ASSESSMENT OF TREATMENT TECHNOLOGIES FOR CLUSTER SCALE WASTEWATER TREATMENT AND RECYCLING IN SEQ

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ABSTRACT

There is an emerging view that decentralised wastewater treatment and recycling is required to provide part of a climate resilient suite of water supply systems to urban developments in this increasingly climate change and energy challenged world. However, technically robust operational data is largely absent to make informed technology selection decisions.

We therefore selected three cluster-scale wastewater treatment and recycling (WWT&R) plants in Queensland for investigation. These plants service small (50 lots) to medium (172 lots) urban developments and utilise different treatment technologies, ranging from a membrane reactor, aerobic biofiltration to zeolite adsorption and biodegradation, although all produce recycled water with class A^+ quality. Treatment robustness and environment burdens, in terms of energy and fugitive greenhouse emissions are the key areas of our investigation.

The data for validating the treatment plants will be obtained through energy and flow metering and analysing gas, liquid and solid samples taken from key components along the treatment process train. System robustness will mainly be assessed through a modelling approach with BioWin 3.1. Using this data in conjunction with life cycle costing and life cycle assessment (other components of our study), we plan to develop a set of objective criteria for the selection of appropriate decentralised scale and technologies in any given greenfield development.

INTRODUCTION

South East Queensland's population is projected to grow by more than 1.5 million people over the next 23 years, with 32,767 hectares being planned for urban residential developments by 2031 (DIP, 2009). This will place an increasing pressure on our water resources, and require major new investment in water infrastructure to avoid the potential future water shortage in urban areas. Possible options to develop new water infrastructure can include continuing to add new centralised systems, build new decentralised systems or a combination of both.

There is an emerging view that decentralised wastewater treatment and recycling (WWT&R) systems can provide part of a climate resilient suite of water supply systems to urban development (Wilderer, 2005). The benefits of decentralisation include providing a substantial substitution of urban potable water use, being largely independent of climate change, deferring the urgent need for infrastructure expansion, upgrade or establishment, and reducing environmental impact due to effluent discharge to waterways.

Decentralised wastewater systems are not a new concept. Initially developed by Mouras in France in the 1860s, they comprised one or more septic tanks to remove solids, followed by percolation through soil to achieve natural disinfection. As discharge limits for nutrients and pathogens are being tightened, a number of newly engineered treatment technologies have continuously been introduced to decentralised systems to produce secondary or higher quality effluent. Table 1 shows the typical technologies that have been recently designed or utilised in medium to large scale decentralised WWT&R systems in Australia. These technologies can be grouped into primary, secondary and advanced treatment units. While septic tanks continue in use as primary treatment units, activated sludge systems, biofiltration or membrane bioreactors are added for secondary treatment. Following this, conventional media filtration, ultrafiltration (UF), ultraviolet radiation (UV) and chlorination are the major advanced treatment units being used. It is worth noting that decentralised systems have a high level of flexibility in mixing and matching various treatment system components to fit into the local environment as well as meeting the quality requirements for various end uses. For example, organic removal can be achieved using conventional activated sludge processes, membrane reactors (MBRs) or biofilm processes. Anoxic reactors can be placed prior to, post to, or merged with aerobic tanks for denitrification. Disinfection can be performed by chlorination or UV. The treatment process design will become even more complex when taking scale issues into account. The scales in Table 1 range from 62 to

Table 1: A selection of decentralised treatment systems used in Australia (Tjandraatmadja *et al.* 2009)

Treatment Process	**Scale (lots)**	Recycled Water Class[1]	**Location**
Activated sludge system, sand filtration and UV	62	Class A$^+$	New Heaven Estate (Adelaide)
Activated sludge system, coagulation, flocculation and sand filtration, plus household scale UV and chlorination	36,000	Class A$^+$	Rouse Hill (NSW)
Activated sludge system, sand filtration, UF, UV and chlorination	8,500	Class A$^+$	Aurora (VIC)
Activated sludge system, dissolved air flotation and filtration, UV and chlorination	4,000	Class A$^+$	Mawson Lakes (Adelaide)
Immersed MBR, UV and chlorination	46	Class A$^+$	Capo di Monte Retirement Village (QLD)
Sequential batch reactor (SBR), UF and RO	20,000 (EP)	Class A$^+$	Sydney Olympic Park (NSW)
Immersed MBR, UV, chlorination and carbon filtration	24	Class A$^+$	Manly EcoVillage
Septic tanks, biofiltration, UF, UV and chlorination	119	Class A$^+$	Currumbin Ecovillage
Septic tanks (Household), zeolite filtration, high velocity disintegrator (for disinfection), sand filters, multimedia filtration, microfiltration, reverse osmosis (RO) and chlorination	172	Class A$^+$	Sunrise @1770

Note: [1]See the Queensland Recycled Water Guideline (http://www.derm.qld.gov.au/water/regulation/recycling/guidelines.html) for water quality specification for Class A$^+$-D

36,000 person equivalent (EP), but could be smaller or larger. The question arises as to what design is technically appropriate for each type of end use. Knowledge gaps exist on the efficiency, reliability, economics and life-cycle impact on the environment. These pose challenges to decision makers, planners, engineers or system operators. Indeed, the absence of scientific studies to validate existing decentralised systems and a practical guidance for decision making have been identified as one of the barriers to the wider uptake of decentralised systems (Tjandraatmadja *et al.,* 2008). This project is part of the Urban Water Security Research Alliance (http://www.urbanwateralliance.org.au/), aiming to develop a framework to assist in decision-making on appropriate selection of technologies and scale for cluster scale WWT&R.

This paper compares the design of the three cluster-scale WWT&R plants that illustrate the implication of treatment performance and environmental burden in terms of energy, fugitive greenhouse gas (GHG) emissions and nutrient exports. The methodology we will apply is also described.

CASE STUDY

The selected studied plants include the Capo di Monte (CDM, on Tambourine Mountain), The Currumbin Ecovillage (CEV, in Currumbin, Gold Coast) and Sunrise at 1770 (Queensland Central Coast). These developments differ in their treatment technologies, geography, development scales, lot sizes and licence limits, although they all produce Class A$^+$ water for potable substitution (mainly toilet flushing and irrigation). The main driver for the development to adopt decentralised systems is also different; while CDM does not have ready access to council's existing sewer collection network, CEV is showcasing its sustainable development, whilst Sunrise at 1770 is located in an environmentally sensitivity area (adjacent to Great Barrier Reef lagoon) and has a strong commitment to protect the environment.

Capo di Monte Plant

CDM development covers 4.3 ha, comprising 46 detached and semidetached residences and a community centre. Each residence has one or two bedrooms catering for "over-50's" people. The cluster-scale WWT&R plant (Figure 1) is designed to treat 11 kL/d of sewage (peak flow) from the village (110 L/EP/day). It utilises a submerged flat sheet MBR (Kubota), incorporating raked screen, anoxic/aerobic zones, alum precipitation of phosphorus, UV disinfection and sodium hypochlorite chlorination. Excess sludge is pumped from the anoxic zone on a fortnightly basis and transported to local Council's sludge plant for further treatment. The produced Class A$^+$ recycled water is stored in a 100 kL storage tank and reticulated to each house via dual pipe systems for toilet flushing and outdoor use. A 6,000 m^2 vegetated buffer zone is used for land application of excess treated wastewater in order to avoid direct discharge into the local waterway.

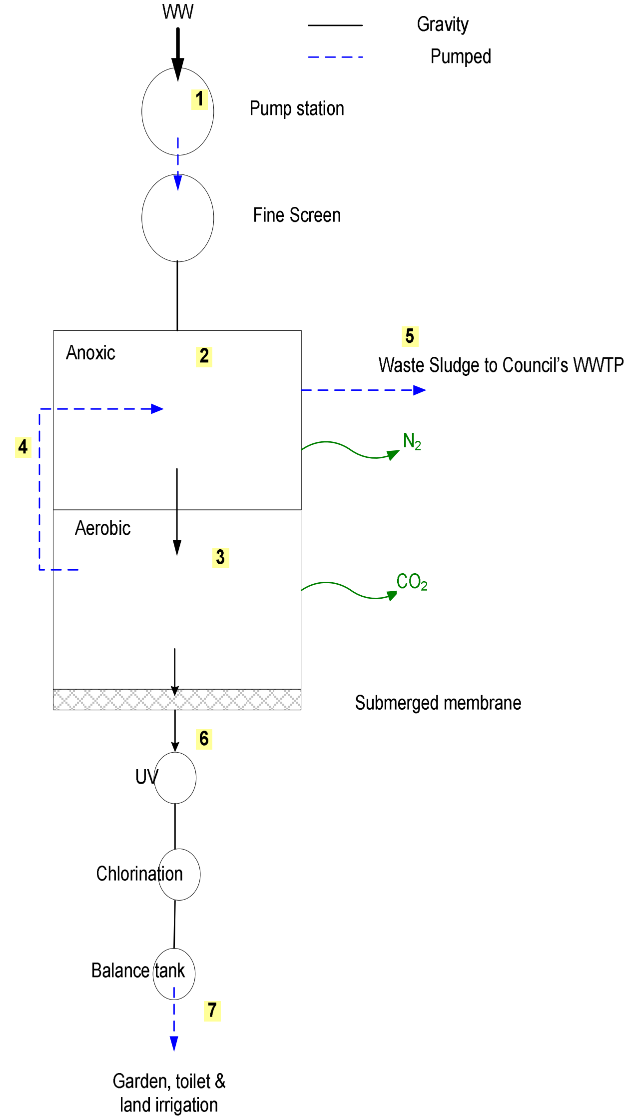

Figure 1 Schematic of the Capo di Monte wastewater treatment and recycling plant. (Locations for fugitive GHG sampling are highlighted in yellow)

The Currumbin Ecovillage

CEV constitutes 110 unsewered lots, ranging from 400 to 1600 m^2, and extensive communal open areas (80% open space to 20% living space). Its WWT&R plant is designed to treat 51 kL/day of sewage. Figure 2 shows the schematic of the WWT&R plant. The wastewater is collected at each home and transported to the plant using a combination of gravity and pumping. There, it is treated to a secondary standard by incorporating anaerobic primary treatment, aerobic biofiltration and denitrification treatment. The anaerobic treatment is performed in three septic treatment tanks in series with a filter (Biotube®) installed in the last tank to remove solids from its effluent. Aerobic degradation of carbon compounds and nitrification process are performed in a low energy packed bed biofilter, an Orenco Advantex® Textile Filter (AdvanTex AX100). An anoxic/recirculation tank located before the biofilter provides denitrification treatment and the required retention time for the primarily treated effluent and biofilter effluent. The reclaimed wastewater is treated to a Class A^+ standard through microfiltration (effective pore size of 0.2 µm), UV disinfection and chlorination, and stored in a recycled water storage tank for reuse.

The key operational parameter of the CEV wastewater treatment process is the ratio of the textile filter effluent flow recycled back to the anoxic/recirculation tank into the total inflow to the anoxic/recirculation tank. The recycling ratio depends on the flowrates into the plant; during low flow periods, 80% of the textile filter effluent flow is distributed to the recirculation zone. When the flow level in the recirculation zone increases, only a portion of the flow is diverted to the recirculation tank (by an automatically adjustable splitting valve). However, at all times 20% of the filter effluent flow returns to the anoxic zone, and a minimum of 64% is directed to the recirculation zone. This allows sufficient residence time for the completion of organic degradation and nitrification. At present, the recycled ratio of the plant is operated in 5 to 1 (Xavier, 2008).

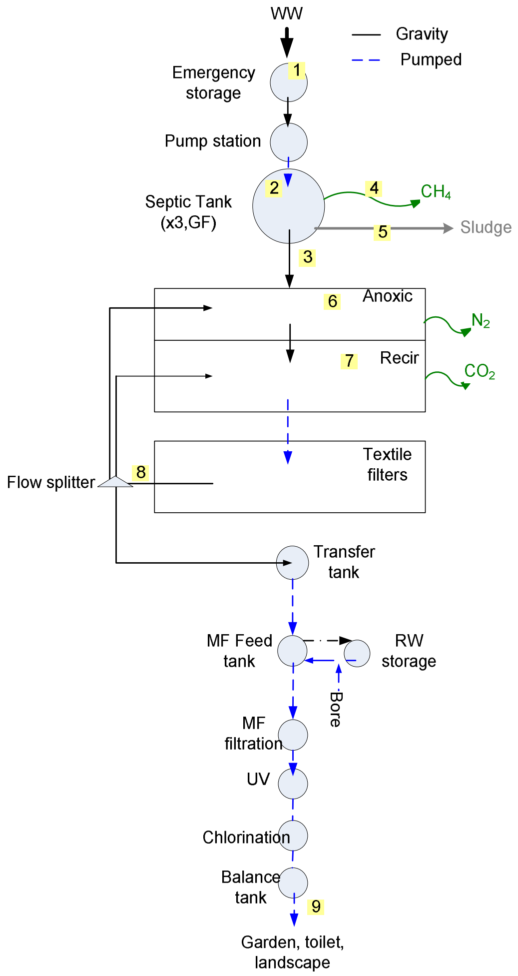

Figure 2 Schematic of the Currumbin Ecovillage wastewater treatment and recycling plant.

(Locations for fugitive GHG sampling are highlighted in yellow.)

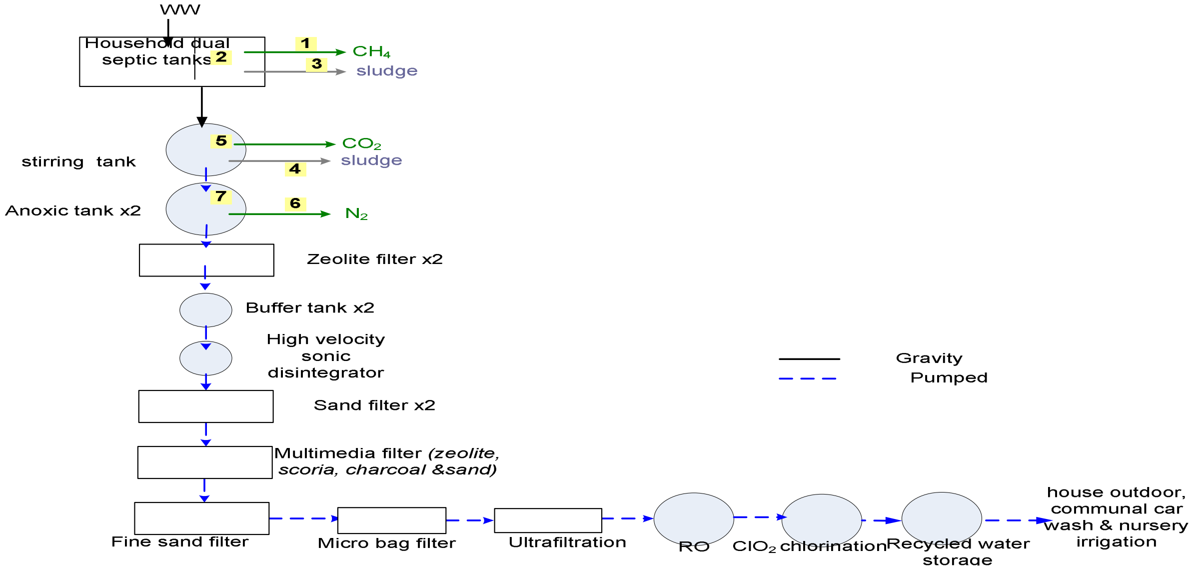

Figure 3 Schematic of the Sunrise @1770 wastewater treatment and recycling plant (Locations for fugitive GHG sampling are highlighted in yellow.)

Sunrise at 1770

Sunrise at 1770 is located in an environmentally sensitive area on the central coast of Queensland. The development covers 650 ha with 172 houses. Wastewater is pre-treated in household dual septic tanks before being pumped via pressure sewers to the cluster-scale recycled water treatment system. Figure 3 shows the schematic of the treatment plant. It was designed to treat a peak flow of 250 kL/d and run as a batch system with a 250 kL buffer tank to cope with a large variation of inflow. Aeration and mixing in the buffer tank are achieved using a mixer (Aspiro Plus). Two anoxic tanks follow the buffer tank and aid denitrification process (but this is not designed as a core process as nitrification hardly occurs in the buffer tank (Kele 2009)). Effluent from the anoxic tanks is split by butterfly valves, with 10% of flow to the buffer tank and the remaining 90% to the downstream treatment systems, which are two upflow filters consisting of zeolite and scoria.

Zeolites are hydrated alumino-silicate minerals with cation exchange capacity to adsorb contaminants such as ammonia and sodium, while Scoria is macrovesicular volcanic rock with very porous structure and has good organic adsorption capacity. Zeolites and scoria were packed in a ratio of 2 to 1 and designed to reduce ammonia to below instrumentally detectable limits (<1 mg/L) and the sodium adoption ratio (SAR) below 4 (Kele 2009). The filtered effluent is gravity fed into storage tanks prior to advanced treatment.

The advanced treatment systems include a high velocity sonic disintegrator, sand filters, multi-medium filters containing a mixture of activated carbon, zeolite, sand and agates, and a micro filter (effective pore size of 1 μm). The high velocity sonic disintegrator applies sound waves to break the microbial cell membrane and then put the cells under pressure to cause them to rupture. Chlorine dioxide is also used as an additional disinfection. Ultrafiltration (UF) and reverse osmosis (RO) units were built in the system following the microfiltration, but their operations are on an “as needed” basis. The advanced treated effluent is stored in a 150 kL recycled water tank with a chlorine dosing to maintain the residual chlorine level between 1 and 3 mg/L. Class A^+ recycled water is distributed via dual reticulation to provide each house with water for toilet flushing and external use. It is also used for irrigation of native plant nursery, a communal car washing facility and emergency fire-fighting.

THE CURRENT CHALLENGES AND OUR KEY STUDY AREAS

To be incorporated into the mainstream urban development, any WWT&R system needs to be cost effective, impose less environmental burdens including fugitive GHG emissions, energy and nutrient export, while still exhibiting robustness under various conditions to reliably produce quality class A^+ recycled water. Accordingly, our study focuses on these areas.

Energy

Cluster scale WWT&R systems provide an appealing option for energy savings that include avoiding the need to construct large scale sewer networks and associated pumping costs. To date, however, virtually no direct measurement has been made on the energy consumption/savings of cluster scale WWT&R systems. Energy consumption is site specific and dependent on treatment technologies, system design and operation. For example, MBR systems are generally considered to consume more energy than biofiltration due to the need for mechanical aeration for control of membrane scaling. If the textile biofilter system at CEV's WWT&R plant was replaced with an MBR (Kubota), operational energy was estimated to increase to approximately 170 kWhr per day from 49 kWhr per day (Bligh Tanner, 2004). However, MBR systems are renowned for their small physical footprint. In the case of the CEV WWT&R plant, given the assumption that both systems used similar type of civil work materials, MBR were estimated to have an embodied energy equivalent to 16 kWhr per day (for 25 years life) compared to 41 kWhr per day for a textile biofilter system (Blight Tanner, 2004).

The operational energy for WWT&R can be theoretically estimated from first principles using a mass and energy balance approach. For example, the operational energy cost for the electric pump can be determined from its power consumption using the equation, $p = \frac{QH\gamma}{\eta}$, where, P = power (J/s); Q = average daily flow rate (m^3/s); H = head (m); γ = specific weight of water (kg/m^2s^2) and η = efficiency of the pump. Similarly, first principle approaches can be extended to every piece of the electrical equipment involved in the treatment system. In the context of decentralised systems, however, we believed that such "first principle" estimation might not be valid. Recurrent start-ups of power-driven plant machinery are likely to occur more frequently and subsequently contribute to a higher use of operational energy. Gardner *et al.* (2006) have also suggested similar behaviour due to the intermittent operation of rainwater tank systems. They observed that the net contribution of irregular pump start-ups accounted for as much as four times the demand of running power.

Considering such uncertainties in operational energy consumption for decentralised WWT&R systems, a system validation stage with concurrent on-site measurement of energy is considered essential to provide a more realistic operational energy estimate. A range of meters are being installed at the key treatment components of the WWT&R plants of CDM, CEV and Sunrise at 1770 to measure water flow and energy consumption. With this on-site data, we can determine coefficient factors compared to the theoretical power calculation, and apply these factors to make more accurate and precise comparisons across small to large scale WWT&R systems.

Fugitive GHG Emissions

Foley and Lant (2009) highlighted the inadequacy of the guidelines published in the federal government's Australian Greenhouse Office workbook for calculating fugitive GHG emissions from wastewater collection, transfer and treatment operations. The guidelines omitted the strong possibility of fugitive emissions of nitrous oxide (N_2O) from biological nutrient removal processes and methane (CH_4) from sewers, biosolids treatment and biosolids disposal. Through laboratory scale experiments and seven full-scale wastewater treatment plant case studies, Foley and Lant (2009) showed that N_2O generation was always positive, with a range of 0.006 to 0.253 kg N_2O-N per kg N denitrified. The wastewater treatment plants (WWTPs) designed for effluent with total nitrogen (TN) concentrations less than 10 mg N/L had lower and less variable N_2O generation potentials than those achieving only partial denitrification.

The Queensland Plumbing and Wastewater Code specifies an effluent limit of 10 mg/L total nitrogen (TN) and 5 mg/L total phosphorus (TP) for decentralised systems with Advance Secondary plus Nutrient Removal. Accordingly, the decentralised systems designed to just meet that requirement are likely to have higher N_2O generation potentials. The licensed effluent limits (50 percentile) were 10, 15, 1.5 mg TN/L for CDM, CEV and Sunrise at 1770, respectively. Therefore, except for Sunrise at 1770, which has a stringent discharge requirement due to its initial design for effluent aquifer recharge and its environmentally sensitive location, both CDM and CEV WWT&R plants have the possibility of generating substantial amounts of N_2O. Adapting the average figure of 0.035 kg N_2O-N /kg N denitrified in a WWTP (Foley and Lant, 2009), the WWT processes in CDM and CEV are estimated to generate 12 kg N_2O per annum (i.e. 3.6 ton CO_2-equivalent per annum, using 310 kg CO_2-equivalent /kg N_2O) and 30 kg N_2O per annum (9.3 ton CO_2-equivalent per annum), respectively. The generation of N_2O from the plant of CDM will be higher that the CEV system, when taking into account biosolids treatment and disposals (i.e. denitrification in the soil after agricultural use or in a landfill operation). The textile filter system at CEV produces insignificant amount of excess sludge, as it is designed with an organic loading which allows microorganisms in the filter to complete a whole life cycle including a complete endogenous process (the energy for microbial expenditure is sourced within cells). Therefore, from the perspective of N_2O generation associated with biosolids treatment and disposals, the CEV textile filter offers an opportunity for GHG reduction (although it limits the system's carbon compound biodegradation efficiency).

CH_4 generation occurs in anaerobic and facultative wastewater processes and is also likely in sewer collection systems, particularly rising mains with long hydraulic retention times (HRT) and/or a large ratio of surface area to volume (Foley and Lant, 2009). While the potential of CH_4 emissions from the sewers of decentralised systems is likely lower because gravity mains are the majority, and the HRT is shorter compared to centralised networks, decentralised WWT&R systems typically consist of septic systems for primary treatment due to their operational simplicity. However, the use of septic systems is at the cost of CH_4 generation. Given the estimation that septic tanks can contribute up to 395 kg CO_2-equivalent per household per year in the form of CH_4 (Lane and Gardner 2009b), thse CH_4 emissions from the WWT&R plants in CEV and Sunrise at 1770 could be 43 and 68 ton CO_2-equivalent per year, respectively.

Our estimates show the potential of fugitive GHG generation from cluster scale WWT&R systems and are supported by the findings from an LCA study by Lane and Gardner (2009b). However, all estimates in this area used the default factor recommended by Foley and Lant (2008) for large scale WWTPs. They also reported a wide variation in fugitive GHG emissions across different scale treatment technologies and designs. Hence, we argue that scientific research on fugitive GHG emissions from decentralised systems is important to assess their environmental sustainability. To the best of our knowledge, this study is the first attempt in Australia to measure fugitive GHG emissions from different decentralised WWT&R systems. Figure 1 to 3 show the points for sampling CH_4 and N_2O. The sample collection and analysis will be performed based on the method published in Foley and Lant (2009).

System Robustness

Decentralised sewer networks have less buffering capacity and residence time and therefore the process design of decentralised systems must be sufficiently robust to cope with a wide variation of influent flow and qualities. However, how the systems respond to external perturbation is specific to the system's technologies, design and operation. To investigate the various possibilities of system shocks created by the local community, direct *"what if"* trials (e.g. increasing BOD shock loads to the plant by adding molasses) may alter the plant's recycled water quality, which is unacceptable to the local community. A process model with a commercial simulator, BioWin 3.1, will be therefore used in this project.

The model will first be calibrated and validated with different sets of data collected from analysis of gas, liquid and solid grab samples taken from various locations. A number of hypothetical system perturbation scenarios will then be created for the model to simulate the system performance. Strategies to improve the system robustness such as utilising the alternatives of system components, or operational parameters will also be investigated through the modelling approach.

CONCLUSIONS

Decentralised wastewater treatment and recycling can be a feasible option in urban areas where the provision of centralised systems is technically, economically or environmentally unviable. However, we found that technically robust operational data is largely absent to make an informed technology selection and system design.

If not designed and operated properly, we believed there is significant potential for N_2O generation from decentralised wastewater systems since the effluent requirement for these systems is usually in the order of 10 mg TN/L. In addition, these systems can contribute a significant amount of CH_4 to the atmosphere due to their wide adoption of septic systems for primary treatment. Hence, scientific research on fugitive GHG emissions from decentralised systems is important to assess their environmental sustainability. We therefore intend to measure N_2O and CH_4 gas emissions by taking gas and liquid samples from key system components in the case study plants.

Recurrent start-ups of power-driven plant machinery are likely to occur more frequently in decentralised WWT&R systems and hence, contribute to a higher use of operational energy, compared to large scale centralised plants. Considering the significant uncertainties in operational energy consumption for decentralised systems, a validation stage with concurrent measurement of energy and water flow is considered essential to provide more realistic operational energy estimates.

System robustness is another important factor concerning the successful adoption of decentralised WWT&R systems because of their smaller buffering capacity, which makes the systems vulnerable to various upsets and shock loads. We propose to apply a process based modelling approach to assess the robustness of the cluster scale WWT&R. A number of system perturbation scenarios will be created for the models to simulate the system performance. Improvement of the system robustness by utilising treatment system component alternatives and changing key operational parameters will be evaluated with the BioWin model.

Using data obtained from direct measurement and modelling in conjunction with life cycle costing and life cycle assessment (other components of our study), we plan to develop a set of objective criteria for the selection of appropriate decentralised scale and technologies in any given greenfield development.

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