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Environmental Life Cycle Assessment of Different Domestic Wastewater Streams: Policy Effectiveness in a Tropical Urban Environment

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Abstract

To enhance local water security, the Singapore government promotes two water conservation policies: the use of eco-friendly toilets to reduce yellow water (YW) disposal and the installation of water efficient devices to minimize grey water (GW) discharge. The proposed water conservation policies have different impacts on the environmental performance of local wastewater management. The main purpose of this study is to examine and compare the impacts of different domestic wastewater streams and the effectiveness of two water conservation policies by means of life cycle assessment (LCA). LCA is used to compare three scenarios, including a baseline scenario (BL), YW-reduced scenario (YWR) and GW-reduced scenario (GWR). The BL is designed based on the current wastewater management system, whereas the latter two scenarios are constructed according to the two water conservation policies that are proposed by the Singapore government. The software SIMPARO 7.3 with local data and an eco-invent database is used to build up the model, and the functional unit is defined as the daily wastewater disposal of a Singapore resident. Due to local water supply characteristics, the system boundary is extended to include the sewage sludge management and tap water production processes. The characterization results indicate that the GWR has a significant impact reduction (22-25%) while the YWR has only a 2-4% impact reduction compared with the BL. The contribution analysis reveals that the GW dominates many impact categories except eutrophication potential. The tap water production is identified as the most influential process due to its high embodied energy demand in a local context. Life cycle costing analysis shows that both YWR and GWR are financially favorable. It is also revealed that the current water conservation policies could only achieve Singapore's short-term targets. Therefore, two additional strategies are recommended for achieving long-term goals. This study provides a comprehensive and reliable environmental profile of Singapore's wastewater management with the help of extended system boundary and local data. This work also fills the research gap of previous studies by identifying the contribution of different wastewater streams, which would serve as a good reference for source-separating sanitation system design.

Keywords: Life cycle assessment; Conventional wastewater management system; Water conservation policy; Life cycle costing

1. Introduction

Since the 1990s, there has been an increased environmental consideration towards the sustainability of conventional wastewater management systems worldwide. The environmental impacts of wastewater management in Singapore are even more critical because of Singapore's land and water scarcity. As a garden state with very limited natural water resources, Singapore enhances its water security by the diversification of the water supply and the implementation of water conservation policies. Singapore has four "national taps": imported water, local rainwater, desalinated water and reclaimed water. Among them, reclaimed water (also known as "NEWater") is from the effluent of wastewater treatment plants (WWTPs). A dual membrane system is used as advanced treatment to ensure the quality of the effluent; however, its associated energy and chemical assumption is always an environmental concern. Therefore, the Singapore government promotes additional water conservation policies rather than entire reliance on the NEWater and other water sources. The proposed policies of water conservation in Singapore are designed to decrease the toilet flushing consumption and grey water disposal. The former can be implemented by using an eco-friendly toilet, while the latter can be achieved by employing water efficient devices, such as low-flow showerheads, instantaneous water heaters and spring-loaded nozzles. These two policies have different impacts on the environmental performance of Singapore wastewater management. To better evaluate these policies, life cycle assessment (LCA) is used to quantify the associated environmental impacts.

LCA is a useful tool to evaluate the environmental impact that is associated with all stages of a product or system during its entire life cycle. It has been used to assess the conventional activated sludge (CAS) wastewater management system since 1995 (Emmerson et al., 1995; Roeleveld et al., 1997; Tillman and Lundström, 1998; Lassaux et al., 2007; Gallego et al., 2008). The previous studies made an attempt to detail the environmental profile of different wastewater management systems; however, these studies have two limitations. Firstly, the previous LCA studies interpreted the environmental contribution of the CAS system from the perspective of domestic wastewater. Domestic wastewater can be subcategorized into yellow water (YW, urine and flushing water), brown water (BW, feces and flushing water) and grey water (GW, cleaning water from the laundry, bathroom and pantry). Otterpohl (2000) highlights the necessity to separate three wastewater streams because they have significant differences in wastewater characterization. YW is rich in nutrients and BW has a higher concentration of volatile solids, whereas GW that comprises the larger portion of domestic wastewater is considered to be less polluted. These distinguished

characteristics would provide supporting information to determine the most appropriate treatment and reuse strategies. Secondly, it is noticeable that most of the previous LCA studies have limited coverage of system boundaries (Emmerson et al., 1995; Tillman and Lundström, 1998; Zhang and Wilson, 2000; Zhang et al., 2010). The sewage sludge management and the production of tap water for domestic usage have not been included into a single system boundary. For sewage sludge management, Singapore engages sludge incineration and offshore landfill of bottom ash as a disposal method to stabilize pollutants and minimize land usage. The trace elements in fly ash and the bottom ash are important concerns to human health and ecosystems. The production of the clean tap water requires additional attention because its embodied energy would lead to significant environmental burdens, especially for Singapore which has limited access to renewable energies.

This study aims to examine whether and to what extent, the environmental performances of domestic wastewater management systems change due to the implementation of different water conservation policies in Singapore. To achieve this goal, this work is featured by two scientific contributions to urban wastewater management fields: (1) the LCA interpretation is extended by differentiating the contributions of three domestic wastewater streams, including YW, BW and GW; (2) the sewage sludge management and tap water production processes are included in the extended system boundary to provide a comprehensive and reliable environmental profile of Singapore's wastewater management. Furthermore, the environmental LCA model is established and followed by results interpretation, including characterization analysis, uncertainty analysis and contribution analysis. Life cycle costing (LCC) is conducted to assess economic feasibility. Recommendations are also provided based on the results that were attained in terms of current water conservation and future wastewater reclamation.

2. Methodology

2.1. Functional unit, scenario setting and scope of the study

The goal of this study is to investigate the environmental improvements of a wastewater management system by implementing different water conservation policies in Singapore. The functional unit is defined as the domestic wastewater that is produced by a Singaporean per day. The daily wastewater production per capita and its stream breakdown are calculated based on the flushing mode and household water consumption. Three scenarios associated with a large-scale municipal WWTP are constructed: baseline scenario (BL), YW-reduced scenario (YWR) and GW-reduced scenario (GWR). Table 1 lists the definition of functional units in the three scenarios.

(Table 1 here)

The BL employs full-flush toilet and conventional water devices. It reflects the current situation in the majority of Singaporean households. The functional unit is derived from the average domestic water consumption (152 L per capita per day) (PUB, 2013a). According to the local water authority, Public Utilities Board (PUB), 16% of the domestic tap water is used for flushing cisterns (PUB, 2011). We assume that there are 5 flushes and one flush for urine and feces, respectively, at home daily. Hence, the average flushing volume is estimated to be approximately 4 L per capita per day.

The YWR is constructed based on the current PUB policy. In recent years, PUB has been promoting eco-friendly toilets that have a dual-flush cistern to reduce water consumption. On average, the cistern remains 4 L full-flush for feces but uses 2.75 L reduced-flush for urine. This results in an approximately 30% volume reduction of YW, but only a 4% volume reduction of overall wastewater. Assuming that the characteristics of human urine remain unchanged, the concentration of pollutants will have a 30% increase in the YW stream, which is equivalent to a 4% increase in the total wastewater stream.

In the GWR, conventional water devices, such as shower taps and sink taps, are replaced by water efficient devices with at least a “one-tick” water efficiency rating in the PUB Mandatory Water Efficiency Labeling Scheme (MWELS) (MEWR, 2010). For easier comparison with the YWR, the replacement is designed for a 30% volume reduction of the GW stream (25% of total wastewater conservation). Nevertheless, the characteristic of GW is assumed to be unchanged rather than concentrated because it is closely related to user behavior rather than GW consumption (Eriksson and Donner, 2010).

Characterization analysis, uncertainty analysis and contribution analysis are used for results interpretation. The details of the characterization model are summarized in Section 2.5. In the uncertainty analysis, Monte Carlo simulation is used to evaluate the statistical significance of environmental improvement. In the contribution analysis, the cut-off criteria are set to neglect the processes whose contributions are less than 20% of the total environmental load.

2.2. System boundary

The system is divided into two parts: foreground and background system. As indicated in Fig. 1, the background system includes the tap water production, chemical manufacture and energy generation. In the foreground system, the sludge line is differentiated from the liquid line to incorporate sewage sludge management into the system boundary. The sludge line entails three sludge treatment processes in the CAS system (thickening, digestion and dewatering), with three additional processes (drying, incineration and offshore landfill of incineration bottom ash). The processes in the liquid line include not only the CAS system (wastewater pumping, preliminary treatment, primary treatment, secondary treatment and effluent discharge), but they also consider the production of the “feed water”, which is the tap water in this study. The process schematic of local CAS system and incineration system are shown in Fig. S1 and Fig. S2 respectively.

(Figure 1 here)

2.3. Life cycle inventory

A reliable LCA depends on a robust life cycle inventory (LCI). In a background system, rather than complete reliance on the eco-invent database, local data on power supply (Zhou et al., 2011a) is used to better represent the Singapore context. Inventory for the foreground system includes energy flow, chemical flow, common indicator flow and trace element flow. The information for the foreground system is collected from local data. For those data that could not be found from Singapore sources, information from other countries was used.

1. Energy flow:

The energy input and output are considered in the liquid and sludge lines. Table 2 shows the local specific energy requirement for the wastewater management system (NEWRI, 2011). It is important to note that energy is produced from two processes: the combustion of biogas after sludge digestion and the direct combustion of dried sludge during sludge incineration. Based on the energy consumption and production, the average energy to achieve 1 kg of BOD removal is 2.40 MJ in this study. Although this value is not exactly the same as the value (3.0 MJ) that was reported by a tropical WWTP case study (Zhang and Wilson, 2000), the variation is acceptable because the two studies differ in plant operation efficiency, which is identified as an influential factor for energy demand (Gallego et al., 2008).

(Table 2 here)

2. Chemical flow:

Various chemicals are used to assist the operation of WWTPs, but only high-dosage chemicals are included in the system boundary, given the common assumption that a small mass leads to negligible impacts in most LCA practices. According to Gallego et al. (2008) and Hopsido et al. (2004), the sludge dewatering polymer is of interest to the environmental impact assessment of WWTPs. In this study, polyacrylonitrile was chosen with the dosage of 20 kg per ton of dry sludge mass (interview with PUB).

3. Common indicator flow:

The common indicator flows are defined as the sum of the following parameters: BOD, COD, TOC, TN, TP and TK. The sum of the parameters along the wastewater management system is calculated based on the substance transfer coefficient of each treatment step (Table S1, S2 and S3).

4. Trace element flow:

The heavy metals and other trace elements could have significant impacts in sewage sludge management and the effluent discharge process (Zhou et al., 2013). Therefore, this study investigates ten additional trace elements, including calcium (Ca), magnesium (Mg), chloride (Cl), copper (Cu), zinc (Zn), cadmium (Cd), nickel (Ni), mercury (Hg), lead (Pb) and chromium (Cr). The inventory of these elements and common indicators in a BL and the corresponding three different wastewater streams is presented in Table S4. It is important to note that almost all sludge is sent to incineration plants in the Singapore context. Therefore, the majority of the trace elements is transferred into bottom ash after incineration and could then leak to the groundwater through the landfill liner after long-term landfilling.

2.4. Common assumptions

Several assumptions are made here to bridge the research gaps:

1. The construction and demolition of water works and wastewater facilities are excluded from the system boundary because of their minor contribution and intensive data requirement (Tillman and Lundström, 1998; Zhang and Wilson, 2000; Zhang et al., 2010).

2. In uncertainty analysis, triangle distribution is used for foreground data, while the default log normal distribution that is defined in the eco-invent database is employed for the background data.
3. It is assumed that there is no water loss during the water cycle. This means that the overall domestic water consumption is equal to the domestic wastewater disposal.
4. The sludge production is calculated based on interviews with a PUB official. The conventional wastewater management system generates 0.078 kg of dry primary sludge and 0.032 kg of dry activated sludge per cubic meter of treated wastewater.
5. In the liquid line, the specific energy requirement for the liquid line is expressed as kWh per unit volume of wastewater stream (Table 2). However, the specific energy requirement for the sludge line is indicated as kWh per unit mass of dry sludge.

2.5. Life cycle impact assessment methodology

CML 2 baseline 2000 is selected as an impact assessment method to calculate potential risks to human health, ecological quality and resources. It provides a list of obligatory impact indicators at a mid-point level, and it is used in most LCA studies (Zhou et al., 2011b). The potential environmental impact categories include Abiotic Depletion Potential (*ADP*), Acidification Potential (*AP*), Eutrophication Potential (*EP*), Global Warming Potential in 100 years (*GWP100*), Ozone Depletion Potential (*ODP*), Human Toxicity Potential (*HTP*), Fresh-water Aquatic Eco-Toxicity Potential (*FAETP*), Marine Aquatic Eco-Toxicity Potential (*MAETP*), Terrestrial Eco-Toxicity Potential (*TETP*) and Photochemical Ozone Creation Potential (*POCP*).

2.6. Life cycle costing

LCC is engaged to evaluate the economic feasibility of implementing water conservation policies discussed in this study. The cost is calculated based on a family of four members with two lavatories. The capital cost for the components used to upgrade current toilet flushing system in YWR is estimated at S\$10, while the devices used to replace shower taps, basin taps, sink tap and showerheads in GWR would cost S\$159 in total (Table S7). All the components and devices are assumed to have a life span of 10 years and can be installed by users.

3. Results and discussion

3.1. Results from characterization analysis and uncertainty analysis

Characterization analysis compares the environmental improvement of two water conservation policies (GWR and YWR) with the current situation (BL). Table 3 shows the characterization results for different impact categories. The scenario with the highest environmental impact in each category was normalized to 100%. The result indicates that the GWR and YWR lead to less environmental burden in all of the impact categories. Although the GW and YW have the same 30% volume reduction in their corresponding wastewater streams, the GWR achieves better improvement than the YWR. It is worth noting that in the GWR, all environmental impacts are improved 22-25% in almost all of the impact categories, except in *EP* (7%). In the YWR, all of the impact categories have a 2-4% improvement, but there is almost no improvement in *EP*. The details of the above observations are discussed further in section 3.2.

(Table 3 here)

Uncertainty analysis is used to understand the reliability of the above observations. Fig. 2 shows the result from the uncertainty analysis (Monte-Carlo simulation) with a 95% confidence level after 1,000 iterations between the BL and GWR. The percentage indicates the probability for a specific scenario achieving lower impacts compared with another one. The environmental savings in the GWR are significant in all of the impact categories with possibilities greater than 99%. Similar results can be found between the BL and the YWR (Fig. 3); the YWR reduces the environmental burden significantly in almost all of the impact categories, except for *EP* (49.9%).

(Figure 2 here)

(Figure 3 here)

3.2. Contribution analysis result

This section includes wastewater stream contribution analysis, process contribution analysis and substance contribution analysis. The three types of analysis are used to differentiate the contribution of three wastewater streams, to identify the influential processes in the system boundary and to identify dominant substances for each impact category.

3.2.1. Wastewater stream contribution analysis

Two analyses are conducted from the volumetric proportion and unit proportion point of view. The former analysis shows a comparison in terms of total pollutant masses, while the latter analysis demonstrates comparison in terms of pollutant concentrations.

Fig. 4 indicates the contribution of each wastewater stream in the BL under their respective volumetric proportion in domestic wastewater. The sum of the contribution (in terms of percentage) from each wastewater stream equals 100% in each impact category. It was determined that the GW stream has the highest contribution in almost all of the impact categories except *EP*. The highest contribution is because of the highest volumetric proportion of the GW stream among the three wastewater streams (approximately 84% of domestic wastewater). Different from the GW stream, the BW stream has the least volume, which is only 2-3% of the volume of the domestic wastewater. However, the BW stream has the greatest influence (43%) on *EP* due to the highest amount of nitrogen- and phosphorous-related pollutants. The YW stream has the second highest influence on *EP* (35%) while its influence in the remaining categories ranges between 9-14%.

Fig. 5 compares the characterization results from the unit proportion of each wastewater stream. The wastewater stream with the highest environmental impact in each category was normalized to 100%. Different from the previous analysis, the BW is the most polluted wastewater stream, followed by the YW and then GW. Among the three wastewater streams, the BW has the highest characterization score in all of the impact categories because it contains the highest pollutant concentration. The YW and GW lead to comparable impacts in all of the impact categories, except *EP* and *MAETP*. The influential pollutants are discussed further in section 3.2.3.

(Figure 4 here)

(Figure 5 here)

According to the findings, the ranking of the BW contribution and the GW contribution towards the overall environmental impact vary differently from the perspectives of volumetric proportion and unit proportion. To further elaborate on this, the concepts of “solute” and “solvent” are introduced here. “Solute” is defined as the pollutant in the wastewater stream, and “solvent” is defined as the tap water that serves as the “feed water” for the YW, BW and GW. The perspective of volumetric proportion not only considers the environmental burden from the “solute” but also the environmental burden from the “solvent”. Tap water itself carries an embodied environmental footprint,

especially an energy footprint from the tap water production. Therefore, a high amount of tap water in the GW is the major contribution. In contrast, the perspective of the unit proportion considers only the impact from the “solute”. It reflects the “real” characteristics of the wastewater stream.

3.2.2. Process contribution analysis

Three of the most influential processes for each category are listed in Table 4. The details on the percentage contribution are summarized in Table S5. Overall, local electricity consumption (including its auxiliary processes) is the most influential process in this study. Palme et al. (2005) reported similar findings: the energy is identified as one of the main sustainable development indicators for wastewater management systems. However, there is a distinct difference in the energy breakdown. Previous studies (Zhang and Wilson, 2000; Gallego et al., 2008) concluded that secondary treatment is dominating the energy consumption because of intensive aeration. By expanding the system boundary, local electricity consumption is subcategorized into the embodied energy of three major treatment processes including tap water production, secondary treatment and pumping. Additionally, the energy requirement to manufacture tap water was determined to be one-fold higher than the secondary treatment (intensive aeration); the pumping process also has a considerable contribution because the wastewater is transported to the centralized WWTP through a Deep Tunnel Sewage System (DTSS).

The energy consumption dominates the indicators of *ADP*, *AP*, *GWPI00*, *ODP*, *HTP*, *TETP* and *POCP*. The results are fairly consistent with the reports of Gallego et al. (2008). The only exception is *TETP* due to the difference in sludge disposal. Gallego et al. (2008) applied sludge directly on agricultural land, which significantly contaminated the arable land with heavy metals. In the current study, the heavy metals contained in the sludge are stabilized by incineration (thermal treatment), and then the incineration ash is disposed of in the offshore landfill. Both the disposal methods cause a very different eco-toxicity impact on the terrestrial ecosystem.

Apart from embodied energy, the air emissions and water discharge from secondary treatment also have significant contributions to *EP* and *MAETP*. The sludge incineration and landfill disposal dominated the *FAETP*. Another influential process to *FAETP* is the disposal of lignite spoil, a sub-process under tap water production in the background system.

(Table 4 here)

3.2.3. Substance contribution analysis

Table 4 summarizes the dominant pollutant(s) for each influential process. The details on the percentage contribution are available in Table S6. Although *ADP*, *AP*, *GWP100*, *ODP*, *HTP*, *TETP* and *POCP* share the same influential process, the dominant substance(s) for each impact category varies. *ADP* is associated with the depletion of natural gas and crude oil. The water emission of barite is the main substance for *HTP*. Barite is a critical mineral in producing “drilling mud” after crushing and mixing with water for oil and gas drillers. The main substances of the remaining categories are solely air pollutants.

In *MAETP*, barite emission and Ni ion that are found in the WWTP effluent after secondary treatment are the main substances. Ni ion mostly originates from BW and GW. To further reduce *MAETP*, there might be a need to improve the removal efficiency of Ni ion in the WWTP effluent. Ni ion (31%) is also the main substance for *FAETP*, but it is associated with water pollution in lignite mining. *EP* is linked with TP and TN from secondary treatment effluent. These major contributors consist of more than 80% of the total *EP*. Among these parameters, TP contributes the most (45-46%) followed by TN (36-37%). Similar results have been found by Hospido et al. (2004) and Gallego et al. (2008).

3.3. Life cycle costing

As indicated in Table S7, neither of YWR and GWR would pose financial burdens due to their considerable savings in water bill. The saving for YWR and GWR in 10 years are 16.69 and 3.49 Singapore dollars respectively. This result implies that both policies would be readily accepted by the end users from the economic point of view.

4. Recommendations

As a resource-scarce state that is dependent on imports, the Singapore government is ramping up its efforts on sustainable development. This section not only evaluates the potential of the two conservation policies to address the short-term challenges in water consumption, but it also tries to build the capability for long-term development in water, energy and land management.

4.1. Singapore's short term targets

According to the Sustainable Singapore Blueprint, the daily domestic water consumption is expected to be reduced from current 152 L per capita to 147 L per capita and 140 L per capita in 2020 and 2030, respectively (PUB, 2013a). The first target could be easily achievable by installing dual-flush toilets (YW conservation policy). However, a further reduction target requires additional measures on GW (GW conservation policy).

PUB has been actively promoting a YW conservation policy since 2006. The effort has been shifted from a voluntary approach to a mandatory approach since July 2009, with the effect of “Mandatory Installation of Dual Flush Low Capacity Flushing Cisterns (LCFCs)”. Under this initiative, dual-flush LCFCs have to be installed in all new developments and existing premises that are undergoing renovation. Currently, the dual-flush LCFC with at least a “one-tick” water efficiency rating is gaining popularity in Singapore households. Although the YW conservation policy has the advantages of mandatory implementation and high social acceptance, the volume reduction of daily domestic water consumption is still limited. The average functional unit of YWR is only 145.75 L per capita per day.

Similarly, the approach of promoting the GW conservation policy has been gradually shifting from voluntary to mandatory since 2009. Under MWELS, all water efficient products are labeled with water efficiency rating so that consumers can make smart purchasing decisions. Apart from showerheads, all water efficient devices with at least a “one-tick” rating must be installed in all new developments and existing premises that are undergoing renovation (PUB 2008). As discussed in section 3.1, the GWR achieves better performance in all environmental indicators except *EP*. However, the findings do not imply that Singapore should give a higher priority to the GW conservation policy because of the difficulties in its implementation. The GW conservation policy involves switching water efficient devices and changing behaviors. Inefficient user behaviors may cause more GW disposal, even with the installation of water efficient devices. Hence, it is advisable to execute the policy along with voluntary approaches, especially public education programs. Apart from government agencies, the continuous support and cooperation from NGOs and the private sector are crucial.

4.2. Singapore’s long-term targets

As mentioned above, Singapore has a diversified supply of water known as the four “national taps” which is comprised of imported water, highly purified reclaimed water known as NEWater, desalinated water and local

rainwater. The imported water will no longer be included as a water resource to Singapore once the agreements expire in 2061. Although the conservation policies could help to alleviate the water shortage, they are not able to fill in the huge gap between the water supply and demand. Therefore, the capacities of another three “national taps” have to be expanded. As projected by PUB, the NEWater will meet half of the total water demand (PUB, 2013b), but consequently, the substantial energy requirement is of an important concern to resource-scarce Singapore. Therefore, two additional reclamation strategies, namely the centralized GW reclamation and the decentralized source-separation, are proposed to meet the long-term water requirement as well as to enhance energy security in Singapore.

A centralized GW reclamation strategy is proposed as a new water resource for water reclamation instead of the WWTP effluent that is being used in the current practice. As suggested by Otterpohl et al. (2003), used water can be considered as the closest water resource in water-scarce urban areas. To make use of the GW, piping systems need to be modified so that GW can be diverted from domestic wastewater. Next, the diverted GW can be further transported from residential areas to the existing NEWater plants. Finally, the GW can be reclaimed by the dual membrane systems in the centralized NEWater plants. The overall energy requirement to reclaim GW is lower than the WWTP effluent. The future energy demand for water security will be reduced if part of the future reclaimed water demand is fulfilled by GW reclamation. This is because the GW is identified as the least polluted and the most abundant wastewater stream in domestic wastewater. The GW is slightly more polluted than the WWTP effluent, and the energy input to treat GW might be slightly higher. However, more energy is required for the WWTP effluent because the GW is mixed with the YW and BW before being treated into the WWTP effluent. In Singapore, there are four NEWater plants that are spread over a limited area of 710 km²; therefore, the impact of the GW transport can be well controlled as long as the piping system is optimized based on the nearest centralized system.

Decentralized source-separation strategy is designed based on the distinguished characteristics of YW, BW and GW to recover nutrient, bio-energy and clean water, respectively. The contribution analysis results from section 3.2.1 provide some new insights for designing sustainable wastewater management systems. To implement this strategy, a source-separation toilet is used to separate the YW and BW. Then, the YW can be treated for nutrient recovery by means of urine hydrolysis followed by struvite precipitation and ammonium stripping to produce fertilizer and soil conditioner (Zhang et al., 2013; Liu et al., 2013). To conserve energy, the separated BW can be

digested in anaerobic conditions to produce biogas, which can be used directly for cooking or converted into heat, steam, or power through a combined heat and power (CHP) system (Rajagopal et al., 2013). Regarding the GW, the treatment method is not restricted to membrane technology, but varies according to the final uses of the reclaimed water. The high-quality treated GW is hygienically safe and it can be reused for non-potable urban uses (Li et al., 2009). In fact, this strategy can minimize the environmental impacts from the wastewater management system and maximize the onsite bio-energy and material recovery from each stream. Nevertheless, this strategy could face more challenges, such as rebuilding piping systems, social acceptance and system maintenance. Land usage is another important issue because those onsite facilities require more space than conventional facilities, especially in land-scarce Singapore.

5. Conclusions

To enhance local water security, the Singapore government promotes two user-related water conservation policies: decrease the flushing water using an eco-friendly toilet and reduce the GW disposed from laundry, pantry and bathroom by installing water efficient devices. This study examines how these two policies affect the local wastewater management system in terms of environmental performance. The results indicate that both policies reduce the environmental costs of the current domestic wastewater management system, but decreasing GW disposal shows more effective improvements.

The first reference to differentiate the contribution of the three different wastewater streams is also addressed. The GW carries the least environmental burdens compared with the YW and BW as estimated by the unit volume of the individual wastewater stream. However, when factoring in the corresponding volume, GW begins to dominate the environmental burdens of the entire wastewater management system. Compared with the previous studies, the system boundary is extended to the sewage sludge management and tap water production. The inclusion of sludge drying and sludge incineration into the system boundary reflects the uniqueness and advantages in TETP reduction. Tap water production is identified as an influential process due to the high embodied energy demand. To further recommend future initiatives, this study examines the potential of two conservation policies for their effectiveness. Both policies would contribute considerable economic savings in water bill, but the implementation and penetration of decreasing GW disposal require further verification because the installation of water efficient devices needs to be complemented with public education on efficient user behavior. To achieve the long-term goals,

two additional strategies, centralized GW reclamation and decentralized source separation, are recommended to supplement the current water conservation policies.

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Appendix. Supplementary data

Supplementary data associated with this article can be found in the online version.

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Figure Captions:

Fig. 1. System boundary that indicates foreground system and background system of this study

Fig. 2. Monte Carlo results by comparing GWR and BL

Fig. 3. Monte Carlo results by comparing YWR and BL

Fig. 4. Contribution of yellow water, brown water and grey water in domestic wastewater volume proportion in BL (the sum of each value equals to 100%)

Fig. 5 Characterization of yellow water, brown water and grey water per unit volume in BL (the highest value was normalised to 100%)

Table 1 Definition of functional units in BL, YWR and GWR.

Table 2 Specific energy consumptions of every process in system boundary.

Table 3 Summary of LCA characterization result of three scenarios.

Table 4 Summary of contribution analysis result of three scenarios (BL, YWR and GWR).

Table 1

Parameter^a (per capita per day)	BL (L)	YWR (L)	GWR (L)
Function Unit (total WW volume)	152.00 (110.56-199.82)	145.75 (106.56-190.82)	114.65 (82.91-149.74)
<i>Stream breakdown</i>			
YW volume	21.00 (14.80-28.20)	14.75 (10.80-19.20)	21.00 (14.80-28.20)
Flush water for urine ^b	20.00 (14.00-27.00)	13.75 (10.00-18.00)	20.00 (14.00-27.00)
Urine volume	1.00 (0.80-1.20)	1.00 (0.80-1.20)	1.00 (0.80-1.20)
BW volume	4.15 (3.60-4.70)	4.15 (3.60-4.70)	4.15 (3.60-4.70)
Flush water for faeces ^c	4.00 (3.50-4.50)	4.00 (3.50-4.50)	4.00 (3.50-4.50)
Faeces volume	0.15 (0.10-0.20)	0.15 (0.10-0.20)	0.15 (0.10-0.20)
GW volume	126.85 (92.16-166.92)	126.85 (92.16-166.92)	88.80 (64.51-116.84)

^a All values are expressed in the format of “average value (minimum value-maximum value)”.

^b Calculated based on 5 flushes per day. The water requirement for one full flush is 4±0.5 L but in YWR, the water requirement for one reduced flush is 2.75±0.25L.

^c Calculated based on 1 flushes per day. The water requirement for one full flush is 4±0.5 L. (PUB 2008)

Table 2

Process	Value	Comments
Potable water production	0.39 kWh/m ³ (0.38-0.40)	Based on (Doka 2009)
Pumping	0.17 ^a kWh/m ³ (0.16-0.18)	By calculation, 60 m vertical displacement, 95% pump energy conversion (interview with PUB)
Preliminary	0.0025 ^a kWh/m ³ (0.002-0.003)	Horizontal flow grit chambers (NEWRI 2011)
Primary treatment	0.0177 ^a kWh/m ³ (0.0156-0.0198)	Gravity sedimentation tank, Equalization tank (NEWRI 2011)
Secondary treatment (Aeration)	0.175 ^a kWh/m ³ (0.159-0.196)	Submerged-fine bubble, Surface-fixed and variable speed aerators and variable speed aerators (NEWRI 2011)
Sludge thickening	0.133 kWh/kg dry sewage sludge	Centrifuge (NEWRI 2011)
Sludge digestion	0.051 ^a kWh/kg dry sewage sludge (0.044-0.055)	Draft tube system, gas injection system, mesophilic, no external heating (NEWRI 2011)
Sludge dewatering	0.091 ^a kWh/kg dry digested sludge (0.073-0.106)	Centrifuge (NEWRI 2011)
Sludge drying	0.717 kWh/kg dry digested sludge (-1.509 ^b -0.396)	Energy flow for sludge drying is based on biogas production from sludge digestion.
Sludge incineration	0 kWh/kg dry digested sludge	Energy production during incineration (4.44 kWh/dry digested sludge) is equal to energy consumption of incineration plant.

^a Average value of several local WWTPs that sharing similar treatment technology.

^b Excess heat will be produced to achieve 90% solid content when sludge production and degradability are high. However, excess heat is not recovered in this occasional condition.

Table 3

Impact categories	BL (%)	YWR (%)	GWR (%)
ADP	100	-3	-25
AP	100	-4	-25
EP	100	±0	-7
GWP100	100	-3	-24
ODP	100	-4	-25
HTP	100	-3	-25
FAETP	100	-3	-23
MAETP	100	-2	-25
TETP	100	-3	-22
POCP	100	-3	-24

Table 4

Impact categories	Main processes ^a (contribution>±20%)	Contribution (%)			Main substances ^a (contribution>±20%)	Contribution (%)		
		BL	YWR	GWR		BL	YWR	GWR
ADP	Potable water production	41	41	41	Natural gas in ground;	61	61	61
	(electricity)				Crude oil in ground	30	30	30
AP	Potable water production	36	36	36	Sulfur dioxide (air);	61	61	61
	(electricity)				Nitrogen oxides (air)	38	38	38
EP	Secondary treatment (brown water) ^b ;	42	42	45	Total phosphorus;	45	45	46
	Secondary treatment (yellow water) ^b	34	35	37	Total nitrogen	36	36	37
GWP100	Potable water production (electricity)	41	41	41	Carbon dioxide from fossil fuel	95	95	94
ODP	Potable water production (electricity)	43	43	43	Halon 1301 (air)	83	83	83
HTP	Potable water production (electricity)	36	36	36	Barite (water)	27	27	27
FAETP	Land-filling of spoil from lignite mining;	35	35	34	Nickel ion (water)	31	31	31
	Sludge incineration process using digested sludge as input	20	21	23				
MAETP	Secondary treatment (grey water);	33	34	31	Nickel ion (water);	27	28	26
	Potable water production (electricity)	21	20	21	Barite (water)	25	25	26
TETP	Potable water production (electricity)	35	34	33	Vanadium (air)	67	66	65
POCP	Potable water production (electricity)	36	35	35	Sulfur dioxide (air)	58	58	57

^a Every impact category has its own major and minor contribution elements that will add up to 100% in term of total contribution. In contribution analysis, the main processes and substances are defined here as those which have more than 20% of total contribution positively or negatively.

^b Contribution from material streams

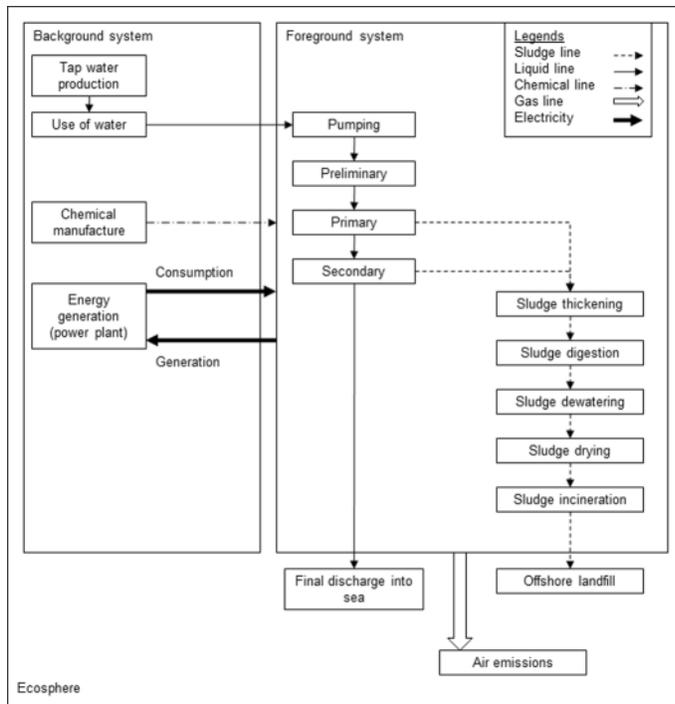


Fig 1

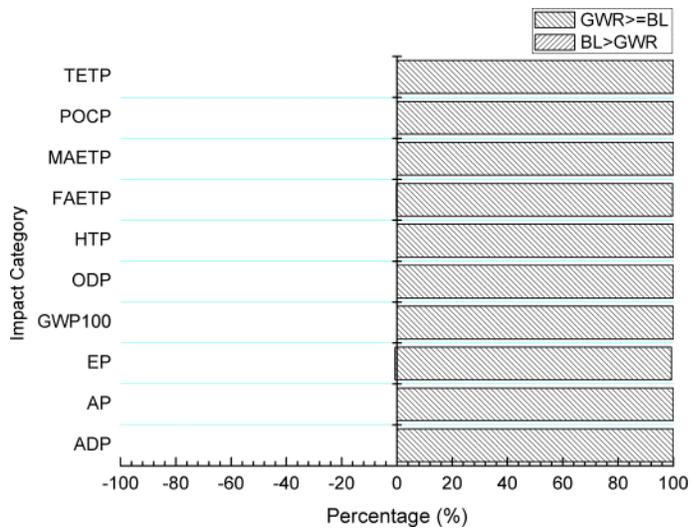


Fig 2

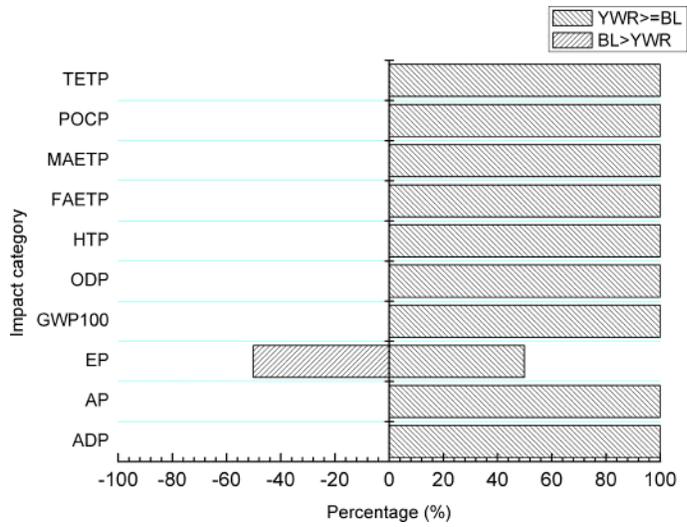


Fig3

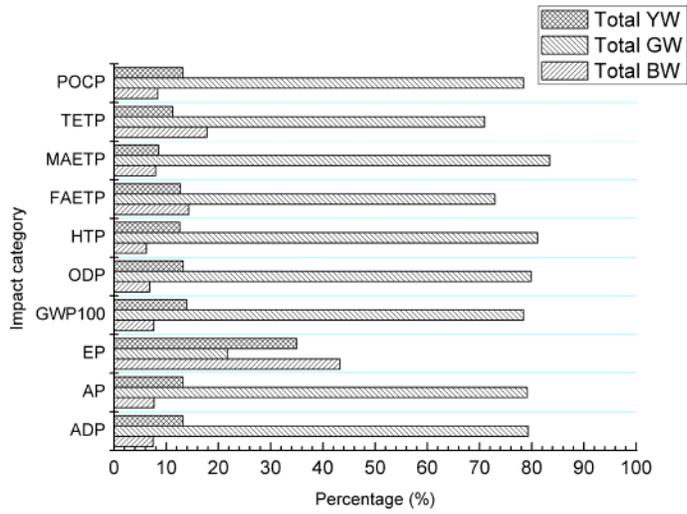


Fig4

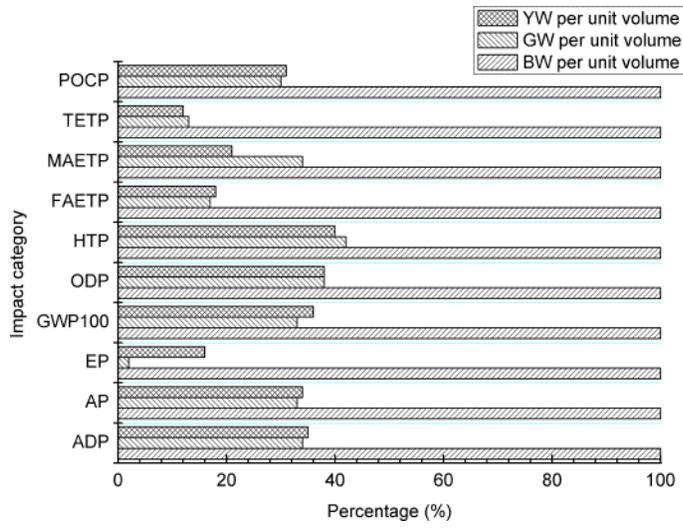


Fig5