitrogen emissions in the form of ammonia gas from sludge, which Foley *et al*. (2010) place at a mid-range value of 20%. These changes were applied in this scenario.

The normalized ratios under the various sensitivity analysis scenarios are summarized on **Figure 5-14**. In general, while there are some cases of large changes in specific indicator values, *none of the sensitivity analysis scenarios above resulted in major changes to the overall conclusions, providing more confidence in the rigour of the results*. In particular, there were no reversals in the relative performance of the two systems under the scenarios. For more details on the results, see **Appendix D**; in addition to noting the change in the individual category indicator values, the revised DRY/WET system ratios by impact category are also calculated, as these ratios inform the comparison of the environmental sustainability of one system versus the other.

As noted in **Section 5.1.4.2**, the system expansion of the WET system with fertilizer supply was found to be a major contributor to the WET system's environmental impacts. The significance of the fertilizer supply's impacts relative to those of the DRY system was evaluated as part of the sensitivity analysis. As a percentage of the total impact of the DRY system, the fertilizer supply was found to contribute the greatest to terrestrial ecotoxicity potential (TEP)(455%), radioactive radiation (RR) (59%), and ozone layer depletion potential (OLDP) (54%). As shown on **Figure 5-13**, the DRY and WET systems perform comparably under the last two impacts (RR and OLDP); potential errors associated with these two impacts could therefore shift the results towards much better or much worse performance of one versus the other. For example, a reduction of the fertilizer supply's RR and OLDP impacts by half would increase the ratios of DRY to WET system impacts from 1.4 and 1.5 to 2.3 and 2.5, respectively (with values greater than 1 indicating worse environmental performance by the DRY system). If the fertilizer supply impacts are instead doubled, the ratios decrease to 0.8 for both impacts. While these differences are significant for comparing the two systems' performance, both sanitation systems actually contribute much less than one percent to the the total RR and OLDP impacts of an average German citizen (see Figure 5-12); therefore, they are not considered "key impacts of concern" as defined above, and fertilizer supply was not included in the scenarios analysed.

Table 5-11. *Sensitivity analysis of LCA results – parameters contributing to the key environmental impacts of the DRY system.*

		PERCENT OF TOTAL IMPACT														
		Faecal Collection		**Faecal Treatment**		**Faecal Reuse/ Disposal**		**Urine Collection**		**Urine Reuse/Disposal**		**Greywater Collection**		**Greywater Treatment**		**System Expansion**
KEY IMPACT CATEGORIES	**TOTAL**	**CONS**	**OPS**	**CONS**	**OPS**	**CONS**	**OPS**	**CONS**	**OPS**	**CONS**	**OPS**	**CONS**	**OPS**	**CONS**	**OPS**	**EXP**
Marine Aquatic Ecotoxicity Potential	100%	66%	7%	3%	5%		1%	8%			0%	4%		2%	4%	0%
		Bricks	***Power***					***Bricks***								
	73%	58%	7%					8%								
Acidification Potential	100%	4%	17%	0%	54%		0%	1%			17%	1%		1%	6%	0%
			Power		***Emissions***						***Emissions***					
	73%		16%		41%						16%					
Eutrophication Potential	100%	1%	1%	0%	19%		0%	0%			7%	0%		0%	71%	0%
					Emissions						***Emissions***				***Emissions***	
	95%				18%						7%				70%	
Photochemical Ozone Creation Potential	100%	15%	33%	1%	26%		0%	2%			6%	2%		2%	12%	1%
		Bricks	***Power***		***Power***											
	68%	9%	33%		26%											
Global Warming Potential	100%	19%	23%	1%	22%		0%	3%			16%	3%		3%	8%	1%
		Bricks	***Power***		***Power***											
	54%	13%	23%		18%											

Table 5-12. *Summary of sensitivity analysis scenarios and results.*

SCENARIO NUMBER AND PARAMETER MODIFIED		OTHER AFFECTED LCA PARAMETERS	ORIGINAL ASSUMPTION	SCENARIO ASSUMPTION/S	RESULTS: % CHANGES IN INDICATOR VALUES[a]
DRY SYSTEM					
SA-1	Urine flush water volume	▪ Required storage time for safety: lower urine dilution rate requires shorter storage time ▪ Material requirements of urine storage tanks ▪ Energy for flush-water supply production ▪ Diesel for urine transport	2.5 L/capita/day	0.5 L/capita/day *37% of the brick (and other material) requirements for the storage tanks* *50% of the diesel for urine transport* *20% of the energy consumption for water supply for flushing*	-0.1 to -5%
SA-2	Mass of bricks for the construction of the basements		---	70% of the original	0 to -22%
SA-3	Power for the faecal collection system (fans and lighting)		Equivalent to 19 Watts per household	Equivalent to 12 Watts per household[d]	0 to -12%
SA-4 – 50%	Power for the composting process (heating and aeration)		---	50% of the original	0 to -13%
SA-4 – 10%				10% of original	0 to -23%
SA-5	Nitrogenous air emissions from the composting process		33% of compost nitrogen emitted to air	10% of compost nitrogen emitted to air	0 to -29%
SA-6	Nitrogenous air emissions from urine application to agriculture		8% of urine nitrogen emitted to air	4% of urine nitrogen emitted to air	0 to -8%
SA-7	Land emissions of nutrients from greywater	▪ Land emissions of heavy metals in greywater	100% emission to industrial soil (disposal via drainage ditch)	100% emission to agricultural[b] soil (reuse via landscape irrigation)	+5.4 to -70%

SCENARIO NUMBER AND PARAMETER MODIFIED		OTHER AFFECTED LCA PARAMETERS	ORIGINAL ASSUMPTION	SCENARIO ASSUMPTION/S	RESULTS: % CHANGES IN INDICATOR VALUES[a]
SA-8	Power consumption of water supply production	* Sensitivity analysis performed for both the DRY and WET systems so that the two systems remained comparable.	0.50 kWh/m^3	1.5 kWh/m^3	DRY: 0 to +0.6% WET: 0 to +22%
WET SYSTEM[c]					
SA-9	Masses of concrete and steel for the STP		---	150% of original	0 to +5%
SA-10	Nitrogenous emissions from the STP		All nitrogen discharged to industrial soil in the form of sludge and wastewater effluent	1% of wastewater nitrogen and 20% of sludge nitrogen emitted to air[e]	-0.3 to +62%

NOTES:

a. Calculated as: [(Scenario Result – Original Result)/Original Result x 100%] for each impact category.

b. “Agricultural” soil was selected in the GaBi software to model landscape irrigation and the uptake of nutrients by vegetation.

c. See also SA-8.

d. Comparable to the electrical consumption of the Separett toilet, which is equipped with its own fan, and was successfully tested at the EETP as a possible alternative.

e. Based on results by Foley *et al.* (2010).

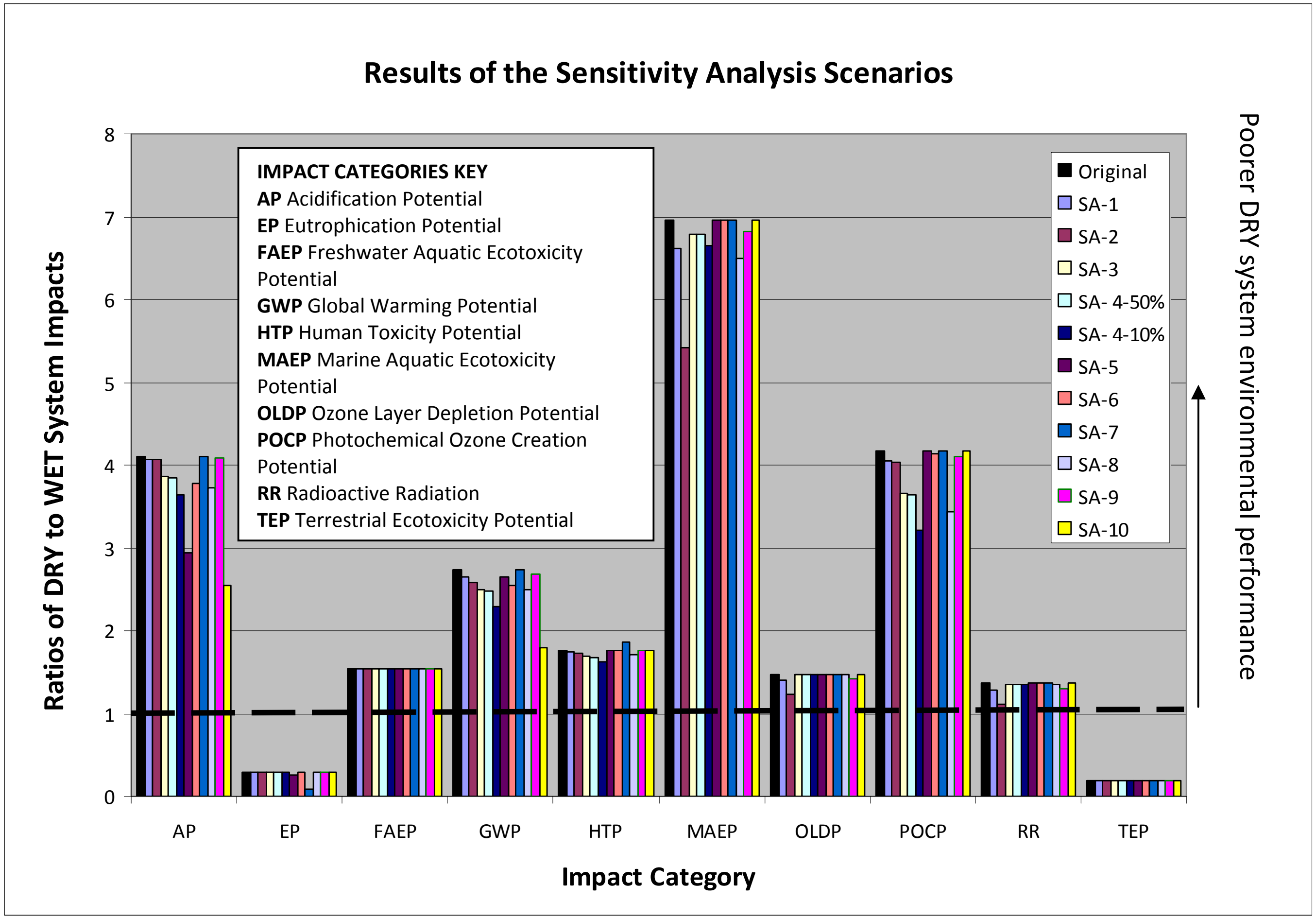


Figure 5-14. *Normalized ratios (DRY/WET) of the indicator values by environmental impact category under the various sensitivity analysis scenarios. Ratios greater than 1 indicate poorer DRY system environmental performance.*

5.1.7 Interpretation: What is not captured by the LCA?

Life Cycle Analysis is unable to capture all of the environmental issues concerning the DRY and WET systems. In particular, the LCA does not account for pressures on finite resources such as water and phosphorus. Water supply is greatly restricted in the District, and has to be imported from the Yellow River, 100 km away. Phosphorus is a nonrenewable resource that is at risk of depletion over the next 125 years according to one estimate, and over the next 50 years if only "clean" sources of phosphorus are included in the estimate (Gilbert, 2009). The soil conditioning value of compost has not been accounted for in the LCA. Finally, LCA software like GaBi performs a generic analysis of environmental impacts without accounting for specific site conditions such as proximity to coastal areas or surface water bodies, the nature of such water bodies (e.g., nitrogen- versus phosphorus-limited), etc.; the results should therefore be re-interpreted in light of what is known about the site conditions to get a sense of the local impacts. A discussion of the ramifications of local versus regional versus global impacts on the evaluation of environmental sustainability is discussed in **Section 8.5**.

5.2 Environmental Indicators

Much of the analysis behind the environmental indicators is based on the LCA approach presented in **Section 5.1**, which also provides details on the assumptions. This section presents the results for the environmental indicators selected for the sustainability evaluation, based on the scenarios described in **Section 3.2.5**.

5.2.1 Resource Consumption: Land Intensity

This indicator evaluates land requirements based on the land used for collection, treatment, and reuse/disposal. Only items that can be exclusively attributed to the sanitation systems have been included. The results are summarized in **Table 5-13**.

The land intensity for the DRY system is equivalent to *3.0 m^2/person or 10,500 m^2 for 1,000 households*. This is composed of the greywater and urine pipelines, the urine storage tanks, and the entire eco-station site including the greywater treatment system and storage pond, the expanded composting facility and urine storage (see **Section 5.1.3.1**), and the O&M office. The agricultural land to which compost and urine are to be applied has not been included as its primary purpose is agricultural production and not sanitation; similarly, any land benefiting from greywater reuse is not included. The land receiving excess treated greywater for infiltration has also not been included.

The land intensity for the WET scenario is equivalent to *0.62-0.68 m^2/person or 2,170 m^2 for 1,000 households*. This includes the hypothetical local wastewater collection system and sewage pipeline to the STP, the existing STP, and estimated sludge landfill requirements over a 20-year period. The sewer system was based on a 7-km pipeline carrying the domestic wastewater from the EETP and surrounding areas normalized on a per person basis, as in the case of the Dongsheng STP. The landfill was based on loading recommendations in USEPA (1979) for a landfill that receives both sludge and other solid waste. The land receiving excess treated wastewater for infiltration, the land occupied by power plants consuming treated wastewater, and the land required for fertilizer production have not been included.

Table 5-13. *Summary of land intensity.*

COMPONENT	LAND		ASSUMPTIONS
	m^2/person	m^2 for 1,000 Households	
DRY System			
Greywater Pipelines (Outdoors)	0.19		Trenches 1.5x width of pipelines
Urine Pipelines (Outdoors)	0.18		Trenches 1.5x width of pipelines
Urine Storage Tanks	0.056		
Eco-station: Greywater Treatment System, Storage Pond, Composting Facility, Additional Urine Storage Tanks, and O&M Office	2.56		Includes expansion of composting facility and urine storage.
TOTAL	**3.0**	**10,500**	
WET System			
Wastewater Pipelines (Outdoors)	0.19		Trenches 1.5x width of pipelines, estimated based on greywater collection system for DRY system.
Sewage Pipeline to the STP	0.11		Trenches 1.5x width of pipelines, estimated based on 7-km long (500-mm diameter) pipeline to STP normalized on a per person basis. Does not include manholes and pump stations.
Dongsheng STP	0.14-0.20		Existing STP normalized on a per person basis; based on the low and high end estimates of people served by the Dongsheng STP (400,000-588,235 people).
Landfill for Sludge	0.18		Estimated based on loading recommendations in USEPA (1979) for a landfill that receives both sludge and other solid waste. Sized for 20-year operation. *(Construction not included in LCI.)*
TOTAL **Average**	**0.62-0.68** **0.65**	**2,170-2,383**	

5.2.2 Resource Consumption: Embodied Energy – Construction

This indicator is a measure of the amount of energy that was used to construct the sanitation systems, and can be used to assess the resource intensity of the physical infrastructure. Only the embodied energy associated with the raw materials is included; the energy associated with the construction process has not been estimated and is therefore not included. In GaBi, embodied energy is taken as the sum of the primary (or cumulative) energy demand from both renewable and nonrenewable resources for the processes included within the system boundaries. The results are summarized in **Table 5-14** below.

Table 5-14. *Summary of embodied energy associated with construction materials.*

SANITATION SYSTEM	EMBODIED ENERGY – CONSTRUCTION	ASSUMPTIONS
DRY	17,000 MJ/person 60×10^6 MJ	Accounts for material replacements over 20 years.
WET	2,500 MJ/person 8.7×10^6 MJ	

5.2.3 Resource Consumption: Energy - Operation

Three ways of looking at energy consumption are presented here (see **Table 5-15**): electrical consumption, diesel consumption, and cumulative energy demand during operation. Coal-derived electricity is used primarily for operating treatment processes, lighting facilities, heating, and ventilation. Diesel is used for transport. Cumulative energy demand is the most comprehensive indicator, accounting for all of the energy demands associated with operations from both renewable and nonrenewable sources.

For the DRY system, electricity is used to run the ventilation fans, light the facilities, operate the greywater treatment plant aeration system and pumps, and heat and aerate the compost. It was also assumed to provide the energy for water treatment and distribution, and for the supply of nonpotable water (included in the system expansion). Diesel is used to transport sawdust from the factories to the EETP, to transport the faecal bins to the composting facility, and to transport the compost and urine to a farm 30 kilometres away from the EETP. As noted previously, in 2009 an organic farm located 30 km away had begun to use EETP compost. For the WET system, electricity is used to transport wastewater to the STP and to run the treatment plant processes (pumping, aeration, heating, and dewatering) and the support facilities (lighting, office equipment, etc.). As in the case of the DRY system, electricity for water treatment and distribution was included.

Table 5-15. *Summary of energy consumption by operations over a 20-year period.*

DRY SYSTEM	WET SYSTEM	ASSUMPTIONS
ELECTRICITY (kWh)		
Water treatment – flush water 31,938 Basement ventilation & lighting 3,326,082 Composting – lighting, aeration, and heating 2,586,960 Greywater treatment system 1,160,700 System Expansion: Nonpotable water supply 100,443 **TOTAL:** **7,105,680 kWh** **2,030 kWh/person** **100 kWh/person-year**	Water treatment – flush water 268,275 Collection system 132,968 Sewage treatment plant 886,457 *System Expansion:* *Fertilizer production* *data not available** **TOTAL** *(not including fertilizer production)*: **1,287,700 kWh** **368 kWh/person** **18 kWh/person-year**	- Water treatment and supply: 0.5 kWh/m^3. - Basement ventilation and lighting demand estimated based on actual bills in 2009 - Greywater treatment demand based on estimate by Zhu (2008) - Assumption for compost heating: 24-hr heating for 22 days of the process during the colder half of the year at 3,000W for 3 sets of chambers - Assumption for compost aeration: compost aeration required daily throughout the year but at half-on/half-off cycles, provided by 1,000W for 3 sets of chambers - Supply of reclaimed water assumed to consume half of that of fresh water: 0.25 kWh/m^3. - **The cradle-to-gate data for synthetic fertilizers in the GaBi database does not list electricity consumption separately.*
DIESEL (kg)		
Transport of sawdust to EETP 1,360 Transport of faecal bins to eco-station 480 Transport of compost to farms 7,332 Transport of urine to farms 97,729 **TOTAL:** **106,901 kg** **1.8 L/person/year**	Transport of sludge to landfill 353 Transport of fertilizer to farms 5,968 *System Expansion:* *Fertilizer production* *Data not available** **TOTAL** *(not including fertilizer production)*: **6,321 kg** **0.11 L/person/year**	Assumptions: - DRY: all compost and urine are processed onsite - DRY: distance to farms of 30 km from EETP site. - WET: transport of equivalent amounts of chemical fertilizer from the city of Baotou (where there exists a factory) to farms 100 km each way. - **The cradle-to-gate data for synthetic fertilizers in the GaBi database does not list diesel consumption separately.*
CUMULATIVE ENERGY DEMAND (MJ) – Gross Calorific Values		
DRY system 89,523,447 Nonpotable water supply 1,183,147 **TOTAL: 90,706,594 MJ** **1,300 MJ/person/year**	WET system 15,187,352 Fertilizer production & transport 18,612,576 **TOTAL: 33,799,928 MJ** **480 MJ/person/year**	

5.2.4 Resource Consumption: Renewable Energy Usage

This indicator is a measure of sustainability from an energy resource perspective. Neither of the two systems uses a renewable energy source. Both systems rely on coal-derived electricity to run the unit processes, while vehicles used for transport consume diesel. Coal is currently available in abundant supply in the Erdos Municipality as it sits atop the largest coalfield in China (Chreod Ltd., 2005); nonetheless, the Municipality has expressed a commitment to renewable energy. In September 2009, the Municipality signed a Memorandum of Understanding to build a 2-gigawatt solar power plant in the area by 2019[25]. Renewable energy use (**Table 5-16**) may therefore improve in the future for both scenarios.

Table 5-16. *Summary of renewable energy usage as a percent of total energy consumption during operations.*

SANITATION SYSTEM	RENEWABLE ENERGY (% of Energy Consumption – Operation)
DRY	0
WET	0

5.2.5 Resource Consumption: Water

The water consumption quantified by this indicator is for the use of the toilets and urinals over a 20-year period, highlighting one of the key differences between the two systems under comparison. The DRY system's toilets and urinals have been designed to operate without water; in reality, households use some water to flush urine down the toilet's urine hole and urinal. Except in cases where the household is grossly misusing the UDDT, water is generally not used during defecation, but a minimal amount is used for cleaning, which is not included the calculation. For the WET system, a dual-flush toilet is assumed to be installed; the toilet model is assumed to use 3 L for flushing urine and 6 L for flushing faeces. The Life Cycle Analysis included the associated energy consumed by the treatment and distribution of flush water in the operational embodied energy calculations. To place the water consumption in the context of the water shortage in the District, the ratio of daily water consumption for toilet and urinal operation to available daily water supply was also calculated. According to Zhu (2008), the daily water availability in the District was 28,000 m^3 before the major project diverting water from the Yellow River supplied an additional 100,000 m^3 per day. Taking 28,000 m^3/day as an estimate of the local sustainable water

25 http://investor.firstsolar.com/phoenix.zhtml?c=201491&p=irol-newsArticle&ID=1328913. Accessed 15 January 2010.

supply and assuming a population of 400,000 people (Zhu, 2008), the daily per capita sustainable water supply is estimated at 70 litres/person/day. The results of the indicator analysis are presented in **Table 5-17**.

Table 5-17. *Summary of water consumption associated with toilet and urinal operation.*

INDICATOR	DRY	WET	NOTES
Water Consumption – Toilet & Urinal Operation			DRY: 0.5 L/urination and 0 L/defecation
Litres/person/day	2.5	21	WET: 3 L/urination and 6 L/defecation
Litres/person/year	913	7,665	(5 urinations/day and 1 defecation/day)
Total litres over 20 years	63,875,000	536,550,000	
As % of local sustainable water supply	3.6%	30%	

5.2.6 Emissions to Water

Both systems discharge to land and therefore do not have direct discharges of organic matter (measured as BOD/COD), nutrients, and heavy metals to surface water during operations; however, the production processes associated with the materials and energy supplies may involve such surface water discharges, leading to environmental impacts like eutrophication and aquatic ecotoxicity. Furthermore, the LCA impact methodology used assumes that discharges to land will eventually make their way to water bodies; in reality, this depends on the specific location.

The summary of water emissions and related environmental impacts are presented in **Table 5-18**. Eutrophication impacts are tied to direct system emissions during operation. For the WET system, eutrophication is a major environmental concern; this is the case for conventional waterbourne systems all over the world that discharge to surface water and is driving costly infrastructure improvements (e.g., see Urban Wastewater Directive by the European Economic Community [1991]). As reflected by its lower eutrophication potential, the DRY system's application of nutrients from urine and faeces to agriculture is an environmental advantage.

The Dongsheng District is located hundreds of kilometers away from the coast and has practically no natural freshwater bodies; the fact that there are marine and freshwater impacts is a result of using LCI data derived for other locations. For example, the cradle-to-gate data for bricks were derived from Germany, where emissions from brick construction are partly discharged to water bodies. **Figure 5-15** shows an excerpt from the LCI outputs of brick production in Germany, listing the distribution of cadmium emissions to the environment as follows: 4% to air, 82% to freshwater, 1% to industrial soil, and 13% to seawater. The percentage breakdown is certainly going to be different for bricks produced in or near the District, with most of the emissions likely going to industrial soil due to the very limited presence of surface water bodies. This scenario would result in higher terrestrial ecotoxicity impacts, and lower freshwater and marine aquatic ecotoxicity impacts. While the environmental impact categories affected may differ, an important point is that there will inevitably be environmental impacts associated with the brick production process that need to be accounted for regardless of where the sanitation system is sited.

Outputs

Flow	Quantity	Amount	Unit	Tra
Butane [Group NMVOC to air]	Mass	3.0506E-006	kg	
Butane (n-butane) [Group NMVOC to air]	Mass	2.4905E-008	kg	
Cadmium [Heavy metals to air]	Mass	1.0081E-010	kg	
Cadmium [Heavy metals to fresh water]	Mass	2.2372E-009	kg	
Cadmium [Heavy metals to industrial soil]	Mass	2.183E-011	kg	
Cadmium [Heavy metals to sea water]	Mass	3.6755E-010	kg	
CaF2 (low radioactice) [Radioactive waste]	Mass	3.6695E-008	kg	*
Calcium [Inorganic emissions to fresh water]	Mass	1.184E-005	kg	

System: No changes. PE-GaBi 20 Last change: System, 11/11/2006

Figure 5-15. *Excerpt from the brick life cycle inventory from Germany as included in the GaBi database and used in the LCA.*

The Freshwater Aquatic Ecotoxicity Potential of the two systems are comparable, with the impact from the sanitation system representing less than 1% of the total impact of a German citizen (see **Section 5.1.5**); it is therefore a relatively minor impact. In contrast, the Marine Aquatic Ecotoxicity Potential of the DRY system is seven times greater than that of the WET system. The DRY system's impact in this area represents the largest percentage of the total impact of a German citizen.

Note that other contaminants present in domestic wastewater such as pharmaceutical and personal care products have not been included in the ecotoxicity assessment due to the limited data currently available.

__Table 5-18.__ Summary of water emissions and related environmental impacts.

EMISSIONS TO WATER AND RELATED ENVIRONMENTAL IMPACTS	DRY SYSTEM	WET SYSTEM
% of BOD/COD, Nutrients, and Heavy Metals in Excreta and Greywater Discharged to Surface Water	0	0
Eutrophication Potential (kg Phosphate Equivalent/person/year)	1.0	3.5
Freshwater Aquatic Ecotoxicity Potential (kg DCB-Equivalent/person/year)	5.4	3.5
Marine Aquatic Ecotoxicity Potential (kg DCB-Equivalent/person/year)	25,000	3,700

5.2.7 Emissions to Air

The DRY system performs worse than the WET system in all of the indicators related to air emissions (**Table 5-19**). The DRY system's acidification potential is mainly caused by direct emissions during faecal treatment and urine reuse, and power consumption during faecal collection. Over half (54%) of its global warming potential is related to the brick production for the faecal collection system and the power consumption during faecal collection and treatment. The same items together contribute 68% to the DRY system's photochemical ozone creation potential.

As discussed further in **Chapter 7**, odour is a big challenge for the DRY system, particularly from a user perspective. While the Dongsheng STP certainly emits bad odours, the ability to site a conventional STP away from populated areas—where there is land available—makes it less problematic. Decentralized onsite systems such as the DRY system are, by definition, sited near the population being served. In both cases, however, scrubbers or some other odour control system can be installed to mitigate odours associated with treatment processes. Mature compost is odour-free so its application to agriculture generally does not present odour problems. Urine, on the other hand, will continue to emit odour as ammonia vapours continue to be released; odours can be minimized through proper application techniques (e.g., shallow incorporation of urine into the soil followed by watering).

__Table 5-19.__ Summary of air emissions and related environmental impacts.

EMISSIONS TO AIR AND RELATED ENVIRONMENTAL IMPACTS	DRY	WET
Acidification Potential (kg SO_2-Equivalent/person/year)	2.4	0.59
Global Warming Potential – 100 yrs (kg CO_2-Equivalent/person/year)	220	81
Photochemical Ozone Creation Potential (kg Ethene-Equivalent/person/year)	0.065	0.016
Odour (O&M)	Poor	Good

5.2.8 Emissions to Land

The results of the indicators for land emissions are presented in **Table 5-20**. Any contaminants remaining in faeces, urine, and greywater/wastewater after treatment are discharged to land. Heavy metals were quantified for both systems, and were generally assumed to be unaffected by the treatment processes; they are the primary cause of terrestrial ecotoxicity potential (TEP). For the DRY system, most of the heavy metals are found in faeces and greywater. For the WET system, the heavy metals in wastewater are eclipsed by those found in mineral fertilizers, which contribute 83% to the TEP. The lower contamination of fertilizers derived from excreta, relative to mineral fertilizers, is one of the strongest arguments for the recovery of nutrients from domestic wastewater.

As in the case of marine and freshwater ecotoxicity, other contaminants present in domestic wastewater—such as pharmaceutical and personal care products—have not been included in the TEP assessment.

Table 5-20. *Summary of land emissions and related environmental impacts.*

Emissions to Land and Related Environmental Impact	DRY	WET
% of Heavy Metals in Excreta and Greywater Discharged to Land	app. 100%	app. 100%
Terrestrial Ecotoxicity Potential (kg DCB-Equivalent/person/year)	1.4	7.5

5.2.9 Resource Recovery

The results of the resource recovery indicators are presented in **Table 5-21**; they are largely based on the assumed complete recovery of nutrients from the DRY system and water from both systems. These do not reflect the actual conditions as of 2009, but the aspirations at that time. Nutrients not recovered by the DRY system for agriculture are lost through gaseous emissions and discharges via greywater. While the organic matter content of wastewater can be harnessed for energy, the DRY system instead uses a large fraction of it for soil conditioning. Sludge discharged to the local landfill by the Dongsheng STP may eventually contribute towards energy recovery (in the form of methane); the details of energy recovery at the landfill, if any, were not known and assumed to be minimal in this analysis. In 2008, the Dongsheng STP recovered 16% of its wastewater for use by a power plant (Wang, 2009), but the government's intention is to recover all of its wastewater (Li, 2009). The EETP's treated greywater had not been formally permitted for reuse as of 2009.

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.

Table 5-21. *Summary of percentages of resources recovered from human excreta and greywater.*

RESOURCE RECOVERY	DRY SYSTEM	WET SYSTEM
% of Nutrients in Excreta and Greywater Applied to Agriculture		
Nitrogen	73%	0%
Phosphorus	71%	0%
% of Energy (from Organic Matter) Recovered for Electricity Generation	0%	0%
% of Water Reclaimed for Irrigation and Other Applications	Up to 100%	Up to 100%

6 *Case Study Results: Economic Indicators*

Professor Zhou and his team at Tsinghua University in Beijing, China were commissioned by the Stockholm Environment Institute to perform a comparative economic analysis of the EETP dry system against a conventional waterbourne sanitation system, comparable to the DRY and WET system scenarios analyzed in this research. The DRY and WET system construction costs and WET system operation and maintenance costs (O&M) calculated by Zhou *et al*. (2007) were used as the baseline in this evaluation, while the O&M costs for the DRY system were calculated based on actual costs over 2007 to 2009. The key assumptions used by Zhou *et al*. (2007) are presented in **Table 6-1**, followed by the summary of the capital and O&M costs for the DRY and WET systems in **Table 6-2**.

Zhou *et al.* (2007) used actual EETP construction costs available during the time of their study in 2007; their calculations therefore do not reflect subsequent corrections and improvements. They also do not account for the necessary changes to the system to allow for complete processing onsite as identified in this research. In particular, the expansion of the composting facility and the urine storage tanks are not included. Their calculations include a solid waste plant for processing of organic kitchen waste, which had not come to fruition as of 2009; this cost item was therefore removed (note that processing of organic kitchen waste was also not included in the environmental analysis). For the WET system, Zhou *et al*. (2007) used available construction cost information for the Dongsheng STP combined with standard or average costs derived from Chinese cost estimation manuals and other literature; whenever possible, cost information for Inner Mongolia was used to reflect regional conditions. As in the DRY system scenario, costs associated with organic kitchen waste processing were removed. The capital costs are broken down by item and by process on **Figures 6-1a and 1b** and **Figure 6-2**. Details of the construction cost items included are also presented in **Appendix E**.

As noted above, actual costs were used to the extent possible in calculating the DRY system O&M costs. These costs include the workers' salaries and greywater treatment plant operation fee, electricity costs based on estimated electrical consumption, estimated fuel costs, and equipment replacement and renewal at 2.4%[26] of the construction cost. Actual bills for electricity and fuel were not used because they were not representative of the conditions modeled in this research; for example, as of 2009, not all of the faecal material

26 After Zhou *et al*. (2007).

was being composted onsite. The number of workers was increased by 20% to reflect the greater population served in the DRY system scenario (1,000 versus 832 households). The greywater management fee was kept the same as the actual fee in 2009 since the treatment system is assumed to be the same and not require additional effort; chemical cost was assumed to be a minimal portion of this cost. O&M costs are broken down by item on **Figures 6-3a and 3b**.

Evaluations of the economic indicators are presented in **Sections 6.1 to 6.4**, and summarized in **Section 6.5**.

Table 6-1. *Key assumptions used in the analysis by Zhou et al. (2007).*

PARAMETER	**VALUES**
# of People per Household	3.5
Number of Flats/Households	832
Total Number of People	2,912
Operating Period	20 years
Land Use Fee	38 RMB/m^2
*Water Consumption**	
DRY System	
Litres (m^3) per person per day	47.7 (0.0477)
m^3 per household per year	61
m^3 total per year (832 households)	50,699
WET System	
Litres (m^3) per person per day	80 (0.08)
m^3 per household per year	102
m^3 total per year (832 households)	85,030 m^3/year
Total Wastewater Production	
DRY System	
m^3 total per day (832 households)	118 m^3/day
m^3 total per year (832 households)	43,094 m^3/year
WET System	
m^3 total per day (832 households)	198 m^3/day
m^3 total per year (832 households)	72,270 m^3/year
Wastewater Recovery Rate	85%
Greywater Treatment Capacity (DRY System)	250 m^3/day 86 L/person/day
Annual Maintenance Cost – Equipment Renewal & Replacement	2.4% of capital investment
Dongsheng District Sanitation Fee (2006)	0.4 RMB/m^3
Operation Cost of WET System	1 RMB/m^3
Price of Reclaimed Water	1.0 RMB/m^3

*For consistency with the rest of the evaluation, the calculation of water fees below uses the water consumption values used in the LCA modeling and not the values presented in this table (see **Tables 6-2 and 6-3**).

Table 6-2. *Comparison of the actual construction and O&M costs (Zhou et al., 2007) of the DRY (as built) with the estimated equivalent costs of a WET system in 2007 values. Note that the* <u>*total*</u> *costs are for 832 households (actual EETP size), and not 1,000 households as modeled in this research.*

ITEM	COSTS[h]	
	DRY SYSTEM	**WET SYSTEM[c]**
Total Capital Cost inc. civil works and equipment, land-use fees, and other fees		
RMB	¥9,468,913[a,i]	¥3,831,058
USD	$1,382,323	$559,279
Total Construction Cost (Civil Works and Equipment)		
RMB	¥9,124,289[i]	¥3,544,715
USD	$1,332,013	$517,477
Capital Cost Per Household (Per Person)		
RMB	¥11,381 (3,252)[i]	¥4,605 (1,316)
USD	$1,661 (475)	$672 (192)
Annualized Capital Cost Per Household (Per Person)[f]		
RMB	¥1,074 (307)[i]	¥435 (124)
USD	$157 (45)	$63 (18)
Total Annual O&M Cost[b]		
RMB	¥605,583	¥175,643
USD	$88,406	$25,641
Annual O&M Cost[b] Per Household (Per Person)		
RMB	¥728 (208)	¥211 (60)
USD	$106 (30)	$31 (9)
Annual Estimated Value of Fertilizer Products Per Person[d]		
RMB	¥19	¥0
USD	$3	$0
Annual Estimated Value of Reclaimed Water Per Person[e]		
RMB	¥19	¥25
USD	$3	$4
Net Annual O&M Cost[b] Per Person (with Byproduct Recovery)		
RMB	¥170	¥35
USD	$25	$5
Net Annual O&M Cost[b] Per Household (with Byproduct Recovery)		
RMB	¥595	¥123
USD	$87	$18
Estimated Annual Sanitation Fees[g] Per Household at the EETP (0.4 RMB/m^3)		
RMB	¥31	¥41
USD	$5	$6

NOTES:

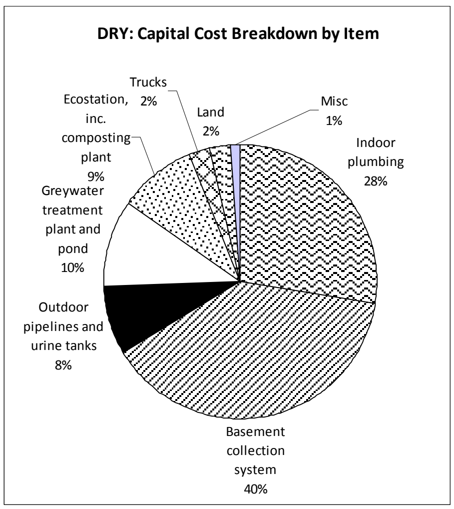
a. Total Capital Cost changed from Zhou *et al*. (2007) to reflect corrected value for item 4 in Table 3-1 (92,347 vs. 94,687 RMB) and remove cost of solid waste plant for kitchen organics. Zhou *et al*. (2007) did not include the cost of the greywater storage pond as they did not deem it critical to the system operation.

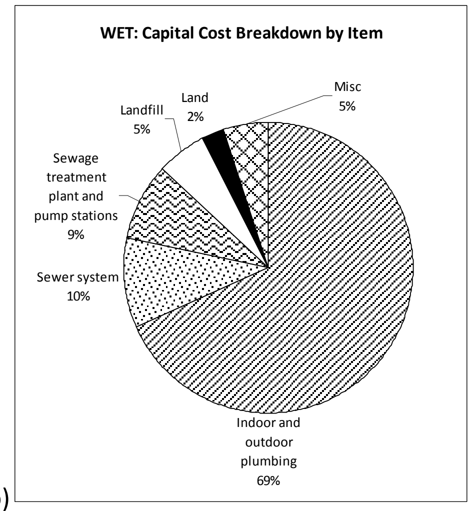
b. Does not include depreciation costs.

c. WET total capital cost and annual O&M cost changed from Zhou *et al*. (2007) to remove costs associated with kitchen organics.

d. Based on unit costs for N and P estimated from Chinese fertilizer prices in Liu (2007) and estimated available N and P in EETP compost and urine: 4.3 RMB (0.63 USD) per kg N and 11 RMB (1.6 USD) per kg P.

e. Reclaimed water price based on 1 RMB/m^3 in the region (Zhou *et al.*, 2007). 85% recovery of wastewater assumed based on the water consumption in item g below.
f. Assuming a 20-year loan period with a 7% interest rate.
g. For consistency, the water consumption values used in the LCA were used in this calculation: 62 and 80 L/person/day for the DRY and WET systems, respectively.
h. The conversion from Chinese currency (RMB) to US dollars (USD) is based on the rate of 6.85 RMB to 1 USD, which was the rate in October 2008[27].
i. Does not include expansion of composting facilities and urine storage.

(a) 

(b) 

Figures 6-1a and 1b. *Capital cost breakdowns by item for the (a) DRY and (b) WET systems.*

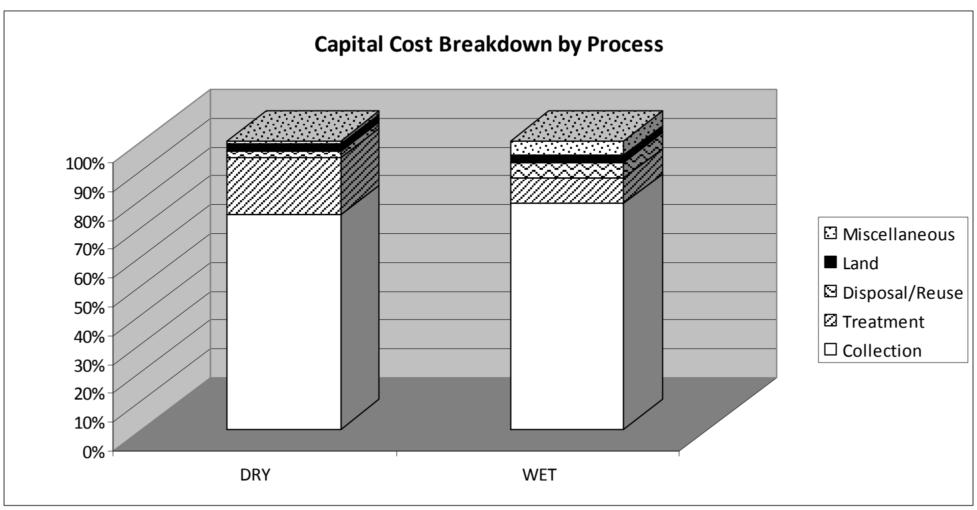
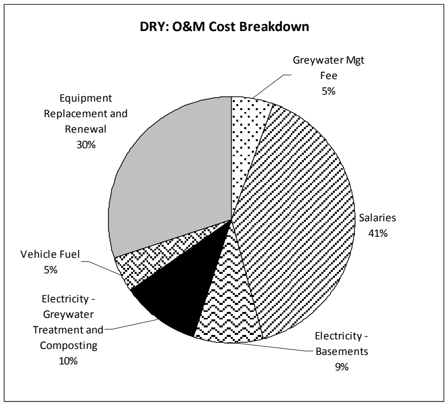
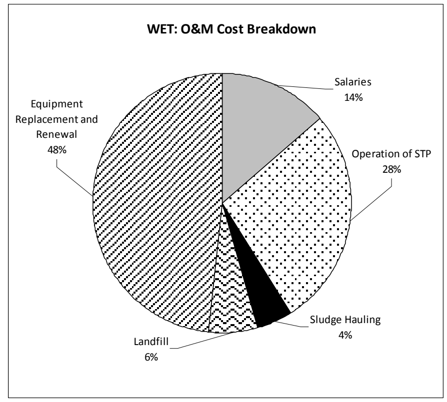


Figure 6-2. *Capital cost breakdowns by process for the DRY and WET systems.*

27 http://www.xe.com/ucc/

(a) 

(b) 

Figures 6-3a and 3b. *Operation and Maintenance (O&M) cost breakdowns by item for the (a) DRY and (b) WET systems.*

6.1 Capital Cost Per Capita

As presented above, the capital cost of the DRY system is 2.5x greater than that of the WET system: $475 versus $192 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 contingency. A main factor in the high cost of the DRY system is the construction of the basements to contain the faecal collection system; it represents 40% of the total DRY system cost and is equivalent to 96% of the entire cost of the WET system. The costs of the DRY system's greywater treatment plant and the composting plant also contribute significantly, resulting in treatment costs totaling $270K for the DRY system versus $50K for the WET system, *even without including the necessary expansion of the DRY system's composting facility and urine storage capacity*. In both cases, the collection system represents a large portion of the total cost at 74-78%. From a cost perspective, the WET system benefits from economy of scale and the use of established technology. It is arguable that the cost of the DRY system can be reduced significantly once the technology has been tested, optimized, and established. As Zhu (2008) points out, the potential for improved and significantly less expensive design of the basements was already observed during the EETP construction.

6.2 Annual O&M Cost Per Capita

The Annual O&M cost of the DRY system is 3.3x greater than that of the WET system: $30 versus $9 per capita per year. When the incomes from recovered byproducts (fertilizer and reclaimed water) are accounted for, the net annual O&M cost of the DRY system becomes 4.8x greater than that of the WET system. This is because the income from the WET system's reclaimed water is a greater percentage of the total O&M cost of this system, as compared to the incomes from fertilizer and reclaimed water for the DRY system. It can be argued that the quality of the reclaimed water from the DRY system should be higher as this system only collects domestic wastewater; however, even if the price of the WET system's reclaimed water is decreased by 50% to 0.5 RMB/m^3 to reflect poorer-quality water, the DRY system's net O&M cost would still be 3.6x greater. Note that as of 2009, the products from the EETP were not being sold—some free compost was being provided to a farmer—partially due to insufficient marketing of the compost and urine and the government's hesitation to allow reuse of the treated greywater.

The future of urine and compost sales from the dry system is currently uncertain. In 2005 and 2006, the Dongsheng Agriculture Technology Extension Service Centre conducted training courses for approximately 300 local farmers from the Erdos Municipality on the benefits of using sanitized human urine and composted faeces in agriculture (Zhu, 2008). As discussed in **Section 5.1.3.4**, in 2006 and 2007, the Erdos Agricultural Centre conducted tests comparing the effects of urine and compost application on the yields of corn and potato as compared to the local practice of using manure and artificial fertilizers (Liu, 2007). The results showed solid evidence of the fertilizing value of excreta collected from the EETP; however, farmers and government officials would have to be convinced of the benefits to allow for the full commercialization of the product and to realize the full economic benefit of the EETP's nutrient recovery system.

The last row in **Table 6-2** lists estimates of sanitation fees for EETP residents based on the District's rate structure in 2006. Like in many parts of China, sanitation fees are based on water consumption in the District at a rate of 0.4 RMB/m^3 in 2006; Zhou *et al*. (2007) point out that this rate is significantly below what is considered a more representative rate nationally in China of 0.8 RMB/m^3. As such, given the assumed water consumption patterns under the two sanitation systems, user revenues are significantly below cost recovery levels for O&M. For the DRY system, the average annual fee paid by households is estimated at $5, as compared to O&M costs of $87 to $106, with and without byproduct recovery.

6.3 User Ability to Pay (Cost as % of Income)

The average annual per capita disposable income of urban residents in the Erdos Municipality as of 2006 was 14,000 RMB while the average net income of the rural population was 5,000 to 8,000 RMB (EcoSanRes, 2007). For comparison, the national average for urban disposable income per capita was 11,759 RMB in 2006, and for rural residents was 3,587 RMB[28]. Assuming a 7% inflation rate[29] between 2006 and 2007, the average annual urban and rural per capita incomes in 2007 were approximately 15,000 RMB ($2,190) and 7,000 RMB ($1,022), respectively. Household income can be estimated by multiplying the per capita figures by 1.5, representing the average number of employed persons in a household[30].

The annual costs per household are listed in **Table 6-3**, broken down by annualized capital cost, O&M cost without byproduct income, and O&M cost with byproduct income. The user ability to pay is evaluated by calculating the costs as a percentage of income. To evaluate the conditions under different scenarios, both rural and urban residents are included. Because of their lower incomes, rural users tend to pay a higher proportion of their income for sanitation, estimated at 16-17% for a DRY system and 5.3-6.1% for a WET system. The higher percentages in these ranges represent conditions in which there is no income for recovered byproducts such as compost. For urban residents, the comparable costs are 7.4-8% and 2.5-2.8%, respectively.

In the Dongsheng District, the capital cost of the EETP's dry sanitation system was included in the purchase price of the flats. Therefore, residents would have been expected to pay only the annual O&M costs on a continuing basis. While some of the residents at the EETP come from rural backgrounds (Spring 2009 Survey), the more typical income profile is urban; therefore, if full cost-recovery was to be achieved, on average the residents would have been expected to pay 2.6-3.2% of their income towards the DRY system's O&M costs only. In contrast, the WET system would have cost 0.55-0.94%. With the District water rates at 3.3 RMB/m^3 (\$0.48/m^3), and using the water consumption values modeled in the LCA, the estimated annual water fees per household for the DRY and WET systems, respectively, are: $38 and $49. Together, the sanitation and water supply charges would equal 3.8-4.4% of income for the DRY system and 2.0-2.4% for the WET system annually. According to the World Bank (2007), "the general range of what is considered 'affordable' for water services is 3 to 5% of household income"; the average DRY and WET income percentages therefore both fall within the 'affordable' range. However, what may be considered an 'affordable' fee is not necessarily easy to implement as it may not be socially acceptable. Chreod Ltd. (2005),

28 http://news.xinhuanet.com/english/2007-09/13/content_6718914.htm. Accessed 23 February 2010.
29 http://www.atimes.com/atimes/China_Business/IL15Cb01.html. Accessed 23 February 2010.
30 http://www.china.org.cn/e-company/05-11-15/page050914.htm. Accessed 23 February 2010.

OECD (2006), and World Bank (2007) all note the challenge of achieving full cost recovery for water and sanitation services in China, where the population is now expected to pay for services that were once provided free by the government. In addition, for those residents whose incomes fall well below the average (possibly elderly retired couples, for example), the EETP water and sanitation fees may become unaffordable particularly under the more expensive DRY system scenario.

Table 6-3. *Data used for evaluating user affordability: costs and incomes.*

COST PARAMETER	DRY SYSTEM	WET SYSTEM
Sanitation		
Annualized Capital Cost Per Household	\$157	\$63
Annual O&M Cost Per Household	\$106	\$31
Net Annual O&M Cost Per Household (Including Byproduct Income)	\$87	\$18
Urban Residents – Estimated 2007 Disposable Income Per Household	\$3,285	
Rural Residents – Estimated 2007 Net Income Per Household	\$1,533	
% of Income - Urban Residents		
Annualized Capital Cost	4.8%	1.9%
Annual O&M Cost	3.2%	0.94%
Net Annual O&M Cost	2.6%	0.55%
Total % - Urban	**7.4-8%**	**2.5-2.8%**
% of Income – Rural Residents		
Annualized Capital Cost	10.2%	4.1%
Annual O&M Cost	6.9%	2.0%
Net Annual O&M Cost	5.7%	1.2%
Total % - Rural	**16-17%**	**5.3-6.1%**
Water Supply[b]		
Estimated Annual Water Fees Per Household	\$38	\$49
% of Income – Urban Residents	1.2%	1.5%
% of Income – Rural Residents	2.5%	3.2%
Estimated Total Sanitation[a] **and Water Supply Charges Per Household for EETP residents (Urban)**	\$126-144	\$67-80
% of Income	3.8-4.4%	2.0-2.4%

NOTES:
a. Assuming full recovery of annual O&M cost only (i.e., does not include capital cost).
b. Based on the water consumption values used in the LCA models and a water rate of 3.3 RMB/m^3 (\$0.48/m^3).

6.4 Potential for Local Business Development and Household Income Generation

Both the DRY and WET systems can generate income from the sales of recovered products such as nutrients and water, but as the calculations in **Table 6-2** above demonstrate, these income streams only offset a portion of the O&M cost of the systems and therefore do not produce a net income.

Since the DRY system is a novel technology, it offers the opportunity for new businesses to work on its development or improvement. The DRY onsite treatment model requires more site-specific elements to design, potentially offering opportunities for local architects and engineers, while local contractors can be trained in their installation. Furthermore, the decentralized model requires management at the site level, generating the demand for local O&M and management teams. For example, a dry system O&M enterprise may sell its service to a cluster of EETP-type settlements.

7 Case Study Results: Societal Indicators

This chapter discusses the results of the evaluation of the socio-cultural and institutional indicators for the DRY and WET system scenarios as described in **Chapter 3**. Because the WET system is well-established and has a long history, the DRY system is discussed in significantly more detail below. The indicators are qualitatively assessed, and use the following rating system: very poor, poor, neutral, good, and very good.

7.1 User Acceptability and Desirability

The evaluation of user acceptability and desirability draws primarily upon the results of a survey conducted in April and May 2009 ("Spring 2009 Survey") as described in **Chapter 3**; however, other sources of information are also used to place the survey findings within a wider context. The findings by the EETP's Head Social Worker in 2006/2007 are first presented below, providing a context for how user acceptability and desirability of the dry system may or may not have changed over time. The results of the Spring 2009 Survey are then discussed to present the most recent assessment of users' feelings towards the DRY system before the conversion to flush toilets. To place the findings in a broader context, experience with dry toilets in China outside of the EETP is subsequently discussed. Finally, the successful lobbying of the EETP Household Committee for flush toilets is discussed, along with a survey that was conducted after the toilet conversion in 2009.

The evaluation of this indicator focuses on the main user interface of the dry sanitation system at EETP: the urine-diversion dry (UDD) toilets and urinals. Note that these components were continuing to be redesigned for improved acceptability as of spring 2009. Flush toilets are not discussed as extensively as the dry toilets since they are well-established; the surveys, however, reflect the relative acceptability and desirability of the UDD toilets and urinals over the flush toilets.

7.1.1 DRY System

7.1.1.1 Findings by the EETP Head Social Worker in 2006/2007

Ren Lingna was the Head Social Worker at EETP charged with addressing education and behavioural-change surrounding the novel DRY system. Her work began in 2006, when the first residents began to occupy the flats. In May 2007, she reported that interviews with 85 households revealed the following opinions regarding the UDD toilets (Lingna, 2007a):

- 79% preferred flush toilets but were either open to persuasion of the merits of the UDD toilet or simply accepted it,
- 13% strongly objected to the UDD toilet and had taken steps to change to a flush toilet, and
- 8% supported the UDD toilets because of their flexibility and convenience, especially under water-stressed conditions.

Figure 7-1. *Instruction poster for the EETP dry toilets. The poster explains how the toilet works, the use of a child-sized seat, the use of the urinals by men, proper cleaning techniques with minimal water, and the O&M support available onsite.*

From 2006 to 2007, Lingna and the maintenance staff put significant effort into increasing the acceptance of the dry toilets by visiting households directly, addressing any technical problems they were having, explaining how the system worked and why they were designed that way, and providing training as necessary. An example of an instruction poster distributed to each household is included as **Figure 7-1**. Lingna (2007b) met with strongly dissatisfied residents twice a week over several months, discussing their complaints and possible solutions, and reviewing the operation and maintenance procedures with them. Based on the staff's daily door-to-door visits with residents in 238 flats (2007a), they identified two main challenges of the dry toilets for the users: separating urine and faeces and keeping the toilet clean while minimizing the use of water and chemicals. Odours had also been problematic. More than a majority of the households (61% or 144) were discharging too much water into the system, which caused or worsened odour problems.

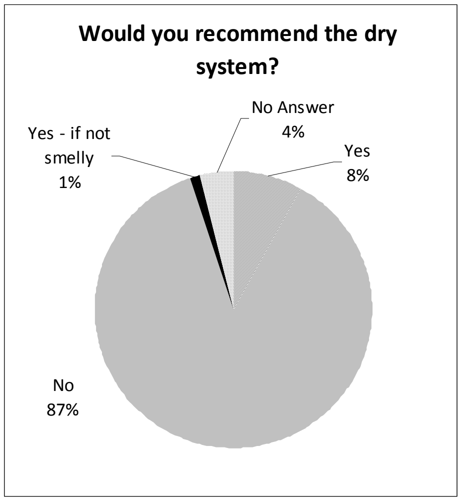
By the end of August 2007, at least 12 families had changed to flush toilets (Zhu, 2008); some had not even tried the UDD toilets and presumably had switched because of feedback from other residents or because of their own refusal to try the toilet.

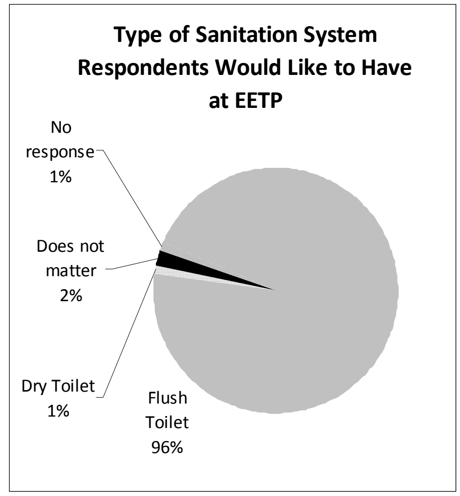
7.1.1.2 Spring 2009 Survey

As noted in **Section 3.2.3.3**, the EETP's residents come from diverse working backgrounds and a large fraction (approximately 75%) likely previously resided in urban areas, as indicated by their use of a private flush toilet prior to moving in to the EETP. The Spring 2009 Survey 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"* (see **Figure 4-2**). The urinals fared slightly better at an average user rating of 3.1.

Only 8% of survey respondents indicated that they would recommend the DRY system (**Figure 7-2a**). In contrast, 96% (95 people) expressed that they would most like to have a flush toilet installed in their households (**Figure 7-2b**); three of the four people who either preferred a dry toilet or had no preference had previously used flush toilets (as described in **Chapter 3**, 75 out of 99 respondents had used flush toilets before moving to the EETP). Approximately 50% of the households identified changes to the UDD toilets that would make the toilets acceptable to them, while the other half stated that flush toilets were the only acceptable alternative (**Figure 7-3**). Households generally felt more ashamed rather than proud of their dry system. On average, the response to the question, *"How do you feel about your sanitation system?"*, was 2.8 on a scale of 1 to 9, with 1 being ashamed, 5 neutral, and 9 proud (**Figure 7-4a**). Households also believed that the value of their investment in their flats was decreased by the DRY system: on average, the response to the question, *"How do you think the toilet and urinal have affected the value of the flat?"*, was 2.1, with 1 being *"lowered the value"*, 5 *"no effect"*, and 9 *"increased the value"* (**Figure 7-4b**).

The survey strongly indicated a low level of acceptance of the DRY system by the households. Perhaps the most poignant illustration of how strongly unacceptable the UDD toilets were to some of the households is that at least three of the households interviewed stated that they actually preferred to use the public toilets rather than their own. The public toilets are located outside the EETPs' main entrance and consist of shallow pit latrines (**Figures 7-5a to 5d**). During a visit on 25 April 2009, the women's toilets were found to smell heavily of urine and faeces, and there was faeces on the floor. Based on observations during field visits, this was not an unusual condition.

(a) 

(b) 

Figures 7-2a and 2b. *Results from the Spring 2009 Survey: Percentages by response to the questions: (a) "Would you recommend the dry system?" and (b) "Which type [of sanitation system] would you most like to have at the EETP?".*

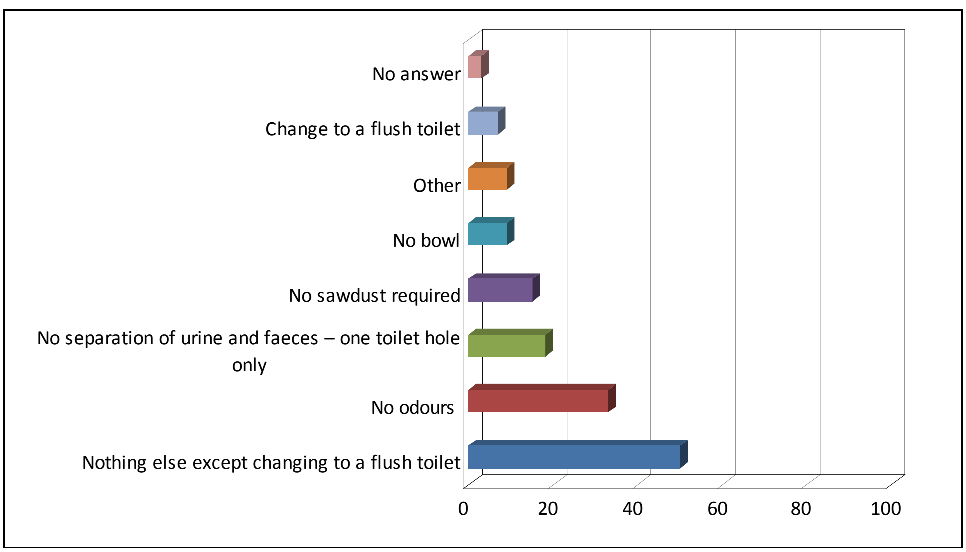
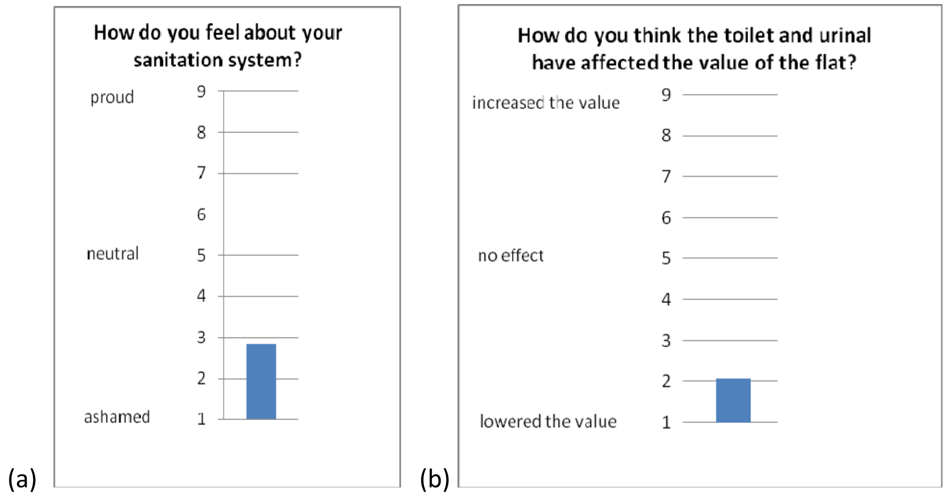


Figure 7-3. *Results from the Spring 2009 Survey: Responses to the question, "Which improvements to the dry system would make it completely acceptable to you?". Respondents could pick multiple answers. About 50% indicated that no changes would make the UDD toilet acceptable to them, while the rest were open to possible improvements.*



Figures 7-4a and 4b. *Results from the Spring 2009 Survey: Feelings about the DRY system and perception of its effect on the value of the flats. Average of responses to the questions: (a) "How do you feel about your sanitation system?". (b) "How do you think the toilet and urinal have affected the value of the flat?".*

Figures 7-5a to 5d. *Images of the public toilets just outside of the EETP. (a) Location of the toilets relative to the EETP, which is seen in the background on the right-hand side. (b) Entrance to the toilets. (c) Inside the women's toilets. (d) Faeces on the floor of one of the women's stalls. [A. Flores, taken 25 April 2009.]*

The application of human excreta to agriculture has been practised in China for several millennia (Shiming, 2002); therefore, the DRY system's ecological sanitation principle of resource recovery from excreta can be expected to be generally more acceptable there than in many other parts of the world without a similar history. More than one million urine-diverting dry toilets have been installed in seventeen provinces in China (Panesar and Werner, 2006). Approximately 26 million households already have household biogas digester systems in which human and animal excreta are anaerobically digested to produce biogas with the residual sludge and effluent applied to agriculture, and the Chinese government continues to promote their installation (Chen *et al*., 2010). However, these applications are mainly limited to rural and peri-urban—and not urban—settings. In addition, users' acceptance of dry sanitation systems is primarily tied to the UDD toilets and urinals, since these are the only aspects of the system with which they interact. In the Spring 2009 Survey, respondents showed little interest in the agricultural reuse aspects of the EETP dry system: only one respondent selected *"Produces organic fertilizer"* as a benefit of the dry system and 74% had not visited the eco-station. The EETP residents were also not very supportive of agricultural application of untreated urine and treated faeces: only approximately 20% found agricultural application of urine acceptable, and approximately 40% in the case of faeces. This may 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.

7.1.1.3 Dry Toilets in China Outside of the EETP

While dry toilets are quite common in China, they are often associated with lower standards of living. In the peri-urban and rural areas surrounding Dongsheng District, most households have private, shallow pit latrines (EcoSanRes, 2006); partially covered—with three low walls and no roof—places of defecation are also quite common. In the latter case, there is often simply a shallow hole or indentation where people defecate, as shown on **Figures 7-6a and 6b.** Faeces accumulates in the hole until it is removed.

Urban residents in the Dongsheng District are aspiring for flush toilets. Discussions with local residents during field visits in 2007 and 2009 indicated that all new multi-storey housing in Dongsheng are equipped with flush toilets. Residents often store water in their bathtubs for toilet-flushing and other purposes in times of cuts to water supply. The local government appears to agree with the view of flush toilets as the improved and modern alternative: the new public toilet facilities installed in 2007 in the downtown Dongsheng District have been equipped with flush toilets while the older facilities use dry pit latrines **(Figures 7-7a and 7b)**. As of 2006 (EcoSanRes), 263 of the 280 public toilet facilities in downtown Dongsheng were either shallow or deep pit latrines.

(a)  (b) 

Figures 7-6a and b. *Example of a private dry toilet owned by a farmer in the rural area around Dongsheng District. [A. Flores, taken 30 August 2007.]*

(a)  (b) 

Figures 7-7a and 7b. *Public toilets in the Dongsheng District. (a) Older public toilet facility in the District with dry toilets, located in a neighbourhood near the Dongsheng Municipal STP. (b) New public toilet facility with flush toilets, located in the newly-developed Dongsheng downtown area. [A. Flores, taken 30 August 2007.]*

In China, wiping is much more common than washing, and most Chinese do not use water for anal cleansing after defecation but instead use newspaper, toilet paper, and other materials to wipe themselves clean. From this perspective, dry toilets are compatible with the traditional toilet habits or norms of the general population.

7.1.1.4 Conversion to Flush Toilets

In December 2008, the residents at the EETP formed a committee ("Household Committee – Daxing Ecosan Complex") specifically to address dissatisfaction with the DRY system. They issued a letter addressed to the District government on 4 January 2009 expressing their concerns and asking for action. In a meeting held on 13 March 2009, representatives from the SEI Project Office and the District Project Office met with three Household Committee members to answer their questions and address their concerns. The members raised issues related to the costs of the DRY system, odour and ventilation, responsibility for long-term operation, sawdust safety, parts replacements, flies, and the contractual agreements amongst the different parties (Rosemarin and Lin, 2009). Most importantly, the members also expressed their emotional stress and troubles and demanded compensation:

> *"Friends and relatives often do not want to visit when the odour problems are occurring. This has caused stress within families. Some people have become sick because of this familial stress. What can be done to improve things?"*
>
> *"The experimentation has caused a lot of stress for families. The household want to be compensated for this."*
>
> *"The households formally demand that either compensation be made available to them for all the troubles they have experienced. An alternative is to be given flush toilets instead by the government. The government should have done these experiments on their own buildings and not the private apartments of the citizens. The experiments could have been restricted to fewer buildings."*
>
> **Source:** Household Committee Meeting (Rosemarin and Lin, 2009)

The Household Committee's comments about the effects of the dry system on the comfort of their guests were echoed in the Spring 2009 Survey. Seventeen out of the 99 respondents specifically commented on the inconvenience of the UDD toilets for guests.

In June 2009, the Dongsheng District Government agreed to the households' demand for flush toilets and began replacing the UDD toilets and urinals (Sun, 2009). This was done in response to the continuously mounting pressure from the households, despite the ongoing improvements to the system and the offer of various dry toilet alternatives to the current UDD toilets and urinals.

7.1.2 WET System

Flush toilets are generally considered comfortable and convenient for use by men, women, and children. Their popularity is reflected by the results of the survey as described above. However, like the dry toilets, they also require proper operation and maintenance to function well. They are relatively easier to clean as water dilutes the urine and waste, and the use of chemicals is generally less restricted if blackwater is led to a sewage treatment plant (STP), as in the case of the Dongsheng District. The *p-traps* under flush toilets (and sinks and drains) are effective at eliminating odours. Flush toilets are suitable for both wipers and washers, and easily degradable wiping materials—particularly toilet paper—can be flushed down the toilet.

In a survey of 103 households conducted in the Fall of 2009 after the UDD toilets had been converted to flush toilets (Lin, 2009a), 91% of the households expressed satisfaction with the flush toilets. However, they were aware of their disadvantages. In particular, 59% of respondents were concerned about periodic cut-offs in the water supply and pipeline blockages. Some respondents also noted odour, increased water consumption, water leakage, and noise as concerns. The problems with odours in the households had not been completely addressed by the toilet conversion; however, the toilet odours had abated: 68% had bad odours in the toilets under the dry system and this number had dropped to 23% with the flush toilets. Odours in the bathrooms had not been eliminated, although they had dropped from 18% to 10% in households. As noted by Rosemarin (2010), the continuing odours are evidence that incorrect installations of greywater pipelines—and not just the dry toilets as many residents presumed—had been contributing to odours. For example, in an inspection of the plumbing conditions at the EETP site, Selke (2008) noted the lack of water traps—and thus odour control—in many greywater pipeline installations. The locally-available water traps had a small reservoir that evaporated quickly, particularly when the floors were heated, allowing gases to escape from the greywater pipelines; water had to be added to the water locks, sometimes as often as every couple of hours, or the drains had to be covered when not in use (McConville, 2010a).

In the survey by Lin (2009a), residents were asked, *"If you were allowed to grow vegetables in a 3-5 m^2 plot in the ecotown [EETP] with the faeces and urine collected and composted by yourself or others, would you like to switch back to the dry toilet?*". Apparently, the opportunity to grow their own vegetables was not sufficient to make the UDD toilet more attractive than the flush toilets to users: 90% of respondents said they would not want to switch back to the dry toilets.

7.2 Accessibility to Different Age, Gender, and Income Groups

7.2.1 DRY System

As with the previous indicator, the evaluation of the accessibility to different age and gender groups is centred around the UDD toilets and urinals. Accessibility to different income groups is based on the dry system overall.

As noted above, the UDD toilets were still being improved by the time they were replaced in the summer of 2009. Some of the improvements required were related to making the toilets more accessible to children, women, and the elderly, who were experiencing difficulties using the UDD toilets related to the following: 1) activation of the turning bowl, 2) use of sawdust, and 3) separation of urine and faeces.. The following comments made by ten households during the Spring 2009 Survey highlight these difficulties:

> *"It's not good for women to use the toilet as it will cause women diseases. The sawdust is not clean."*
>
> *"The design of the toilet is not suitable for children to use because of the wide distance between the faeces and urine holes."*
>
> *"It is unacceptable to use this toilet. It's inconvenient for guests and children to use."*
>
> *"Older people, children, and guests are not able to operate the toilet."*
>
> *"Children are not able to use the dry toilet.*
>
> *"The children are unable to use the dry toilet."*
>
> *"The dry toilet is too complicated and inconvenient for old people to use."*
>
> *"The separation of urine and faeces makes the dry toilet inconvenient to use by women."*
>
> *"The children can't use it [UDD toilet]."*
>
> *"The dry toilet is inconvenient for children to use, and the urinal is too high for our child."*
>
> **Source:** Spring 2009 Survey

As noted in **Section 3.2.3.1**, the first prototype of the UDD toilet design had a non-stick turning bowl that was activated (i.e., turned upwards for use) via pressure or weight on the toilet seat. The required weight was found to be too high to allow small children or very light adults (primarily women) to fully activate the bowl, making the toilet difficult to use properly (Zhu, 2008). A partially turned bowl was susceptible to fouling as the faeces and sawdust fell on the outside of the bowl, thereby requiring extra cleaning. As of early 2009, 808 of the 832 flats still had this toilet type[31]. To address the problem with the turning bowl activation, a second prototype was created in which a lever connected to the toilet cover automatically turns the bowl 180° as the user lifts the toilet cover; this design was installed in one household in 2006 and was found to be satisfactory (Zhu, 2008). As of early 2009, two households had this prototype[31].

The use of sawdust had been found to be problematic for a number of reasons; some women expressed concern regarding the exposure of their genital area to sawdust when they are using the UDD toilet, and the potential for detrimental health impacts. The sawdust was collected directly from factories, sifted, dried outdoors or indoors depending on weather conditions, then bagged for distribution to households. A microbiological analysis of the sawdust found significant levels of *Escherichia coli* or *E. coli* (Zhu, 2008), a type of

31 Survey done by SEI Project Office in 2009 (SEI Project Office, 2009).

bacteria found in the intestinal tracts of vertebrates and commonly used as an indicator of the *potential* for faecal contamination of surface water bodies and drinking water supplies. The issue of sawdust use, as related to public health, is discussed further in **Section 7.3**.

To address the problems related to the turning bowl design, a third toilet prototype was developed with a sliding plate mechanism. This design obviated the application of sawdust into the toilet, addressing concerns by women; instead, sawdust could be added directly to the bins by the maintenance staff. Zhu (2008) reported that the first household supplied with this third design gave it a favorable review. Ultimately, 22 households had been fitted with a sliding plate UDD toilet by early 2009[31].

Households complained that the UDD toilet was difficult or inconvenient for women, children, and the elderly to use properly due to the requirement to direct urine and faeces into different receptacles (front for urine and back for faeces). The distance between the centerlines of the urine and faecal holes is 16.5 cm. Men and older boys were generally expected to use the urinals for urination and the toilets only for faecal excretion, posing less of a challenge.

As in the case of the conventional flush toilet, a child-sized seat may need to be placed on top of the UDD toilet seat to allow small children to use it comfortably without fear of falling into the toilet.

From an income perspective, the EETP DRY 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. As discussed in **Chapter 6**, the DRY system is significantly more expensive than the WET system. However, 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, 2005b). Faeces (after dehydration in the Guangxi case) and urine are similarly source-separated and applied to agriculture.

7.2.2 <u>WET System</u>

Connection to the Dongsheng Municipal STP requires flush toilets. These toilets are quite adaptable to different age and gender groups and have been in use for many decades all over the world in different forms (in China, for example, many people prefer the squatting version without a raised pedestal). As noted above, these toilets sometimes require the use of child-sized seats to allow small children to use them comfortably. In most households, the toilet is used for both urination and defecation by men, women, and children.

WET systems can be quite expensive and generally not affordable at all income levels. For rural residents in Dongsheng District, for example, the cost of the WET system is disproportionately expensive compared to their income (see **Chapter 6**).

7.3 Minimization of Public Health Risk

This evaluation is based on the qualitative risk assessment procedure and the biological and chemical hazards commonly found in wastewater as described in **Chapter 3**. In the case of the DRY system, there is also a potential biological hazard associated with the sawdust; the WET system has potential for additional biological and chemical hazards due to the mixing of domestic wastewater with stormwater runoff and industrial discharges. **Figures 7-8 and 7-9** provide an overview of the risk assessment findings for the DRY and WET systems, respectively, identifying the hazard exposure points and the associated health protection measures for reducing risk. The sizes of the circles are proportional to the qualitatively estimated relative risk (low, medium, and high). The DRY and WET systems are discussed separately below.

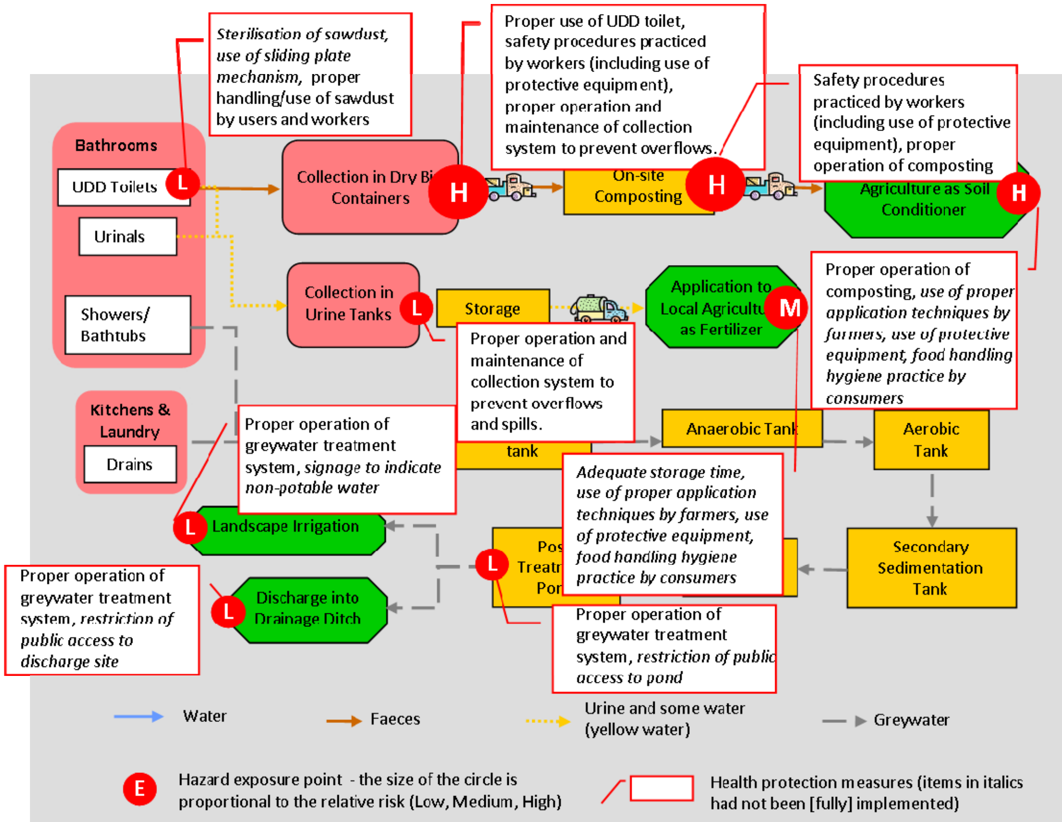


Figure 7-8. *The hazard exposure points and associated health protection measures to reduce exposure and risk for the DRY system.*

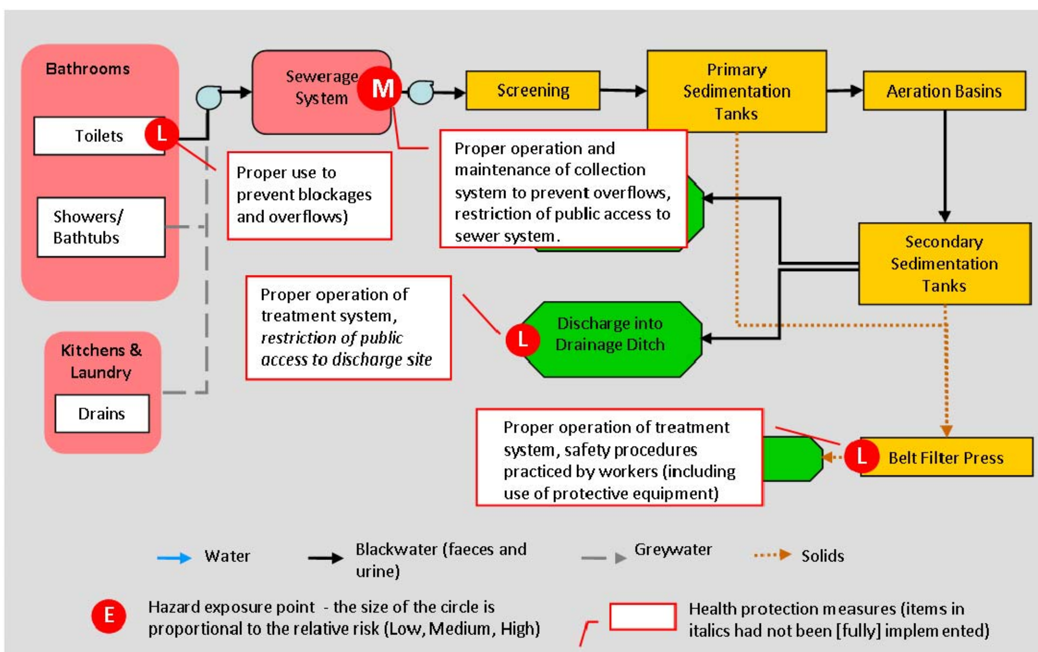


Figure 7-9. *The hazard exposure points and associated health protection measures to reduce exposure and risk for the WET system.*

Figure 7-10. *Workers at the EETP processing the sawdust at the eco-station. [A. Flores, taken 27 April 2009.]*

7.3.1 DRY System

For the DRY system, key hazard exposure points occur during: UDD toilet use; the faecal bin collection, transport, and cleaning; on-site composting; application of compost to agriculture; urine collection and transport; application of urine to agriculture; storage of treated greywater in the pond; greywater recycling for landscape irrigation; and treated greywater discharge. During toilet use, two potential sources of hazards are the faeces and sawdust. Particularly for users who find the use of the toilet challenging (children, women, and the elderly), misuse of the UDD toilet can lead to faecal contamination outside of the turning bowl; because cleaning requires minimal use of water and chemicals, it is possible that the UDD toilet may not be sufficiently cleaned or disinfected to minimize exposure of users to residual faeces.

The trapping of sawdust and faecal mixture in the turning bowls provided a breeding ground for pathogenic microorganisms. A study by Williams *et al.* (2008) on the persistence of *E. coli* in butcher shop floors found that damp sawdust in contact with *E. coli* increased the survival rates of the bacteria. This is consistent with the findings from a study that concluded that the sawdust was a good media for cultivating microorganisms and found *E. coli* in the sawdust in significant concentrations of 4.5×10^4 and 7×10^5 colony-forming units per gram (CFU/g) (Zhu, 2008); for reference, the standard for Class B biosolids—sludge derived from domestic wastewater with allowable restricted application to agriculture—in the USA is 2×10^6 CFU/g dry weight (USEPA, 2003). In general, the hygienic quality of the sawdust is not tightly controlled. **Figure 7-10** shows workers at the EETP processing the sawdust in the eco-station area.

Sawdust exposure has been a concern for users, particularly women. Fine sawdust was reported to re-suspend and stick to exposed skin during toilet use. One possible health impact of such an exposure is increased risk from infections; however, there has been no documented evidence of this.

Exposure to air pollution was another possible health risk from the use of sawdust. Refilling of sawdust containers releases sawdust into the air. Workers processing the sawdust are also exposed during the drying and bagging processes. In a risk assessment study of sawdust ("wood dust"), Savolainen and Husgafvel-Pursiainen (2004) concluded that the data available in the scientific literature collectively suggest "*an elevated risk of pulmonary disorders due to repeated exposure to wood dust*". The risk is mainly associated with workers regularly exposed to sawdust (e.g., workers at sawmills, woodworks), and users and workers at the EETP can be expected to be exposed at much lower levels. Nevertheless, from a health standpoint, the goal of policies is towards eliminating or avoiding exposure to sawdust (and other fine dusts) whenever possible (e.g., European Agency for Safety and Health at Work, 2009).

A major health risk concern for the DRY system is the handling of faecal matter—likely the most hazardous component of domestic sanitation systems—by the maintenance personnel. As WHO (2006b) states, "*From a risk perspective, exposure to untreated faeces is always considered unsafe, due to the potential presence of high levels of pathogens, depending on their prevalence in a given population*". According to the Erdos Epidemic Prevention Station (2009), intestinal worm infections and other waterborne diseases are not common in the Erdos Municipality. If this is indeed the case, it may partly be attributable to the use of deep groundwater aquifers in Dongsheng, and the provision of treated water supplies. However, the lack of washing facilities in the older public toilets around Dongsheng District[32], the existence of open defecation[33], the application of untreated faecal materials from dry public toilets in agriculture (Rosemarin, 2007), and the contact between domestic animals and human faeces[34] suggest that the conditions are still ripe for faecal transmission of diseases.

The pre-composting procedure at the EETP was as follows (Zhang, 2009): 1) maintenance personnel collected the filled bins approximately once a month from the basements and loaded them onto a truck using a winch (**Figure 7-11**), 2) the bins were transported to the composting station, where the contents were manually dumped into the top of a sifter, 3) maintenance staff used a rake to move the sifted faecal mixture from the sifter and onto the floor of the composting station, where they further manually removed any solid non-compostable waste (e.g., plastic bags), and 5) the sifted material was then loaded onto a

32 As observed on 30 August 2007 and 25 April 2009.
33 As observed on 5 September 2007 (at the EETP) and on 22-25 April 2009 (in areas outside of the EETP).
34 As observed on 30 August 2007.

Figure 7-11. *Collection of faecal bins from the basement. [Source: http://www.adb.org/, accessed 11 November 2009.]*

Figure 7-12. *Sifting of materials from the faecal bins. [Source: Mertens, 2009.]*

Figure 7-13. *Contamination of the composting facility walls with faecal material from the bins. The sifter is on the left. [A. Flores, taken 24 April 2009.]*

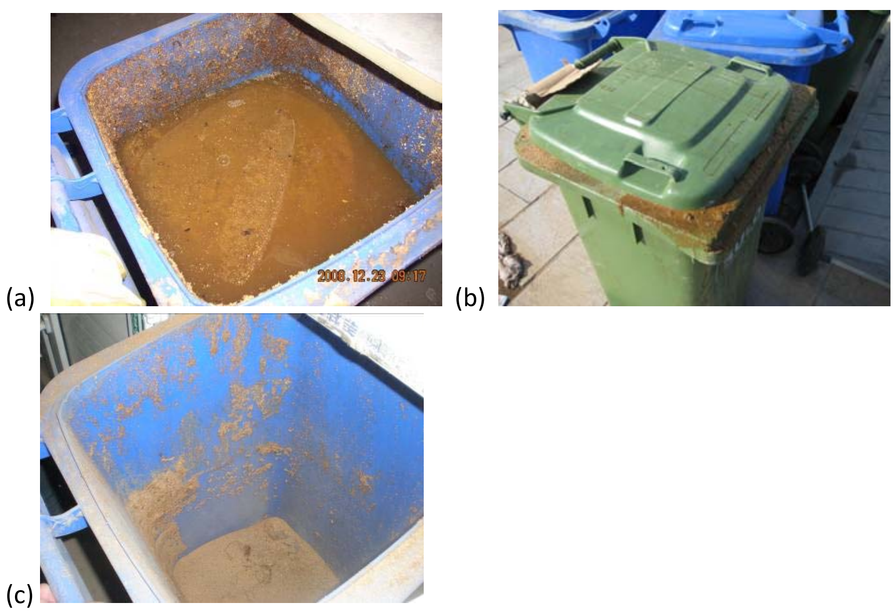
wheelbarrow for transport to the composting chambers. **Figure 7-12** shows the workers in the midst of steps 2 and 3, wearing their protective equipment.

At each step throughout the procedure described above, the personnel—although covered in protective clothing and masks—are exposed to raw faecal matter, and there is ample opportunity for contaminating surfaces (**Figure 7-13**) and tools with raw faecal material. Furthermore, excessive discharge of water into the UDD toilets resulted in heavy water-filled bins that required special handling (**Figures 7-14a to 14c**). After collecting and transporting a water-filled bin—which was susceptible to spillage—a worker poured the contents onto a field outside the eco-station and disposed of any non-compostable solid waste into a garbage bin. The bin was then washed outside the compost plant, using a high-pressure water jet. The washwater was collected and later used for watering a vegetable garden (Lin, 2009b). The use of this washwater, which was likely high in faecal pathogens, additionally represents a health risk.

Fly breeding was a problem in the

faecal bins, providing an additional source of faecal pathogen transmission to the environment and to people. Maintenance workers limited insect breeding by applying repellant to the bins (Mertens, 2009). The toxicity of the repellant and its effects on the quality of the compost is an important consideration that needed to be analyzed (Mertens, 2009).

The public health risks from the use of composted faeces for agriculture can be minimized through proper operation of the composting process, appropriate application techniques by farmers, and the practice of hygienic food handling by consumers. To render faecal material safe for agricultural application, WHO (2006b) states: "*To treat excreta, thermophilic digestion (50°C for 14 days) and composting in aerated piles for one month at 55-60°C (plus 2-4 months of further maturation) are recommended and generally accepted procedures…*". WHO (2006b) refers to the work of Haug (1993), which showed that, "*under controlled conditions, composting at 55-60°C for 1-2 days is sufficient to kill essentially all pathogens*"; the longer recommended processing periods are intended to provide a safety margin related to the handling of the faecal materials.



Figures 7-14a to 14c. *Pictures of the faecal collection bins. (a) and (b) Bins resulting from improperly used UDD toilets, with users discharging excessive water into the faecal chute. (c) A bin from a properly-used dry toilet. [(a), (c): W. Zhang, SPO staff member, taken in 2008; (b): J. McConville of SEI, taken in September 2009.]*

The composting procedure at the EETP became fully operational starting in December 2008. No microbial (e.g. helminth eggs, faecal coliform) analyses were performed once the composting process was fully operational; therefore, it is not possible to look at how the actual microbial contents of the raw materials were reduced in the compost end-product. To minimize risk from handling the faecal materials and compost, workers were provided with protective clothing, which included rubber boots, work jackets, work pants, gloves, caps, and dust masks (Mertens, 2009). Tools dedicated to the composting plant were also provided, as well as washing facilities for the equipment and the workers. Mertens (2009) trained the compost plant workers on proper hygiene practices (e.g., no smoking, frequent hand-washing), which required constant reinforcement.

In the case of urine, the potential for health risk was primarily attributable to faecal cross-contamination, as stated by WHO (2006b): "*…the faecal cross-contamination that may occur by misplacement of faeces in a urine-diverting toilet is associated with the most significant health risks*". The same applies for greywater: "*the main hazards of greywater originate from faecal cross-contamination*" (WHO, 2006b). As noted previously, some users found the separation of faecal and urine streams difficult, making cross-contamination a real problem. Excessive use of water to clean the bowls could also have resulted in faecally-contaminated washwater being directed into the urine tanks. Finally, pipeline misconnections—both intentional and otherwise—made cross-contamination of both urine and greywater systems a reality at the EETP. As noted in **Section 7.1.1**, by August 2007, at least twelve families had installed flush toilets, which were connected either to the urine or greywater pipelines. The more complex piping system of source-separation systems requires more careful installation than a conventional mixed wastewater system; unfortunately, this level of care was lacking at the EETP. An investigation in April 2008 revealed that the plumbing at the EETP was done in a very haphazard manner, increasing the risk for cross-contamination from cross-connections and blockages (Selke, 2008). Construction quality control, strict enforcement of the dry sanitation system design (i.e., making pipeline cross-connections illegal or against the EETP contract), and education of the households on the dangers of cross-contamination are some of the measures that could have been used to reduce the risk from cross-contamination.

If the urine collection system were operated properly—that is, urine is collected with minimal cross-contamination from faeces and greywater and minimal dilution with water—then storage can provide effective treatment. The WHO (2006b) published guidelines for storage times as presented in **Table 7-1** below. Note that for a household system where the urine is applied only to the household's garden or plot, no storage is required.

Table 7-1. *Recommended guideline storage times for urine mixture[a] based on estimated pathogen content[b] and recommended crop for larger systems[c]. (Reproduced from WHO [2006b]).*

Storage Temperature (°C)	Storage Time	Possible pathogens in the urine mixture after storage	Recommended crops
4	≥1 month	Viruses, protozoa	Food and fodder crops that are to be processed
4	≥6 month	Viruses	Food crops that are to be processed, fodder crops[d]
20	≥1 month	Viruses	Food crops that are to be processed, fodder crops[d]
20	≥6 months	Probably none	All crops[e]

NOTES:

a. Urine or urine and water. When diluted, it is assumed that the urine mixture has at least pH 8.8 and a nitrogen concentration of at least 1g/L.

b. Gram-positive bacteria and spore-forming bacteria are not included in the underlying risk assessments, but are not normally recognized as causing any of the infections of concern.

c. A larger system in this case is a system where the urine mixture is used to fertilize crops that will be consumed by individuals other than members of the household from which the urine was collected.

d. Not grasslands for production of fodder.

e. For food crops that are consumed raw, it is recommended that the urine be applied at least one month before harvesting and that it be incorporated into the ground if the edible parts grow above the soil surface.

According to the WHO (2006b), if the system is clearly mismanaged—as in the case of the pipeline cross-connections at the EETP—then prolonged storage should be applied. Additionally, because concentrated urine provides a harsher environment for microorganisms, the less concentrated or more dilute the urine is, the longer the storage time required. Interviews with fourteen households in 2007 indicated that these households used water regularly for flushing urine (Harada, 2008). This is corroborated by the results of the analysis of eighty samples from the urine tanks between April and July 2007, which indicated that urine was diluted 1 to 3.5 times (Liu, 2007). These factors, along with the fact that the urine tanks are located underground and therefore experience low temperatures even during the warmer months, suggest that the urine should be stored for at least several months. While the urine tanks were originally designed for monthly emptying, the tanks were filling up more frequently due to water addition and therefore providing less than one month of storage time (Zhu, 2008). To reduce the public health risk associated with the collected urine—for workers and farmers—additional storage capacity was needed at the

EETP site or on farmers' plots to ensure adequate storage time before agricultural application. The excess storage capacity would have the additional benefit of allowing more flexibility with timing of the application to agricultural land.

The application of composted faeces and urine to agriculture—as envisioned for the EETP system but had not been fully implemented as of 2009—could be done with minimal risk to public health provided that the collection and treatment systems are operated properly as discussed above; the farmers use appropriate application techniques; and the agricultural products are handled safely from harvest all the way to consumption.

Finally, according to the LCA, the Human Toxicity Potential (HTP) of the DRY system is nearly twice that of the WET system (**Figure 5-14**). The manufacture of PVC for the DRY system construction is a major contributor to this impact, representing 61% of the total impact.

7.3.2 WET System

In the case of the conventional waterbourne system, key hazard exposure points occur during: flush toilet use, wastewater transport in the sewer system, treated wastewater discharge, and transport of sludge from the STP to the landfill.

One of the problems with flush toilets is that they can get blocked, often due to non-faecal waste being stuck in the trap[35]. At the EETP, a variety of solid waste was discarded down the faecal chutes, including plastic bags (Zhu, 2008) and personal hygiene products (e.g., sanitary napkins)[36] etc. When the dry toilets were changed to flush toilets, some residents continued to discard other household and personal waste down the flush toilets, resulting in blockages (Lin, 2009b); this occurred despite the EETP residents' previous experience with flush toilets as noted earlier. Drains for toilets are typically only designed to transport flush water, faeces, and toilet paper. Disposal of waste down flush toilets is a common problem, even for societies that have been using flush toilets for many decades. In the United Kingdom (UK), for example, there is an active water industry-led campaign called, "Bag It and Bin It"[37], intended to stop people from flushing their personal waste (condoms, disposable nappies, syringes, etc.) down the toilet. The campaign supporters estimate that 2 billion articles of such waste are flushed down toilets each year in the UK. Aside from concerns about the waste ending up on beaches and causing harm to wildlife and the marine environment, waste in toilets also results in flooding in homes—when wastewater backs up into toilets

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35 http://drainrescue.wordpress.com/2009/02/17/clogged-toilet-the-drain-rescue-solution/. Accessed 20 November 2009.
36 As observed during inspection of faecal bins on May 2, 2009 by the researcher.
37 http://www.water.org.uk/home/resources-and-links/bagandbin. Accessed 20 November 2009.

and sinks due to blockages—and in streets and other places when solid waste collects in the sewer lines and blocks them (Consumer Council for Water, ND). Household waste disposed of in kitchen sinks and other drains, as well as grease, which can solidify in the sewer lines, also cause blockages and flooding. These flooding events expose people to raw sewage, causing a public health risk. Education of the public to change behaviors is a critical component of the risk management strategy for preventing this hazard exposure, as is the regular maintenance of the sewer system.

As **Figure 7-15** shows, from the household to the treatment plant, the pipeline sizes increase along the sewer system as the system carries greater volumes of wastewater. The centralized nature of WET systems means that sewer systems are designed ultimately to collect large volumes of wastewater. Therefore, the system is more susceptible to catastrophic event, with large volumes of wastewater, containing faecal pathogens and other contaminants, being released into the environment. Combining this fact with the high costs of sewer maintenance—especially in areas with sewer systems that are decades old—such catastrophic spills are not uncommon, even in developed countries. Recent examples include 10.2 million litres of treated and raw sewage spilling into Richardson Bay in California, USA in 2008[38], an estimated 1.2 billion litres of raw sewage spilling into a river in Ottawa, Canada in 2008[39], and more than 4.5 million gallons [17 million litres] of raw sewage pouring into the Ohio River in Kentucky, USA in 2009[40].

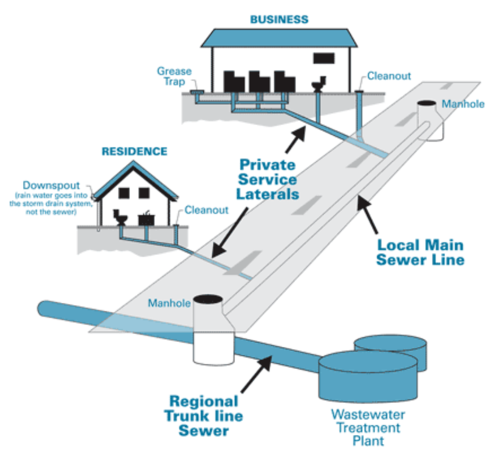


Figure 7-15. *Illustration of a typical sewer system. The laterals carry one house's or one building's volume of wastewater, local mains carry a sub-area's volume of wastewater, and trunk lines carry a region's volume of wastewater. [Source: http://www.ocwatersheds.com.]*

38 San Francisco Chronicle. Available at http://articles.sfgate.com/. Accessed 2 April 2010.
39 CBC News. Available at http://www.cbc.ca/. Accessed 2 April 2010.
40 Louisville News. Available at: http://www.wlky.com/. Accessed 2 April 2010.

The risk of flooding and people's potential exposure to raw sewage depend on: 1) where the spill occurs along the system, 2) the duration and rate of the release, and 3) the proximity of the spill location to people and its accessibility to the public. It is difficult to quantitatively evaluate the health impact of sewage spills on public health; in the USA, for example, where spills have occurred in hundreds of thousands of basements and thousands of streets, there is no national record-keeping of illnesses they may have caused (Duhigg, 2009). However, Duhigg (2009) describes one study that indicated that the cases of serious diarrhea amongst children rose whenever local sewer systems overflowed.

According to the Dongsheng STP Director (Lin, 2009d), the sewer system is monitored regularly, and that sewage spills due to broken pipelines occur four to five times per year on average. Broken pipelines are reported to be fixed promptly. If this is indeed the case, then the management of the District's sewer collection system is unusual in China based on the following statement from the World Bank (2007): *"the performance of the drainage system is hardly monitored or considered in the evaluation of an urban wastewater management system in China*." Inadequate performance monitoring, coupled with the general neglect of sewer systems in China (World Bank, 2007), means that the risk of failures of sewer systems there is significant, and will grow as the sewer systems age.

In addition to direct contact with the sewage spill from pipelines, people may also be affected by bathing in waters that receive untreated sewage[41] or drinking water that has been contaminated by spilled sewage[42]. Since the Dongsheng STP does not discharge into recreational waters, the associated public health risk does not apply in this particular case. For the most part, water supply in the District is not derived locally, so any sewage spills from the Dongsheng STP system is not likely to affect the water source itself; however—as in any other place—there is always a risk from sewer line leaks contaminating broken water supply lines.

During the treatment process at the Dongsheng STP, workers normally have minimal contact with untreated wastewater. Workers, however, handle sludge as they load it onto a truck for transport from the belt filter press to the landfill for disposal. The sludge is not analyzed so there is no data available for its chemical and biological characteristics (Li, 2009). Pathogens

41 This may be intentional or unintentional. In places where the sewer system is "combined" (that is, it receives both wastewater and stormwater), when the system is overwhelmed due to heavy rainfall, excess wastewater is discharged into surface waters. Since 1986, the Dongsheng District has not had such a combined system (Zhou et al., 2007).

42 For example, it is estimated that up to four million gastro-intestinal illness episodes and up to 700,000 respiratory illness episodes result from bathing in waters potentially contaminated with untreated sewage in California, USA (Brinks et al. [2008], cited by Duhigg [2009]).

normally present in sludge include bacteria (e.g., *Salmonella*), enteric viruses (e.g., norovirus), protozoa (e.g., *Cryptosporidium*), and helminths (*Ascaris*), with their concentrations dependent on the initial concentrations—which depend on the health of the source populations—and the solids treatment processes applied (Pepper *et al*., 2006). To protect the workers, similar health protection measures apply as in the case of compost handling: the use of protective equipment, the use of dedicated tools, and other hygienic practices.

As of 2009, approximately 16% of the treated wastewater from the Dongsheng STP was being reused by a power plant for cooling (Lu, 2009) while the remainder was being discharged via drainage ditches. Wastewater effluent is transported by pipelines to the power plant, and presents no significant health risk due to minimal human contact (except in case of spills/leaks). The main potential health risks associated with the drainage ditches are public access to the effluent, which can be prevented by fencing the drainage area and restricting access, and contamination of groundwater that may be used as a water supply, which can be prevented by disallowing any wells to be constructed or used within a reasonable distance from the drainage area. According to the District's Environmental Health Director, there are no water supply wells in the vicinity of the STP discharge site (Lin, 2009d). Note, however, that while the Dongsheng STP itself may not be responsible for contaminating the District's own water supply, one of the major sources of drinking water for the District, the Yellow River, suffers from receiving high volumes of domestic and industrial wastewater. A news article on 11 May 2007[43] cited a study that estimated that one-tenth of the river's flow is derived from wastewater.

7.4 Legal Acceptability and Institutional Compatibility

Under this indicator, three aspects will be compared between the DRY and WET systems: conformity with the current national policies, compatibility with existing institutional structures and compatibility with existing physical infrastructure.

7.4.1 Conformity with National Policies

Wastewater management is primarily regulated at the national level in China. Murray (2009) provides a detailed review of national environmental policy and practice in China, particularly as they relate to the "deliberate design of sanitation infrastructure for reuse, and the management of wastewater and treatment byproducts as resources". The following

43 Reuters News Agency. Available at http://www.reuters.com/. Accessed 2 April 2010.

discussion analyzes the Dongsheng District's sanitation strategy in the context of China's national policies in order to evaluate how well the DRY and WET systems conform to the current regulatory and institutional landscapes. An overview of the key national policies in China that are relevant to the environment, and sanitation in particular, is provided in **Table 7-2**.

Based on her review of the policies and interviews with key stakeholders in the government and industry, Murray (2009) concluded that the policies presented in **Table 7-2** provide a basic framework for driving the development of an energy-efficient and reuse-oriented sanitation infrastructure in China but that the government needs to provide more explicit directives—with associated sanctions—to the sanitation sector. In the Chengdu Municipality in China, for example, the sanitation strategy has been primarily driven by the Five-Year Plan's directive to treat a certain percentage of wastewater by 2010; failing to meet this particular directive directly affects the promotion prospects of the local government leaders and the reputations of the leaders and the city with which they are affiliated (Murray, 2009). Consequently, despite the promotion of resource recovery by the other national policies, the Chengdu Municipality has been aggressively directing its efforts on expanding the total capacity of its STPs based on the conventional model of waterborne sanitation and without any facilities for resource recovery. To the Chengdu Municipality, this represents the path of least resistance, and presumably the greatest expediency towards meeting targets and avoiding sanctions. While there is certainly a need for increasing wastewater treatment coverage in China, Murray (2009) notes that the numbers are deceptive: official statistics cite the total (or *design*) wastewater treatment plant capacity and not the *actual* capacity, which is significantly lower due to an inadequate sewer network.

Table 7-2. *Overview of major national policies in China with an impact on the environment, and on sanitation in particular. (As translated and interpreted by Murray [2009] – italics indicate direct quotes).*

National Policy	Year of Adoption	Provisions Applicable to Sanitation
People's Republic of China Water Pollution Prevention and Control Law (PRC WPPCL)	1984 (amended 1996)	"*The primary objective of the PRC WPPCL is to prevent and control water pollution, protect and improve the environment, and safeguard human health, while ensuring effective utilization of water resources.*"
People's Republic of China Water Law (PRC WL)	1988 (amended 2002)	The primary objective of this law is to "*to rationally develop, utilize, conserve, and protect water resources, prevent and control water disasters, and bring about sustainable utilization of water resources, while meeting the needs of national economic and social development*".
Cleaner Production Promotion Law (CPPL)	2002	The purpose of the CPPL is to "*promote cleaner production, increase the efficiency of the utilization rate of resources, reduce and avoid the generation of pollutants, protect and improve environments, ensure the health of human beings and promote the sustainable development of the economy and society*".
Renewable Energy Law (REL)	2005	The REL "*calls for 15% of all China's energy to come from renewable sources by 2020*".
11th Five-Year Plan (2006-2010)	2006	The Five-Year Plan states that "*at least 50% of wastewater generated in urban areas must be treated by 2010…prefecture and county-level cities must treat at least 60%, and provincial capitals must treat 70% of their wastewater by 2010*".
Circular Economy Promotion Law (CEPL)	2008	The purpose of the CEPL is "*to promote the development of the circular economy, improve resource utilization efficiency, protect and improve the environment, and realize sustainable development*".

There is a parallel but slightly different situation in the Dongsheng District with regards to their sanitation strategy. One major difference between the Chengdu Municipality and the Erdos Municipality lies in their access to water supply. There is a well-known north-south disparity in per capita water availability in China[44]: according to the Asian Development Bank (2008), the available water resources in the north were 524 m^3 per year in 2005 as compared to 2,370 m^3 in the south. Because of the water scarcity in the north, there is

44 An official plan to divert 38 to 48 billion m^3 of river water northwards per year (the "South-North Water Diversion Project") was launched in 2001 (http://english.people.com.cn/ on March 5, 2001. [Accessed November 27, 2009.]

greater pressure there for wastewater reuse. The 11th Five-Year Plan sets out ambitious goals: 1,825 million m^3 per year to be reused in northern China alone by 2010, as compared to the 961 million m^3 of wastewater reused in the entire country in 2006 (Asian Development Bank, 2008). Wastewater is intended to be reused for "*irrigation, public amenities, street cleaning, toilet flushing, and non-potable domestic and industrial uses*."

7.4.1.1 DRY System

The philosophy behind the DRY system appears to embody the aspirations of the Chinese government at the highest levels. According to the literature prepared by the District government for the 2007 International Conference on Sustainable Sanitation[45] ("Brief Introduction of China-Sweden Erdos Eco-town Project"):

> *"Prime Minister Wen Jiabao and Vice Prime Minister Zeng Peiyan have attached high importance to this project and urged the State Environmental Protection Administration and the Ministry of Construction to offer full supports [sic] to this project…This project is highly valued by all circles of the [sic] society."*

In his opening speech at the conference, Hao Yidong, Vice-Chairman of the Government of Inner Mongolia Autonomous Region, commended the efforts at the EETP as follows[46] [*sic*]:

> *"Living waste treatment system including the ecological sanitation is an important part of the living environment improvement, and is an effective way of the realization of environment friendly society and is also a necessity for building small towns and new countryside and pasture area…research, design, trial, and promotion of ecological sanitation have practical significance in terms of improving living conditions and ecological environment and establishing water saving cities, towns and rural areas ."*

The resource conservation and recovery concepts employed at the EETP (e.g., water conservation, nutrient recovery, wastewater reuse) contribute to the circular economy promoted by the CEPL, and the EETP sanitation system complies with the national policies' general directives to treat urban sewage and prevent pollution. Reuse of greywater also helps northern China to meet its water reuse goals as presented in the 11th Five-Year Plan. As noted above, China currently encourages a centralized model of treatment, rather than the decentralized model at the EETP; however, this does not appear to be a major barrier for

45 This conference was centred around the EETP (Dongsheng District, August 2007).
46 An official transcript of the speech was distributed at the conference: "Speech Given at the Opening of 2007 International Ecological Sanitation Conference, Mr. Hao Yidong, Vice-chairmen [sic], Government of Inner Mongolia Autonomous Region".

the implementation of decentralized systems given the initial support provided by government officials. The effluent quality standards (see **Table 4-1**) are problemmatic because they are presented in concentrations, as is commonly done around the world, rather than in mass loadings; as noted in **Chapter 4**, concentrations of constituents in the EETP's treated greywater may have been elevated due to the low water consumption and hence low dilution. The composting of faeces and its application to agriculture is also supportive of national goals to reduce sludge disposal in landfills as noted by Murray (2009).

The application of sanitized urine to landscapes and agriculture appears to pose no problems from a policy perspective. The Olympic Forest Park in Beijing, a high-visibility project related to the 2008 Olympics, recently implemented a urine-diversion program in which the urine is to be used for landscape vegetation, and also off-site for food and non-food crops[47].

7.4.1.2 WET System

The national government's directive for sharply increased reuse in the north is a good driver for the District's efforts at achieving zero emissions from their STPs[48], along with their urgent need to decrease demand on freshwater supply. As discussed in **Chapter 3**, the District has insufficient water supply to meet its needs. The District's goal is to reuse 100% of their wastewater for landscape irrigation, power plant cooling, construction, and aquatic scenery[48]. The new STP under construction in 2009 is designed to achieve Grade IB standards, while the existing STP is expected to produce effluent meeting the less stringent Grade II standards (Wang, 2007) (see **Table 4-1** for standards). Fifty percent of the treated effluent from the existing STP is to be diverted to the new STP, where it will undergo the additional treatment necessary to meet Grade IB standards.

While it is not clear how the District can achieve 100% reuse without infrastructure in place to distribute reclaimed water to customers other than the power stations, this is their stated intent. As of 2008, the geographical coverage of the sewer system was 85% and the wastewater collection rate was estimated at 90%[48] (much higher than that of the Chengdu Municipality at 30%); the high collection rate combined with the intent to reuse 100% of wastewater means that the District intends to recycle most of the wastewater produced by its residents. This plan is consistent with the national policies related to resource recovery and conservation. The construction of the new STP and the expansion of the sewer network

47 Case study of sustainable sanitation projects: Olympic Forest Park, Beijing, China. Available at the Sustainable Sanitation Alliance website at: http://www.susana.org/images/documents/06-case-studies/cn/en-susana-cs-china-beijing-forest-park-2009.pdf. Accessed December 2, 2009.
48 A description of the Dongsheng District's plans for achieving zero emissions and the current state of its wastewater infrastructure is described at http://www.ordosep.gov.cn/. [Accessed May 5, 2009.]

are also aligned with the centralized treatment model of urban sewage stipulated in Article 19 of the PRC WPPCL. Centralised STPs are currently the standard in China and are used as a benchmark for wastewater management performance, particularly for cities and towns (World Bank, 2005; OECD, 2001).

In the case of sludge, however, there is no similar resource recovery plan in place. Sludge is disposed of at the landfill because of concerns with heavy metal contents (Li, 2007). China has been increasingly regulating sludge from municipal STPs starting in the early 2000s (for a summary of relevant sludge regulations, see **Table 7-3**). In 2007, China issued two major regulations that set pollutant limits for sewage sludge being discharged out of STPs and made distinctions amongst the various sludge application or disposal techniques for regulatory purposes (He, 2008). Landfill disposal is regulated under CJ/T249-2007, which stipulates sludge characteristics, and sampling, monitoring, and operating requirements at the landfill. The District appears to be operating within these regulations currently; however, He (2008) notes that the State Environmental Protection Administration of China and the Chinese Ministry of Construction are in the midst of preparing new or revised sludge management standards designed "*to achieve the goals of sludge reduction, stabilization and resource recovery*". It is possible that tightening standards that are more oriented towards resource recovery may require the District to consider alternative disposal or reuse applications for sludge. Land application, for example, would allow for nutrient and organic matter recovery; this practice is already encouraged in China, with 48% of sludge being applied to agriculture and gardening (He, 2008).

Table 7-3. *Relevant regulations related to sludge management in China (sources: He [2008] and Zhong [2008]).*

Code	Year	Title	Level and Subject of Regulations
GB4284-84	1984	Pollutants Control Standard of Sludge for Agricultural Application	National - land application
GB8172-87	1987	Control Standards for Urban Wastes for Agricultural Use	Ministerial - urban domestic wastes and products from urban compost plants for agricultural use
GB18918-2002	2002	Pollutants Discharge Standard of Municipal Wastewater Treatment Plant in China	National - discharge control, dewatering
CJ247-2007	2007	Sludge Characteristics of Municipal Wastewater Treatment Plants	Ministerial - discharge control, dewatering, stabilization
CJ/T239-2007	2007	Classification of the Technologies for Sludge Disposal	Ministerial - classification of disposal options
CJ/T249-2007	2007	Sludge Characteristics of Landfill with Municipal Solid Waste from Municipal Wastewater Treatment Plant Disposal	Ministerial - landfill
GB16889-2008	2008	Standard for Pollution Control on the Landfill Site for Domestic Waste	National - landfill

7.4.2 Compatibility with Existing Local Institutional Infrastructure

In China, municipalities such as the Erdos Municipality are typically responsible for the provision of essential public services such as water supply and wastewater management (World Bank, 2007). Wastewater utilities are run either by a municipal wastewater company, a private company, or a combination of the two. An environmental protection bureau oversees wastewater discharges and a public health bureau monitors water supply quality. The following sections discuss how well the DRY and WET systems fit within the local administrative and other institutional infrastructure.

7.4.2.1 DRY System

In February 2003, the Erdos Environment Protection Bureau, in consultation with the Stockholm Environment Institute (SEI), selected Dongsheng District as the candidate site for the large-scale ecological sanitation demonstration project being proposed by SEI. The Dongsheng District government was enthusiastic about the opportunity: local officials committed 5 million RMB in 2004 (730,000 USD in 2009) to the project, and provided incentives towards project development such as providing tax exemptions to the developer and promising to undertake the construction of roads around the chosen site. While support from the municipality and district governments was critical to the project, there was no formal involvement from the provincial-level government of the Inner Mongolia Autonomous Region because it had not been sought either by SEI or Erdos Municipality. Zhu (2008) believes that leadership support at that level—and preferably even higher at the State level—would have improved the viability of the EETP dry sanitation system in the long-term.

One of the major challenges of implementing a new technology such as the DRY system is the lack of standards or guidelines. The EETP's DRY system was unprecedented, and therefore no applicable standards existed in the District and elsewhere in China; this was problematic particularly for the indoor plumbing and outdoor pipeline systems, which were more complex than those for the WET systems, and the ventilation system. Given the premature state of the design and the technology, close supervision of the construction process was critical; unfortunately, this was absent at the EETP. Rosemarin (2009) noted: "*40 sub-contractors had been given the job of installing pipes by the building company and there was no post-work inspection or approval carried out. Blueprints were made available but in some cases were not followed properly resulting in ad hoc pipe sizes and drainage slopes*." Sun, Chief Director of the Dongsheng Project Office (DPO), acknowledged that the government did not provide adequate supervision of the construction process (Sun, 2009).

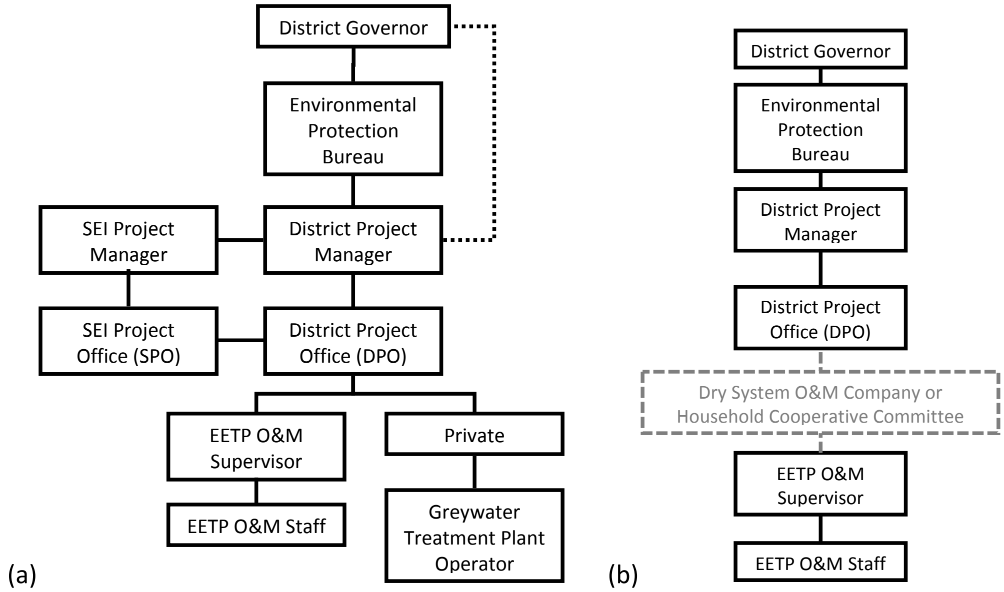
Construction problems were not restricted to the sanitation system; throughout the EETP, poor construction quality was evident as shown in **Figures 7-16a to 16d**. While the developer, Daxing Estate Development Co Ltd (Daxing), clearly evaded their responsibility for providing oversight of the construction and ensuring quality[49], Zhu (2008) believed that the situation was exacerbated by the passive attitude of the District later in the project. This attitude appeared to have been the result of a lack of incentives for local officials and doubts about the ultimate benefits of a complex and expensive project (Zhu, 2008). While the planning and design processes could have been improved[50], the poor construction quality and management certainly had a serious impact on the operation of the EETP dry sanitation system and ultimately the households' acceptance of it. For example, Daxing refused to install S-traps under the urinals and ventilation fans in the basements, thereby contributing to odour problems (Zhu, 2008). It is evident that the lack of oversight and enforcement by the District was partially responsible for the ultimate unsustainability of the DRY system at the EETP from technical and user acceptability perspectives (Zhou *et al*., 2007). It is clear

49 For specific examples, see Zhu (2008).
50 For example, the toilets installed in 832 flats at the end of 2006 were of a new prototype that had not been tested rigorously, and were found to have operation problems (see Section 7.2).

that the construction of an innovative DRY system requires more participation and oversight by the local government than what was normally expected.

Figures 7-16a to 16d. *Examples of poor construction at the EETP. Clockwise from top left: badly-installed electrical socket, poorly done paving and building foundation, and disintegrating concrete decorations in the outdoor play area. (Source: USTB-CSES and Envirosystem Ltd., 2008)*

The management of a decentralized or onsite system such as the EETP DRY system requires a new model different from the prevailing centralized, government or utility-managed model. The management structures for the EETP dry system (as of 2009 and as envisioned) are presented in **Figures 7-17a and 17b**. As of 2009, the DRY system was being managed by a site-based team of eight maintenance personnel. If the EETP model were to be replicated, alternative management models include: management of several neighbourhoods by one team (private service provider or a governmental department) or the development of specific service providers serving different communities (e.g., composting, transport of urine or compost to agricultural fields).



Figures 7-17a and 17b. *Management structures for the DRY system (a) as of 2009 and (b) as envisioned.*

In order for the envisioned management structure of the DRY system to function properly, a strong engagement was required from the District government. This declined as the political will to support the DRY system waned. During a site visit in the spring of 2009, it was apparent that the District had been providing very limited oversight to the DRY system's operations: for example, a visit to the outfall for the treated greywater revealed that the pipeline was blocked (due to a poorly-constructed and consequently damaged manhole) and effluent was overflowing aboveground (**Figure 7-18**). These types of problems usually surfaced only after investigation by the SEI Project Manager and the local SEI staff; clearly, the District would have to be convinced to take greater oversight responsibility for the DRY system were it ever to be transitioned completely to the local institutions.

Figure 7-18. *Overflowing treated greywater effluent from a damaged manhole. [A. Flores, taken 22 April 2009.]*

7.4.2.2 WET System

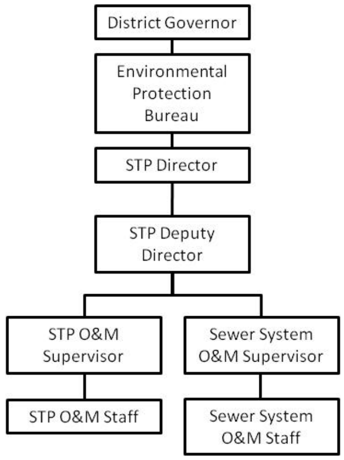


Figure 7-19. *Management structure for the WET System.*

The construction of STPs in China is typically overseen by the local Construction Bureau. For smaller towns and cities in China, the design work is often commissioned from firms located in the bigger cities. The existing Dongsheng STP, for example, was designed in Shanghai (Li, 2007). Thus, it is fairly common that local expertise does not exist for sophisticated technology initially in smaller cities; the main difference, however, is that while expertise on conventional waterbourne systems exist elsewhere in China, experts on the DRY system installed in the District are mainly located in Europe. Experts on various components of the system (e.g., ventilation) exist in China, but because the dry system as a whole is relatively limited in application—particularly in the case of multi-storey buildings—no experts are available locally or nationally.

While the operation of the Dongsheng STP is designed to fit within the current local administrative structure **(Figure 7-19)**, there is in fact limited local institutional capacity to operate and maintain the STP and sewer system properly. Experts from other parts of the country were hired to provide training to local staff to operate the system. During a site visit in September 2007, a monitoring and control system expert was at the STP training local staff. According to the STP Director, sewer systems for new development are currently not well-monitored and not well-coordinated with government plans (Wang, 2007).

7.4.3 <u>Compatibility with Existing Physical Infrastructure</u>

7.4.3.1 DRY System

Zhu (2008) describes the EETP as "an island of eco-town surrounded by the sewage system". When the EETP was first conceived, the economic and housing development situation in the Dongsheng District was quite different. As described above, by 2008, 85% of the Dongsheng District had been covered by a sewer network. A second STP was set for completion in late 2009, even while the first Dongsheng STP was operating under capacity. While the sanitation infrastructure at the EETP did not conflict with the existing conventional waterbourne system, the benefits of an onsite system were harder to appreciate when connection to a centralized system had become so accessible. Zhu (2008) notes that Hantai Town, which is 20 kilometres away from the District and where the sewerage system is not expected to be extended, or Azhen of Yijinhele Banner, where the population only has access to public latrines, may be more appropriate sites for an EETP-type DRY system. In these cases, the lack of existing sanitation physical infrastructure would have made them more compatible with the EETP system.

There is currently no reclaimed water pipeline infrastructure within the Dongsheng District; therefore, the reuse of treated greywater is limited to the immediate vicinity of the EETP.

One of the key advantages of the DRY system is the facilitation of the recovery of nutrients and organic matter from excreta for application to agriculture. There is limited agriculture within the immediate vicinity of the EETP site, requiring transport of compost and urine at a considerable distance, and resulting in higher transport costs and greater environmental impacts. For example, one farmer who had agreed to accept the compost in 2009 was located 30 kilometres away.

7.4.3.2 WET System

The District government has already invested quite heavily in the conventional waterbourne system infrastructure. The WET system already allows for some wastewater reclamation with pipelines from the STP supplying water to a power plant. However, as noted above, the District's stated goal of reusing 100% of wastewater currently does not seem realistic as there is no reuse pipeline infrastructure available to handle the rest of the wastewater produced at the existing and newly constructed STPs.

7.5 Summary of Results

The results of the societal indicator evaluation are summarized in the table below.

Table 7-4. *Summary of the results of the societal indicator evaluation.*

SOCIETAL INDICATORS	DRY SYSTEM	WET SYSTEM
User Acceptability and Desirability (Compatibility with Habits and Preferences)	Poor	**Very good**
Accessibility to Different Age, Gender, and Income Groups	Poor	**Good**
Minimisation of Public Health Risk	Poor	**Neutral**
Legal Acceptability and Institutional Compatibility	Neutral	**Good**

8 Discussion

As discussed in **Chapter 3**, the methodology used here intentionally precludes a quantitative ranking exercise that results in a single numerical sustainability index. It is believed that the value of this multi-dimensional sustainability evaluation lies primarily in the rigorous analysis of individual indicators, the combination of these indicators to get an overall sense of system performance at the dimensional level, and the examination of the various dimensions to identify any tradeoffs that occur. The distillation of this wealth of information into a single sustainability index is not helpful to engineers and planners who need to identify specific components or processes that can be modified towards improved sustainability. Furthermore, developing a single sustainability index requires the weighting of the various indicators, which further adds subjectivity as has been noted by others (e.g., Bohringer and Jochem, 2007; Gasparatos *et al*., 2008).

This chapter begins by presenting the results of the individual indicator evaluations from **Chapters 4 to 7** in a summary table, which is then used to evaluate the results at the dimensional level, comparing them to detect patterns and any common findings. Recommendations are subsequently made for improving the sustainability of the EETP dry sanitation system (DRY) and the conventional waterbourne (WET) sanitation system while identifying the tradeoffs that may occur amongst the indicators. Finally, the issue of who is impacted versus who pays is discussed.

8.1 Summary of Indicator Results

Table 8-1 below presents the summary of indicator results, followed by a discussion of the results at the dimensional level.

Table 8-1. *Summary of results: technical, environmental, economic, and societal Indicators for the DRY and WET systems. Results that are considered better from a sustainability perspective are highlighted in bold (accounting for uncertainty in the assumptions, only differences greater than 100% between LCA impact category indicator values are considered to be significant).*

INDICATORS[c]	**DRY SYSTEM**	**WET SYSTEM**
TECHNICAL		
Ability to meet treatment standards	Neutral	Neutral
Ability to meet capacity requirements	Good	**Very good**
Ease of system operation and maintenance (O&M)		
Users	Very poor	**Very good**
O&M Staff	Neutral	Neutral
ENVIRONMENTAL		
Resource Consumption		
Land – Treatment System (m^2/pe)	3.0	**0.65**
Energy		
Embodied Energy – Construction (MJ/pe)[a]	17,196	**2,473**
Electricity – Operation (kWh/pe-yr)	102	**18.4**[h]
Diesel – Operation (L/pe-yr)	1.8	**0.11**[h]
Cumulative Energy Demand – Operation (MJ/pe-yr)[b]	1,296	**483**
% Renewable Energy – Operations (% of Total Energy)	0%	0%
Water		
Consumption - Toilet/Urinal Operation (L/pe-yr)	**913**	7,665
Resource Depletion (% of Sustainable Water Supply)	**3.6%**	30%
Emissions to Water		
% of BOD/COD, Nutrients, and Heavy Metals in Excreta and Greywater Discharged to Surface Water[d]	0	0
Eutrophication Potential (kg Phosphate Equivalent/pe-yr)	**1.0**	3.5
Freshwater Aquatic Ecotoxicity Potential (kg DCB-Equivalent/pe-yr)	5.4	3.5
Marine Aquatic Ecotoxicity Potential (kg DCB-Equivalent/pe-yr)	25,418	**3,652**
Emissions to Air		
Acidification Potential (kg SO_2-Equivalent/pe-yr)	2.4	**0.59**
Global Warming Potential – 100 yrs (kg CO_2-Equivalent/pe-yr)	221	**81**
Photochemical Ozone Creation Potential (kg Ethene-Equivalent/pe-yr)	0.07	**0.02**
Odour (O&M)	Poor	**Good**
Emissions to Land		
% of Heavy Metals in Excreta and Greywater Discharged to Land	app. 100%	app. 100%
Terrestrial Ecotoxicity Potential (kg DCB-Equivalent/pe-yr)	**1.4**	7.5
Resource Recovery		
% of Nutrients in Excreta and Greywater Applied to Agriculture[f]		
Nitrogen	**73%**	0%
Phosphorus	**71%**	0%
% of Energy (from Organic Matter) Recovered for Electricity Generation, etc.	0%	0%
% of Water Reclaimed for Irrigation and Other Applications[f]	100%	100%
ECONOMIC		
Capital Cost Per Household – Sanitation	$1,661	**$622**
Annual O&M Cost Per Household – Sanitation[g]	$87-106	**$18-31**
User Ability to Pay (Annual O&M Cost of Water and Sanitation as % of Income)[g]	3.8-4.4%	**2.0-2.4%**
Potential for Local Business Development and Household Income Generation	**Good**	Poor

INDICATORS[c]	DRY SYSTEM	WET SYSTEM
SOCIETAL		
User Acceptability and Desirability (Compatibility with Habits and Preferences)	Poor	**Very good**
Accessibility to Different Age, Gender, and Income Groups	Poor	**Good**
Minimization of Public Health Risk	Poor	**Neutral**
Legal Acceptability and Institutional Compatibility	Neutral	**Good**

Notes: a. Equivalent to Cumulative Energy Demand for construction; b. includes system expansion; c. pe = person, yr = year; d. both systems discharge to land and thus do not have direct discharges to surface water; e. for life cycle impact categories, the total indicator values (construction + operation, including system expansion) were averaged over 20 years; while this approach may not represent physical reality (e.g., construction impacts are generally created during the production time of the materials, a much shorter time period than 20 years), it was taken to simplify the comparison between the two systems. f. Based on assumed scenarios of complete recovery of nutrients from the DRY system and water from both systems. g. smaller values include income from byproduct recovery. h. does not include electricity for fertilizer production.

From a technical perspective, the two systems are both generally capable of meeting treatment standards and capacity requirements. The DRY system is technologically less mature than the WET system, and therefore requires further improvements particularly with regard to odour control, toilet design, and faecal material handling. The proper operation of the WET system's centralised STP, as well as of the DRY system's onsite greywater treatment plant, is fairly complex and requires skilled workers.

From an environmental perspective, while the DRY system offers some distinct advantages, overall it performs poorly compared to the WET system. Reflecting the drivers for the development of the DRY system, it offers superior environmental performance based on its lower water consumption, lower eutrophication potential, and greater nutrient and organic matter recovery during operation. It also offers lower terrestrial ecotoxicity potential by reducing the use of fertilizers that contribute to heavy metal application to agricultural land. However, these environmental advantages come at a cost: the DRY system's greater land, material, and energy requirements cause it to perform poorly relative to the WET system based on land and energy consumption, and the potential for marine aquatic ecotoxicity, acidification, global warming, and photochemical ozone creation.

From a purely financial perspective, the DRY system is a more costly system as it requires greater infrastructure and therefore higher capital costs, has higher operational costs, and does not benefit from economy of scale. As a novel technology, however, it does offer the potential for local business development. Incomes from the resources recovered from the DRY system are not sufficient to overcome its greater costs relative to the WET system.

The WET 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. 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”. An important concern with the DRY system is the health risk associated with its faecal management system.

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. As noted previously, eutrophication is not a particularly significant issue in the area. However, as currently designed and operated, the DRY system has some serious disadvantages that limit its prospects for sustainability. The next section discusses the robustness of the results and how the sustainability of the DRY system can be improved, followed by a more general discussion of how the WET system’s sustainability can also be improved.

8.2 Robustness of Results

This section discusses the levels of uncertainties associated with the analysis that could affect the results presented above.

While the technical indicators are qualitatively assessed, and can therefore be viewed as subjective, they are grounded in a combination of quantitative methods (e.g., effluent chemical analysis, surveys, analysis of treatment process capacities) and site-specific observations. The data used for the technical indicator analysis are considered to be quite reliable and representative of actual conditions.

For the environmental indicators, uncertainties in the data—particularly those used in the Life Cycle Analysis—are addressed through the sensitivity analysis presented in **Section 5.1.6**. The sensitivity analysis revealed that even while accounting for possible errors in the data within a reasonable range, or feasible changes or improvements to the DRY system, the overall conclusions hold. The environmental indicators are largely driven by material and energy consumption, and because there is such a large difference in the consumption patterns between the DRY and WET systems, the conclusions are quite robust. Some researchers stop at the Life Cycle Inventory (LCI) stage in assessing environmental impacts in order to avoid the uncertainties and complexities associated with contaminant fate and transport modeling (e.g., Foley *et al*., 2010). The challenge of accounting for site-specific fate and transport conditions is highlighted in **Section 5.2.6**, which discusses emissions to water bodies. In this research, the indicators are a combination of LCI results and Life Cycle Impact Assessment indicator values; both sets of indicators lead to the same general conclusions regarding the detrimental impacts on sustainability of the DRY system's high resource consumption.

The economic analysis of the DRY system is based on actual costs and estimates based on actual operating conditions (e.g., calculated power consumption for the composting process). The results for the DRY system costs should be viewed in light of potential optimizations that were not implemented before the DRY system was converted to a WET system in mid-2009. One important issue to note, however, is that a decentralized system is naturally less likely to benefit from economies of scale. This is particularly true of labour costs. In the system scenarios analyzed, by itself the salary for the DRY system workers was greater than the total operational cost of the WET system. The WET system costs were derived by Zhou *et al*. (2007) from surveys of waterbourne systems in China, and are considered representative of average conditions there if not exactly those of the Dongsheng STP system.

The societal indicators are qualitatively assessed, but are grounded in actual field observations and surveys. Multiple sources of evidence are used to form conclusions. Based on current conditions, the superior acceptability and accessibility of the WET system is unquestionable, and the health risks from the DRY system are fairly obvious. The issue of legal acceptability is fairly straightforward, although subject to various political players, and institutional compatibility is a somewhat subjective issue. Rather than whether the societal indicator evaluation is accurate, perhaps the more relevant question is how much can the results be improved for the DRY system.

8.3 Recommendations for Improvements to the DRY System

The recommendations presented below are intended to improve the sustainability of the DRY system; they place more emphasis in areas where the DRY system performance is weak relative to that of the WET system.

8.3.1 <u>Technical</u>

In the DRY system scenario, the design has been modified to include sufficient infrastructure to handle all compost onsite and store urine for the time required to achieve treatment. There are some actions that can be taken to improve the composting process and ensure reliable treatment, such as:

- addition of organic kitchen waste to optimize the carbon/nitrogen ratio without using excessive sawdust and to provide a better structure for ventilation (Mertens, 2009);
- processing of sufficient volume of raw compost material to generate enough heat and maintain high temperatures (Mertens, 2009);
- use of a more powerful blower and more rigorous or frequent manual aeration to maintain aerobic conditions;
- removal of non-compostable solid waste after the completion of the composting process to improve aeration of the pile (Jonsson, 2009)
- insulation of the composting chambers to maintain high temperatures and optimized use of solar heating.

To ensure adequate reuse or disposal capacity, the managers of the DRY system (as of 2009, a combination of onsite O&M staff, SEI personnel, and District employees) need to work closely with the farmers to ensure that there is no disruption to their receipt of compost and urine deliveries that could affect operations. Some additional storage space onsite at the EETP could provide a buffer in case of problems at the farmers' receiving end. Note, however, that any infrastructure expansion would add to the system's material requirements. There is more flexibility with compost as it does not require an elaborate storage facility (e.g., compost bags can simply be piled outdoors on agricultural land and covered with a waterproof tarp until needed). The treated greywater drainage ditch needs to be

Figure 8-1. *Promotional leaflet for the EETP advertising "47% green area".*

modified to enhance percolation rates and prevent flooding. More importantly, the District government should work with the EETP managers to facilitate the safe reuse of the greywater. At a minimum, reuse of the greywater for irrigation would not only reduce the freshwater demand at the EETP, but would also enhance the greenery at the EETP in line with the original vision of the developers (**Figures 8-1**).

To improve the ease of operation and maintenance of the UDD toilets for users, the design of these units needs to be modified. Stream separation of urine and faeces is challenging for users, and one alternative is to do a combined collection of faeces and urine; this will however result in reduced nutrient recovery. If urine is composted with faeces, much of the nitrogen will be lost as ammonia under aereobic conditions (Jonsson *et al*., 2004); the released ammonia will not only reduce the fertilizer value of the DRY system but can also contribute to eutrophication[51]. A low-flush toilet that collects urine and faeces together and diverts them to a separate blackwater treatment process offers the advantage of addressing problems with odour, sawdust use, struvite precipitation, and manual collection of faeces simultaneously while still allowing for separate treatment of excreta and greywater. This would require a different technology for the excreta processing, such as anaerobic digestion, which is particularly suited for processing concentrated wastewater. The potential of anaerobic digestion processes to improve the sustainability of sanitation systems is described by Segehezzo *et al*. (1998). Use of low-flush toilets (e.g., 3 L for urine and 6 L for faeces) would of course increase the DRY system’s water consumption and the associated energy demand. Ultra-low flush toilets can employ vacuum technology for transporting the concentrated blackwater, but vacuum systems, like the DRY system, would require a reliable electrical supply to operate the collection system.

Another alternative to the use of dry toilets is the use of urine-diversion (UD) flush toilets; urine continues to be collected separately, with minimal water (e.g., 0.15 L, which is less than the amount currently used at EETP), but faeces is collected with a small volume of flush water (e.g., 5 L) and diverted to a separate treatment process, such as anaerobic digestion. One example of such a UD flush toilet is the NoMix toilet produced by Roediger, which is discussed further in **Chapter 9**. Nutrient recovery from urine and faeces continues to be high while eliminating or minimizing challenging O&M issues such as odour problems, sawdust use, and manual collection of excreta.

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51 Atmospheric deposition of nitrogen can be a leading contributor to eutrophication (e.g., see Boyer *et al*., 2002). The emission of N into the air extends the potential eutrophication impact of the sanitation system beyond the immediate vicinity of the District.

Additional recommendations for technical improvements are discussed in the sections below, as they relate to specific indicators.

8.3.2 Environmental

The recommendations for improving the environmental performance of the DRY system emphasize those parameters that make significant contributions to the system's impacts, as identified in the sensitivity analysis in **Section 5.1.6**, and in those areas where the DRY system does not perform as well as the WET system.

8.3.2.1 Land Intensity

The high land requirement of the DRY system's current design makes it unsuitable for high-density areas where land is a premium. Given its current design, its land requirement is nearly 5x that of the WET system. The treated greywater storage pond makes up 53% of the total land area; reducing the required storage will therefore significantly improve the DRY system's footprint. The pond is currently oversized for greywater storage as it serves the additional function of stormwater retention. The depth of the pond was sized to prevent blockage of the inflow pipe with ice; a minimum depth of 1.8 m was estimated to be required since the water can freeze down to approximately 0.8 m from the surface (Zhu, 2008). Increasing the depth of the pond to reduce the area would have to take into account the need to keep the water aerated to prevent odour-causing anaerobic conditions in the pond bottom. Hydrogeologic conditions would have to be taken into account as well: e.g., rocky ground and high groundwater levels would make deeper construction more challenging and expensive. Reliable and regular reuse of the treated greywater, as well as alternative stormwater control measures, would reduce the required storage volume. Note that at the EETP, the pond was also designed to enhance the landscape.

8.3.2.2 Energy Consumption

Embodied Energy – Construction: The DRY system is material-intensive, with an embodied energy 7x greater than that of the WET system. The faecal collection system contains 71% of the embodied energy; reducing its material requirements would therefore significantly reduce the DRY system's overall embodied energy. The basement, which houses the faecal collection bins, is the most material-intensive portion, with the bricks alone accounting for nearly 50% of the system's total embodied energy. One alternative to explore for eliminating the need for a basement would be to have the faecal materials discharged to the side of the buildings. The faecal chutes would be sloped to the exterior side of the buildings—with as steep an angle as possible—then drop down vertically to a common collection area at the base of the building. This would have the potential added benefit of minimizing the interior space required to run faecal chutes through each floor (currently the bathrooms in the ground floor flats are smallest as they need to accommodate the faecal chutes coming down from the floors above). This sloped-chute outdoor design would require some consideration of how to minimize fouling of the chutes as it would result in greater surface area contact between faeces and the chutes.

Finding an alternative basement design would not only reduce the environmental impacts of the DRY system, it would also significantly reduce the costs. According to Zhu (2008), the basement represents approximately 60% of the overall toilet cost. Finally, if a basement design is necessary, then perhaps the basement space can be expanded to include space for other functions (e.g., storage); this would require some consideration of health and safety issues as access to and contact with the faecal bins should be minimised. Note, however, that while expanding the basement's function will reduce the environmental impact associated with sanitation, it will add to the overall impact of the building.

If source-separation is the primary goal, then a vacuum low-flush toilet system to collect urine and faeces separately may be worthy of consideration; this type of system would of course require a different pipeline infrastructure and would require electricity and water to operate. According to Zhu (2008), a quote for a vacuum system by EnviroSystems was similar in price as the entire household installation for the DRY system (toilets and urinals, faecal chutes, bins, cabinets, and basements.

Cumulative Energy Demand – Operation: The cumulative energy demand associated with the DRY system operation is 2.7x that of the WET system, even accounting for the energy associated with chemical fertilizer use. Surprisingly, 44% of the cumulative energy demand derives from the power required for the faecal collection system (ventilation and lighting). To minimize odours in the households, the bins are kept at negative pressure with air exhausts located at the rooftops. The fans run 24 hours per day, 365 days per year and consume electricity equivalent to 19 Watts per household. In contrast to flush toilets, which rely on a water seal for odour control, mechanical ventilation may be the only effective way to deal with any odours. While proper use of the toilets (e.g., keeping the faecal bins as dry as possible) can greatly minimize odours, it may be difficult to completely eliminate them. Optimizing the design of the ventilation system may reduce the size of the fan required, and the associated energy demand. For comparison, the Separett Villa 9000 dry toilet[52], which

52 http://www.separett.eu/default.asp?id=2069&ptid=2052. Accessed 20 January 2010.

was tested at the EETP, includes a 11.5-Watt fan to expel odours and condensation from individual toilets.

The next biggest contributor to energy demand is the composting process at 34%. Because of the low temperatures during the fall and winter in the Dongsheng District, heating the faecal materials has been necessary to achieve the required temperatures for sterilization. The current composting process also requires aeration to maintain aerobic conditions and a low-odour breakdown process of the organic matter. The addition of kitchen waste to the composting process would add bulking materials and enhance aeration, possibly reducing the aeration needs. This would also reduce the amount of sawdust necessary to achieve the right carbon/nitrogen ratio, reducing the diesel consumption of sawdust transport and the labour associated with sawdust processing. An alternative toilet design (e.g., sliding plate design) that eliminates or minimizes sawdust use is needed. Finally, a redesign of the composting area may allow for greater insulation and solar exposure, and reduced heating costs.

8.3.2.3 Emissions to Water

Both the DRY and WET systems discharge to land; therefore, impacts associated with emissions to water bodies are related to the production of materials and energy supplies and the transport of contaminants from land to water bodies. Emissions into the air (e.g., ammonia) also ultimately contribute to water body impacts due to atmospheric deposition; these impacts extend beyond the vicinity of the District. There are very few surface water bodies in the area surrounding the Dongsheng District; therefore, in reality, any contaminants in the direct discharges from the DRY or WET systems are likely to stay bound in soil.

Freshwater Aquatic Ecotoxicity Potential: Both construction and operation contribute significantly to this environmental impact, at 59% and 41% respectively. The three sets of polyvinyl chloride (PVC) pipelines for the collection system make up 95% of the impact associated with the infrastructure. The combined collection of urine and faeces and any flush water (“blackwater”) would reduce the pipeline requirements, but this would require a different type of treatment process and combining the two streams may reduce the recovery of nutrients for agriculture. The discharge of heavy metals from the greywater treatment system is the primary contributor (71%) during operations; however, as noted previously, the heavy metal discharges are unlikely to reach freshwater in the District. In this case study, therefore, this portion is perhaps more accurately allocated to terrestrial ecotoxicity poential. Conventional systems face the same problem of discharging heavy metals, and face a bigger problem when the system collects both domestic and industrial wastewater; the DRY system's separate collection of domestic wastewater is therefore a step in the right direction.

Because PVC has such a large environmental impact relative to high density polyethylene (HDPE), particularly with regards to toxicity (see **Figure 8-2**), one potential environmental improvement to the DRY system (and the WET system) is the substitution of PVC by HDPE pipelines. The environmental problems associated with PVC are described by Thornton (2008) as follows:

> *"The PVC lifecycle presents one opportunity after another for the formation and environmental discharge of organochlorines and other hazardous substances. This apparently innocuous plastic is…one of the most hazardous materials on earth, creating large quantities of persistent, toxic organochlorines and releasing them into the indoor and outdoor environments. PVC has contributed a significant portion of the world's burden of POPs and endocrine disrupting chemicals…that are now in the environment and the bodies of the human population. It is beyond doubt that vinyl has caused considerable occupational disease and contamination of local environments as well."*

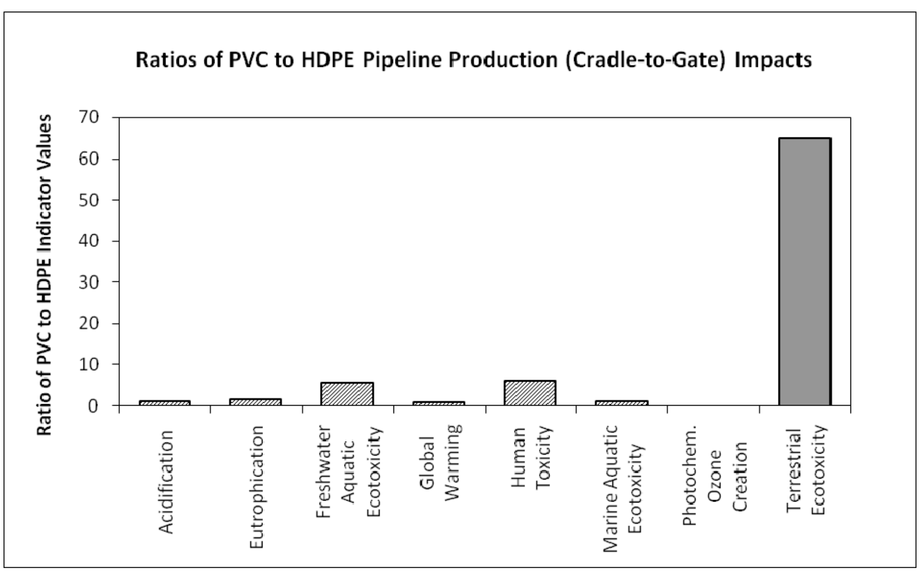

Figure 8-2. *Ratios of the cradle-to-gate life cycle environmental impacts of one meter of 27-cm PVC pipeline versus HDPE pipeline.*

While PVC is well-established in the water and wastewater industry, HDPE is increasingly being used, not (just) for its environmental advantages but because it offers performance and construction advantages as well. Some advantages of HDPE noted by its advocates are: leak-free joints; high resistance to corrosion; quick, efficient, and cost-effective installation compared to other pipelines; flexibility; and customizable design[53,54].

Marine Aquatic Ecotoxicity Potential: The DRY system performs worse in this category relative to the WET system. Construction is responsible for 83% of this environmental impact, with the bricks alone for the basement accounting for 60% of the total. Again, reducing the material requirements for the basement or reconfiguring the faecal collection system would help reduce this impact, or any other impacts resulting from the toxic emissions from the brick production process.

8.3.2.4 Emissions to Air

Acidification Potential: The acidification potential of the DRY system is 3.5x greater than that of the WET system. Operation is responsible for 93% of this environmental impact. The emissions from the faecal treatment process, followed by the power production for the faecal collection system and the emissions during urine application to agriculture are the primary contributors. Emissions during the faecal treatment process can be captured through scrubbers, similar to the one currently installed. As noted above, optimizing the design of the ventilation system for the faecal collection system could result in lower power consumption. Proper urine application techniques in agriculture could reduce emissions.

Global Warming Potential: The global warming potential (GWP) of the dry system is 2.7x greater than that of the WET system. Operation is responsible for 70% of the total impact for the DRY system. Together, the bricks for the faecal collection system, and the electrical consumption of the faecal collection system and the composter, account for 65% of the total impact. Therefore, recommendations for reducing the infrastructure requirement for the basements and reducing the power consumption during operations as noted above would help reduce this impact as well.

Photochemical Ozone Creation Potential: Operation is responsible for 78% of this impact. As in the case of GWP, the bricks and electricity for the faecal collection system, and the

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53 http://www.estormwater.com/Confidence-in-HDPE-Pipe-Growing-article8344. Accessed 8 April 2010.

54 http://www.undergroundconstructionmagazine.com/hdpe-pipe-plays-major-role-city%E2%80%99s-sewer-expansion. Accessed 8 April 2010.

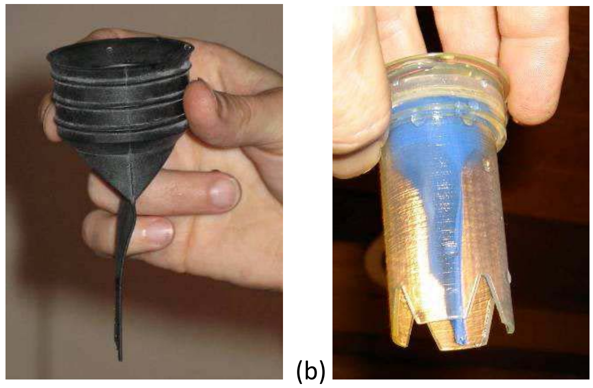
electricity for the composter make up a large percentage of the total impact at 74%. The same recommendations therefore apply.

Odour: The faecal and urine collection systems are the primary sources of odour problems. Poor drainage of greywater due to poor construction of the odour traps also contributed to odour problems (Rosemarin, 2010); odours associated with greywater can therefore be improved through proper construction. An improved design of the ventilation system for the UDD toilets intended to reduce power consumption would need to ensure that odours are adequately expelled. The Separett Villa 9000 toilets, for example, appear to have a lower power requirement for ventilation, and the provision of individual fans sited directly at the toilets may be a more effective way of expelling odours. Siting the toilets next to an outside wall may also be helpful, as noted by Li (2009), since this would allow for improved ventilation of the bathrooms via a window at least during the warmer months; additionally, this would allow for the sloped-chute outdoor design discussed in **Section 8.3.2.2.**

The odour traps at EETP that use paraffin oil as a sealant liquid work somewhat to mitigate odours but do require regular maintenance, which the households seem unwilling to do; a less cumbersome odour prevention device may better ensure regular odour control. von Munch (2009) describes various options that currently exist for odour control in waterless urinals; two popular options in Europe are rubber tube seals and curtain valve seals (**Figures 8-3a and 3b**). The two seals work on similar principles: they are essentially flat tubes that are normally closed, sealing off any odours from below; when urine flows from above, they open to allow urine to drain, then close again. There are also other odour control models of the sealant-liquid type, such as the one produced by Uridan. Von Munch (2009) notes that it is not clear which of the models above are best for low-maintenance and low-cost applications; however, there is some evidence that the rubber tube and curtain valve seals may require less maintenance efforts.

Finally, as noted previously, the use of low-flush toilets (urine-diversion or not) would allow for greater odour control.

(a) (b)



Figures 8-3a and 3b. *Alternative odour control mechanisms for waterless urinals: (a) rubber tube seal produced by Keramag and (b) curtain valve seal ("EcoSmellStop") produced by Addicom. (from Munch [2009])*

8.3.2.5 Emissions to Land

Heavy metals are some of the key contaminants of concern in wastewater, and their discharge to soil results in terrestrial ecotoxicity. They are of course also problematic in aquatic ecosystems. Upstream reduction of heavy metals in the food cycle and in material use would lower their emission to land from sanitation systems; this is something that would have to be addressed at the national level through policy. The recovery of nutrients in the DRY system and the resulting reduction in the use of chemical fertilizer—which contains heavy metals—reduces the overall loading of heavy metals to agricultural soil; this is one clear benefit of the DRY system from a sustainability perspective. As noted in **Section 8.3.2.3**, the production of bricks for the basements is associated with heavy metal emissions, which in the case of the Dongsheng District are likely to be discharged to land; therefore, reducing the material requirements for the basement or reconfiguring the faecal collection system are likely to decrease this impact.

8.3.3 Economic

As discussed in **Chapter 6**, the capital cost of the DRY system is 2.7x greater than that of the WET system while the annual O&M cost of the DRY system is 3.5x greater. In addition to having a large environmental impact, the basements also have a large impact on the capital cost. An alternative design to lower the embodied energy of the faecal collection system may also result in lower cost. As Zhu (2008) points out, the potential for improved and significantly less expensive design of the basements was already recognized during the EETP construction.

The costs of the DRY's system's greywater treatment plant and the composting plant also contribute significantly. The higher cost of the DRY system can of course be partially attributed to the use of novel technology; further optimization of the design and the establishment of markets for "standard" designs and material supplies are likely to lead to lower costs in the future. Through policy, the government can encourage the growth of such markets. Because the DRY system is based on a decentralized model of wastewater management, it follows that it benefits minimally from economy of scale; this will thus limit the extent to which costs can be reduced.

With regards to operation cost, one major way to reduce it is by reducing the staffing requirement. As of 2009, there were eight O&M workers at the EETP. Conservatively assuming that there were 832 households or 2912 people being served at that time, this equates to 364 people served per worker. In contrast, the Dongsheng STP and sewer system had a total of 45 workers serving approximately 320,000 people (Zhou *et al*., 2007) or the equivalent of 7,111 people served per worker. Increased mechanization of the system—requiring a change in the faecal collection and treatment process—may help decrease costs provided it does not come at the expense of a high increase in energy cost. The creation of service providers dedicated to operating and maintaining multiple decentralized systems may lead to reduced operation costs. Reducing the capital cost by reducing the material intensity of the dry system could also lead to reduced O&M cost, since ongoing equipment replacement and renewal costs are often tied to initial investment costs. Finally, reducing the energy requirements, as discussed above, would lead to reduced operation cost. With reduced capital and O&M cost, the DRY system would of course become more affordable to users.

As noted above, through policy, the government can encourage greater implementation of EETP-type systems and the associated business development opportunities described in **Section 6.4**.

8.3.4 <u>Societal</u>

8.3.4.1 User Acceptability and Desirability

As discussed in **Section 7.1**, the toilets and urinals of the DRY system have low user acceptability and desirability relative to the WET system. This mainly stems from problems with odours, the greater demands of the UDD toilets' operation and maintenance, the inconvenience of using sawdust, and the established nature of the water-flushed toilets as a symbol of modernity and prosperity. There is much to be done to make dry toilets more acceptable and desirable. First and foremost, more education and sensitization upfront are necessary. Many residents of the EETP were unaware of the kind of sanitation system they were receiving when they purchased their flats. In the Spring 2009 Survey (Flores, 2009), the average response to the question, *"How much did you know about the sanitation system before you purchased the flat/moved in?"*, was 2.1 on a scale where 1 is *"Nothing at all."* and 9 is *"Knew about the dry toilet and how it worked."* The households were clearly unprepared to deal with a novel and unfamiliar system, and were consequently disappointed and embittered because they felt cheated.

All potential buyers should have been fully informed about the dry sanitation system and its advantages and disadvantages, trained in its operation and maintenance, and shown a properly functioning dry toilet so they can see how well it can work given proper care. Potential buyers should also have been fully educated about how the dry system works overall so that they can appreciate the reasons for certain restrictions, such as minimizing the use of water and ensuring that only faeces, sawdust, and toilet paper are discharged down the faecal chutes. In this way, the users are less likely to treat the faecal chutes as a kind of black hole for disposing of all kinds of undesirables. Furthermore, the users should have been made aware of the experimental nature of the system, preparing them for using a system that has not been optimized and having to deal with necessary changes and adjustments to the system to improve it and encouraging them to contribute to the learning process by providing feedback in a constructive way. Finally, the novelty of the system, combined with the greater O&M requirements, requires a responsive and capable O&M team willing to provide continuous education and training. The 24-hour O&M hotline set up at the EETP was certainly a step in the right direction, although of course the labor associated with such a hotline comes at a cost. This may only have been necessary at the early stages, and certainly if the dry system technology becomes more common, there will be fewer new users to train.

But none of the above recommendations is likely to fully address the need to make the system acceptable and desirable if the system does not work properly. Problems with odours have to be corrected through better design, as well as user training. As previously noted, the ventilation system for the faecal collection system has to be improved towards lower energy consumption, lower cost, and better odour control. Improved odour control for urine is also needed as discussed in **Section 8.3.2.4**. An alternative toilet design that eliminates sawdust may also improve user acceptability and desirability as the sawdust is associated with health concerns and operational issues. A non-separating low-flush toilet may address problems with odours and sawdust, but a UD low-flush toilet would have the same problems associated with stream separation.

The government also has an important role to play in making the DRY system more acceptable and desirable to its constituents. The users should be fully aware of problems with water shortage and the high cost of water, which are key drivers for the DRY system. The price of water should reflect its high cost, sending a price signal that incentivizes reduced water consumption. Greater encouragement of DRY system installations by the government through tax incentives and co-sponsorship of project development may encourage more widespread installation, and, in the long-term, reduced costs and greater familiarity with and acceptance of the system. The government would also need to stop expanding the conventional waterbourne system as this reduces the incentive to install an alternative system; furthermore, once the system is built and the construction impacts have been made, there is less environmental benefit to switching to a DRY system.

8.3.4.2 Accessibility to Different Age, Gender, and Income Groups

As noted in **Section 7.2**, an alternative toilet design is needed to address problems experienced by children, women, and the elderly in activating the turning bowl and in separating the waste streams. The sliding plate mechanism addresses the former problem, and also eliminates the need for sawdust. A low-flush toilet that collects urine and faeces together eliminates the challenges with stream separation and sawdust use. Efforts to reduce capital and O&M costs, as discussed above, would make the system more accessible to lower-income groups.

8.3.4.3 Minimization of Public Health Risk

The health risks—perceived and real—of the DRY system are related to the workers' exposure to faecal material, user and worker exposure to sawdust, and the agricultural workers' exposure to potentially pathogenic materials in urine and compost. There are also more dispersed risks associated with the contaminants emitted during the production of the materials used in the DRY system (e.g., PVC pipelines). More mechanized collection of faeces can potentially be implemented through the use of the outdoor-sloped chute design. A low-flush gravity system or ultra-low flush vacuum system would allow for the waterbourne conveyance of faecal material with reduced water consumption relative to the WET system and elimination of sawdust use. The elimination of sawdust can also be achieved through an alternative dry toilet design. The public health risks from the use of composted faeces for agriculture can be minimized through training of O&M workers in the proper operation of the composting process, of farmers in safe compost application techniques, and of consumers in hygienic food handling (see WHO [2006b] for specific recommendations[55]). Technical improvements to the composting process to make it reliably achieve thermophilic conditions will make the compost safer to handle. Training of users, and improved toilet design, to improve separation of faecal matter from urine is also important as this reduces the risks associated with urine application to agriculture. Finally, plumbers would need to be trained, and possibly certified, in the proper design and installation of separate pipelines for the different waste streams to avoid cross-contamination. Building codes would also need to specify proper labeling of the pipelines.

8.3.4.4 Legal acceptability and institutional compatibility

As noted in the previous sections, the government has a large role to play in making the DRY system more sustainable particularly from economic and societal perspectives. Currently, the WET system is strongly encouraged by national policies in China as discussed in **Section 7.4.1**, but the DRY system actually meets the aspirations of the Chinese government at the highest levels. To make the DRY system—and other similar resource-recovery systems—more legally acceptable and institutionally compatible, policies would need to be improved as follows:

- Implement clearer directives to encourage and reward resource recovery in sanitation systems (e.g., provide grants to cover the additional capital cost of installing a biogas recovery system).
- Reduce the emphasis on and rewards for centralised STP construction, especially when its actual value can not be demonstrated (e.g., when there is an inadequate sewer network to collect and transport waste to the STP)
- Enforce water conservation especially in water-stressed areas such as Dongsheng District, while educating the people on the need for it.
- Encourage pricing of water and wastewater services to reflect actual costs.
- Support business development efforts related to the DRY system (or other forms of resource-oriented sanitation system) technology.
- Amend wastewater discharge standards to account for mass loadings and not just concentrations.

55 E.g., application of urine close to the ground to avoid aerosol formation, application of urine and compost to crops that need to be cooked before consumption, availability of clean water for washing agricultural products at the markets.

- Develop standards for alternative sanitation system construction.
- Allow for the efficient and effective management of decentralized sanitation systems by private parties or by government departments.
- Lead by example: well-designed and well-managed dry toilets (or other toilets that facilitate resource recovery) should be installed in new and modern public toilet facilities.

8.4 Recommendations for Improvements to the WET System

One of the keys to improving the STP's technical performance is the investment of the District in well-trained staff. This may also result in reductions in resource consumption (e.g., energy) as the staff learns to optimize the treatment processes. Finally, well-trained staff will reduce health risks to themselves and to the public.

From an environmental perspective, the WET system performs worse than the DRY system based on its eutrophication and terrestrial ecotoxicity potential impacts. Problems with high environmental emissions of nutrients from treated effluent and sludge and the application of mineral fertilizers containing high levels of heavy metals to agricultural land can both be addressed through nutrient removal and recovery. Note that the impacts of mineral fertilizers are not just confined to heavy metal emissions: **Figure 5-7b** shows that the production and transport of chemical fertilizers have a large environmental impact relative to the construction and operation of the conventional wastewater system in other categories as well (e.g., acidification). Furthermore, because phosphorus is a non-renewable resource, its recovery is critical for long-term sustainability. Thus, nutrient removal and recovery have the potential for greatly improving sustainability. One must be cautious, however, that the processes implemented do not have environmental impacts that outweigh those of the existing system. This point is often overlooked by environmental regulations that are increasingly pushing for nutrient removal while focusing solely on receiving water quality.

Foley *et al*. (2010) illustrate the potential environmental trade-offs that can occur when nutrient removal processes are implemented. In analyzing various wastewater treatment system configurations and effluent qualities, they conclude that infrastructure resources, operational energy, direct greenhouse gas (GHG) emissions and chemical consumption generally increase with increasing nitrogen removal. In the case of phosphorus, while infrastructure resources and chemical consumption increase sharply with increasing phosphorus removal, operational energy and direct GHG emissions are largely unaffected. Foley *et al*. (2010) stop at the Life Cycle Inventory stage in their analysis; to evaluate the net environmental impacts, these inventories would have to be analyzed in a Life Cycle Impact Assessment.

The recovery of phosphorus is much easier to implement than that of nitrogen; removal by precipitation often simply requires the addition of chemicals such as ferric chloride. However, one problem faced by wastewater utilities—particularly those receiving both domestic and industrial wastewater, or those vulnerable to illegal discharges— is the heavy metal content of the sludge, which may exceed standards. Upstream reduction in heavy metal discharges is one way to counter this problem.

Without additional treatment at the STP, recovery of nitrogen and phosphorus can be achieved through the use of treated wastewater for agricultural irrigation. Again, one must evaluate the potential environmental impacts of constructing the reuse infrastructure, particularly if the receiving site is not near the STP.

Reducing power consumption is another means of improving the WET system's environmental performance (as well as economic performance); the power for the STP alone contributes 59% to the total acidification potential of the system. Other studies have recognized power consumption as the key indicator of environmental performance for a conventional STP (e.g., Pillay, 2006). Reduced power consumption may be possible to achieve through process optimization, such as the use of variable frequency drives for pumps and blowers and improved monitoring and control of the aeration process. Aeration can represent nearly 50% of the energy demand of a secondary treatment plant (Ong-Carrillo, 2006) and therefore represents opportunities for significant energy reduction. Energy recovery from sludge may offset energy demands, but this will require additional infrastructure.

To minimize public health risks from the conventional waterbourne system, proper construction, operation, and maintenance of the sewer system is critical. Proper construction will prevent leaks while regular inspections to ensure drainage systems are not blocked will prevent overflows. Users also need to be properly trained in what can safely be disposed of in sewer drains.

It is important to note that there remain some unresolved issues regarding the safety of the application of domestic wastewater to agriculture. One such concern that applies to both the DRY and WET systems is the presence of pharmaceutically-active compounds and their impact on the safety of food produced from land to which the products of domestic wastewater has been applied. Upstream reduction of these compounds in wastewater is one way to address this issue, perhaps through improved user education. Researchers are also currently investigating how such compounds can be removed from wastewater effectively and economically.

8.5 Who is Impacted? Who Pays?

The indicators have different scopes of geographic impact, as identified in **Table 8-2**. In performing the sustainability evaluation, the technical, economic, and societal indicators were evaluated mainly from the perspectives of those who are most affected. Depending on the specific indicator, this group included the users, the sanitation system workers, the government officials, the other residents of the District, and the farmers and other workers who may be handling the byproducts of the treatment systems. In other words, the evaluation mainly focused on local impacts. In the case of the environmental dimension, however, the impacts can extend to a regional, and even global, population. Global warming, acidification, and recovery of nutrients (P is an internationally-traded commodity) have global impacts, while acidification, photochemical ozone creation (smog), and water depletion have regional impacts.

Table 8-2. *The indicators and their scopes of geographic impact: personal (P), local (L), regional or national (R/N), and/or global (G).*

INDICATORS	IMPACTS			
	P	L	R/N	G
TECHNICAL				
Ability to meet treatment standards		✓	✓	
Ability to meet capacity requirements		✓	✓	
Ease of system operation and maintenance (O&M)				
Users	✓			
O&M Staff	✓	✓		
ENVIRONMENTAL				
Resource Consumption				
Land – Treatment System (m^2/pe)		✓		
Energy		✓	✓	✓
Water		✓	✓	
Emissions to Water				
% of BOD/COD, Nutrients, and Heavy Metals in Excreta and Greywater Discharged to Surface Water[d]		✓		
Eutrophication Potential (kg Phosphate Equivalent/pe-yr)		✓	✓	
Freshwater Aquatic Ecotoxicity Potential (kg DCB-Equivalent/pe-yr)		✓	✓	
Marine Aquatic Ecotoxicity Potential (kg DCB-Equivalent/pe-yr)		✓	✓	

INDICATORS	IMPACTS			
	P	L	R/N	G
Emissions to Air				
Acidification Potential (kg SO_2-Equivalent/pe-yr)			✓	✓
Global Warming Potential – 100 yrs (kg CO_2-Equivalent/pe-yr)		✓	✓	✓
Photochemical Ozone Creation Potential (kg Ethene-Equivalent/pe-yr)		✓	✓	
Odour (O&M)	✓	✓		
Emissions to Land				
% of Heavy Metals in Excreta and Greywater Discharged to Land		✓		
Terrestrial Ecotoxicity Potential (kg DCB-Equivalent/pe-yr)		✓		
Resource Recovery				
% of Nutrients in Excreta and Greywater Applied to Agriculture[f] Nitrogen Phosphorus		✓	✓	
% of Energy (from Organic Matter) Recovered for Electricity Generation, etc.		✓	✓	
% of Water Reclaimed for Irrigation and Other Applications[f]		✓	✓	
ECONOMIC				
Capital Cost Per Household – Sanitation	✓	✓		
Annual O&M Cost Per Household – Sanitation[g]	✓	✓		
User Ability to Pay (Annual O&M Cost of Water and Sanitation as % of Income)[g]	✓	✓		
Potential for Local Business Development and Household Income Generation	✓	✓		
SOCIETAL				
User Acceptability and Desirability (Compatibility with Habits and Preferences)	✓			
Accessibility to Different Age, Gender, and Income Groups	✓	✓		
Minimization of Public Health Risk	✓	✓		
Legal Acceptability and Institutional Compatibility		✓	✓	

Another geographic issue is related to the production of the materials used for the construction of the sanitation system and other resources such as fertilizers and energy. For example, any organic chemicals released to a freshwater body during PVC pipeline production would result in freshwater aquatic ecotoxicity in that freshwater body. If the factory is located 200 kilometres away from the case study site, then that particular impact would not directly affect the users of the sanitation system but may affect, for example, fishermen who rely on that freshwater body for fish to sell.

In addition to the differences in geographic impacts, which can also be described as "intra-generational" differences, there are also differences in the timing of the impacts, particualrly with regards to which generation/s are affected. These latter differences can be contrasted from the former as "inter-generational" impacts. Global warming potential, for example, is likely to be more relevant to future generations; in contrast, user acceptability and desirability is of great relevance to the current generation using the sanitation system.

What the examples above illustrate is that often there is not a clear connection amongst who benefits, who is harmed or disadvantaged, and who pays. How, therefore, should costs be allocated? Should the benefits and disadvantages be weighted differently depending on the recipients? Often, impacts at the global and national level are considered in policy development and translated into regulations; these regulations then become mandatory considerations for people making the decision at the local levels. At the personal level, the most important considerations are typically those that directly impact the user: monthly fees to be paid, level of comfort, etc. Less personal and more abstract or generalized benefits may be of less or minimal importance. For example, at the EETP, the Spring 2009 Survey indicated that people had little interest in the benefits of recovering nutrients from wastewater. A study in Switzerland on urine-diversion technologies similarly found that survey participants were much more concerned about health risk issues than sustainable development issues (Larsen and Lienert, 2007).

Competing or contradictory interests, such as those described above, need to be discussed openly in planning processes that involve the stakeholders. Together, a consensus needs to be reached on the issues important for consideration; the list of indicators selected should then capture these issues, allowing them to be evaluated side-by-side. While not all indicators may be equally important to everyone, and may not equally affect the outcome of the decision-making process (i.e., which type of system to implement), evaluation of the indicators side-by-side helps prevent stakeholders from focusing on too narrow a set of issues and reveals the tradeoffs that occur.

9 Bridging the Gap: Urine Diversion as a First Step

Chapter 8 discusses the challenges, and opportunities for improvement, of the complete source separation and full resource recovery approach envisioned for the DRY system at the Erdos Eco-Town Project (EETP). It is clear that the separate dry collection of faeces is associated with a high demand for infrastructure, resulting in high environmental impacts, and operational challenges, resulting in user dissatisfaction and health risks. How well would the DRY system perform based on the sustainability indicators if it were less of a radical departure from conventional sanitation systems, collecting urine separately but flushing faeces with (a low amount of) water? In one alternative scenario, the urine could continue to be collected as purely as possible (*i.e.,* minimal dilution) and used for agriculture while the blackwater (faeces and flush water) could be treated along with the greywater. A second alternative scenario could have urine diversion and collection onsite while the blackwater and greywater could be delivered to the centralized sewage treatment plant (STP) that already exists in the Dongsheng District.

Previous authors have recognized urine diversion (UD) as a significant step towards making sanitation systems more sustainable. In their report on the results of the NOVAQUATIS project in Switzerland, a project that thoroughly investigated the potential of UD as an element of wastewater management, Larsen and Lienert (2007) cited the following advantages from the perspective of industrialized countries:

- lower nutrient loads to STPs, allowing for reduction in STP sizes,
- facilitation of the recovery of nutrients from urine for agriculture, resulting in more effective protection of water bodies from nutrients and decreased reliance on mineral fertilizers,
- more effective treatment of micropollutants in urine, such as hormones and pharmaceutical products, since they are not diluted with wastewater, and
- improved wastewater quality for reuse since urine micropollutants are eliminated or greatly reduced.

Kvanstrom *et al*. (2006) note advantages as well from the perspective of developing countries with less sophisticated sanitation systems. For those using pit latrines, for example, UD can reduce the odours and simplify the maintenance required; it can also reduce the risk of pathogen transport to groundwater since the faecal material is kept drier and reduce nitrate contamination of drinking water supplies. As in industrialized countries, UD facilitates the application of urine and its nutrients to agriculture in developing countries, where having this source of fertilizer can make a big impact on food security and poverty.

This chapter explores how the indicator results change for the EETP under the two alternative scenarios described above. The changes in the environmental indicators are quantified via Life Cycle Analysis (LCA) while changes to the technical, economic, and societal indicators are discussed qualitatively. The toilet envisioned in the alternative DRY system scenarios is one similar to the NoMix toilet manufactured by Roediger Vacuum GmbH headquartered in Germany. The NoMix has two compartments for collecting urine and faeces separately (**Figures 9-1a to 1c**); urine can be collected undiluted or with minimal flushing water while faeces is flushed away with water like in conventional water-flushed toilets. A valve below the urine hole is normally closed; when the user sits on the toilet, the valve opens allowing urine to drain into the urine collection pipeline (grey pipeline in **Figure 9-1c**). The user needs to be off the seat when the toilet is flushed to close the urine pipeline valve and prevent water from entering the urine pipeline. Note that there are other models of UD flush toilets in the market; two examples manufactured in Sweden are: the GBG 393U toilet by Gustavsberg and the EcoFlush toilet by Wostman Ecology.


(a)

(b)

(c)

Figures 9-1a to 1c. *The NoMix toilet produced by Roediger: UD toilet with water-flushing for faeces. (a) Picture of the NoMix toilet showing the front compartment (bottom) where urine is collected separately with minimal or no flushing water and the back (top) where faeces is collected with flush water. (b) NoMix in flushing mode. The flush water cleans both the urine and faecal holes. (c) Bottom view of NoMix showing the piping for separate urine collection and the wire that activates the valve. [Image (a) provided by C. Ruester of Roediger in March 2009 to the Sustainable Sanitation Alliance, (b) taken by E. v. Munch in October 2006, and (c) taken by L. Ulrich in December 2008. Source: http://www.flickr.com/photos/gtzecosan/. Accessed on 22 March 2010.]*

9.1 Alternative DRY System Scenario Descriptions

9.1.1 Scenario 1 (Alt-DRY-1): Urine Diversion with Onsite Treatment of Blackwater and Greywater

Under Alt-DRY-1 (**Figure 9-2**), the following changes are assumed to the DRY system scenario:

- The UDD toilets at the EETP are replaced with UD low-flush toilets similar to the NoMix. As in the original scenario, the manufacture of the toilets is not included in the Life Cycle Inventory (LCI). The toilets (UDD toilet, NoMix, and conventional flush toilet) are assumed to be of similar materials and environmental impacts.
- The faecal collection and treatment system (faecal chutes, ventilation, basements and sealed cabinets, bins, composting facility) is removed from the LCI; blackwater is collected in the same pipelines as greywater. (The increase in wastewater production under the conversion to the NoMix is only approximately 6%, which the greywater pipelines should be able to handle.)
- Urine and faeces are flushed with 0.15 litres and 5 litres of water, respectively, based on the flush volumes listed in Lienert and Larsen (2006). (The original DRY system scenario assumes 0.5 L of water is used to flush urine while faeces is collected dry.)
- Urine continues to be collected in separate pipelines and in storage tanks onsite. The volume of urine is decreased but the tanks were kept the same volume, which allows for longer storage times.
- The greywater treatment plant is assumed to be capable of treating the combined greywater and blackwater, with minimal operational adjustments. Its nutrient and metal emissions are increased to include the inputs from faeces and 25% of the inputs from urine (as in the original scenario, urine recovery is assumed to be 75%).
- Because more greywater is produced in the Alt-DRY-1 due to the additional flushing water for faeces, the non-potable water supply system expansion is adjusted accordingly.
- The equivalent WET system scenario is adjusted to reflect the reduced nutrient recovery from the DRY system; specifically, the fertilizer amounts in the WET system expansion are decreased accordingly.

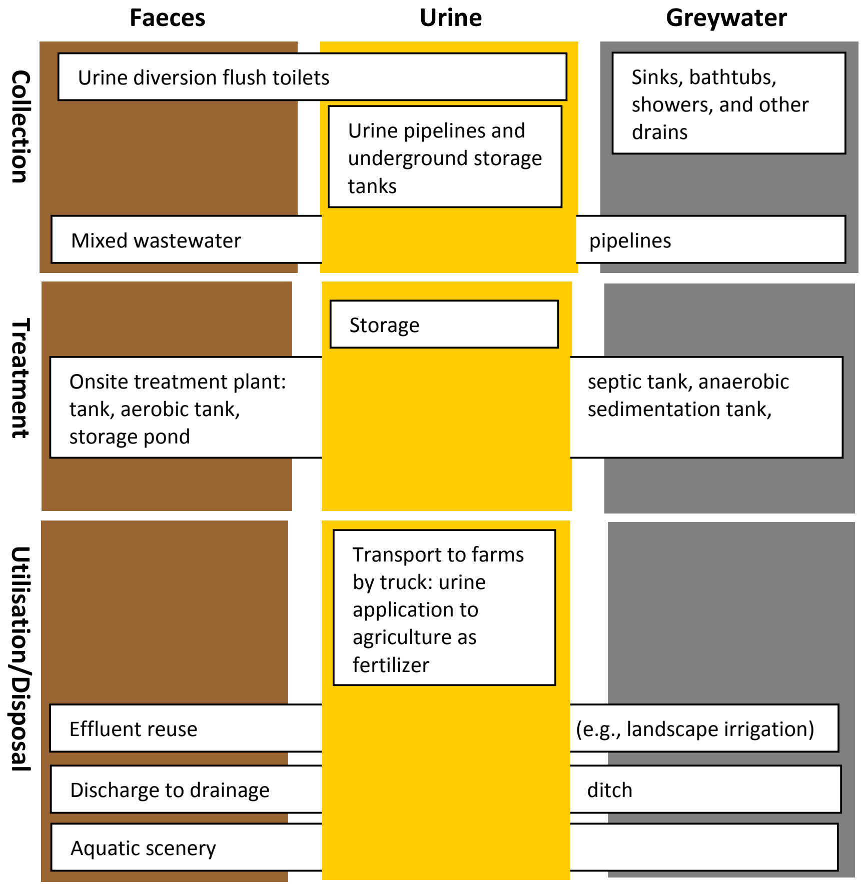


Figure 9-2. *Alternative DRY System Scenario 1 (Alt-DRY-1) process schematic: Urine diversion with onsite treatment of blackwater and greywater.*

9.1.2 <u>Scenario 2 (Alt-DRY-2): Urine Diversion with Treatment of Blackwater and Greywater at the Dongsheng STP</u>

Under Alt-DRY-2 (**Figure 9-3**), the following changes are assumed to the DRY system scenario:

- The UDD toilets are replaced with UD low-flush toilets similar to the NoMix, as in the Alt-DRY-1 scenario.
- All of the EETP onsite sanitation components are removed, except for the urine collection system (pipelines, tanks, and vacuum truck) and the local greywater pipelines, which collect both blackwater and greywater.
- Urine and faeces are flushed with 0.15 litres and 5 litres of water, respectively, based on the flush volumes listed in Lienert and Larsen (2006).

- The combined wastewater is transported from the EETP to the Dongsheng STP via a 7-km sewer pipeline for treatment (the same as the sewer pipeline for the WET system scenario).
- The equivalent WET system scenario is adjusted to reflect the reduced nutrient recovery from the DRY system; specifically, the fertilizer amounts in the WET system expansion are decreased accordingly.

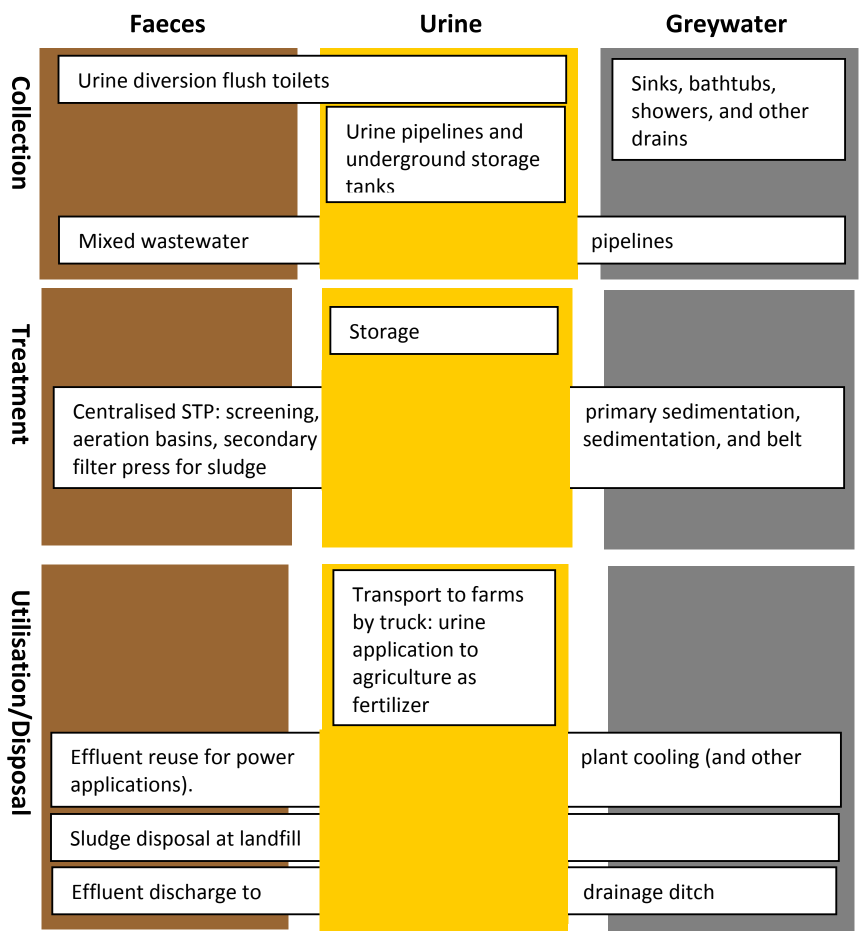


Figure 9-3. *Alternative DRY System Scenario 2 (Alt-DRY-2) process schematic: Urine diversion with centralized treatment of blackwater and greywater at the Dongsheng STP.*

9.2 Alternative DRY System Scenario Results – Life Cycle Analysis

Figure 9-4 below presents the percent differences in the DRY system impacts under the alternative scenarios. All impacts, except for eutrophication, decreased. Acidification, global warming, human toxicity, marine aquatic ecotoxicity, ozone layer depletion, photochemical ozone, and radioactive radiation potential experienced large decreases between 65 and 82%. Their environmental performance is fairly similar, suggesting that the impacts of using an onsite treatment plant for wastewater and connecting to a centralized STP for the treatment of blackwater and greywater are comparable environmentally.

Figure 9-5 shows how the normalized values for the DRY system against the WET system change based on the alternative scenarios. By employing urine diversion only, the impacts of the DRY system relative to the WET system improve greatly; under the various impact categories, both the Alt-DRY-1 and Alt-DRY-2 scenarios either have similar impacts as the equivalent WET system or significantly lower impacts.

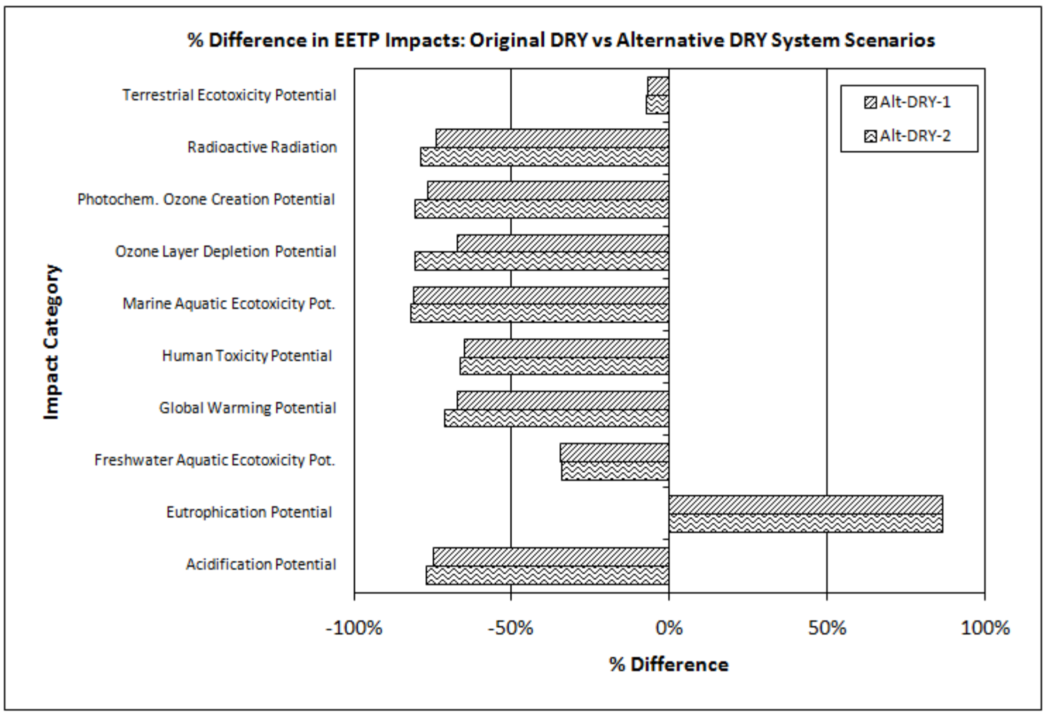


Figure 9-4. *Results of the Alternative DRY System Scenario Analysis: % Difference in DRY System Impacts. The % Difference was calculated as follows: [(Alternative Scenario Impact – Original DRY System Impact)/Original DRY System Impact x 100%]. Negative % Differences reflect reduced negative environmental impacts, or improved environmental sustainability based on that indicator.*

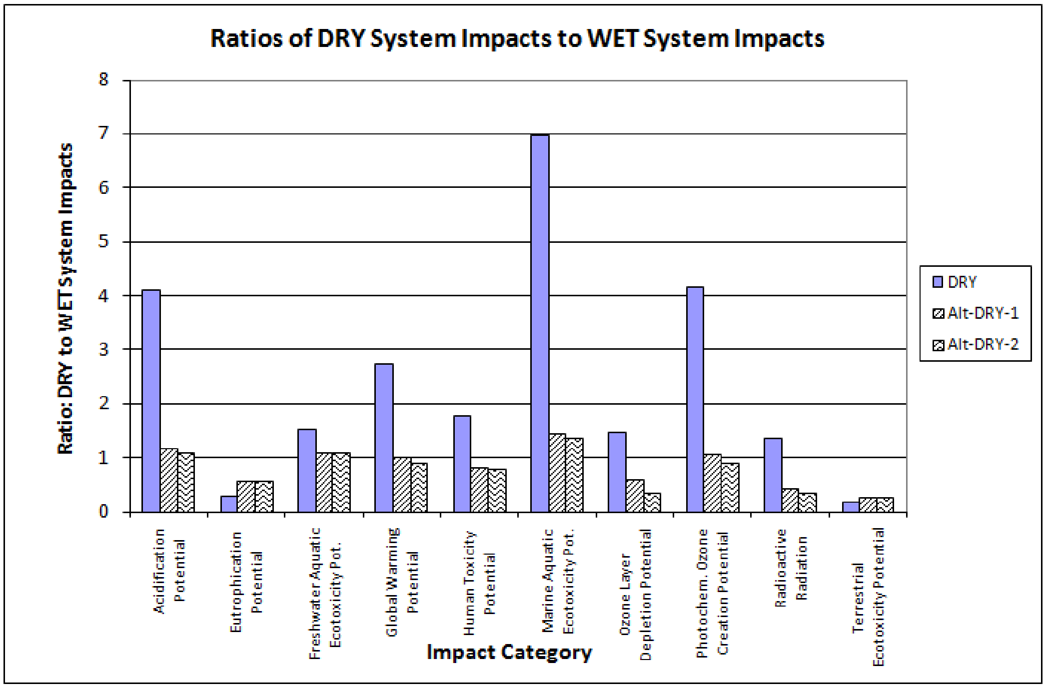


Figure 9-5. *Results of the Alternative DRY System Scenario Analysis: Comparison of the Ratios of the Original and Alternative DRY System Impacts to WET System impacts. Ratios >1 indicate poorer environmental performance by the DRY System (original or alternative) relative to the equivalent WET System for that impact category. For Alt-DRY-1 and Alt-DRY-2 scenarios, the WET system used in the comparison was modified to ensure equivalent functionalities by the two systems.*

9.3 Alternative DRY System Scenario Results – Sustainability Indicators

The sustainability indicators were evaluated for the two alternative dry system scenarios, and the results are presented in **Table 9-1** below.

For the economic evaluation, the economic analysis for the original DRY and WET system scenarios were used as the base, then adjusted to account for the assumed modifications to the two systems. For the Alt-DRY-1 and Alt-DRY-2 scenarios, the numbers of workers were reduced from 10 to 2 and 1 O&M staff, respectively, to reflect the reduced requirements for onsite processing.

The qualitative indicators, particularly the societal ones, were evaluated based on knowledge about the EETP residents' experiences with and perceptions of the DRY system, information in the literature about other people's experiences, and an understanding of how the alternative systems would operate differently from the DRY system.

Overall, the alternative systems perform better than the original DRY system based on the technical, economic, and societal dimensions of sustainability. As discussed in **Section 9.1.2**, the alternative systems also offer overall better environmental performance. Compared to the WET System, the alternative systems perform similarly based on technical indicators, although they still present some user O&M challenges due to the operation of the UD toilets. The alternative systems have lower water consumption, higher embodied energy, lower operational energy demand, lower eutrophication potential, lower land toxicity, and greater nutrient recovery. From an economic perspective, the alternative and WET systems perform similarly. The novel nature of the alternatives will still require improved integration into society's cultural preferences and institutions relative to the WET system.

Table 9-1. *Results of the sustainability evaluation for the alternative DRY systems (Alt-DRY-1 and Alt-DRY-2).*

INDICATORS	Alt-DRY-1	Alt-DRY-2
TECHNICAL		
Ability to meet treatment standards	**Neutral** – With the assumed decrease in the water addition to urine, and the same storage volume, urine will be both more concentrated and stored for longer periods and therefore treated more effectively. The onsite treatment plant will be subject to greater organic and nutrient loading, but is expected to be able to handle the treatment requirement with some adjustments.	**Neutral** – As in Alt-DRY-1, urine is expected to be treated more effectively. The removal of a large fraction of the nutrients (58% and 35% for N and P, respectively) from the wastewater discharged to the Dongsheng STP is expected to result in better performance by the plant in meeting nutrient effluent standards not only due to the reduced input but also due to potential improvement in process performance if urine diversion is implemented on a wider scale[a].
Ability to meet capacity requirements	**Good** – Urine processing capacity is improved, and the onsite plant is expected to be able to handle the increased flow of wastewater.	**Very good –** Urine processing capacity is improved, and the Dongsheng STP is able to handle the increased flow of wastewater.
Ease of system operation and maintenance (O&M)		
Users	**Neutral** – Stream separation will continue to be a challenge for women and children; however, the UD flush toilet will have significantly less or minimal odour issues, eliminate sawdust use, and have less cumbersome daily cleaning requirements.	**Neutral** – Stream separation will continue to be a challenge for women and children; however, the UD flush toilet will have significantly less or minimal odour issues, eliminate sawdust use, and have less cumbersome daily cleaning requirements.
O&M Staff	**Neutral** – The most cumbersome aspect of the DRY system O&M—the faecal collection and treatment system—is eliminated, making the Alt-DRY-1 system O&M much easier. However, the onsite plant still requires skilled workers to operate.	**Neutral** – While the cumbersome faecal collection and treatment system is eliminated from the EETP, the O&M of the STP is challenging and requires skilled workers.
ENVIRONMENTAL		
Resource Consumption		
Land – Treatment System (m^2/pe)	2.5	0.9
Energy		
Embodied Energy – Construction (MJ/pe)	4,428	4,212

INDICATORS	Alt-DRY-1	Alt-DRY-2
Electricity – Operation (kWh/pe-yr) Diesel – Operation (L/pe-yr) Cumulative Energy Demand – Operation (MJ/pe-yr) % Renewable Energy – Operations (% of Total Energy)	19 0.9 263 0	14 0.01 209 0
Water Consumption - Toilet Operation (L/pe-yr)	2,099	2,099
Emissions to Water		
% of BOD/COD, Nutrients, and Heavy Metals in Excreta and Greywater Discharged to Surface Water	0	0
Eutrophication Potential (kg Phosphate Equivalent/pe-yr)	1.95	1.94
Freshwater Aquatic Ecotoxicity Potential (kg DCB-Equivalent/pe-yr)	3.51	3.52
Marine Aquatic Ecotoxicity Potential (kg DCB-Equivalent/pe-yr)	4,867	4,590
Emissions to Air		
Acidification Potential (kg SO_2-Equivalent/pe-yr)	0.61	0.57
Global Warming Potential – 100 yrs (kg CO_2-Equivalent/pe-yr)	73	64
Photochemical Ozone Creation Potential (kg Ethene-Equivalent/pe-yr)	0.015	0.013
Odour (O&M)	Good	Good
Emissions to Land		
% of Heavy Metals in Excreta and Greywater Discharged to Land	app. 100%	app. 100%
Terrestrial Ecotoxicity Potential (kg DCB-Equivalent/pe-yr)	1.28	1.28
Resource Recovery		
% of Nutrients in Excreta and Greywater Applied to Agriculture Nitrogen Phosphorus	 53% 35%	 53% 35%
% of Energy (from Organic Matter) Recovered for Electricity Generation, etc.	0%	0%
% of Water Reclaimed for Irrigation and Other Applications	Up to 100%	Up to 100%
ECONOMIC		
Capital Cost Per Household – Sanitation	$665	$520
Annual O&M Cost Per Household – Sanitation	$33	$31
User Ability to Pay (Annual O&M Cost of Water and Sanitation as % of Income)	1.7-2.2%	1.6-2.1%
Potential for Local Business Development and Household	**Neutral** – There remains some potential for the	**Poor/Neutral** – There is potential for business

INDICATORS	Alt-DRY-1	Alt-DRY-2
Income Generation	design, construction, and O&M of urine-diversion decentralised wastewater management systems.	development related to the urine diversion system, but the rest of the system is essentially conventional and managed centrally by the government.
SOCIETAL		
User Acceptability and Desirability (Compatibility with Habits and Preferences)	**Good** – While the UD toilet is a new technology and stream separation will require some adjustment, the ease of O&M is greatly improved and odours minimized or eliminated relative to the UDD toilets[b]. It is worth noting that the UD toilet may require a special adjustment for men, who will need to sit to urinate in the UD toilet.	
Accessibility to Different Age, Gender, and Income Groups	**Neutral** – stream separation is challenging for women and children in particular. From a cost perspective, this is a cheaper option and is therefore accessible to a wider income group.	
Minimization of Public Health Risk	**Neutral** – The greatest source of health risk—the onsite faecal collection and treatment system—is eliminated.	**Neutral** – As with Alt-DRY-1, the onsite faecal system has been eliminated; however, there continues to be health risks from the transport of sewage across a long distance in large volumes and the processing of wastewater always comes with some risk.
Legal Acceptability and Institutional Compatibility	**Neutral** – Urine diversion and application to agriculture are still fairly new in China and need to be integrated into policy, regulations, and institutions. Onsite wastewater management systems in urban areas are legally acceptable but not yet widely disseminated.	**Good** – For the most part, the system relies on the conventional model that is widely accepted in China and that is already implemented in the District. However, urine diversion and application to agriculture are still fairly new in China as noted under Alt-DRY-1.

NOTES:

a. See Wilsenach *et al*. (2006) for a study evaluating STP performance under reduced nutrient loads from various urine diversion scenarios; for most STPs, 50% urine diversion is enough to cause significant improvement in plant performance.

b. In studies by Larsen *et al*. (2007), the NoMix toilet received favorable reviews by users: “around 80% rated NoMix toilets as equivalent or superior to conventional toilets with regard to design, hygiene and odour” and “86 % would move into an apartment fitted with a NoMix toilet”.

10 Summary, Conclusions, and Recommendations

10.1 Summary

This research has aspired to contribute to the increased sustainability of sanitation systems in urban and peri-urban areas and has set out to achieve the following specific research goals:

1) to evaluate and compare the sustainability performance of a dry sanitation system with complete resource recovery and a conventional waterbourne system in an urban area and
2) to develop engineering and policy-oriented recommendations for the improved sustainability of such systems.

To meet these goals, it began by translating *environmental* sustainability principles into operational features in the context of wastewater management systems. Adaptability to local conditions, resource conservation, resource recovery, and waste minimization are the sustainability principles that were deemed relevant to sanitation systems. These principles were then translated into the following physical operational features: decentralisation, waste flow stream separation, water conservation, nutrient and organic matter recovery, water recovery, energy recovery, and minimisation of waste sludge. Sanitation systems that are built upon these features embody an alternative philosophy of looking at wastewater, treating it as a resource rather than a waste, and are therefore described as “resource-oriented”.

The tools that have been used to evaluate the sustainability of engineered systems—sanitation systems in particular—were reviewed, and the use of indicators was selected as a means of simultaneously examining the technical, environmental, economic, and societal dimensions of sustainability. The indicators, in turn, require input from other analytical tools. Life Cycle Analysis was identified as a particularly useful tool for quantitatively and holistically assessing the environmental performance of sanitation systems; a rigorous evaluation of the environmental dimension was deemed critical because alternatives to conventional sanitation systems are often proposed on the basis of superior environmental performance.

The research employed a unique case study to investigate the sustainability of resource-oriented sanitation systems. The Erdos Eco-Town Project (EETP) in the Dongsheng District of

China implemented the world's largest full-scale urban dry sanitation system with complete resource recovery, representing an ambitious attempt to fully integrate the principles described above. The EETP's innovative dry system was compared against a conventional waterbourne system. To further explore how society can make the transition towards more sustainable sanitation systems, less radical resource-oriented sanitation systems utilizing urine-diversion were also evaluated.

10.2 Conclusions and Recommendations

Based on the EETP case study, **Sections 8.3** and **8.4** presented specific engineering and policy-oriented recommendations for improving the sustainability of both a full resource-recovery dry sanitation system and a conventional waterbourne system. More general conclusions and recommendations about the research results, and the research process itself, are presented below. The limitations of the work are subsequently described. Finally, this section concludes with recommendations for topics of future research work.

Implementing Resource-Oriented Sanitation Systems

- Dry sanitation systems can lead to reduced water consumption, the recovery of valuable resources from domestic wastewater, reduced eutrophication, and reduced toxicity of agricultural soils. They therefore offer the greatest potential benefits in areas that suffer from: low water availability, limited access to synthetic fertilizers (e.g., due to costs), surface water bodies impacted by eutrophication, and agricultural lands affected by heavy metals. These benefits, however, will need to be weighed against possible negative environmental impacts. In particular, resource-intensive infrastructure and high energy consumption during operation can make a large negative contribution to the system's overall environmental impacts.
- The research has underlined the strong feelings or opinions people have about the sanitation system they use, particularly the type of toilet. A transparent and participatory decision-making process—integrating user education and training—is therefore critical when considering sanitation options. While people may appreciate the regional, national, or global benefits of a particular system, their preference may ultimately be shaped by the advantages and disadvantages at the household level.
- The international development field has promoted increasing emphasis on designing for local context over the last twenty years; the EETP, however, illustrates that there remains a gap in translating this concept into practice.

- Given the failure of EETP to deliver in the area of nutrient recovery, a rigorous feasibility evaluation needs to be conducted for each site to determine whether a sanitation system that recovers nutrients for agriculture is viable, and under what conditions. Aside from the typical technical feasibility studies that are conducted for major engineering projects, the evaluation needs to include a market study to understand the following: 1) Are farmers willing to accept products derived from human excreta? If so, in what form (e.g., urine, compost, sludge, treated effluent)? 2) Would farmers be willing to pay for these products? At what prices? 3) Is there a seasonality to the demands? 4) What is the size of the market? (i.e., how many potential customers? quantities of demand for the various products?). The legal feasibility also needs to be explored: Do the policies and regulations (at the national and local levels) allow the use of human excreta/wastewater in agriculture? Under what conditions? Is it supported or encouraged? The findings from the market and legal feasibility analyses must then be integrated into the technical feasibility evaluation for the process selection and design processes.
- Urine diversion by itself can make a positive contribution towards making sanitation systems more sustainable; in the EETP case study, it offered overall better environmental performance and comparable costs to the conventional waterbourne system. Furthermore, because it is a less radical departure from conventional systems, it has a greater ease of implementation and a more likely chance of being accepted by users.
- Sanitation system decentralisation offers the potential advantages of quick deployment (especially where there is no capable centralized institutional infrastructure in place or no financial ability to implement larger centralized systems), greater local control, and reduced energy costs; however, these may not apply in every situation and will need to be evaluated for each case. Furthermore, these advantages will need to be weighed against the potential disadvantages related to the loss of economy of scale.
- It is important that the sanitation system selected not only has legal acceptability but support at the local policy level amongst the various government departments affected. A resource-oriented sanitation system differs from a conventional waterbourne system in that it requires greater coordination and cooperation amongst different sectors.
- Sanitation policy should acknowledge the need to balance onsite, local, national, and global concerns. This balance will need to reflect local socio-economic considerations such as: What is locally culturally-acceptable? What is the local government's perception

of its role in the region, in the country, in the world? What is affordable to the various stakeholders and can costs and benefits be allocated fairly?

- Policies should encourage the upstream reductions of contaminants in wastewater in order to facilitate the safe recovery of resources from it.
- Alternatives to conventional waterbourne systems are clearly needed. Policies should encourage their development through: financial support of research programmes, enactment of regulations that require the recovery of resources from wastewater and adequately account for the reduced contaminant loading, incentives for resource recovery (e.g., grants), openness to innovative technologies, and education of the public to facilitate acceptance.
- In places suffering from water shortage, all potential sources of reductions in water consumption need to be considered, and their costs and benefits compared. For example, there appears to be great potential for reducing water use in agriculture in China through improved technology (Chreod Ltd., 2005). The use of dry toilets in urban settings has some significant social and technical disadvantages, which should be weighed against their benefits, including the amount of water that they can save relative to other options in each location.

Research Methodology

- Life Cycle Analysis has been shown to be a useful tool for evaluating environmental impacts from a system-wide perspective, illuminating the trade-offs that can occur amongst different impacts. It was particularly useful for testing the claim that ecological sanitation or ecosan systems—which represent a more restrictive definition of resource-oriented systems—are environmentally superior to other types of systems.
- The use of indicators to perform a comparative sustainability evaluation was found to be an effective means of simultaneously examining the technical, environmental, economic, and societal dimensions of sustainability. It facilitated the explicit analysis of specific issues of concern in the context of the case study, and highlighted trade-offs amongst the different facets of the systems. The use of indicators does not necessarily directly point to a clear decision on the more sustainable alternative; however, it does lay the foundation for such a decision-making process. A number of options are available for arriving at a decision. For example, stakeholders could make a choice based simply on their overall opinion after being presented with the various advantages and disadvantages of the options. An example of a more formal and quantitative decision-

making process is Multi-Criteria Analysis, which allows stakeholders to develop their own weighting of the criteria and ranking of the alternatives (for examples of its applications, see Gamper and Turcanu [2007]).

- The case study approach proved to be an effective means of examining the unique application of an innovative technology and the contextual conditions that ultimately played a pivotal role in its unsuccesful implementation. It allowed for a richer and more detailed analysis, and a more flexible approach to the research methodology than would otherwise be possible with a purely survey-based study. Lessons were derived from this single case study that have broad implications on the engineering and policy requirements (as described here and in **Chapter 8**) of resource-oriented sanitation systems in locations elsewhere in China, and in the world.
- Requiring a translator to collect and analyze data, and to deal with logistics, posed some challenges and limitations. While the translator hired for the survey was trained, and the accuracy of her work was verifiable to some extent, it was difficult to assess how well the translator was capturing all of the information conveyed in the interviews. It was also difficult to grasp the nuances of the reactions of the EETP residents when information was being filtered through a translator. Finally, relying on a translator made field work less efficient as it essentially limited much of the research activity to when the translator was available.

Limitations

The limitations of this work have been identified throughout the previous chapters. Perhaps most note-worthy is the lack of site-specific data for some of the parameters, particularly in the environmental and economic analysis. The research also required the analysis of systems that had not been optimized, which may obscure the true potential of the systems. It would have been ideal to have other similar case studies to compare this to, but this deficit is an inherent limitation of analyzing a pioneering case study. Finally, as noted above, some of the data collection may have been affected by the limitations of the use of a translator.

Future Research and Education Needs

Future research is greatly needed for improving the design of resource-recovery systems, from better toilets to better integration of such systems into new and existing urban/peri-urban infrastructure. As noted in the previous chapters, some of the key technical areas that require attention include: ventilation systems in multi-storey buildings, odour control in urine-diversion systems, prevention of struvite precipitation, safe collection of faecal material, and minimisation of water in collected urine. Conventional waterbourne systems are quite prevalent; therefore, improved resource recovery and minimization of resource consumption by these systems require attention. More efficient phosphorus recovery from STPs, less expensive treatment methods to render wastewater effluent safe for reuse (e.g., improved removal of pharmaceutically-active compounds and salts), and less energy-intensive biological removal of organic carbon and nitrogen are some of the promising and potentially high-impact areas of research.

Because wastewater has historically been seen as a “waste” and therefore a disposal problem, there is much work required in educating future engineers and planners, and the public and its leaders, about its value as a resource. The media can play an important role in informing the public about wastewater management, its impacts, and the benefits of integrating resource-recovery into sanitation systems. For example, the recently-published book *The Big Necessity: Adventures in the World of Human Waste* (George, 2008) has been successful in reaching out to a broad audience in a discussion of such issues. Outreach to regulators and policy-makers is critical in order to address one of the key barriers to resource-oriented sanitation systems: the lack of a legal framework for using less conventional approaches to sanitation, or the existence of prohibitive or discouraging regulations. For example, in 2008, sanitation professionals in Europe organized a seminar designed to bring together practitioners and European Commission officials to discuss the need for improved policies and regulations that accommodate, perhaps even encourage, alternative approaches to sanitation (WECF, 2008). Finally, engineering and planning curricula in universities need to integrate a broader scope of alternatives—both conventional and alternative—for wastewater systems.

* * *

Despite the fact that the EETP ultimately did not realize its vision of a dry system with complete resource recovery, it signifies a great leap forward in understanding the practical realities of a resource-oriented sanitation system in an urban setting. It is also a sharp reminder that much work needs to be done towards making sanitation systems more sustainable. How the fate of the EETP will ultimately affect the future of ecosan in an urban context in China, and in the rest of the world, remains to be seen. It has undeniably raised more awareness of the challenges and disadvantages of urban ecosan, particularly amongst those who have been its most resolute supporters. And it seems likely that the Chinese government—and its citizens—would be wary of innovative dry, or perhaps even waterbourne, sanitation systems in the near-term. This is unfortunate, given that China’s new urban areas offer such ripe potential for breaking away from conventional sanitation systems and their sustainability limitations. For those who have been harsh critics of ecosan , it may be tempting to point to the EETP as proof that ecosan can not work and therefore should be abandoned—but this would be misguided. The resource-oriented principles at the heart of ecosan remain fundamental to the movement towards more sustainable sanitation solutions; there simply needs to be a broader, longer-term, and more practical view of how these principles can be implemented.

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APPENDIX A

HOUSEHOLD SURVEY FOR ERDOS ECO-TOWN PROJECT

We are using this survey to get feedback from the households on the EETP dry sanitation system. This information will be used to evaluate how the system is working, and how it can be improved. Thank you very much for agreeing to complete this survey!

1. HOUSEHOLD BACKGROUND

1a. What is your name? ____

1b. Please indicate your: Flat Number_____ Building Number_____ Floor Level_____

1c. Please provide the following information about the household members.

Occupant No.	Male (M)/ Female (F)	Age (Years)	Highest Level of Education/Occupation	How many days per week is s/he at home?
Example	M F	*40*	*University/Public Servant*	*5 days*
1 (SELF)	*M F*			
2	*M F*			
3	*M F*			
4	*M F*			
5	*M F*			

1d. Do you (or someone else in the household) own the flat? *YES NO*

1e. When did you move in to the EETP?____ ___

1f. Why did you move in to the EETP? (or Why did you purchase a flat at the EETP?) Place an X on all that apply.

( ) Good location ( ) Attractive flat ( ) Affordable flat ( ) Good Investment

( ) Environmentally-friendly sanitation system

( ) Cost-saving sanitation system – runs with very little water

( ) Convenient sanitation system – can be used when there is no water

( ) Other ____

1g. How much did you know about the sanitation system before you purchased the flat/moved in?

Nothing at all. 1 2 3 4 5 6 7 8 9 Knew about the dry toilet and how it worked.

1h. Which type of sanitation system did you use most often before moving in to the EETP?

( ) Traditional Chinese Toilet - Private ( ) Traditional Chinese Toilet - Public

( ) Flush Toilet - Private ( ) Flush Toilet - Public

( ) No structure (field)

Which type would you most like to have at the EETP? Why?____________________________

____

____

1i. How are urine, faeces and greywater (this is the water from the kitchen, shower, sinks and laundry) processed at the EETP? How is this different from other new housing with flush toilets?____

____

____

____

2. OPERATION AND MAINTENANCE OF SANITATION SYSTEM

2a. What is your level of satisfaction with your urine-diverting toilet?

V*ery Unhappy 1 2 3 4 5 6 7 8 9 Very Happy*

2b. What is your level of satisfaction with your urinal?

V*ery Unhappy 1 2 3 4 5 6 7 8 9 Very Happy*

2c. How convenient/easy is the toilet to use?

Very Inconvenient/Difficult 1 2 3 4 5 6 7 8 9 Very Convenient/Easy

2d. How convenient/easy is the urinal to use?

Very Inconvenient/Difficult 1 2 3 4 5 6 7 8 9 Very Convenient/Easy

2e. Is the toilet more of a benefit or more of a problem?

More of a problem 1 2 3 4 5 6 7 8 9 More of a benefit

2f. What are the benefits of your dry sanitation system?___________________________________

____

____

____

2g. What are the problems with your dry sanitation system?________________________________

____

____

____

2h. How often do you clean the urinal?

( ) 1-2x per week ( ) 3-5x per week ( ) Everyday ( ) Every use

How do you clean it?____

____

2i. How often do you clean the toilet?

( ) 1-2x per week ( ) 3-5x per week ( ) Everyday ( ) Every use

How do you clean it?____

____

2j. How often do you clean the urine odour trap in the toilet and how?________________________

____

2k. Would you recommend this type of sanitation system? *YES NO*

2l. Which improvements to the dry sanitation system would make it completely acceptable to you?

( ) No odours

( ) No sawdust required

( ) No separation of urine and faeces – one toilet hole only

( ) No turning bowl

( ) Other ____

2m. How do you feel about your sanitation system? *(5 is Neutral)*

Ashamed 1 2 3 4 5 6 7 8 9 Proud

2n. How do you think the toilet and urinal have affected the value of the flat? *(5 is No effect)*

Lowered the value 1 2 3 4 5 6 7 8 9 Increased the value

3. TRAINING

3a. Did you receive training on using and cleaning the toilet and urinal? *YES NO*

3b. If *YES* to 3a, how many times did you receive training?______Who did the training session/s and when did the session/s occur (before or after you moved in)?______________________________

____

3c. Was the training helpful? *Not helpful at all 1 2 3 4 5 6 7 8 9 Very helpful*

3d. What are the difficult aspects of operating the toilet and urinal? Are there any aspects of the urinal and toilet operation on which you would you like more training?______________________

____

____

3e. When you have a guest or a new member in the household, do you train him/her to use the toilet? *YES* *NO*

3f. Are you able to get information/receive additional training when you need it? *YES* *NO*

4. AGRICULTURAL APPLICATION OF EXCRETA

4a. Did you know that the excreta recovered from the EETP is being applied to agriculture? *YES* *NO*

4b. Have you visited the eco-station and compost station at the EETP? *YES* *NO*

4c. Do you think the application of the following in agriculture is acceptable? That is, would you purchase/consume the following items if urine/faeces/greywater is applied?

PRODUCT	**Urine (no treatment)**	**Faeces (after treatment)**
Flowers or household plants	*YES* *NO*	*YES* *NO*
Animal food	*YES* *NO*	*YES* *NO*
Human food	*YES* *NO*	*YES* *NO*

4d. Is irrigation of the landscaping around EETP with treated greywater acceptable to you? *YES* *NO*

4e. If *NO* to 4d, why not?____

4f. Is application of urine to the landscaping around EETP with urine acceptable to you? *YES* *NO*

4g. If *NO* to 4d, why not?____

5. ANY ADDITIONAL COMMENTS?

5a. Your comments are very welcome! Would you like to add anything that we have not covered?__

____

____

____

____

____

____

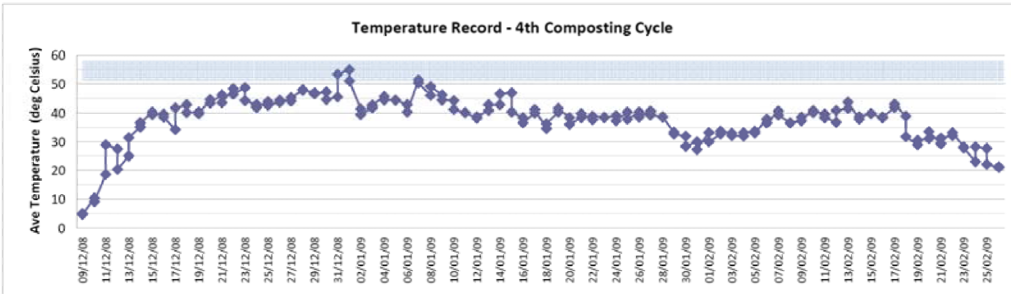
____

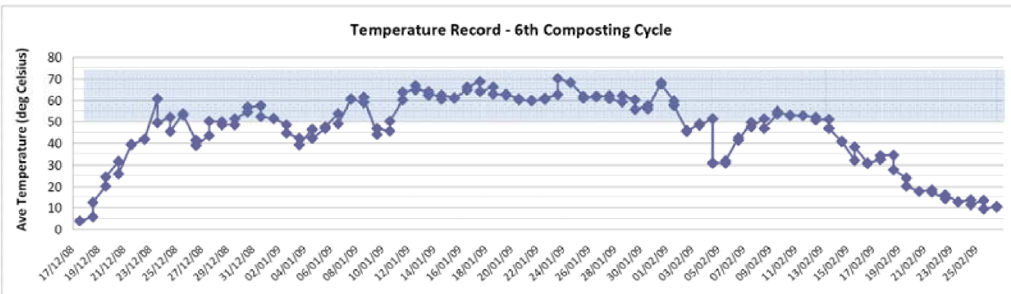
Thank you very much for participating in this survey!

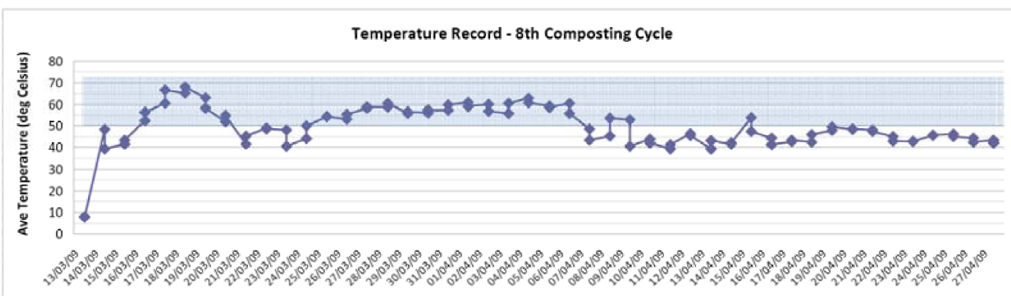
APPENDIX B

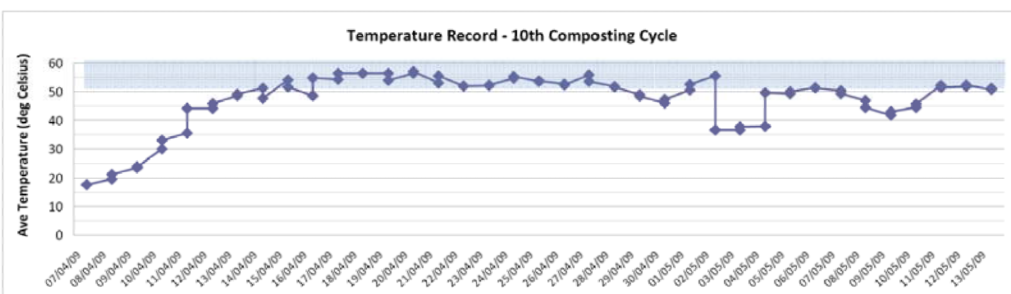
DRY SYSTEM COMPOSTING TEMPERATURE* RECORDS
(DECEMBER 2008 TO JULY 2009)

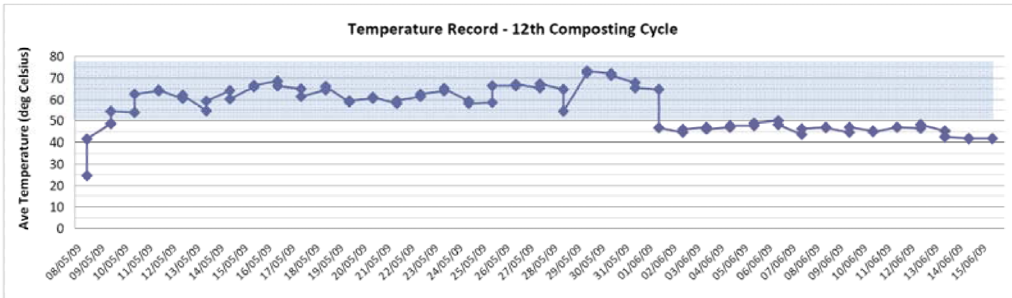
*Temperatures above 50 degrees Celsius are highlighted in the graphs.

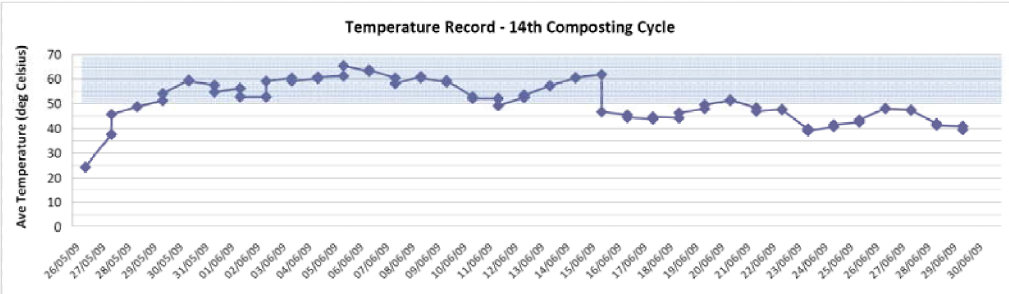


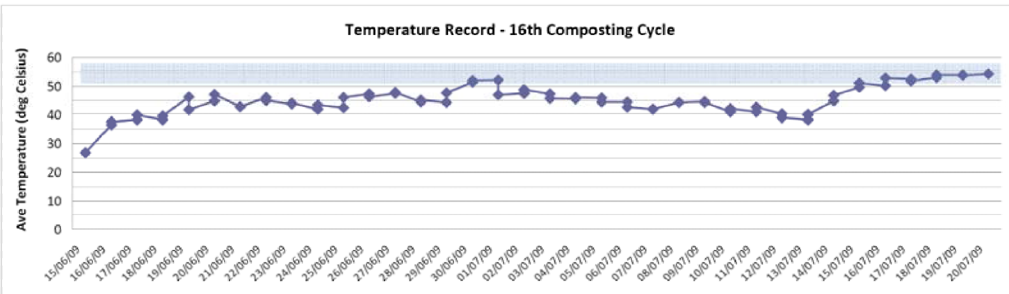







Temperature Record - 12th Composting Cycle
Ave Temperature (deg Celsius)


Temperature Record - 14th Composting Cycle
Ave Temperature (deg Celsius)


Temperature Record - 16th Composting Cycle
Ave Temperature (deg Celsius)

APPENDIX C

GaBi LCA PLANS

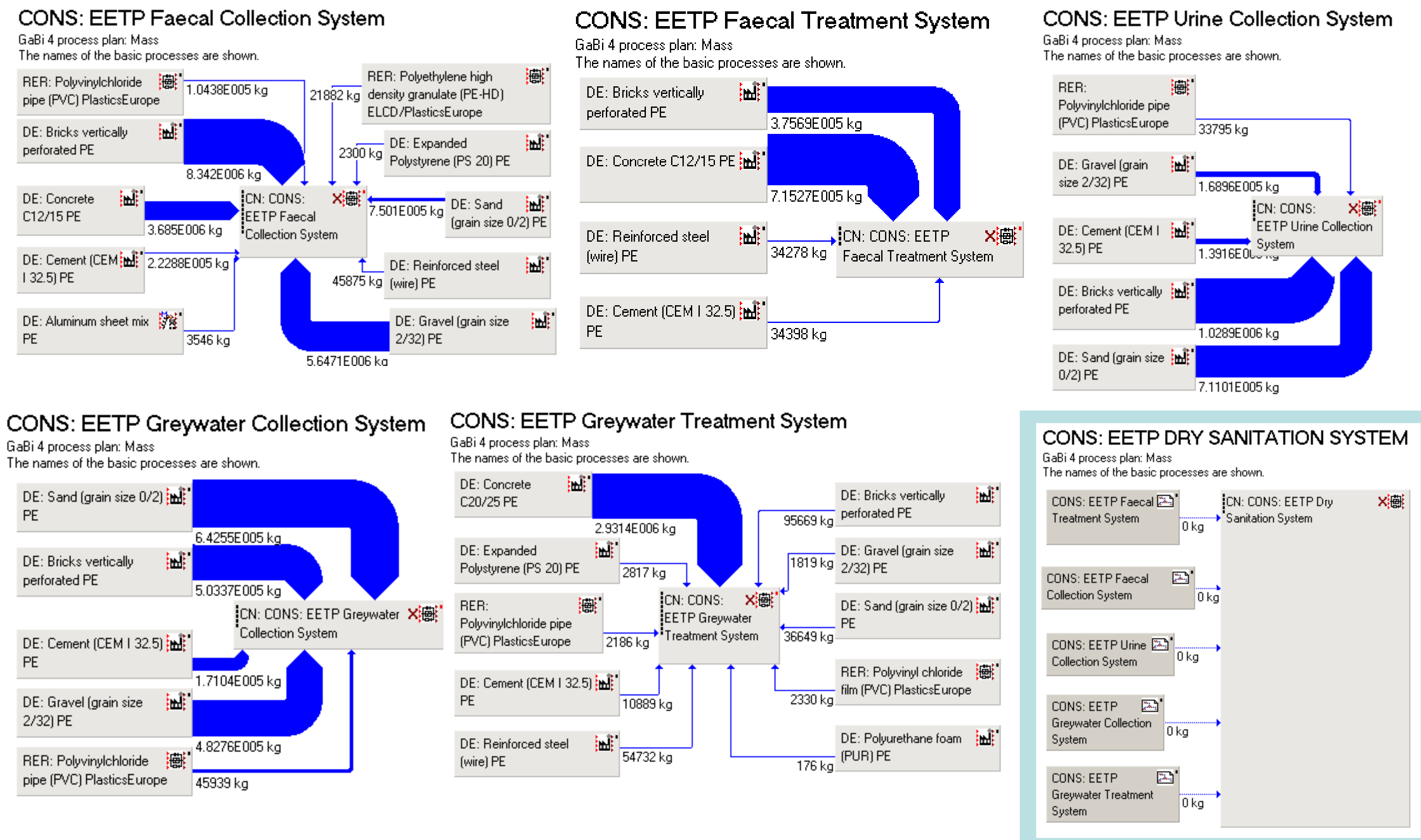


Figure C-1. GaBi LCA Plans: Construction of the EETP Dry Sanitation System (DRY System).

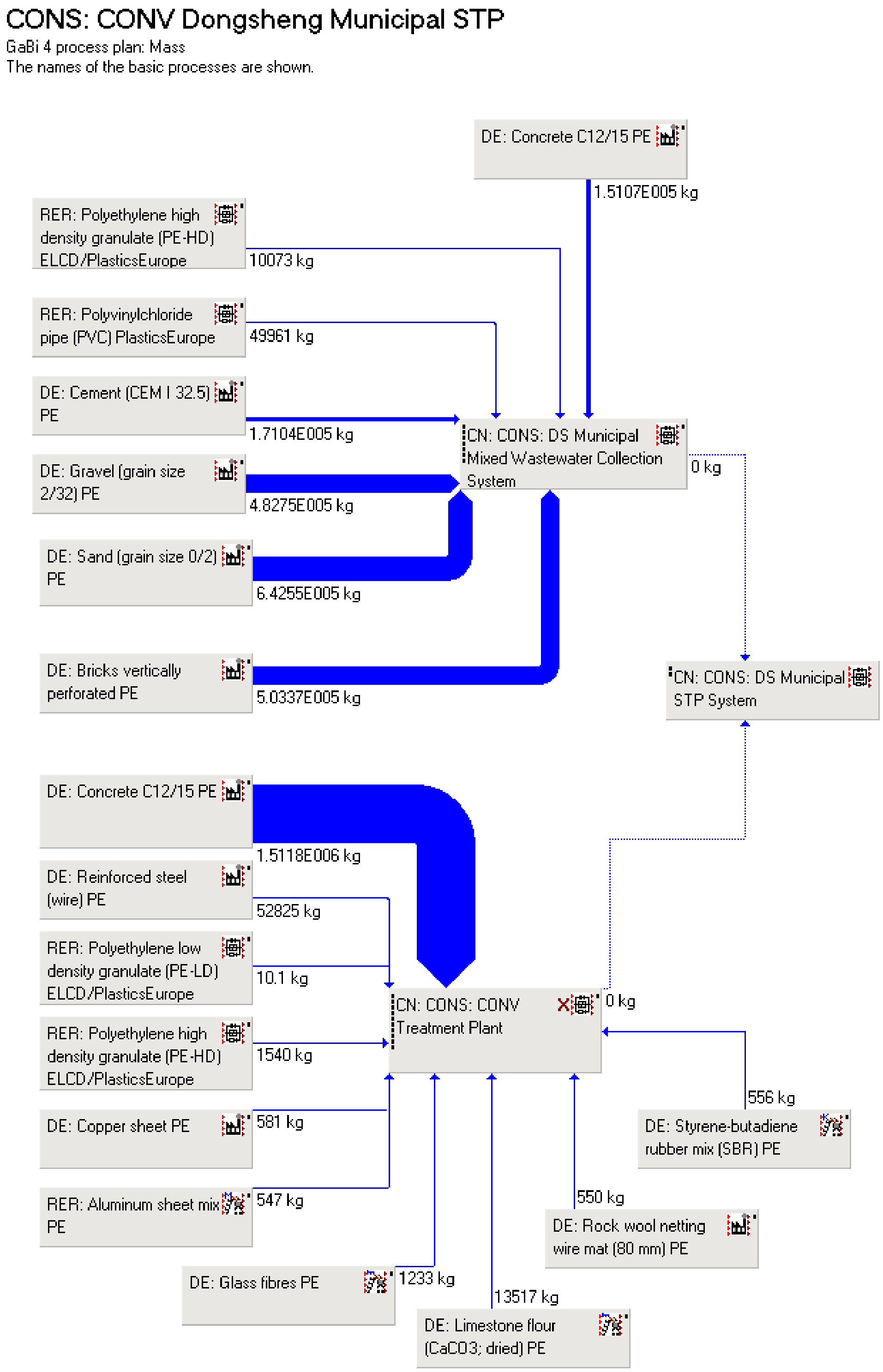


Figure C-2. GaBi LCA Plans: Construction of the Conventional Waterbourne System (WET System).

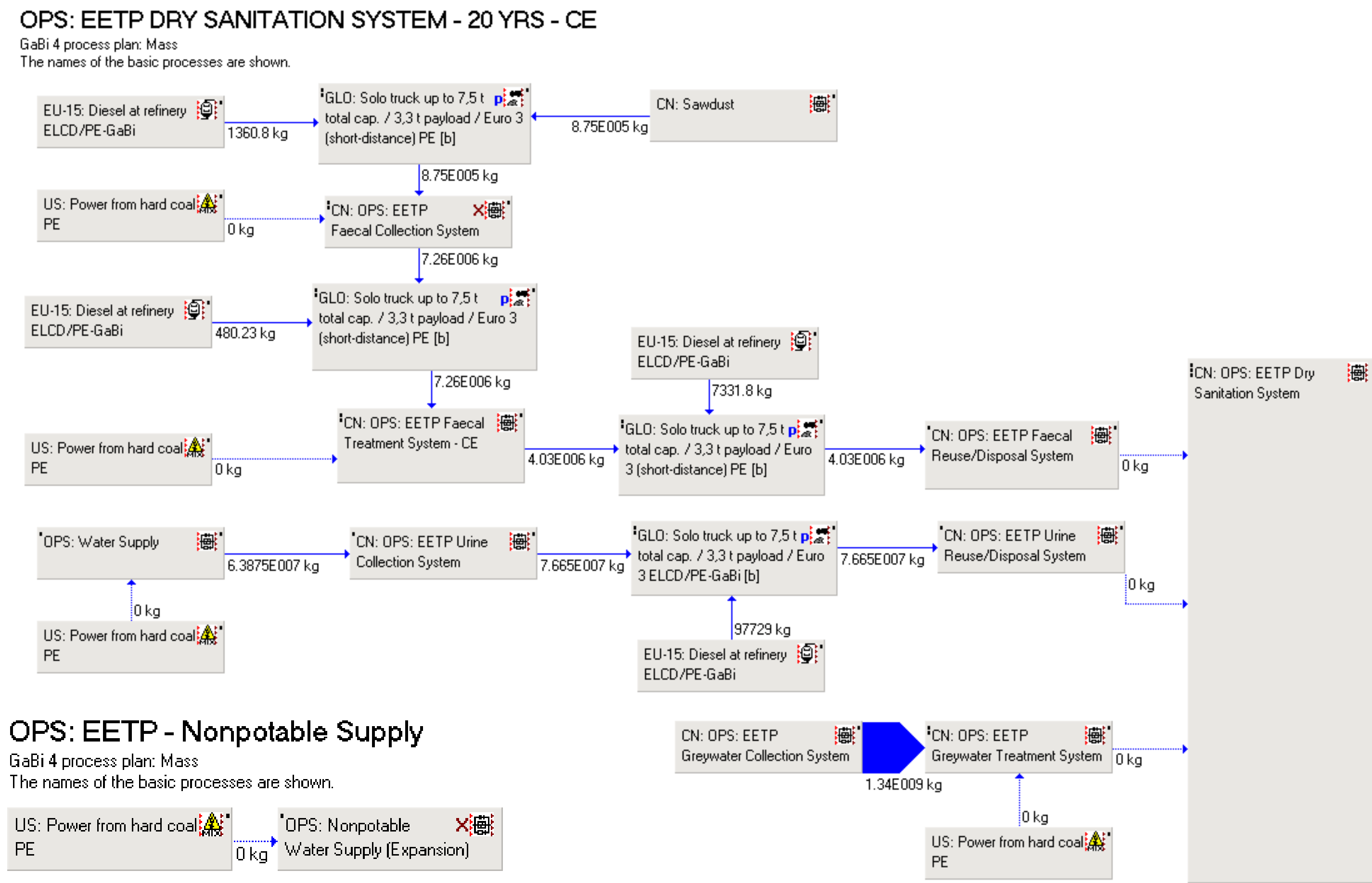
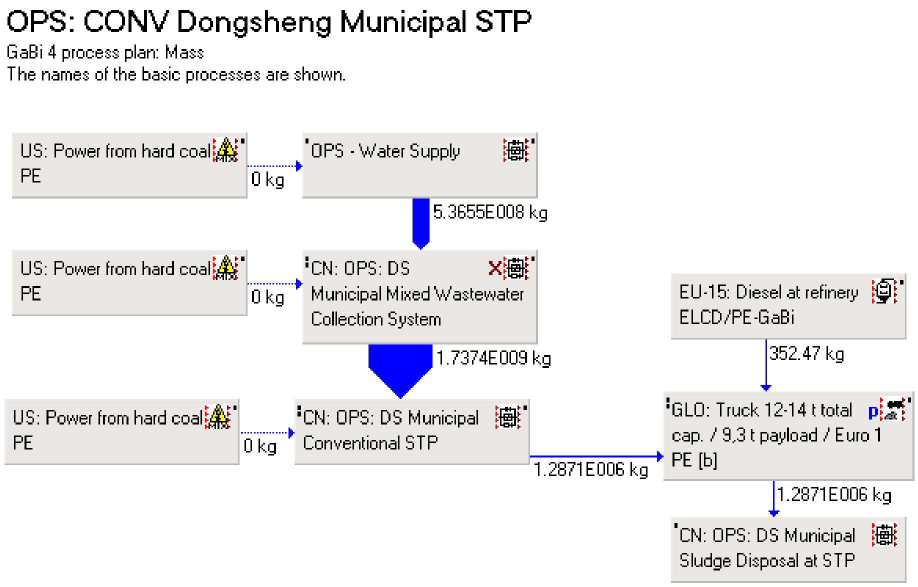


Figure C-3. GaBi LCA Plans: Operation of the EETP Dry Sanitation System (DRY System) and System Expansion (Nonpotable Water Supply) over a 20-Year Period.



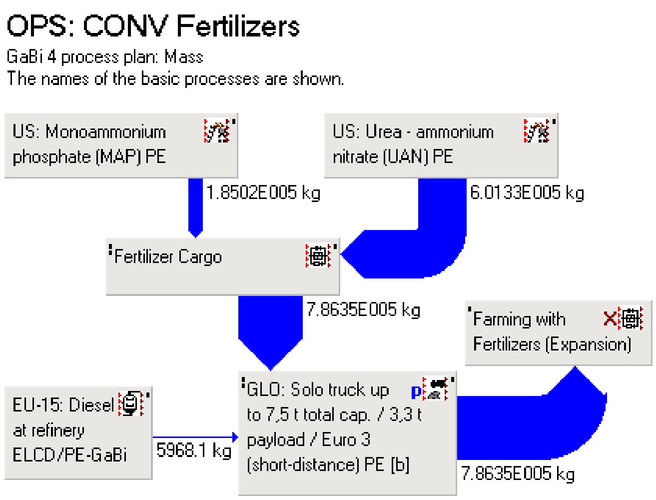


Figure C-4. GaBi LCA Plans: Operation of the Conventional Waterbourne System (WET System) and System Expansion (Fertilizer Supply) over a 20-Year Period.

APPENDIX D

SENSITIVITY ANALYSIS RESULTS

Revised Indicator Values and Ratios of DRY/WET System Impacts and % Differences*

	SA1: Reduced Urine Flush Water		% Difference	SA2: Reduced bricks for basements		% Difference
	TOTAL - DRY	DRY/WET	TOTAL - DRY	TOTAL - DRY	DRY/WET	TOTAL - DRY
Acidification Potential (AP) [kg SO2-Equiv.]	168,360	4.07	-1.1%	168,632	4.07	-0.9%
Eutrophication Potential (EP) [kg Phosphate-Equiv.]	72,632	0.30	-0.3%	72,693	0.30	-0.2%
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	374,443	1.54	-0.1%	374,313	1.54	-0.1%
Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	15,024,590	2.65	-2.8%	14,636,909	2.58	-5.3%
Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	1,921,923	1.75	-0.8%	1,903,737	1.73	-1.8%
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB-Equiv.]	1,692,663,045	6.62	-4.9%	1,385,839,122	5.42	-22.1%
Ozone Layer Depletion Potential [kg R11-Equiv.]	0	1.41	-4.8%	0	1.23	-16.8%
Photochem. Ozone Creation Potential [kg Ethene-Equiv.]	4,422	4.04	-3.2%	4,403	4.03	-3.6%
Radioactive Radiation (RAD) [DALY]	0	1.29	-5.3%	0	1.11	-18.4%
Terrestrial Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]	95,956	0.18	-0.3%	95,890	0.18	-0.3%
	min	0.18	-5.3%	**min**	0.18	-22.1%
	max	6.62	-0.1%	**max**	5.42	-0.1%

	SA3: Reduced power for basements		% Difference	SA4-50%: Reduced power for		% Difference
	TOTAL - DRY	DRY/WET	TOTAL - DRY	TOTAL - DRY	DRY/WET	TOTAL - DRY
Acidification Potential (AP) [kg SO2-Equiv.]	159,975	3.86	-6.0%	159,425	3.85	-6.3%
Eutrophication Potential (EP) [kg Phosphate-Equiv.]	72,515	0.30	-0.5%	72,497	0.30	-0.5%
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	374,087	1.53	-0.2%	374,049	1.53	-0.2%
Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	14,137,862	2.50	-8.5%	14,067,388	2.48	-9.0%
Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	1,855,878	1.69	-4.2%	1,851,459	1.68	-4.5%
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB-Equiv.]	1,736,336,382	6.79	-2.4%	1,734,034,372	6.78	-2.5%
Ozone Layer Depletion Potential [kg R11-Equiv.]	0	1.47	-0.5%	0	1.47	-0.5%
Photochem. Ozone Creation Potential [kg Ethene-Equiv.]	4,010	3.67	-12.2%	3,981	3.64	-12.9%
Radioactive Radiation (RAD) [DALY]	0	1.35	-0.5%	0	1.35	-0.6%
Terrestrial Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]	95,476	0.18	-0.8%	95,436	0.18	-0.8%
	min	0.18	-12.2%	**min**	0.18	-12.9%
	max	6.79	-0.2%	**max**	6.78	-0.2%

	SA4-10%: Reduced power for		% Difference	SA5 - N Air Emissions 30%		% Difference
	TOTAL - DRY	DRY/WET	TOTAL - DRY	TOTAL - DRY	DRY/WET	TOTAL - DRY
Acidification Potential (AP) [kg SO2-Equiv.]	150,784	3.64	-11.4%	121,677	2.94	-28.5%
Eutrophication Potential (EP) [kg Phosphate-Equiv.]	72,201	0.29	-0.9%	63,827	0.26	-12.4%
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	373,449	1.53	-0.4%	374,799	1.54	0.0%
Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	12,960,439	2.29	-16.1%	15,014,178	2.65	-2.8%
Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	1,782,054	1.62	-8.1%	1,935,633	1.76	-0.1%
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB-Equiv.]	1,697,876,462	6.64	-4.6%	1,779,231,759	6.96	0.0%
Ozone Layer Depletion Potential [kg R11-Equiv.]	0	1.47	-0.9%	0	1.48	0.0%
Photochem. Ozone Creation Potential [kg Ethene-Equiv.]	3,511	3.21	-23.1%	4,568	4.18	0.0%
Radioactive Radiation (RAD) [DALY]	0	1.35	-1.0%	0	1.36	0.0%
Terrestrial Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]	94,808	0.18	-1.5%	96,221	0.18	0.0%
	min	0.18	-23.1%	**min**	0.18	-28.5%
	max	6.64	-0.4%	**max**	6.96	0.0%

	SA6 - N Air Emissions		% Difference	SA7 - GW Emissions		% Difference
	TOTAL - DRY	DRY/WET	TOTAL - DRY	TOTAL - DRY	DRY/WET	TOTAL - DRY
Acidification Potential (AP) [kg SO2-Equiv.]	156,736	3.78	-7.9%	170,226	4.11	0.0%
Eutrophication Potential (EP) [kg Phosphate-Equiv.]	70,355	0.29	-3.4%	21,597	0.09	-70.4%
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	374,799	1.54	0.0%	374,799	1.54	0.0%
Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	14,389,026	2.54	-6.9%	15,451,074	2.73	0.0%
Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	1,935,902	1.76	-0.1%	2,043,111	1.86	5.4%
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB-Equiv.]	1,779,231,759	6.96	0.0%	1,779,231,759	6.96	0.0%
Ozone Layer Depletion Potential [kg R11-Equiv.]	0	1.48	0.0%	0	1.48	0.0%
Photochem. Ozone Creation Potential [kg Ethene-Equiv.]	4,529	4.14	-0.8%	4,568	4.18	0.0%
Radioactive Radiation (RAD) [DALY]	0	1.36	0.0%	0	1.36	0.0%
Terrestrial Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]	96,221	0.18	0.0%	96,221	0.18	0.0%
	min	0.18	-7.9%	min	0.09	-70.4%
	max	6.96	0.0%	max	6.96	5.4%

	SA8 - 1.5 - Water Power Supply			% Difference		
	TOTAL - WET	TOTAL - DRY	DRY/WET	TOTAL - DRY	TOTAL - WET	DRY/WET
Acidification Potential (AP) [kg SO2-Equiv.]	45,884	170,759	3.72	0.31%	10.8%	-9%
Eutrophication Potential (EP) [kg Phosphate-Equiv.]	245,523	72,884	0.30	0.03%	-0.1%	0%
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	243,862	374,836	1.54	0.01%	0.0%	0%
Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	6,235,956	15,519,404	2.49	0.44%	10.1%	-9%
Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	1,136,123	1,942,500	1.71	0.22%	3.3%	-3%
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB-Equiv.]	274,251,953	1,781,463,710	6.50	0.13%	7.3%	-7%
Ozone Layer Depletion Potential [kg R11-Equiv.]	0	0	1.47	0.02%	0.3%	0%
Photochem. Ozone Creation Potential [kg Ethene-Equiv.]	1,337	4,597	3.44	0.63%	22.2%	-18%
Radioactive Radiation (RAD) [DALY]	0	0	1.36	0.03%	0.3%	0%
Terrestrial Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]	526,357	96,260	0.18	0.04%	0.0%	0%
		min	0.18	0.0%	-0.1%	-17.7%
		max	6.50	0.6%	22.2%	0.1%

	SA9 - STP Concrete and Steel		% Difference	SA10 - Nitrogen Air Emissions - STP		% Difference
	TOTAL - WET	DRY/WET	TOTAL - WET	TOTAL - WET	DRY/WET	TOTAL - WET
Acidification Potential (AP) [kg SO2-Equiv.]	41,606	4.09	0.46%	66,882	2.55	0.46%
Eutrophication Potential (EP) [kg Phosphate-Equiv.]	245,755	0.30	0.01%	245,091	0.30	0.01%
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	243,846	1.54	0.03%	243,550	1.54	0.03%
Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	5,760,088	2.68	1.71%	8,628,796	1.79	1.71%
Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	1,103,660	1.76	0.31%	1,101,491	1.76	0.31%
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB-Equiv.]	260,858,400	6.82	2.05%	255,503,570	6.96	2.05%
Ozone Layer Depletion Potential [kg R11-Equiv.]	0	1.41	4.77%	0	1.48	4.77%
Photochem. Ozone Creation Potential [kg Ethene-Equiv.]	1,112	4.11	1.66%	1,093	4.18	1.66%
Radioactive Radiation (RAD) [DALY]	0	1.30	4.81%	0	1.36	4.81%
Terrestrial Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]	526,307	0.18	0.03%	526,031	0.18	0.03%
	min	0.18	0.0%	min	0.18	0.0%
	max	6.82	4.8%	max	6.96	4.8%

APPENDIX E
ITEMISED CONSTRUCTION COSTS

Table E-1. Itemisation of EETP construction costs as calculated by Zhou *et al.* (2007). Calculation errors were corrected.

	ITEM	**COST (RMB or YUAN)**
1	Total investment of civil works and equipment	9,124,289
1.1	Expenses of basement civil works based on optimal basement arrangement	3,667,456
1.2	Ecosan equipment of the residential area building and its installment fees	2,610,816
1.2.1	Urine-diversion dry toilets	416,000
1.2.2	Urinals	58,240
1.2.3	Faecal pipes	486,720
1.2.4	Faecal bins	249,600
1.2.5	Cabinets	603,200
1.2.6	Fans	62,400
1.2.7	Primary ventilation pipes	170,560
1.2.8	Branch ventilation pipes	166,400
1.2.9	Basement electricity	51,584
1.2.10	Indoor urine collection system	346,112
1.3	Outdoor greywater pipelines	526,656
1.4	Outdoor urine pipelines and urine storage tanks	242,112
1.5	Greywater treatment plant (including septic tank)	985,531
1.6	Eco-station project	857,718
1.6.1	Composting plant	167,152
1.6.2	*Solid waste plant*	*Not included*[1]
1.6.3	Office building	221,418
1.6.4	Eco-station roadway	172,775
1.6.5	Fence	54,267
1.6.6	Grand entrance	11,345
1.6.7	Other projects	100,761
1.6.8	Planting	130,000
1.7	Equipment purchase: urine vacuum truck and truck for faecal bin transport	234,000
2	Land-use fee	227,273
3	Other fees	26,108
4	Contingency	91,243
	TOTAL	**9,468,913**

[1] Organic kitchen waste was not being processed at the EETP as of 2009 so its processing was removed from the calculations for the two systems. Costs were based on proportional load represented by kitchen waste of 531 tons per year, as compared to 236 tons of sludge per year (loads estimated by Zhou *et al.*, 2007).

Table E-2. Itemisation of conventional waterbourne system construction costs as calculated by Zhou *et al.* (2007).

	ITEM	COST (RMB or YUAN)	NOTES
1	Sanitary ware, pipeline and installation	2,620,800	For 832 households, including per household: • Sanitary ware 600 Yuan • Indoor pipeline, 800 Yuan/household • Exterior drainage pipe, 700 Yuan/household • Installment and other expense, 1050 Yuan/household
2	Sewer line to STP	375,309	1,895 Yuan/m^3/d; according to the World Bank, the sewer line investment in Inner Mongolia accounts for 52.5% of total investment of the wastewater system.
3	Construction cost of secondary STP and pumping station	339,565	1,715 Yuan/m^3/d; annual mean price index of fixed asset investment in Mongolia from 2000 to 2005 is 2.37%.
4	Construction cost of sludge landfill disposal	209,041[1]	• Annually generated moisture percentage is 80% and excess sludge is 236 Ton. • Normal operational life of design landfill is 20 years.
5	Land-use fee for sewage treatment plant and landfill site of solid waste	92,168[1]	38 Yuan/m^2
6	Other expenses	152,861	• Pilot-testing expenses: 0.7% of construction cost • Construction management: 2.0% of construction cost; • Joint commissioning fee: 1.0% of construction cost (including staff training and purchase of office furniture).
7	Contingency	41,314	1.0% of construction cost
	TOTAL	**3,831,058**	