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Sustainability trade-offs in the planning and design of cluster scale greywater reuse systems

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Abstract: It is becoming increasingly accepted that the conventional approach to urban water resources management (WRM) is unsustainable and that securing urban water supplies for both anthropogenic and environmental uses requires a different approach. Water sensitive urban design (WSUD) is a holistic approach that seeks to integrate the management of the potable water, stormwater and wastewater cycles that provides such an alternative.

WSUD has been well recognised in Australia, particularly in the area of stormwater management. However, there is less guidance in the area of wastewater management. The management of wastewater in a WSUD context involves initiatives such as minimising the volume of wastewater generated and reusing wastewater where appropriate. Despite a number of examples of large-scale and individual household wastewater reuse schemes throughout Australia, there has been little experience with reuse schemes at the intermediate, cluster scale. Furthermore, the sustainability of these reuse schemes is often not considered.

This paper discusses the design of a cluster scale greywater reuse scheme for a proposed development in Streaky Bay, South Australia, using two components of sustainability, economic and environmental with the corresponding assessment criteria of net present value and total energy. Several different sized cluster scale reuse schemes are considered, and the trade-offs between the two sustainability criteria are obtained. The results of the analysis over a 50-year time period indicate that cluster scale greywater reuse is significantly more sustainable than individual reuse schemes. The results also suggest that, for this case study, reuse schemes that service a larger number of houses are more sustainable than smaller schemes.

The trade-offs between the pipe materials selected are investigated and it is found that trade-offs between cost and energy only exist for certain materials. The sensitivity of the design to the population density is also investigated and the results compared to the initial analysis. It is found that increasing population density reduces the total cost and total energy of the reuse scheme. These results are important, as they illustrate the types of trade-offs that should be taken into consideration in the planning and design of greywater reuse schemes at the cluster scale.

Keywords: *Greywater, water sensitive urban design (WSUD), wastewater, sustainability, cost-energy trade-offs, cluster scale reuse*

1. INTRODUCTION

Australia is the driest of the inhabited continents; on average, only 12% of rainfall becomes run-off (Radcliffe, 2004). With increasing uncertainty over the security of current water sources and continuing high potable water use in Australia (Marsden and Pickering, 2006), there is a critical need to improve and investigate better management strategies for water resources.

Water sensitive urban design (WSUD) is based on the integrated, sustainable management of wastewater, stormwater and potable water in cities. It is a distinct shift away from conventional practice, providing a holistic approach to water resources management (WRM) (Wong, 2006). WSUD has been well recognised in Australia, particularly in a stormwater management context. However, much less guidance is provided for wastewater management, and, given that over 85% of wastewater is not utilised in Australia (CSIRO, 2005), there is certainly scope to adopt better management strategies in this area. In particular, there is significant potential to offset mains water use through the increased use of treated wastewater in areas that do not require water of a potable standard, such as the garden and some indoor areas.

There are a number of examples of wastewater reuse schemes in Australia, though these tend to be implemented using either a large, centralised scheme, such as the Virginia Pipeline Scheme in South Australia (SA Water, 2004) and Rouse Hill in New South Wales (Radcliffe, 2004), or at the individual household level (e.g., Mobbs, 1998). Very few examples of cluster scale reuse schemes exist in Australia (however, the Inkerman D'Lux is one example (Goddard, 2006)). Cluster scale reuse schemes offer flexibility in their design, allowing reuse to occur near to where the wastewater is being generated (Crites and Tchobanoglous, 1998). They have the potential to be more sustainable than both centralised and individual reuse schemes through reduced infrastructure needs and the shared use of the system.

When planning wastewater reuse schemes (and water infrastructure generally), there are inherent trade-offs between different objectives, especially in the context of sustainability. For example, environmental impacts must be balanced against economic and social impacts. However, this is a consideration often neglected in practice, where the conventional design approach is to minimise costs only (Acreman, 2001). Accordingly, there is a need to provide a robust design methodology for wastewater reuse schemes that allows explicit consideration of their sustainability.

This research proposes to address these shortcomings in conventional practice by applying a systems approach to the design of cluster scale greywater reuse schemes. This approach will allow the trade-offs inherent in the system design to be discussed, as well as allowing a comparison to be made between the sustainability of individual reuse schemes and cluster scale reuse schemes. The potential implications for the current practice of encouraging reuse at the individual household level will also be investigated.

2. METHODOLOGY

A systems approach was used as the basis for the methodology as it is a useful tool for decision makers (Checkland, 1981), particularly when addressing complex systems (Kelly, 1998). It was suggested in the context of WRM by Biswas in 1976, but more recently the literature has endorsed its use in WRM (Wilsenach et al., 2003; Jakeman et al., 2006).

In the context of designing greywater reuse schemes, the systems approach enables the selection and comparison of different designs, refining them until the best design (in terms of the assessment criteria selected) is achieved. Multiple assessment criteria, in the form of sustainability objectives, may also be used. The key steps of the systems approach are given in Figure 1.

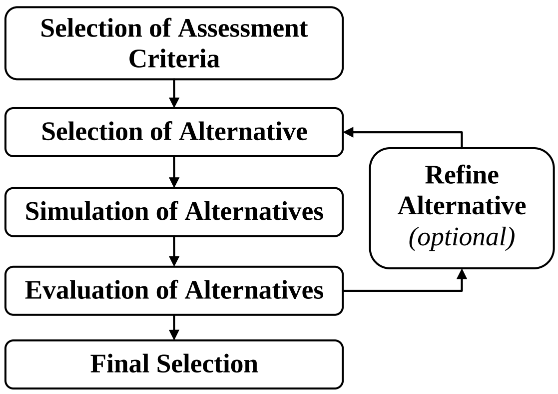

Figure 1. Steps involved in the systems approach (adapted from Biswas, 1976)

Etneir et al. (2007), note that the absence of a systems approach in decision making is one of the impediments to the uptake of cluster scale wastewater reuse schemes. Together with the capacity to consider the sustainability of reuse schemes and its utility to decision makers, a systems approach has substantial practical merit.

3. CASE STUDY: STREAKY BAY, SOUTH AUSTRALIA

A proposed development in Streaky Bay, South Australia (Figure 2) was used as the case study for this research. A plan of the development is provided in Figure 3.

Figure 2. Locality map (adapted from Google Maps, 2009)

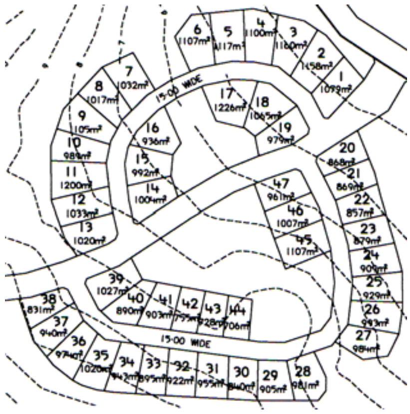

Figure 3. Streaky Bay development

The sustainability benefits of cluster scale greywater reuse schemes over individual reuse schemes have not been quantified in the literature. Accordingly, the reuse of greywater at an individual household level was compared with reuse schemes at a number of different sized clusters in the development. In the latter case, the entire development would be provided with recycled greywater through several cluster scale systems each supplying their own cluster of houses. The scales considered in this case study (Table 1) were selected based on the layout of the development and from available contour data.

Table 1. Number of houses per scale in case study

Scale	No. of Houses
Individual	1
1	9
2	19
3	47

3.1. Selection of Assessment Criteria

The sustainability of a reuse scheme will be maximised when its various impacts (environmental, economic and social) are minimised. In this research, two components of sustainability were considered: economic and environmental, with corresponding assessment criteria of net present value (NPV) and total energy.

The NPV of the reuse scheme includes all capital and operating costs (Equation 1). Discount rates vary markedly between institutions. In South Australia, discount rates used by the Government have varied between 5-7% for the 2004-2007 period (Government of South Australia, 2004; 2006), and 7-8% was used by SA Water in 2003 (National Competition Council, 2003). Owing to this variability, a discount rate of 5% was selected for the NPV calculation.

$$NPV = CC + OC \times \frac{(1-(1+i)^{-t})}{i} \qquad (1)$$

Where, CC = capital cost ($), OC = annual operating cost (including maintenance of components) ($); i = economic discount rate (5%) and t = life of the project (taken as 50 years).

The total energy of the reuse scheme includes the embodied energy of the materials (Treloar, 1994) and the annual operating energy (Equation 2). Total energy can be used to estimate greenhouse gas emissions when the sources of the electricity are known, but since these are likely to vary with time (for example, with the uptake of different electricity sources), total energy was used in preference to greenhouse gas emissions as an assessment criteria. Discount rates for greenhouse gas emissions have been suggested at 0-2% (Azar and Sterner, 1996; Fearnside, 2002); rates that the Australian Greenhouse Office (2006) has indicated can apply to discounting of operating energy.

$$\text{Total Energy} = EE + OE \times \frac{(1-(1+i)^{-t})}{i} \qquad (2)$$

Where, EE = embodied energy of the materials (GJ); OE = annual operating energy (GJ/annum); i = social discount rate (1%) and t = life of the project (taken as 50 years).

Annual operating costs and operating energy were assumed to be constant throughout the life of the project.

3.2. Selection of Alternatives

In applying the systems approach to the case study, the "alternatives" being considered are the different possible designs for the greywater reuse scheme. This involves selecting from sets of available pipe materials, pipe diameters, pumps and greywater treatment systems. In this case study, greywater was sourced from the bathroom (taps, shower and bath) and laundry and reused in the garden and toilet.

Greywater Treatment System

Greywater treatment systems are available for a range of duties, from reuse at an individual household up to reuse for over 1,000 allotments. Numerous treatment systems are commercially available for these different scales, all of which have widely varying cost and energy impacts. For the four different scales considered in this case study, several different treatment systems were chosen and their cost and energy impacts averaged. The NPV and total energy of the averaged greywater treatment systems used for each scale are presented in Table 2. A prerequisite for the systems to be considered was their capacity to treat greywater to Class A standards (Government of South Australia, 1999).

Table 2. Greywater treatment stations data

Scale	NPV ($)	Total Energy (GJ)
Individual	38,500	40
1	90,100	120
2	188,800	250
3	386,900	600

Pipe Networks

Two pipe networks are required for cluster scale greywater reuse schemes: a collection network and a distribution network. The layout of both networks was assumed to be the same and was determined using the topography and layout of the case study. All pipes within a network were deemed to be of the same material in order to facilitate constructability, though the two networks did not necessarily have to be made from the same material. The SA Water Network Infrastructure Standards (NIS) for wastewater gravity mains and recycled water mains were used to guide the selection of the available pipe diameters and materials. Polyethylene (PE) and unplasticised polyvinyl chloride (PVC-U) were used for the collection network and PE and oriented-PVC (PVC-O) were used for the distribution network. Collection network pipes were sized using Manning's equation with a design velocity of 0.6 m/s, the in-situ slope and Manning's coefficient corresponding to the material type. The diameters of these pipes were adjusted (together with the design longitudinal slope) to ensure the pipes had sufficient capacity under the peak expected flow. Distribution network pipes were sized to convey the probable peak simultaneous flow (AS/NZS 3500.1:2003) and to meet a minimum pressure constraint of 15 m at each household.

The NPV and total energy of the collection network and distribution networks were determined using cost and embodied energy data for the pipes (Rawlinsons, 2007 and Ambrose et al. 2002, respectively). Costs for trenching and backfilling were also included for both networks.

Pumps

A range of pumps from the manufacturers Grundfos and Thompson, Kelly & Lewis were considered. For the individual household reuse scheme, a pump was selected manually using the minimum pressure constraint of 15 m at the house. For the cluster scale reuse schemes, pumps were selected such that they could deliver the probable peak simultaneous demand of the cluster (AS/NZS 3500.1:2003).

The NPV and total energy of the pump were determined using Equations 1 and 2. The capital cost of the pump was approximated using Machell and Lim (2008) with maintenance costs assumed to be 1% of the capital cost. The operating cost of the pump was determined from its power consumption (Equation 3) assuming the pump was running for 20 hours each day at an electricity price of 21.3 ¢/kWh and a $35 service fee per quarter (Origin Energy, 2008).

$$P = \frac{QH\gamma}{\eta} \qquad (3)$$

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 (assumed to be 75%).

It was assumed that each pump was made entirely from steel. Thus, the embodied energy of the pump was estimated using its stated weight and an embodied energy coefficient for steel of 0.085 GJ/kg. The operating energy of the pump was calculated using Equation 3 assuming the pump was running for 20 hours each day.

3.3. Simulation of Alternatives

Hydraulic simulation of the distribution networks is required for each of the scales to ensure that the pressure constraint of 15 m is satisfied at each household. This is due to the interdependencies between pump head, friction losses and pipe roughness. Hydraulic simulation was performed using the EPANET2 software package. The collection networks do not require simulation, as they are non-pressurised. No simulation was required of the individual household reuse scheme as it consists only of a single treatment station and pump.

3.4. Refine Alternatives

An arbitrary selection of the components of the scheme may result in the scheme failing to meet all of the pressure requirements within the network. Accordingly, there is a need to refine the design of the scheme by choosing different pumps or different pipe diameters until these requirements are met.

In order to investigate the trade-offs in the design of the scheme, more than one pipe material was considered for each of the networks. This allowed several points for each scale, correlating to the different materials, to be plotted in order for the trade-offs to be seen, not only between scales, but between materials as well.

3.5. Evaluation of Alternatives

Once the reuse scheme had been refined to satisfy the pressure constraint at all houses, the NPV and total energy for the reuse scheme were calculated (using Equations 1 and 2) to give a measure of the scheme's sustainability. To enable comparisons between the cost-energy trade-offs of the different scales, the NPV and total energy were divided by the number of houses serviced at that scale (i.e. normalised). This also facilitated comparison with the individual household reuse scheme.

4. RESULTS

It can be seen from Figure 4 (hollow points) that the sustainability of a reuse scheme increases with an increase in the scale at which it is implemented. There is no suggestion from these results that this trend towards more sustainable solutions with a larger size scheme is reducing or reaching a plateau. Whether this trend of increasing sustainability continues, reverses or plateaus as the scale of application increases beyond those considered in this study is unknown and is a point for further research.

The shape of the series in Figure 4 and the distribution of the hollow points are similar for each of the three scales, which indicates that the trade-offs between the different network materials are similar for each scale. There were no trade-offs between the two collection network materials because PVC-U is cheaper and lower in energy than PE. Therefore, in all cases assessed PCV-U is the more sustainable collection network material and would be selected by the designer for each scale. However, trade-offs do exist between the two

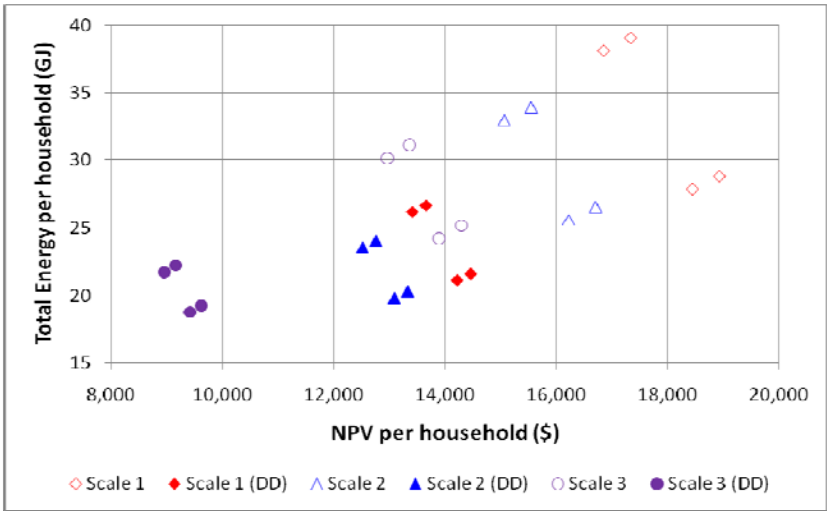

Figure 4. Total Energy and NPV per household for all three scales of the base case (hollow points) and the population density (DD) sensitivity analysis (solid points)

distribution network materials because PE has greater embodied energy (per metre), but lower cost (per metre) than PVC-O. Thus, determining which distribution network material is preferred depends on which objective is more important to the designer. For example, the move from PE to PVC-O at Scale 3 increases the NPV by roughly $1,000 per household but saves 282 GJ over the life time of the project. This is an increase in expense that may be desirable in order to reduce energy consumption and in turn the associated GHG emissions.

4.1. Individual Household Results

The NPV and total energy for the individual household scale are $41,400 and 43 GJ respectively. The NPV and total energy is far greater than that of any of the cluster scales. This suggests that in relation to the sustainability assessment criteria of NPV and total energy, an individual household greywater reuse scheme is far less sustainable than a cluster scale reuse scheme. This is due to the cost and energy involved in the reuse of the greywater being borne by a single house, rather than being shared amongst several houses, as is the case with the cluster reuse schemes. This is an important conclusion as it suggests that encouraging the installation of individual household greywater reuse schemes is not the most sustainable way of implementing greywater reuse.

4.2. Population Density Sensitivity Analysis

One feature of the case study was the relatively large allotment sizes; between $830m^2$ and $1230m^2$. There is a degree of uncertainty as to whether the results of the original design scenario are directly applicable to developments in inner city urban areas where block sizes are usually smaller. Therefore, a sensitivity analysis was undertaken that assessed the consequences of having two houses on each allotment, effectively doubling the population density (Table 3).

Table 3. Number of houses per scale in sensitivity analysis

Scale	No. of Houses
Individual	1
1	18
2	38
3	94

Figure 4 (solid points) illustrates that doubling the population density decreases the NPV by 31-33% and decreases the total energy by 22-29% per house, thus increasing the sustainability of the greywater reuse system. The shape of the graphs and thus the trend between the scales is very similar to the base case results, which indicates that the same trade-offs are present between the different pipe materials (Section 4).

4.3. Comparison of Reuse Costs

As noted, there have been no attempts in the literature to quantify the sustainability of greywater reuse schemes. However, there are some data regarding the cost per kilolitre of recycled wastewater in a combined greywater and blackwater reuse scheme. Whilst direct comparisons are not possible, they provide a benchmark against which to measure the benefits of the systems approach to the design of greywater reuse schemes.

The Rouse Hill dual reticulation scheme in Sydney, NSW, services approximately 17,500 houses. Radcliffe (2004) has reported on indicative costs of around $3/kL of recycled wastewater. The costs per kilolitre obtained in this case study are $4.20-$6.10 for the base case and the doubled population density case achieved $2.40-$3.90. These values are comparable to those achieved in Rouse Hill, which suggests the system designs are not entirely unreasonable. This suggests that, if applied in general practice the systems approach and the associated refining of alternatives could yield solutions with greater sustainability than conventional design methods.

5. CONCLUSIONS

The key findings of the research is that the application of a systems approach to the design of a greywater reuse scheme has produced a clear trend – reuse schemes that service a larger number of houses are more sustainable than smaller clusters or individual household schemes. This suggests that when encouraging greywater reuse the size of the scheme will heavily affect the sustainability of the scheme and the current push towards reuse at the individual household is not the most sustainable solution.

It was shown that trade-offs exist between the two sustainability assessment criteria, (NPV and total energy) with respect to the choice of the distribution network material, but not with respect to the choice of collection network material. The sensitivity of the design to population density was investigated and it was found that doubling the population density of the case study increased the sustainability of the system, resulting in a decrease in NPV by approximately 30% and total energy by approximately 25%.

The consideration of energy, an environmental assessment criteria, and cost in the design is a departure from conventional practice which considers cost minimisation as the sole objective. Incorporating other sustainability objectives (e.g. social, temporal or technical) would provide further insight into how the sustainability of cluster scale reuse schemes is affected by the scale of its implementation.

These results also emphasise the trade-offs that should be taken into consideration during the planning and design of cluster scale greywater reuse schemes: no longer is simply minimising the cost of a reuse scheme an appropriate design approach.

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