ECONOMIC AND ENVIRONMENTAL ANALYSIS OF RESIDENTIAL GREYWATER SYSTEMS FOR TOILET USE

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ABSTRACT

The use of greywater for residential toilet flushing could decrease freshwater demand considerably if adopted nationally. Before this is done, a full understanding of the estimated environmental and economic impacts for greywater systems is needed. New and retrofit residential systems were studied using life-cycle assessment (LCA) and life-cycle cost (LCC). Health considerations were not evaluated as part of this study. The LCA results indicate that both systems have a net environmental benefit over their lifetimes. Based upon current potable water costs, the net present value of the LCC indicates that both systems have net costs. As water rates increase to reflect scarcity, these net costs should decrease or become net savings. Using grey water systems for toilet flushing is environmentally feasible for individual homes whether new or retrofitted. Implementing these systems on a larger scale would reduce the demands on potable water supplies and on sewage treatment facilities and may improve their economic feasibility.

INTRODUCTION

The availability and use of the world's freshwater resources are of increasing concern. On a global scale, estimates indicate that "the six billion inhabitants are already appropriating 54% of all accessible freshwater contained in rivers, lakes, and underground aquifers" (2003 International Year of Freshwater, nd). A shift from fossil fuels to biomass will add increasing pressure on freshwater supplies. In the United States (US), this increased water stress is already apparent with the growth of the ethanol industry (Institute for Agricultural and Trade Policy 2006; Renewable Fuels Association 2008). As the population grows and the demands on freshwater increase, the importance of conserving and finding new water sources will increase.

One of the ways to decrease freshwater demands in the built environment is through the use of greywater systems for toilet flushing and irrigation. Greywater is wastewater from processes such as bathing, dish washing, and clothes laundering. Notwithstanding water rights, health impacts, and public understanding issues; greywater systems can provide an important source of water conservation thereby reducing the demands on potable water supplies and on sewage treatment facilities. The residential built environment is a major untapped resource that could be exploited for water conservation. Residential water use accounts for approximately 8% of total potable water use in the US (Solley, Pierce, and Perlman 1995). Approximately 1/5 of residential water use is for toilet flushing and 1/3 is for landscape irrigation (Christova-Boal, Eden, and McFarlane 1996; Oasis Design 2008). Also, 50% - 80% of residential waste water is greywater (Oasis Design 2008).

In addition to conserving freshwater resources, greywater systems may also provide an environmental and economic benefit to property owners as well as water and sewer providers. A simulation of two greywater systems, one new and one retrofitted, in homes located in Fort Collins, Colorado analyzed these potential benefits using life cycle assessment (LCA) and life cycle cost (LCC) methodologies. LCA analyzes the total environmental impacts for a system over each phase of its existence: material mining, manufacturing, operation and maintenance, and end-of-life. LCC accounts for the total costs for a system over each phase of its existence. For the LCA portion of the study, process diagrams for greywater systems were developed for both a newly constructed residential housing unit and for the retrofitting of an existing residential structure. For the LCC portion of the study, the associated costs for the greywater system construction, use and maintenance as well as the water use and treatment costs were estimated using local prices. The results of the LCA and LCC studies of new and retrofitted systems are not meant to be compared. Instead, both systems were studied for the feasibility of greywater systems in both new and existing single-family residences. The issues of water rights, health implications, and public acceptance of greywater systems are beyond the scope of this work.

BACKGROUND

Potable water is used in domestic residential settings for drinking, food preparation, bathing, laundry, toilet flushing, and lawn and garden watering. The consumption of potable water in US residential applications for 1995 is estimated to be 98,800 Million L/d (Solley et al. 1995). Greywater is defined as all wastewater from non-toilet plumbing fixtures in a home. The breakdown for the “average” family water use by fixture type is approximately: bathroom, showers and hand basins 26%, laundry 15%, gardens 34%, kitchen 5%, and toilets 20% (Christova-Boal et al. 1996).

The two main concerns with greywater use are storage and distribution. Greywater contains several micro-organisms: fecal coliforms, total coliforms, lipids, tea, coffee, soluble starch, dairy products, and clay and glucose from kitchen sinks. In addition, water from bathrooms and laundry add several detergents, bleaches, soaps, sand, perfumes, and shampoos (Eriksson, Auffarth, Henze and Ledin 2002). Storage of greywater promotes generation of odors as the micro-organisms grow. For this reason, greywater poses environmental and health concerns. These concerns can be mitigated or eliminated with proper secondary treatment prior to reuse (Jeppesen 1996). Once properly treated, greywater use for toilet flushing and outside irrigation could substantially reduce the demands on potable water consumption. Frieder and Hadari estimate that these savings could reduce individual in-house use by 40-60 L/d per capita (2006). The UK's Millennium Dome reclaims greywater from hand wash-basins, rainwater from the dome's roof and groundwater; supplying up to 500 m^3 per day to flush toilets and urinals on the site (Smith, Khow, Hills and Donn 2000). The Solaire, a high rise residential building in New York City, treats its wastewater to produce 94,635 Liters (L) of treated water per day: 34,069 L for toilet flushing, 43,532 L for the building's cooling towers and 22,712 L for landscape irrigation (Wilson 2008). The average single household in Sydney (3 persons per household) uses 825 L of water each day (Sydney Water, 2005). By reusing greywater for irrigation, a household has the potential to save between 50,000 and 100,000 L of drinking water per year. Also, the estimated amount of greywater that can be used for toilet flushing is 924 L per week for a full flush (one button) or 302 L per week for dual flush (two buttons) fixture type (Department of Energy, Utilities and Sustainability 2007). No LCA and LCC studies were found for residential greywater systems.

METHODOLOGY

To get a true understanding of the total environmental and economic impacts of residential greywater systems, the impacts from all life cycle phases must be studied. The main life cycle phases for greywater systems are: raw materials mining and manufacturing, construction, use and maintenance, and end-of-life. LCA and LCC are ideal methods to obtain total life cycle impacts and will be applied to two different greywater systems: a system built as part of a newly constructed single family house and a retrofitted system for an existing single family house.

Life Cycle Assessment (LCA)

LCA estimates the environmental impacts from all life cycle phases of a product or process. The LCA process involves three main steps: (1) inventory analysis, (2) impact analysis, and (3) improvement analysis (Ciambrone 1997). As part of the inventory analysis, inputs of resources and energy as well as outputs of the product, waste, and emissions are identified and quantified for each product or process component. The resulting data are used in an impact analysis to determine the associated impacts to human health and the environment. Efforts in improvement analysis can then focus on determining what steps to take in order to improve the product or process to reduce the environmental impacts.

Traditional LCA involves the creation of process models to describe the system. The study boundary only includes those elements included in the model. An alternate method, Economic Input-Output LCA (EIO-LCA) is able to estimate direct emissions from manufacturing processes as well as indirect effects from supply chain emissions using data from the US Department of Commerce's commodity-by-commodity input-output matrix augmented by various resource use, waste, and emissions factors (Hendrickson, Horvath, Joshi and Lave 1998; Carnegie Mellon

University Green Design Institute (CMUGDI) 2008). This work will be a hybrid approach of both traditional process-based LCA and EIO-LCA. Process-based LCA is used for the construction, maintenance, and end-of-life phases; EIO-LCA is used for all other phases.

Environmental impacts associated with the material acquisition and transportation from the manufacturer to the job site in Fort Collins, Colorado were obtained using (CMUGDI 2008). The calculation of the transportation costs were obtained from several sources. The manufacturing plant locations were determined through contact with the manufacturers. The mileage and shipping rates were determined through a local freight broker. Weights for the systems also came from the manufacturers. For the use phase of the systems, emissions associated with electricity and water supply were calculated using (CMUGDI 2008). The energy costs used were calculated based on amp rating, pump motor voltage, and time of use. A fill time of 1 minute was used in both cases for the toilets to determine watt hours. Water costs were calculated using expected freshwater savings of 121 L/day (Heemer Engineering, 2006).

Life Cycle Costing (LCC)

LCC is an analysis method used to determine the total cost of ownership of a product or system over its useful life (ASTM 1999). It accounts for all relevant costs over all life cycle phases of a product or process, adjusting for differences in the timing of those costs (US Department of Commerce 1980). Cost data for materials, equipment and labor associated with all phases of each greywater system were obtained from manufacturers' web sites, local wholesale houses and freight brokers while the City of Fort Collins, Colorado provided electric and water rate schedules. These costs were used to determine the net present value (NPV) of the system. End of year discounting is used with a 5% nominal discount rate (not including inflation).

Simulation Study Selection

This simulation utilized a convenience sample to choose the residence. This method of selection was necessitated by the calculation requirements of the data used in both the LCA and LCC methodologies. The residence is in Fort Collins, Colorado and has three bedrooms and two baths. The expected occupancy of this residence is 4 people. Water usage estimates for toilet flushing are based on a6.06L toilet flushed 5 times per day for each occupant for an expected water use of 121 L/day (Heemer Engineering 2006). Specifying the location of the structure allows for the determination of transportation distances as well as water, electric, and shipping costs. This study estimates the environmental impacts and life cycle costs of each system independently.

NEW RESIDENTIAL GREYWATER SYSTEM

The BRAC RGW-250 greywater system was chosen for its quality, constructability, price, expandability, ease of maintenance, aesthetics and its 250 L capacity which allows for expansion for irrigation, if desired. This allows the home designer to determine if all greywater producing fixtures in the residence should be plumbed to the tank or only expected high-use fixtures. The upper portion of the tank houses the filter and pump systems. A bypass overflow diverts excess greywater from the storage tank into the sewer system. The lower part of the tank is storage. A greywater supply line is connected to each individual toilet. The system should last the duration of the residence (assumed to be 45 years) but the pump must be replaced every 15 years.

Process Diagram for the New System

A process diagram was created for the construction phase of the BRAC system to identify sources of pollution. Figure 1 includes the installation and testing requirements for the additional plumbing needed to isolate the bathroom sink and shower greywater from toilet wastewater (blackwater) in new residential construction.

***Figure* 1.** BRAC Greywater System in a New Residential Construction Application.

Data Values for the New System

The data values in Table 1 were determined using the hybrid method of LCA. Process-based LCA was used for the construction, maintenance, and end-of-life phases; EIO-LCA was used for all other phases. Global Warming Potential Metric Tons CO_2 Equivalent (GWP $MTCO_2E$) is the standard unit of measure for environmental impacts based on green house gasses and is the sum of the remaining columns. The estimated savings of environmental emissions from reduced water consumption (<WSave>) due to greywater use in toilet flushing is also shown.

The LCC used the following parameters for the 45 year system. A new pump will be required in years 15 and 30 at a cost of $334 each with a plumber in year 15 at $125, and year 30 at $150 to replace the pumps. The initial system costs were $2,190 for the BRAC and $1,360 for the plumber ($85/hour, two day duration). The annual electricity expense is $4.07 (50.86 KwH/yr at $0.08/KwH); annual chemical expenses are $14.80 and annual water savings are $23 (121 L/day at $1.97/3,785 L).

Table 1. Estimated Greenhouse Gas Impacts for Each Phase of the BRAC System

	GWP **$MTCO_2E$**	**CO_2** **$MTCO_2E$**	**CH_4** **$MTCO_2E$**	**N_2O** **$MTCO_2E$**	**CFCs** **$MTCO_2E$**
MFG	1.36	1.15	0.13	0.05	0.03
CONST	0.03	0.03			
USE	1.26	1.17	0.05	0.00	0.00
MAINT	0.68	0.56	0.06	0.00	0.00
<W Save>	(5.27)	(0.50)	(3.15)	(1.67)	0.00
Total	(1.94)	2.41	(2.91)	(1.62)	0.03

Data Analysis for the New System

Table 1 indicates that the BRAC system has net savings of 1.94 $MTCO_2E$ GWP over its lifetime. Although total system CO_2 increased, the overall GWP decreased due to the CH_4 and N_2O savings. Both CH_4 and N_2O are greenhouse gasses that persist longer in the atmosphere than CO_2. The NPV of this system is $4,520. This cost should be considered with the expected environmental impacts in the decision making process of installing a greywater system for toilet flushing. These costs are conservative because the analysis assumes that water prices remain low. Historically this has been the trend, but in the future it is conceivable that these prices will rise as water supplies diminish.

RETROFITTED RESIDENTIAL GREYWATER SYSTEM

The AQUS® system by WaterSaver Technologies was chosen for several reasons. The system is non-invasive in installation. It is a small self-contained under-sink unit with a 3/8" hose and a two-pair wire running through the side wall of the vanity base to the toilet. An 18.9 L greywater tank is stored under the sink for on-demand use. There is a control switch inside the toilet that operates the greywater flow and switches on the potable water supply fill feature if the greywater supply runs low. The unit and the filter are made of high impact plastic which reduces maintenance costs. The system installs in about three hours and connects into the existing sink tailpipe assembly which provides an automatic overflow into the sewer system once the storage tank fills to capacity. This system is designed for a single toilet application and has a life expectancy of 15 years.

Process Diagram for the Retrofitted System

A process diagram was created for the construction phase to identify expected pollution sources. Figure 2 shows the diagram for the AQUS® system and includes activities both on- and off-site.

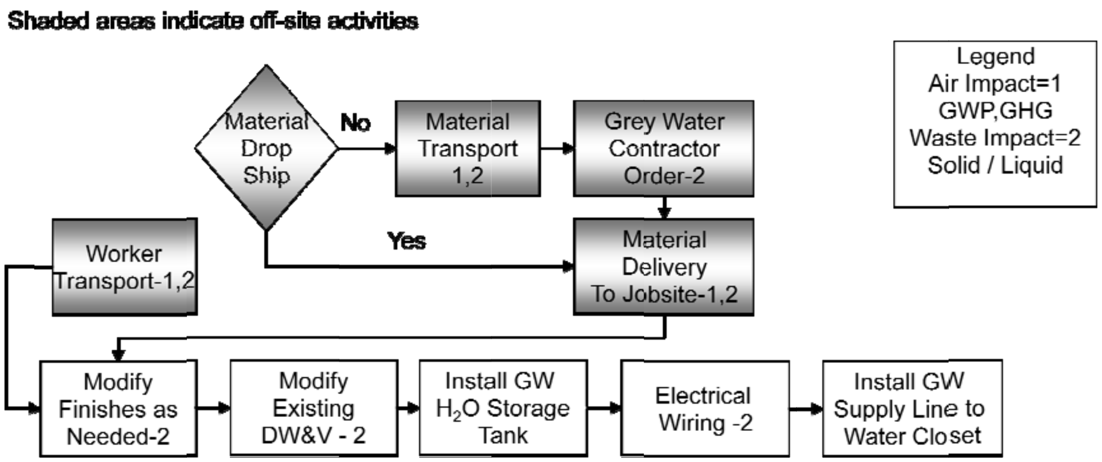

***Figure* 2.** AQUS® Greywater System in a Residential Retrofit Application.

Data Values for the Retrofitted System

The data values in Table 2 were determined using the hybrid method of LCA. Process-based LCA was used for the construction, maintenance, and end-of-life phases; EIO-LCA was used for all other phases.

Table 2. Estimated Greenhouse Gas Impacts for Each Phase of the AQUS® System in a Retrofit Application

	GWP $MTCO_2E$	CO_2 $MTCO_2E$	CH_4 $MTCO_2E$	N_2O $MTCO_2E$	CFCs $MTCO_2E$
MFG	0.25	0.21	0.03	0.01	0.01
CONST	0.02	0.02			
USE	0.05	0.05	0.00	0.00	0.00
MAINT	0.09	0.08	0.00	0.00	0.00
End-of-life	0.02	0.02			
<W Save>	(1.76)	(0.17)	(1.05)	(0.56)	0.00
Total	(1.34)	0.20	(1.03)	(0.55)	0.01

The LCC used the following parameters for the 15 year system: AQUS cost $295, installation $225 (3 hours at $85/hr), annual electricity expense $0.23 (2.92 KwH/yr at $0.08/KwH), annual chemical expenses of $5, and annual water savings of $23 (121 L/day at $1.97/3,785 L). These numbers are for each system (one for each of the two toilets) except for annual water savings which are per household.

Data Analysis for the Retrofitted System

Table 2 indicates that the AQUS system has net savings of 1.34 $MTCO_2E$ GWP over its lifetime. As with the new system, the net increase in CO_2 is outweighed by the net decrease in CH_4 and N_2O emissions. The NPV of this system is $1090 for the two AQUS units. This net cost should be considered with the expected environmental impacts in the decision making process of installing a greywater system for toilet flushing.

VALIDATION OF RESULTS

Validity and reliability are important in all research. This simulation used the accepted methodologies of the traditional LCA and EIO-LCA in a hybrid model and LCC to estimate the NPV of each investment including use, maintenance, and end-of-life. The ability to repeat and verify the results of a study are important to validity. This study used a free analysis tool found online (CMUGDI, 2008). The main concern in using databases is the disclosure of the assumptions, logic, data sources, and values used in the program. (CMUGDI, 2008) does this online. The use of databases should make the results of a LCA repeatable and verifiable (Norris & Yost, 2002). The parameters for the LCC are stated.

LCA is still in its infancy and the use of multiple tools to run the analysis may produce different results that are correct in regards to program internal logic but different in outcomes. Despite this concern, using multiple tools may be a useful process for comparative purposes given the high level of uncertainty in LCA as data capacity is built. A high level of uncertainty in the model is estimated to be between 10-20% (Hendrickson, Lave and Matthews, 2006). In both LCA and LCC, the further into the future the projected estimates are, the greater the uncertainty of the results. In this case, the new system has an expected life of 45 years and the remodel system is 15 years. In either case, the use of tools for replication is the preferred method as long the weaknesses of the methodologies are disclosed.

CONCLUSION

There are two areas in which additional research is needed. One is to validate the predicted outcomes with long term studies of installed systems to determine if the actual and predicted results are similar. This will provide important information in the capacity building of databases and possible codification of system use for water conservation. It is important to note that the location of the installation, water and electric rates, and system type are important variables in estimating both LCA and LCC results. There is a need for further system evaluation and testing in specific applications before any inferences can be made.

The second is the addition of greywater landscape irrigation supply to see if the life cycle costs are reduced significantly making a greywater system more economically feasible. The results of the life-cycle analysis can be used in conjunction with the results of ongoing studies on greywater health issues to better understand the proper level of use of this alternative water resource. Health impacts and remediation of these impacts needs to be studied to ensure that greywater use for landscape watering is safe. Research also needs to be performed on the treatment systems inside greywater storage tanks to ensure that bacteria do not flourish in this environment. Education on the benefits and special needs of greywater system owners also needs more work. To truly be sustainable, greywater systems must minimize environmental, economic, and social impacts.

Future research will not only increase our knowledge of the economic costs of installing a greywater system but it will start the dialogue of the environmental impacts associated with the widespread adoption of greywater systems in the residential housing sector. If all existing houses in the US (127,958,000) were retrofitted with the AQUS system, household water consumption for toilet flushing would be reduced by 15,500 million L/day (calculated from Heemer 2006, US Census Bureau 2008). This would result in a savings of 171 million $MTCO_2E$ over the next 15 years which is the equivalent of removing 31 million typical passenger vehicles emitting 5.5 million $MTCO_2E$ yearly off of US roads (calculated from US Census Bureau 2008; US EPA 2005).

The full impact of the potential residential water savings attributed to greywater use both economically and environmentally is still in its infancy. As the US population increases and manufacturing is off-shored, the residential share of water consumption may increase. The potential rewards for adopting greywater use appear to be positive once the economies of scale are determined for a project.

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