Grey water characterisation and its impact on the selection and operation of technologies for urban reuse

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Abstract Characterisation of grey water reveals a source water that is similar in organic strength to a low-medium strength municipal sewage influent but with physical and biodegradability characteristics similar to a tertiary treated effluent. The characteristics of the water suggest biological processes are the most suitable unit processes for treating grey water. The highly variable nature of the source requires that selected technologies must be inherently robust in their operation. One potential area of concern is the high COD/BOD ratio and nutrient deficiency in terms of both macro and micro nutrients which grey water exhibits potentially retard the efficacy of biological processes.

Keywords Grey water; technology selection; urban recycling

Water Science and Technology **Vol 50 No 2 pp 157–164** © IWA Publishing 2004

Introduction

The motivations for recycling are manifold and can include water shortage caused by either low rainfall or excessive demand, environmental and economic drivers. It is also the case that recycling is an emotive issue which increases commensurately with the proximity of the public to the recycling application. Consequently, public perception issues can often out weigh technical ones as barriers to uptake and can ultimately terminate otherwise feasible and economic reuse schemes.

Water recycling within urban environments is perhaps the least well developed of the four generic water recycling options available for water resource management. Currently urban reuse focuses on the recycling or grey or rain waters for applications such as toilet flushing. Grey water is defined as urban wastewater without any input from toilets and so generally includes sources from baths, showers, hand basins, washing machines, dishwashers and kitchen sinks. Further sub division is common by restricting the sources to human washing operation such as water available from baths, showers and hand basins. The selection of which sources to include is a balance between available water and the level of pollution contained within it. At small scales this tends to exclude kitchen and clothes washing as they represent more heavily polluted sources but at larger scale all non toilet sources tend to be included to maximise water savings.

The most commonly described application for grey water reuse is toilet/urinal flushing which can reduce water demand within dwelling by up to 30% (Karpiscak *et al.*, 1990). However, grey water has been considered for many other applications including irrigation of lawns at cemeteries, golf courses and college campuses (Okun, 1997), vehicle washing, fire protection, boiler feed water, concrete production (Santala *et al.*, 1998) and preservation of wetlands (Otterpohl *et al.*, 1999). The water quality requirements for each application are geospecific but normally contain criteria based on organic, solids and microbiological content of the water. At its most restrictive the criteria require a BOD_5 of less than 10 mg.L^{-1}, a turbidity below 2 NTU and a non detectable level of either total or faecal coliforms (Palmer, 2001). However, standards in other countries are slightly less restrictive and permit higher concentrations of the different parameters or do not include them at all.

A wide variety of technologies have been used or are being developed for grey water treatment and reuse including natural treatment systems, basic coarse filtration, chemical processes, physical and physiochemical processes and biological processes. The exact selection of the most appropriate technology is dependent on many factors such as the scale of operation, end use of the water, socioeconomic factors relating to cost of water and regional customs and practices. Whilst remembering this some general commonalities can be observed. In the UK where single house grey water recycling is practiced the cost issues control process selection restricting selection to simple coarse filtration devices coupled with chemical disinfection. Throughout the world it is more common for larger residential buildings to be considered. The majority of these schemes include a biological stage to the treatment train. The most common configurations are membrane bioreactors, sequence batch reactors and biologically aerated filters which all produce high effluent standards. The current paper aims to describe the characteristics of grey water and relate this to appropriate technology selection.

Materials and methods

Grey water was collected from 102 individuals made up of a distribution of ages, gender and washing applications (bath, shower and hand basin). Sample were collected on the day of production (preferably within 2 hours) and either immediately analysed or stored at no more than 5°C for a maximum of 24 hours. Samples stored for longer periods or at higher temperatures were discarded from the study.

All chemical analysis were carried out as described in *Standard Methods* (APHA, 1992), using its adapted versions for the Hach methods or in accordance to the suppliers instructions. Total organic carbon was analysed using a TOC-5000A (Shimadzu, Milton Keynes, UK), metal content with a thermo Jarrell ash ICP-AES (Sci-tek Instruments, Olney, UK) and turbidity with a Hach 2100N turbidimeter (Camlab Ltd, Cambridge, UK) after being dispersed in a ultrasonic bath (Scientific Laboratory Supplies, Hull, UK). Samples for bacteria counts were asceptically collected in autoclaved 100 mL nalgene bottles (Merck Ltd, Leicester, UK). The analysis procedure was carried out asceptically using sterilised deionised water and Colilert18 and Enterolert reagents (Idexx Ltd, Chalfort, USA) for determining total/E Coli and faecal streptococci respectively. For both sets QuantiTray2000 and QuantiTray sealer were used as proscribed by the supplier.

Results

Characterisation

Grey waters collected from the shower, bath and hand basin sources all displayed similar biodegradable contents as demonstrated by BOD_5 concentrations of 146 ± 55, 129 ± 57 and 155 ± 49 mg.L^{-1} respectively at a 76% confidence level (Table 1). Much greater variability was observed in terms of non biodegradable fraction as observed by total COD concentrations of the same sources of 420 ± 245, 367 ± 246 and 587 ± 379 mg.L^{-1}. Correspondingly, COD:BOD ratio were generally lower in the bath (2.9 ± 1.3) and shower samples (2.8 ± 1.0) than in the hand basin (3.6 ± 1.6). This compares with 2.2 ± 0.6 for typical domestic sewage and 3–10 for final effluent and indicates that grey water is likely to contain a higher non biodegradable content than sewage (Metcalf and Eddy, 1991). However, the most important facet of grey water with regard to biodegradation is its nutrient imbalance. COD:N:P ratio for the bath, shower and hand basins sources were averaged at 100:2.25:0.06, 100:2.91:0.05 and 100:1.77:0.06 respectively. Comparison with the literature suggests ratios between 100:20:1 (Metcalf and Eddy, 1991), 250:7:1 (Franta *et al*., 1994) and 100:10:1 with trace sulphur (Beardsley and Coffey, 1985) indicating that grey water is deficient in both nitrogen and phosphorus in roughly equal proportions. The nitrogen and phosphorus deficiencies are to be expected as the majority of nitrogen compounds are excreted into the toilet bowl during urination and so not normally expected in grey water. Similarly most phosphorus originates in detergents used in washing powders and so will only be present if the laundry is included in the source waters. More detailed analysis reveals grey water to deficient in trace metals such as Iron, Manganese. Copper, Aluminium, Zinc and total devoid of Cobalt and Molybdenum (Table 2). Balancing the nutrient requirements within grey water has been shown to greatly enhance biotreatment enabling the maximum loading rates of biological processes to almost double compared to the unbalanced systems (Palmer, 2001).

The main characteristic of the organic pollution in grey water is however its variability. A series of experiments were conducted to establish the limit of this by two individuals conducting as near identical washing operations as possible over the course of a month. In each case the individual was asked to use exactly the same products, the same volume of water and wash for the same length of time (within reason). Variability within the resulting sets of grey water samples showed a BOD_5 of 90 ± 26 $mg.L^{-1}$ for the shower repeats and 185 ± 31 $mg.L^{-1}$ for the bath repeats representing relative standard deviations of 29 and 17% respectively. This compares to 38% and 44% for the shower and bath samples collected in the main sampling program. Comparison with operational grey water recycling schemes reveals an even larger variation between the different schemes with BOD_5 levels varying between 33 and 300 $mg.L^{-1}$. This represents a range of concentrations equivalent to a medium strength influent municipal sewage at one end to a final effluent at the other. The variability of the samples reflects the commensurate variability in lifestyles, customs, installations, product preferences and washing habits of the population.

The physical pollution within the grey water samples varied considerably between the three sources with suspended solids concentrations of 89 ± 113, 58 ± 46 and 153 ±

Table 1 Microbial nutrient requirements and the concentrations present in grey water

Nutrient	Required	Measured	Role of trace metal
N, P, S		5.00, 1.37, 16.3	
Ca	0.4–1.4	47.9	Cell transport systems and osmotic balance in all bacteria. Bridging anionic ECP and aiding flocculation.
K	0.8–>3.0	5.79	Cell transport systems and osmotic balance in bacteria.
Fe	0.1–0.4	0.017	Growth factor in bacteria, fungi and algae. Adsorbed in proportion to the concentration available.
Mg	0.4–5.0	5.29	Enzyme activator for a number of kinases and phosphotransferase in heterotrophic bacteria.
Mn	0.01–0.5	0.04	Activates bacterial enzymes. Often interchangeable with magnesium in kinase reactions.
Cu	0.01–0.5	0.006	Bacterial enzyme activator required in trace quantities. Can inhibit metabolism
Al	0.01–0.5	0.003	Not known. Affects the species found in sludge (Annaka, 1977).
Zn	0.1–0.5	0.03	Bacterial metallic enzyme activator of carbonic anhydrase and carboxypeptidase A. Dissociable on active site of enzymes. Stimulates cell growth.
Mo	0.2–0.5	0	Molybdenum is a common limiting nutrient (Grau, 1991)
Co	0.1–5.0™	0	Bacterial metallic enzyme activator. Dissociable on active site of enzymes. Activates carboxypeptidase for synthesis of vitamin B_{12} (cyanocobalamin) but otherwise toxic. Can inhibit metabolism.

226 mg.L^{-1} for the shower, bath and hand basins respectively (Table 1). Turbidity profiles were similar to the solids concentrations with suspended solids to turbidity ratios of 1.04, 0.96 and 0.93 which is much lower than normally observed for sewage or potable water systems but is only slightly lower tertiary effluent (Metcalf and Eddy, 1991). Comparison with the operational grey water recycling sites revealed a generally higher concentration at the sites with suspended solids concentrations up to 380 mg.L^{-1} (Table 1). The very high concentration sources are normally related to either clothes washing operations such as washing machines or hand washing or kitchen sinks (Eriksson *et al.*, 2002). The low suspended solids to turbidity ratios found in grey water are partially explained by the size distribution data which reveals the particles to be mainly within the 10 to 100 _m range (volume weighted) (Figure 1). The size distributions are characterised by d_{50} (median size) of 33.2 ± 4.9, 29.6 ± 2.7 and 27.1 ± 0.11 μm for showers, baths and hand basins respectively. In each case a small second peak in the distribution is observed between 200 and 2,000 μm probably representing lumps of soap, skin and hairs. Molecular weight profiles of combined grey weight were measured using high performance size exclusion chromatography with UV detection (Figure 2). The elution time is linked to the apparent molecular size of the molecules as they pass through the chromatography column. The exact correlation is dependent on the nature of the organics but calibrations with natural organic matter suggest peaks at 6.4–6.7 minutes, 7.6–7.8 minutes and 9.7–9.9 minutes refer to molecular sizes of >5 kDa, 3–4 kDa and 0.5–1 kDa respectively suggesting that grey water is made up of molecules similar in size to humic and fulvic compounds.

Bacterial counts in freshly sampled grey water reveal an average total coliform count of 3 log±3 log cfu.100 mL^{-1} for all sources tested. Faecal coliform indicators as either *E. coli* or faecal streptococci showed greater variability with lower concentrations in the bath

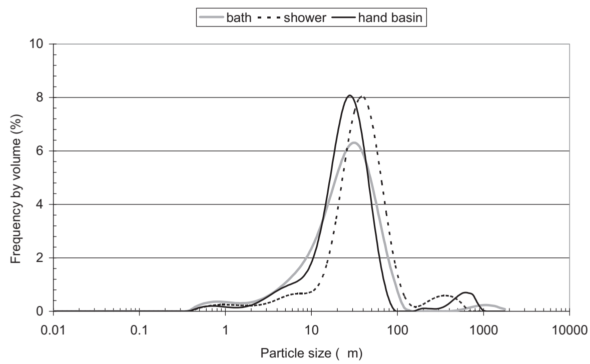

Figure 1 Typical size distributions of grey water

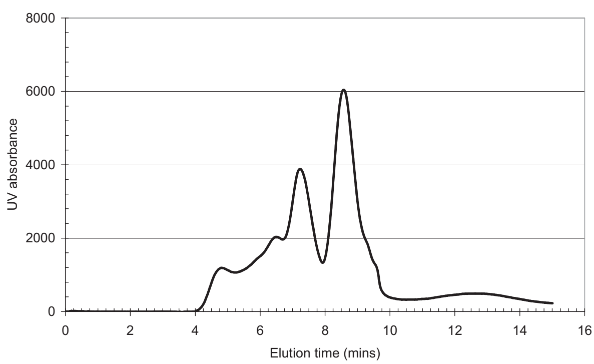

Figure 2 Typical molecular size profile for grey water

Table 2 Comparison of real grey water characteristics

	Shower	Bath	Hand basin	Combined	Shower repeat	Bath repeat	HoR 1 (Ward et al., 2000)	HoR 2 (Ward et al., 2000)	HoR 3 (Suren et al., 1999)	Single house (Sayers et al., 1999)	USA Brandes (1979)	Sweden Olsson (1968)	Australia
BOD_5 (ppm)	146 (55)	129 (57)	155 (49)	146 (54.3)	90 (26.1)	185 (31)	80	33	96 (103)	50–300	162	196	159 (69)
COD (ppm)	420 (245)	367 (246)	587 (379)	451 (289)	181 (63.4)	651 (112)	146	40	168 (91)	–	366	–	–
TOC (ppm)	65.3 (44.6)	59.8 (43)	99 (142)	72.6 (79.3)	–	–	–	–	49 (53)	–	125	–	–
Turbidity (NTU)	84.8 (70.5)	59.8 (43)	164 (171)	100.6 (109)	17.9 (3.8)	51.7 (11)	59	20	57 (138	–	–	–	113 (55)
SS (ppm)	89 (113)	58 (46)	153 (226)	100 (145)	25.8 (8.5)	49 (10.6)	–	–	45 (66)	380	162	141	113 (91)
TC (cfu/100 ml)	6,800 (9,740)	6,350 (9,710)	9,420 (10,100)	7,387 (9,759)	17,000 (11,000)	23,900 (20,000)	–	–	5,200,000 (3,600,000)	–	2,400,0000	3,600,000	–
E. coli (cfu/100 ml)	1,490 (4,940)	82.7 (120)	10 (8,750)	2,022 (5,956)	590 (1,630)	21,800 (22,100)	–	–	–	–	–	–	–
FS (cfu/100 ml)	2,050 (4,440)	40.1 (48.6)	1,710 (5,510)	1,740 (4,488)	31.5 (40.6)	10.2 (0.48)	–	–	479 (859)[a]	$>10^4$	1,400,000	880,000	–
TN (ppm)	8.7 (4.8)	6.6 (3.4)	10.4 (4.80	8.73 (4.73)	–	–	–	–	–	–	–	6.5	11.6 (10.2)
PO_4^- (ppm)	0.3 (0.1)	0.4 (0.4)	0.4 (0.3)	0.35 (0.23)	–	–	–	0.4[b]	2.4 (0.7)	<2	–	7.8	–
NH_3 (ppm)	–	–	–	–	–	–	10	1.1	0.8 (0.7)	0.05–1	–	–	–
NO_3 (ppm)	–	–	–	–	–	–	–	–	1.3 (0.7)	–	–	–	–
pH	7.52 (0.28)	7.57 (0.29)	7.32 (0.27)	7.47 (0.29)	7.74 (0.26)	7.74 (0.02)	7.6	–	7.7 (0.4)	–	6.8	–	7.3 (0.6)

compared to the other sources tested (Table 1). Operational sites generally contained much higher coliform concentrations with as high as 7 log being reported (Table 1). This has been shown to be a result of microbial growth in the collection and storage facilities within the sites (Dixon *et al*., 2002). Several attempts has been made to identify specific pathogenic micro organisms within grey water but no real trends have been observed. *Candida albicans, Pseudimonas aeruginosa* and *Straphylococcus aureus* have been identified but are commonly found in the mouth, nose and throat of humans (Eriksson *et al*., 2002). Attempts to find known pathogens such as *Campylobacter* spp, *Crytosporida*, *Salmonella* spp, *Shigella* and *Entamoeba* have all found non-detectable levels in all the samples tested.

Public perception

A recent survey in the UK explored some of the attitudinal determinants of public acceptance of urban water recycling in the UK (Jeffrey and Jefferson, 2002). The survey was set up to assess the nature and boundaries of individuals thinking about, and attitudes towards, water recycling. The survey restricted itself to members of the population who were (a) over 18 years old, (b) live in England or Wales, (c) have a water supply connected to a house and (d) have some responsibility for paying the water charges. Overall the survey contained over 300 respondents which were distributed sufficiently to ensure that the findings of the survey were representative of the population of England and Wales to within ±6% at a 95% confidence level. Overall, the survey revealed a broad willingness to accept urban recycling as long as public health is not compromised. The percentage of respondents willing to recycle decreased from 88% from within a person's own house down to 50% when conducted throughout a neighbourhood or within a hospital (Jeffrey and Jefferson, 2002).

Assessment of the acceptability of poor aesthetic quality water was also considered by showing the respondents containers of coloured (commercial blue dye), turbid (dispersed kaolin, ≈ 15 NTU) and suspended solid laden (flakes of croissant) waters. In each case the respondents were asked if they were willing to use the water for a series of different applications assuming the safety of the water had been guaranteed by an organisation they trusted. Overall, poor aesthetic water quality was seen to have only a minor detrimental effect on the frequency of acceptance. Turbid water was seen as the least acceptable ranging from *ca*. 70% for toilet flushing down to *ca*. 4% for drinking (Figure 3). This compares to acceptance levels of *ca*. 88 and *ca*. 84% for toilet flushing and *ca*. 12 and *ca*. 18% for drinking with the coloured and solid containing waters respectively. The most important parameters appear to be the potential for human contact and ingestion which significantly reduces the

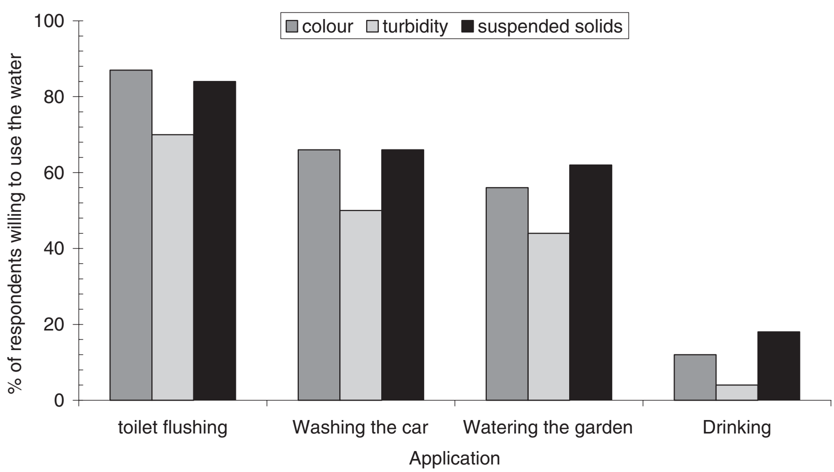

Figure 3 Willingness to use recycled water of poor aesthetic quality

willingness to recycle. Interestingly, no correlations as a function of age or gender where revealed which is perhaps somewhat surprising form a survey of this type.

Technology selection

Grey water is difficult to classify as a wastewater type due to its inherent variability. However in general grey water has a similar organic strength to a low to medium strength influent municipal sewage with a characteristic similar to tertiary sewage effluent in terms of the biodegradability and the physical pollution it contains. In terms of treatment the major issues are related to the organic strength of the water due to its relationship with the aesthetic and health characteristics of the product water and directly through legislative requirements. The impact on health concerns is a direct result of the chlorine demand that residual organics exert on the system which if not probably controlled can result in insufficient disinfection prior to reuse.

The nature of the wastewater and in particular its high organic strength direct the selection of appropriate processes towards biological systems. It is unlikely that physical processes or simple coarse filtration devices will remove sufficient pollution to be suitable as a main stream process except in situations where the organic strength is naturally low. Reported performance data suggest that biological systems can effectively produce treated grey waters with BOD_5 concentrations below 10 $mg.L^{-1}$ relatively straightforwardly. This has added value in that in enhances the natural aesthetic quality of the water and reduces, and more importantly, stabilises disinfectant demand. The solution to the selection question is however not straightforward as the highly variable load, high COD/BOD ratio coupled with a nutrient and micro metal imbalance suggest biological processes may encounter performance and operational difficulties. The problem centres around the ability of the selected technology to produce a robust effluent quality which is unaffected by the above issues and can be achieved at small scales and relatively low costs. Previous reported experiences (Laine, 2001) suggest that the main operational cause of performance deterioration is due to solids processing issues. Consequently more stable effluent quality is normally observed with biological systems that contain a robust barrier to solids such as a membrane (membrane bioreactor) or a depth filter (biologically aerated filter). Interesting this links well with the public perception survey which highlighted turbidity as the main acceptability concern.

Conclusions

The main characteristics of grey water can be described as:

1. highly variable organic concentration ranging from that equivalent to a medium strength influent municipal sewage to a tertiary effluent
2. an high COD/BOD ratio
3. a macro and micro nutrient imbalance equally split between nitrogen and phosphorus
4. Low suspended solids to turbidity ratio with the majority of particles falling in the 10–100 μm range
5. 3 log concentration of coliforms without the identification of known pathogenic organisms

The above characteristics suggest that advanced biological processes which combine bioreactor with efficient solid separation process are likely to be the most suitable technology for grey water recycling.

Acknowledgements

The authors thank the UK Engineering and Physical Sciences Research Council (EPSRC) who sponsored the research and Thames Water and Yorkshire Water for their financial and technical support during the research. The authors would also like to thank everybody that supplied samples for analysis with especial thanks to Gillian Bullock, Brenda Alvarez and Clare Diaper from the School of Water Sciences, Cranfield University.

References

Beardsley, M.L. and Coffey, J.M. (1985). Bioaugmentation: optimizing biological wastewater treatment. *Pollut. Eng.* December, 30–33.

Dixon, A., Butler, D., Feweks, A. and Robinson, M. (1999). Measurement and modelling of quality changes in stored untreated grey water. *Urban Water*, **1**, 293–306.

Eriksson, E., Auffarth, K., Henze, M. and Ledin, A. (2002). Characteristics of grey wastewater. *Urban Water*, **4**(1), 85–104.

Franta, J., Wilderer, P.A., Miksch, K. and Sykora, V. (1994). Effects of operation conditions on advanced COD removal in activated sludge systems. *Wat. Sci. Tech.*, **29**(7), 189–192.

Jeffrey, P. and Jefferson, B. (2003). Public receptivity regarding in-house water recycling: Results from a UK survey. Wat.Sci.Tech: Water Supply **3**(3) 109–116.

Karpiscak, M.M., Foster, K.E. and Schmidt, N. (1990). Residential water conservation. *Water Research*, **26**, 939–948.

Laine, A. (2001). Technologies for grey water recycling in buildings. Thesis (PhD) Cranfield University.

Metcalf and Eddy, Inc. (1991). *Wastewater Engineering – Treatment, Disposal and Reuse*. In: Tchobanoglous, G. and Burton, F.L. (eds). McGraw-Hill series in water resources and environmental engineering, 3rd edition. New York.

Okun, D.A. (1997). Distributing reclaimed water through dual systems. *American Water Works Association Journal*, **89**(11), 153–160.

Otterpohl, R., Albold, A. and Olgenburg, M. (1999). Sources control in urban sanitation and waste management: Ten systems with reuse of resources. *Wat. Sci. Tech.*, **39**(5), 153–160.

Santala, E., Uotila, J., Zaitsev, G., Alasiurua, R., Tikka, R. and Tnegvall, J. (1998). Microbiological greywater treatment and recycling in an apartment building. IN: *AWT98 – Advanced Wastewater Treatment, Recycling and Reuse*: Milan, 14–16 September 1998, 319–324.