Environmental and economic assessment of rainwater use in a university dormitory

Hannah Elizabeth Schlachter

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entitled

Environmental and Economic Assessment of Rainwater use in a University Dormitory

by

Hannah Elizabeth Schlachter

Submitted to the Graduate Faculty as partial fulfillment of the requirements for

the Master of Science Degree in Civil Engineering

Dr. Defne Apul, Committee Chair

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Dr. Youngwoo Seo, Committee Member

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College of Graduate Studies

The University of Toledo

August 2011
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The University of Toledo
August 2011

With higher water demand and decreasing supply, harvested rainwater is becoming a popular alternative to using potable water throughout a building. However, the economic and environmental impacts of these systems, and the feasibility of applying these systems in both existing and new non-residential buildings still remains to be explored. This thesis analyses a typical dormitory at the University of Toledo in Toledo, Ohio. Five scenarios were developed which allowed the comparison of using rainwater for flushing toilets and irrigating in an existing dormitory, a new dormitory and a dormitory with fewer occupants. The effects of the sewer system on payback was also researched. The scenarios were compared using life cycle assessment and discounted payback period methods and with respect to their return on investment, their energy consumption and the global warming potential due to carbon emissions. It was determined that cost requires the longest payback followed by energy and then CO₂ emissions. If rainwater is to be utilized for toilet flushing it is both economically and environmentally advantageous to install the system when the building is initially constructed to avoid construction associated with retrofitting the existing structure. The optimum end use at Crossings
based on cost, energy and CO₂ payback is irrigation. It was observed that an increase in roof area per occupant will result in shorter energy and CO₂ paybacks when analyzing a building. When considering emissions per person an increased roof area will however result in longer paybacks. It was also observed that sites with combined sewer systems correlate to shorter environmental paybacks of rainwater harvesting systems due to the elimination of treatment of the rainwater at the wastewater treatment facility. No two sites are the same. There are many unique characteristics that will affect tradeoff times of rainwater harvesting systems. A model was developed in order to provide results unique to specific sites and buildings.

Environmental and Economic Analysis of Sanitation Technologies (EEAST) is an excel based strategic planning model developed by the water sustainability group at the University of Toledo. The purpose of this software is to allow users to compare sanitation technologies within buildings with respect to cost, energy consumption and environmental footprint. The model is aimed at a broad audience which includes contractors, building owners, homeowners and researchers that seek a model that is capable of assessing long term economic and environmental impacts relating to sanitation technologies including; standard toilets, low flush toilets, composting toilets, and toilets and flushed with harvested rainwater. In addition to sanitation technologies, EEAST also models use of rainwater to irrigate. EEAST provides information needed to support budget and planning decisions, identify environmental and economic tradeoffs for each technology and determine the optimum choice for specific projects.
Acknowledgments

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Preface

This thesis presents a complete case study that includes the environmental and economic implications of a commercial rainwater harvesting system utilized at a dormitory. Two end uses were compared and include irrigation and toilet flushing. Building stage was also compared by considering implementing the rainwater harvesting system when the building was originally constructed and comparing the results to the results associated with retrofitting the existing building. All aspects related to construction of the system were included and the cost as well as energy and CO$_2$ emissions related to production of the materials were determined.

This thesis is a result of two years of analyzing the impacts of rainwater harvesting at several buildings at The University of Toledo. It was observed that each building and site has unique characteristics which affect the tradeoff periods of cost, energy and CO$_2$ emissions. Environmental and Economic Assessment of Sanitation Technologies (EEAST) was created to allow site specific tradeoff times to be generated. EEAST is useful to a broad audience which includes contractors, building owners, homeowners and researchers that seek a model that is capable of assessing long term economic and environmental impacts relating to sanitation technologies. EEAST provides the necessary information to support budget and planning decisions, identify environmental
and economic tradeoffs for each technology and determine the optimum choice for a specific building and site.
Chapter 1

Cost, Energy and Greenhouse Gas Emission Implications of Using Harvested Rainwater in a University Dormitory

1.1 Introduction
Municipalities supply cities with a single quality of water for potable as well as non-potable purposes. Harvested rainwater is an alternative water source for buildings especially for non-potable uses such as irrigation and toilet flushing. Rainwater harvesting is perceived as a sustainable design approach because it is expected to improve the resilience and the efficiency of the infrastructure by decentralizing the water source, by matching water quality to its intended use (and thereby not over-treating the water), and by reducing the volumes of water pumped large distances\(^1\). In the United States, indoor and outdoor residential water use averages 382 L per day per person and of this amount 19 % and 25 % are used for toilet flushing and lawn irrigation, respectively\(^2\). Therefore, major reductions in municipal potable water demand are possible by using harvested rainwater as the water source for irrigation and toilet flushing.
Harvested rainwater also offers benefits from a surface runoff perspective. Typically, engineers consider rainwater as a nuisance for urban areas. Approximately 800 cities in the U.S have combined sewer systems in which both the sewage from buildings and rainwater runoff from impervious areas are directed towards the wastewater treatment systems\(^3\). The city of Toledo, Ohio has experienced several issues with its sewer systems. Even with the EPA’s clean water act which required the city to more than double their sewage treatment capacity, over 4 billion liters of raw sewage are discharged into area waterways each year due to the combined sewer system throughout the city\(^4,5\). Nationwide, combined sewer annual overflows are estimated to reach 3.2 billion cubic meters\(^3\). Rainwater is one of the most easily and freely available sources of water that can be used for non-potable purposes. Use of rainwater for non-potable purposes not only reduces the demand for potable water but it also reduces the influent flows to the wastewater treatment plants, which helps mitigate sewer overflows and therefore reduces the stress over the water and wastewater infrastructure.

Rainwater harvesting is not a new technology but it has been receiving much attention recently due to rising interest in sustainable urban design. There is a rapidly growing body of literature on how rainwater harvesting can improve water resource management at building, community or city scales\(^6,7,8,9,10\). The cost of implementing rainwater harvesting systems has also been studied by several authors\(^9,11,12,13,14\). Yet, research on energy and greenhouse gas emission implications of rainwater harvesting systems is in its incipient phase and has been reported in only a few studies\(^13,15,16\). Much remains to be studied on environmental and economic viability and optimization of rainwater harvesting systems. Previous studies have either been ambiguous or lacked information
on the comparative benefits of using harvested rainwater; i) for lawn irrigation versus for flushing toilets, ii) in new construction versus renovation projects, and iii) in combined versus separate sewer settings. In addition, most of the previous studies focused on residential buildings and none modeled a dormitory building using a life cycle perspective. Finally, previous studies presented results from the perspective of the building. However, with the onset of growing population and growing interest to understand an individuals’ impact on the environment, it can be argued that effects should also be measured on a per person basis to inform society and engineering design. The goal of this study was to address these knowledge gaps by analyzing the economic and environmental implications of five different design scenarios in an existing University of Toledo dormitory.

1.2. Methods

1.2.1 Building Description

University of Toledo’s Crossings building was analyzed in this study. In North America, it has become imperative for most universities to make progress towards sustainability due to the push of campus climate action plans organized by the Association for Advancement of Sustainability in Higher Education (AASHE)\textsuperscript{17}. On this path, it is common to direct sustainability efforts to residence halls with a goal of exemplifying sustainable living for students. Crossings was selected in this study because it is representative of other higher education dormitories. It is a 5 story building with a total living area of 20,465 m\textsuperscript{2}, roof area of 4,093 m\textsuperscript{2}, and lawn area of 11,660 m\textsuperscript{2}. Crossings has 24 suites on each floor. Each suite includes a furnished living room and a private
bathroom. The structure houses in-hall dining, laundry and a recreation room for the students. Crossings houses 626 students in 6-person suites with three double bedrooms in each suite. There are also 3 apartments for staff and 20 single residence assistants’ rooms.

1.2.2 Scenarios

Five scenarios were developed to investigate the best way to utilize rainwater harvesting at the Crossings building (Figure 1-1). Currently, the potable municipal water is the only source of water used in Crossings. Potable water use in sinks, showers, and laundering were assumed to be the same among scenarios. Effects of using rainwater for toilet flushing and irrigation were modeled. The scenarios varied with respect to source water, end use, building type and occupancy load.

![Diagram showing five design scenarios for Crossings]

Figure 1-1 Five design scenarios modeled for Crossings. Scenario 2 uses potable water for toilet flushing. Scenarios 3, 4 and 5 use potable water for irrigating.
• **Scenario 1 (Baseline scenario)** – Current, existing system in Crossings building. City supplied potable water is used for both flushing toilets and irrigation.

• **Scenario 2** – Crossings was modeled as being *renovated* to collect roof runoff for its use in *irrigation*. In this scenario, since the volume of water required to irrigate at the site was larger than the volume available from rainwater collection, both rainwater and potable water were required to irrigate.

• **Scenario 3** – Crossings was modeled as being *renovated* to collect roof runoff for its use in *toilet flushing*. In this scenario, rainwater was supplemented with potable water in flushing toilets because collected rainwater was not sufficient to meet the flushing demand in the building.

• **Scenario 4** – Crossings was modeled as a *new construction*. Rainwater harvesting system was assumed to be implemented at the time of constructing the building. In this scenario, collected roof runoff was used for *flushing toilets*.

• **Scenario 5** – Crossings was modeled as a *new construction*. However, its occupancy was assumed to be lower (248 instead of 649) so as to be able to supply all toilet water demand from rainwater harvesting. In this scenario, roof runoff was used for *flushing toilets*.

Using rainwater for both toilets flushing and irrigating was not considered in a single scenario because the volume of rainwater available at Crossings is too small to supply both end uses. The demand for flushing toilets was nearly four times greater than the volume of rainwater available for collection at the site and the harvested rainwater could only supply 12% of the irrigating demand.

### 1.2.3 Life cycle assessment

The life cycle assessment (LCA) method was used to compare each scenario with respect to energy and global warming implications. LCA is a technique that assesses the environmental impacts associated with a product, process or service\(^{18,19}\). The Economic Input-Output Life Cycle Assessment (EIO-LCA) method, developed at Carnegie Mellon University\(^{20}\), was used to estimate the energy and global warming potential (GWP) from manufacturing as well as operational phases associated with each scenario.
Functional units previously used for LCA of buildings and water infrastructures include environmental impacts from the whole building or from per square meter of building, impacts from a unit volume of water or impacts from flushing per person per day. In this study, the functional unit for the life cycle assessment was environmental impact per occupant where scenarios 1-4 considered 649 occupants and scenario 5 considered 248 occupants. This functional unit was selected over other options to be able to more directly evaluate impacts from an individual’s perspective. From a sustainability perspective, it is relevant to evaluate impacts of not only the buildings themselves but the impacts from the building for each person they serve.

1.2.4 Rainwater harvesting

The volume of rainwater available for collection was estimated using the average monthly precipitation for Toledo (7.6 cm per month) and the building’s roof area (4,093 m²) (Figure A-1). It was assumed that roof runoff would not be collected during winter months (November through February) since the rainwater tank is placed above grade and collected water may freeze. For each centimeter of rainfall, each square meter of roof collects 10 liters of rain. Of that, 25%-30% can be lost before entering the cistern. Using these parameters, the volume of roof runoff available for capture was determined at approximately 233,693 liters per month. Combined sewers are common in the Midwest of the U.S. and in Toledo. Rainwater collected from the roof was assumed to be conveyed out of the site via combined sewers and treated at the local wastewater treatment plant.
The water demand for flushing toilets was estimated assuming 5.1 flushes per occupant per day at 6.05 liters per flush\(^2\). Using these assumptions, the calculated water demand for flushing toilets for the 649 people that reside at Crossings is approximately 611,432 liters per month, which is nearly three times the total amount of roof runoff that can be captured. Due to the high occupancy of the crossings building, the implementation of a rainwater harvesting system to be used for flushing toilets was also analyzed for an occupancy (248 occupants) in which the supplied rainwater met the demand for toilet flushing (Scenario 5).

In Ohio, the irrigation recommendation for lawns is 2.5-5 cm once a week\(^24\). Based on the lower range of this recommendation, approximately 1,407 m\(^2\) of lawn area can be irrigated using the harvested rainwater. It was assumed that irrigation would not occur during winter months. The actual irrigation area at Crossings is 11,660 m\(^2\) (Figure A-2). The harvested rainwater could supply approximately 12% of the irrigation demand.

The cistern was sized based on the volume of rainwater collected per day and the average number of days without rain in Toledo, Ohio\(^25\). A steel cistern capacity of 153,293 liters was selected based on available commercial cisterns\(^26\). Since the harvested rainwater was used completely for each scenario, the cistern size did not differ with each case. The dimensions for diameter, height and weight of the cistern were 7.52 m, 3.43 m and 3,178 kg respectively.

**1.2.5 Life Cycle Inventory**

EIO-LCA was used to evaluate the energy and CO\(_2\) equivalence emissions associated with the materials and labor that are required to implement each scenario. Materials
required for the manufacturing phase of the scenarios and the associated EIO-LCA sector and cost can be found in table 1.1. Costs for the cistern ($1.04/L), piping ($1.59/m) and pumps were obtained from respective vendors\textsuperscript{26}. It was assumed that additional piping was only needed for scenarios 3, 4 and 5 which use rainwater for flushing toilets. Piping was not considered for irrigation purposes as it was assumed that standard sprinkler systems would be installed in all cases. The cost of the concrete pad required for stabilization of the cistern and the construction cost associated with running the new piping to use rainwater for flushing toilets were estimated using Win Estimating software\textsuperscript{®} (Table A.1). Estimation of a sprinkler system is not included for this study because it is not an additional expense that is related to using harvested rainwater and would be required even if potable water were used to irrigate.
Table 1.1 Life cycle inventory. Operational data is on per month basis.

<table>
<thead>
<tr>
<th>System</th>
<th>Phase</th>
<th>Sector #</th>
<th>Sector Name</th>
<th>Materials required</th>
<th>No of Units</th>
<th>Total cost $</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1 - Baseline</td>
<td>Manufacturing</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Operational</td>
<td>Sahely, H.R. and Kennedy, C.A (2007)</td>
<td>Potable Water</td>
<td>2547.1 m³</td>
<td>$2824.73</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sahely, H.R. and Kennedy, C.A (2007)</td>
<td>Waste water</td>
<td>2547.1 m³</td>
<td>$2824.73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 2 - Rainwater for Irrigating</td>
<td>Manufacturing</td>
<td>230103</td>
<td>Other non-residential structures</td>
<td>Concrete Pad</td>
<td>9.5 m³</td>
<td>$3,490.43</td>
</tr>
<tr>
<td></td>
<td>Sahely, H.R. and Kennedy, C.A (2007)</td>
<td>Potable Water</td>
<td>2313.4 m³</td>
<td>$2565.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sahely, H.R. and Kennedy, C.A (2007)</td>
<td>Wastewater</td>
<td>611.4 m³</td>
<td>$678.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Operational</td>
<td>Sahely, H.R. and Kennedy, C.A (2007)</td>
<td>Potable Water</td>
<td>2313.4 m³</td>
<td>$2565.56</td>
<td></td>
</tr>
<tr>
<td>Scenario 3 - Rainwater for toilet flushing (existing structure)</td>
<td>Manufacturing</td>
<td>230103</td>
<td>Other non-residential structures</td>
<td>Concrete Pad</td>
<td>9.5 m³</td>
<td>$3,490.43</td>
</tr>
<tr>
<td></td>
<td>Sahely, H.R. and Kennedy, C.A (2007)</td>
<td>Potable Water</td>
<td>2313.4 m³</td>
<td>$2565.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sahely, H.R. and Kennedy, C.A (2007)</td>
<td>Wastewater</td>
<td>611.4 m³</td>
<td>$678.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sahely, H.R. and Kennedy, C.A (2007)</td>
<td>Energy use by pumps</td>
<td>63.6 kWh</td>
<td>$4.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 4 - Rainwater for toilet flushing (new construction)</td>
<td>Manufacturing</td>
<td>230103</td>
<td>Other non-residential structures</td>
<td>Concrete Pad</td>
<td>9.5 m³</td>
<td>$3,490.43</td>
</tr>
<tr>
<td></td>
<td>Sahely, H.R. and Kennedy, C.A (2007)</td>
<td>Potable Water</td>
<td>2313.4 m³</td>
<td>$2565.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sahely, H.R. and Kennedy, C.A (2007)</td>
<td>Wastewater</td>
<td>611.4 m³</td>
<td>$678.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sahely, H.R. and Kennedy, C.A (2007)</td>
<td>Energy use by pump</td>
<td>34.6 kWh</td>
<td>$2.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 5 - Rainwater for toilet flushing with fewer occupants (new construction)</td>
<td>Manufacturing</td>
<td>230103</td>
<td>Other non-residential structures</td>
<td>Concrete Pad</td>
<td>9.5 m³</td>
<td>$3,490.43</td>
</tr>
<tr>
<td></td>
<td>Sahely, H.R. and Kennedy, C.A (2007)</td>
<td>Potable Water</td>
<td>467.4 m³</td>
<td>$518.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sahely, H.R. and Kennedy, C.A (2007)</td>
<td>Wastewater</td>
<td>233.6 m³</td>
<td>$259.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sahely, H.R. and Kennedy, C.A (2007)</td>
<td>Energy use by pump</td>
<td>63.6 kWh</td>
<td>$4.42</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1.2.5.1 Operational phase
Operational phase components are shown on a monthly basis in table 1.1. Inventory in the operational phase for each scenario includes potable and wastewater treatment and distribution and energy use by the pump. The costs used for potable and wastewater utilities were $0.38 and $1.11 for every 1,000 L of water treated based on Toledo’s water and wastewater utility rates. The cost of sending roof water to combined sewers was estimated at the same rate as the wastewater utility rate ($1.11 for every 1,000 L of storm water removed from site). The costs for the additional inventory items were obtained from suppliers. The sectors listed in Table 1.1 represent the source for the energy and carbon data for each of the inventory items. Pumps and filters were assumed to be replaced every 5 and 20 years, respectively.

EIO-LCA models both the water and wastewater treatment sectors into one, which is not entirely accurate. Wastewater treatment has shown to result in higher energy and CO$_2$ equivalence emissions than water treatment. After evaluating each reference, detailed values from Sahely and Kennedy 2007 were chosen for this study. The Sahely study provides detailed values for the energy usage in kWh per gallon of treated water and wastewater. CO$_2$ emissions per gallon of treated water and wastewater were also provided from this study.

Booster pumps would be required to transport the rainwater for flushing toilets. The sizing of the pumps and their annual energy requirements were estimated using the standard pump power equation and assumed pumps would be running nonstop throughout the year.
Equation 1. Pump Power

\[ P = \left( Q \cdot \gamma \cdot (h_e + h_p) (1+\alpha) \right) / \eta \]

Where,

\[ P = \text{power input to pump [W]}, \]
\[ \eta = \text{combined mechanical and hydraulic efficiency of the pump [-]}, \]
\[ Q = \text{flow rate [m}^3/\text{s}], \]
\[ \gamma = \text{specific weight of water [N/m}^3], \]
\[ \alpha = \text{percentage of energy lost to friction [-]}, \]
\[ h_e = \text{elevation head provided by pump [m]}, \]
\[ h_p = \text{pressure head provided by pump [m]}. \]

The annual water demand from the first and second floor restrooms was used as the flow rate \((Q)\). Since the harvested rainwater could only supply up to 45 toilets, only the first and second floor restrooms were analyzed for scenarios 3 and 4. For scenario 5, which considered fewer occupants, restrooms on all 5 floors were analyzed. The height of the second and fifth floor, \((5 \text{ and } 14 \text{ meters})\) was used as \(h_e\) and \(207 \text{ kPa (30 psi)}\), which is the minimum pressure required by flush valves, was used for \(h_p\). Head loss due to friction was assumed as \(30\%^{34}\). A pump mechanical and hydraulic efficiency of \(65\%\) was assumed\(^{35}\).

1.2.6 Economic Analysis

Economic analysis was performed in order to evaluate the payback period for utilizing rainwater for either flushing toilets or irrigating at Crossings. The criteria used in assessing the economic viability of the scenarios in which rainwater is utilized were net present value and discounted payback cash flow analysis. The length of time required to recover the initial cash outflow from the discounted future cash inflows was determined.
using the cash flow analysis method for scenarios 2 through 5 which utilize the harvested rainwater. This approach considers present values of cash inflows which cumulate until they equal the initial investment. For purposes of this study, a lifetime of 75 years and discount rate of 2.7% was assumed\(^\text{36}\). Filters and pumps were assumed to be replaced every 5 and 20 years respectively. Net present value was calculated using the following equation:

Equation 2. Net Present Value

\[
NPV = \sum_{t=0}^{75} \frac{C_t (1+i)^t}{(1+r)^t}
\]

Where,

- \(NPV\) = net present value ($),
- \(t\) = cash flow period (75 years),
- \(i\) = interest rate assumed (0%)
- \(r\) = discount rate assumed (2.7%)
- \(C_t\) = difference in cash flows between alternative scenarios and scenario 1
1.3. Results

1.3.1 Construction and Operation Costs

The cost of implementation associated with each scenario is shown in Figure 1-2. The cistern is the most expensive item for rainwater systems used in new construction buildings (Scenarios 2, 4, and 5). One reason for designers and practitioners to shy away from rainwater use in toilets is due to perceived extensive costs incurred by dual piping. However, the costs of dual piping and the pump were found to be considerably smaller than the costs of the cistern and the material and installment costs of the concrete pad. In Crossings, tearing out the walls to be able to install the dual piping almost doubled the implementation cost of the rainwater system. If the dual piping was installed when...
Crossings was originally constructed (Scenarios 4 and 5) $32,000 could be saved with respect to construction costs.

The monthly operational costs for all alternative scenarios were lower than those of the manufacturing costs (Table 1.1). Since the baseline scenario (Scenario 1) considered an existing building, there were no construction costs. However, this scenario had the highest operational cost from use of potable water for both toilet flushing and irrigation.

### 1.3.2 Cash Flow Analysis

As expected, if harvested rainwater is to be used to flush toilets in a building, it would be most advantageous to implement it in new construction (Scenario 4) instead of an existing building (Scenario 3). It was observed that utilizing rainwater for flushing toilets in new construction (Scenario 4) would require 61 years to payback (Table 1.2).

<table>
<thead>
<tr>
<th>Item</th>
<th>Scenario</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Initial cost per person</td>
<td>($51.0)</td>
<td>($102.4)</td>
<td>($53.6)</td>
<td>($146.1)</td>
</tr>
<tr>
<td>NPV at year 75 per person</td>
<td>5.2</td>
<td>($48.5)</td>
<td>0.4</td>
<td>($8.0)</td>
</tr>
<tr>
<td>NPV at year 75</td>
<td>$3410</td>
<td>($31,000)</td>
<td>250</td>
<td>($1982)</td>
</tr>
<tr>
<td>Payback year</td>
<td>46</td>
<td>N/A</td>
<td>61</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Applying the rainwater toward irrigating (Scenario 2) would require 46 years to pay back. Using the rainwater for irrigation (Scenario 2) required lower construction costs as compared to the scenarios which utilize the harvested rainwater for toilet flushing. The cost to set piping that would be needed to transport the rainwater to the second floor resulted in a higher initial investment for scenario 4. Since each scenario utilized the
maximum amount of water available for capture, the water savings per month are equal for each case. The only operational expense that differed was the small cost associated with pump energy. When potable water savings are equal for each scenario, a higher initial investment will result in a longer payback period.

When analyzing the cash flow at the end of the assumed building life (75 years), using the rainwater to irrigate proved to be the most economical choice and resulted in $3,410 in savings as compared to the baseline scenario. The factors contributing to savings were the elimination of piping cost as well as pumps and pump energy. Scenario 4 which utilizes rainwater for toilet flushing with a newly constructed building also resulted in positive net present value at the 75 year mark. If the building housed 248 residents (Scenario 5), the payoff period would require more than 75 years. The net present value at year 75 for this alternate scenario is negative due to the additional cost in piping needed to transport rainwater to the fifth floor rather than just the second as scenario four requires.

The factors that affect return on investment vary depending on the location. Ghisi et.al (2007) analyzed the potable water savings at two existing residential buildings and reported payback periods of 21 and 64 years\(^8\). The latter case reported high payback even though it had a larger roof area. In addition, the water demand was comparatively lower due to the minimum tariff of water per month. Rahman et al (2010) reported a payback period of 60 years for a multi-story residential building\(^12\). Discount rate is also one of the factors that impacts the payback period. For this study, a 2.7% discount rate was assumed. Reduction in payback time with an increase in the discount rate has been previously reported for rainwater harvesting\(^13\).
The financial viability of rainwater harvesting was tested by Rahman et al. (2010) in multistory residential buildings using life cycle costing, under various scenarios to determine a financially sustainable scenario for rainwater harvesting. The assessments suggest that large roof areas are preferred to make rainwater scenarios economically and environmentally sustainable. The studies also suggest that rainwater harvesting is not beneficial when rainwater is less utilized. Therefore its application in areas where the demand is high is comparatively beneficial. The study finally suggests that at current water prices rainwater harvesting is not a viable option. However, future increase in water prices combined with a low interest rate will make rainwater harvesting financially sustainable.

Studies have compared use of high efficiency systems with use of rainwater harvesting systems. The results show that the high efficiency systems outperformed the rainwater harvesting system when compared based on environmental factors. It has been observed that large roof areas are not the optimum solutions to environmental sustainability of rainwater harvesting systems. As the roof area is increased; the water savings also increase, however, the savings in energy and greenhouse gas emissions decrease due to the use of larger tanks.

Crettaz et al. (1999), conducted an economic and environmental assessment of rainwater harvesting systems for domestic use. The study was restricted to rainwater use for toilet flushing. The study suggests that high efficiency scenarios are better than rainwater scenarios unless the energy requirements for potable water supply are higher than 0.8 kWh/m³. This study also reports that use of high efficiency toilets is preferred compared to the use of rainwater harvesting systems.
1.3.3 Energy Implications

Figure 1-3 Energy consumption on per person basis. Initial and lifetime energy are to be read off of primary axis while payback year is read off of secondary axis.

Figure 1-3 shows the energy from implementation, the lifetime energy usage and the payback period for each scenario on a per person basis. Initial and lifetime energy per person shows similar trends with each scenario. When considering energy consumption on a per person basis, fewer occupants result in higher energy per person (scenario 5). This is because the total energy from implementation is similar to scenario 4 but the occupancy is 248 people rather than 649. When actual occupancy is considered (649 people), energy per person is highest with scenario 3 which utilizes rainwater for toilet flushing in the existing Crossings building. This is due to the construction required to set the dual piping in the existing walls. When comparing scenarios 2-5 which utilize rainwater to scenario 1 (baseline scenario), and considering the tradeoff year, utilizing the rainwater for irrigating proves to be the optimum choice. Scenario 5 is the only scenario
which does not payback in terms of energy consumption within the buildings estimated 75 year lifetime because the emissions per person are highest in this case.

### 1.3.4 Carbon Implications

![Graph showing CO2 emissions and payback period for different scenarios.](image)

Figure 1-4 Carbon emissions on per person basis. Initial and lifetime CO\(_2\)e are to be read off of primary axis while payback year is read off of secondary axis.

Similar to the energy usage, the CO\(_2\) equivalence emissions due to implementation were highest when rainwater is used for flushing toilets with fewer occupants (figure 1-4). This resulted in the highest payback period of 56 years. When analyzing CO\(_2\) emissions on a per person basis, utilizing the harvested rainwater for irrigation is the most suitable choice because the payback period and CO\(_2\) emissions per person are lowest for this scenario. Scenario 4, which utilizes rainwater for toilet flushing but considers Crossings as new construction provides the second best overall result. With 248 occupants at Crossings rather than the 649 actual occupants, the potable water savings per person would increase, but the initial and lifetime CO\(_2\) per person would increase drastically. This is due to the construction and materials required to implement the rainwater...
harvesting system. Piping would be needed up to the fifth floor rather than only the second floor since all toilets could now be supplied with rainwater.

Aside from the energy and CO₂ equivalence associated with the construction required to set piping, the cistern accounted for the highest emissions. Much consideration should be applied when selecting a rainwater cistern. For purposes of this study, a steel tank was chosen. Steel tanks are manufactured in a variety of volumes ranging from tens of gallons to several thousand which was needed at the Crossings site. Current rainwater tanks are made of a variety of materials including concrete, metal, plastic, fiberglass etc. With varying costs and emissions per dollar, the tradeoff periods could vary greatly depending on the material of the cistern that was chosen.

Using values from Sahely and Kennedy 2007 for operational analysis resulted in very small annual CO₂ equivalence emissions. As discussed in the methods section, EIO-LCA energy and CO₂ equivalence values for water and wastewater treatment are not accurate for this analysis because they are modeled into one sector. Had EIO-LCA been used in the Life Cycle analysis for water and wastewater treatment, the payoff period for using rainwater for toilet flushing considering new construction would have decreased to 5.5 years and resembled similar studies such as Anand and Apul, 2010.

1.4.0 Discussion

1.4.1 Building payback comparison

When investing in sustainable technologies such as rainwater harvesting systems, building owners are often most concerned as to when the technology will pay for itself and begin to reduce operational expenses. For purposes of this study a functional unit of
energy, cost and emissions per person was chosen in order to properly compare scenarios. A building owner however would most likely look at the entire building when analyzing payback. When disregarding per person analysis, the payback period would decrease to 25 years when fewer occupants reside in the building (figure 1-5). This is due to the elimination of dividing annual energy consumption by building occupancy which caused scenario 5 to result in a high payback period because energy usage was divided by 248 occupants and then compared to the baseline which was divided by 649 occupants.

![Figure 1-5 Comparison of per person and building energy payback](image)

1.4.2 Effect of building design

The residence hall houses 649 people in total and has a roof area of 4,039 m². Crossings is in compliance with codes with respect to number of plumbing fixtures\(^\text{37}\). However, the building does not have sufficient roof area to supply rainwater to all the toilets in the building. This implies the need for specific roof area codes associated with rainwater.
harvesting systems in both new and existing buildings. With larger roof area requirements, it is also important to address the increase in emissions due to use of a larger cistern. It is imperative that building codes be adapted to address rainwater harvesting systems. At the current Crossings, a total roof area of 11,620 m² (18 m² per person) would be needed to supply enough rainwater to accommodate for all of the potable water needed to flush toilets. This is nearly 3 times larger than the actual roof area. This implies that dormitories, which are commonly multi-story and have high occupancies, may not be the most suitable choice when applying rainwater to flush toilets. It is important to note that while a larger roof area per occupant will decrease payback on a building scale, the per person emissions will increase.

1.4.3. Effect of water utility rates

The payback time for all scenarios is more than two decades for cost as well as energy and carbon emissions. One reason for a high payback time for all the scenarios is the low water prices. Current water prices used are approximately $0.53 per 1000 liters. With the EPA’s estimated $335 billion needed to fix the countries aging water distribution system, water prices are expected to increase in the near future. Studies have reported a decrease in payback time of rainwater scenarios with increase in water prices.

1.4.4 Implications on sustainable construction rating system, LEED

The U.S. Green Building Council’s newest version of LEED (Version3.0) promotes Life Cycle Analysis (LCA). The credits are now weighted according to LCA. By applying LCA to the existing credits of version 2.0, the total score for a project has increased from 69 to a maximum of 100 points. The water efficiency credits points in version 3.0 were
adjusted by evaluated impact using Simapro and the USA Input/Output 98 library for the consumption of water throughout the lifetime of the building. This research suggests that while LEED is considering LCA in their program, there are still flaws in the system. If a rainwater harvesting system were implemented for toilet flushing at an existing dormitory such as Crossings, the environmental impact could be substantial. It is important to analyze not only the water usage, but also the materials and construction process associated with the harvesting system. The energy tradeoff for using rainwater to flush toilets at Crossings requires over 70 years and LEED LCA estimates are based on a 50 year building lifetime.
1.4.5 Effect of Sewer System

The energy and CO₂ paybacks were attributed greatly to the lack of rainwater being sent to the combined sewer system. Crossings was analyzed using combined sewer systems since a large portion of Toledo’s sewer system remains combined. The department of justice recently posted a press release which stated that Toledo plans to spend $315 million to eliminate the combined sewers throughout the city. When the excess rainwater is not being sent to the wastewater treatment facility, the energy and CO₂ payback period will be affected. When treatment of the rainwater at the wastewater plant is eliminated, the emissions and energy consumption associated with the volume of

Figure 1-6 Comparison of tradeoff given combined and separate sewer systems and increased roof area per occupant.
rainwater in question are neglected. This study showed that energy and CO₂ payback periods are shorter when combined sewer systems are present (figure 1-6).

As previously mentioned, the building’s roof area also contributes greatly to the payback times. A sensitivity analysis was performed to compare increased roof area with energy payback. The actual roof area (6.31 m²/person) results in a payback period of 51 years when combined sewers are considered. As the roof area per person increases, the payback period decreases until the optimum roof area per person (18 m²/person) is reached. After this point the payback period will remain constant because the volume of harvested rainwater exceeds the toilet flushing demand.

1.4.6 Limitations

The results of this study are not representative of all buildings. The cost, energy and CO₂ equivalence payback periods may vary greatly depending on building type and use. While this study suggests that utilizing harvested rainwater for toilet flushing in a university dormitory requires over 70 years to overcome the initial energy emissions, dormitories that have larger roof areas per occupant will result in a shorter payback time. While this study shows that combined sewer systems are most favorable when considering environmental payback periods, combined sewer overflows are detrimental to aquatic environments and may result in more extreme environmental emissions which were not considered in this study.
1.5 Conclusions
This thesis provides an economic as well as environmental assessment of the use of harvested rainwater for toilet flushing and irrigation for an actual dormitory with 646 or 248 people using life cycle assessment methodology. This research also provides a quantitative database for decision making concerning the use of a rainwater harvesting system for a dormitory. Five different scenarios were considered. Several observations and recommendations can be concluded from this study.

Tradeoff times were highest with cost followed by energy and then CO$_2$ emissions. The most favorable scenario based on cost, energy use and carbon emission would be to apply the rainwater toward irrigating. Scenario 5 which considers fewer occupants requires the largest payback periods when analyzing the building on a per person basis. When analyzing on building scale, the larger roof area per occupant results in the shortest payback time for the same scenario. This research is the first to compare payback times when analyzing the whole building and per person costs, energy and emissions. Results vary drastically between the two methods.

If rainwater is to be used to flush toilets, it is both financially and environmentally beneficial to install the rainwater harvesting system when the building is initially constructed rather than retrofitting an existing structure. The rainwater harvesting system, if implemented in an existing building, might not pay back within the useful life time of the building. However, to reduce the use of potable water it can be applied toward irrigating.
The annual potable water savings at Crossings is 1.87 million liters. By applying this volume of captured rainwater toward non-potable needs, it will help to mitigate the combined sewer overflows, thus reducing the stress over the water and wastewater infrastructure. The city’s sewer system plays a large role in payback analysis when considering the environmental viability of rainwater harvesting systems. If at Crossings the sewer system was upgraded to separate sewers, energy and CO$_2$ payback years would increase.

Crossings was constructed in accordance to the international building codes. However, the building’s roof area is not sufficient to collect a large enough volume of rainwater to supply for meeting toilet flushing demand. This study suggests a need for new building codes that specifically address rainwater harvesting. It is important that roof area per person is determined in order to collect and use sufficient volumes of rainwater for non-potable uses in buildings. The codes should be developed for several regions in order to account for varying precipitation data as the amount of rainfall in an area is one of the main factors that impacts harvesting of rainwater.
Chapter 2

Environmental and Economic Analysis of Sanitation Technologies (EEAST)

2.1 Introduction:
The use of alternative sanitation technologies is becoming prevalent around the world. Such technologies include low flush toilets, rainwater used to flush toilets and composting toilets. Building owners are often concerned as to when these technologies pay back. An issue arises when one such number is desired. No two buildings or sites for that matter are the same. There are a variety of building and site characteristics that affect the tradeoff time of the aforementioned technologies. Such characteristics include; roof area, occupancy, the buildings intended use, height of the structure, number of toilets and its location. Along with the unique characteristics of the building and site, interest rates from loans and discount rates affect tradeoff times. Environmental and Economic Assessment of Sanitation Technologies (EEAST) is the only available model which provides a comparison of sanitation technologies specific to a site. EEAST is useful to a broad audience which includes contractors, building owners, homeowners and researchers that seek a model that is capable of assessing long term economic and environmental impacts relating to sanitation technologies. EEAST provides the necessary information to support budget and planning decisions, identify environmental
and economic tradeoffs for each technology and determine the optimum choice for a specific building and site.

2.2. Methods

2.2.1 Scenarios Modeled

EEAST models five scenarios that vary with respect to sanitation technology and water source. EEAST also considers rainwater used to irrigate because it is the most widely adopted end use of rainwater. Users can define standard or low flush toilets within the model. All five scenarios are modeled at the same time which allows the user to compare each scenario in terms of tradeoff year considering cost, energy consumption and CO₂ emissions. The scenarios assume that the building is new construction. Renovation projects require tearing down walls which cannot be modeled in the current version of EEAST. The five scenarios modeled by EEAST are depicted in figure 2-1 and explained below:

Figure 2-1 Scenarios Modeled by EEAST
- Scenario 1 – Models use of potable water for toilet flushing and harvested rainwater to irrigate.
- Scenario 2 – Models use of harvested rainwater for toilet flushing and city supplied potable water for irrigating.
- Scenario 3 – Models use of harvested rainwater for both toilet flushing and irrigating.
- Scenario 4 – Models use of composting toilets in place of standard toilets and city supplied potable water for irrigating.
- Scenario 5 – Models use of composting toilets in place of standard toilets and harvested rainwater for irrigating.

2.2.2 User Inputs

The user must input monthly precipitation data and building characteristics that allow the model to calculate the amount of rainwater available for collection (Figure 2-2). Building characteristics include building height, width, length, number of stories and number of toilets per story. Precipitation data specified by city and state are easily obtainable by the user via an internet link. End use data required by the user includes irrigation area, building type (corresponds to flushes per person/day), occupancy load and toilet type (standard or low flush). The current city supplied pressure in psi and the variable discount rate are the last two items needed to run the software. EEAST will calculate the initial cost corresponding to each scenario and allow the user to select whether or not a loan will be required to finance the project. If a loan is to be taken, specific loan data can be entered and includes annual interest rate, loan period, number of payments and start date. The user may also choose the default loan settings that are provided in the model.
2.3 Calculations
2.3.1 Cistern Sizing and Water Demand Calculations

EEAST performs several calculations ranging in complexity from roof area to specific pump requirement calculations (Figure B-1). One of the most important calculations is the selection of cistern volume for the site. The model considers precipitation data, roof area and efficiency factors to determine the volume of rainwater available for capture (Equation 3). It is important to not oversize the cistern due to the high cost and energy consumption associated with manufacturing of the cistern. EEAST chooses the optimum cistern volume by comparing supply with demand. If the volume of water required to irrigate and/or flush toilets is smaller than the volume of rainwater available to harvest, the model sizes the cistern based on demand and not supply (Equation 4). The total demand \( V_{\text{Tot}} \) is the sum of the volume required to flush toilets (Equation 6) and the volume required to irrigate (Equation 7) and is listed as Equation 5. A concrete pad to
support the weight of the cistern is also analyzed by the software and is sized based on the diameter of the tank (Equation 8).

Equation 3. Volume of rain available for capture

\[ V_r = R_{avg} \times 0.6233 \times 0.75 \times A \]

Where,
\( V_r \) = Volume of rain available for capture (gallons/month)
\( R_{avg} \) = average monthly precipitation (in)
0.6233 = gallons of rainfall captured for each sf of roof area and each inch of rainfall
0.75 = rainwater catchment system efficiency
\( A \) = roof area (sf)

Equation 4. Volume of Cistern

\[ V_c = V_r, \text{If } V_r < V_{Tot} \text{ otherwise, } V_c = V_{Tot} \]

Where,
\( V_c \) = Volume of cistern (gallons)
\( V_{Tot} \) = Total volume of water required to flush toilets and irrigate (gallons/month)
\( V_r \) = Volume of rain available for capture (gallons/month)

Equation 5. Total Demand

\[ V_{Tot} = V_T + V_I \]

Where,
\( V_{Tot} \) = Total volume of water required to flush toilets and irrigate (gallons/month)
\( V_T \) = Volume of water required to flush toilets (gallons)
\( V_I \) = Volume of water required for irrigating (gallons per month)
Equation 6. Volume of water required to flush toilets

\[ V_T = \frac{f}{p} \times O \times gpf \times \left( \frac{365 \text{days}}{12 \text{months}} \right) \]

Where,
- \( V_T \) = Volume of water required to flush toilets (gallons)
- \( f/p \) = flushes per person per day, Educational building (3), office (4), Dormitory (5), Home (6)
- \( O \) = building occupancy (persons)
- \( gpf \) = gallons per flush, Standard toilets (1.6 gal), Low flush toilets (1.28 gal)

Equation 7. Volume of water required for irrigating

\[ V_I = 1.5 \text{in} \times \frac{1 \text{ft}}{12 \text{in}} \times A_I \times \frac{7.48 \text{gal}}{1 \text{ft}^3} \times \frac{52 \text{wks}}{\text{year}} \times \frac{1 \text{year}}{12 \text{months}} \]

Where,
- \( V_I \) = Volume of water required for irrigating (gallons per month)
- \( 1.5 \text{in} \) = watering depth (in)
- \( A_I \) = Irrigation area (sf)

Equation 8. Volume of Concrete

\[ V_{\text{conc}} = (\varphi^2 \times t) \times 1/27 \text{cy/ft}^3 \]

Where,
- \( V_{\text{conc}} \) = Volume of Concrete
- \( \varphi \) = Diameter of tank
- \( t \) = thickness of pad (assumed 4")

### 2.3.2 Dual Piping and Pump Power

When rainwater is used to flush toilets, dual piping must be installed from the cistern to the toilets. Plumbing regulations require the dual piping to avoid cross contamination with the city supplied potable water. In addition to the piping required for scenarios that utilize harvested rainwater for toilet flushing, pumps would be required to transport the rainwater from the cistern to the toilets. EEAST estimates the length of pipe required
(Equation 9) and the pump power needed (Equations 10 -14) specific to each building that is analyzed.

Equation 9. Length of piping required

\[ LP = \left( Ht \times \frac{T}{f} \right) \times \left( \frac{Ht}{#floors} \right) \times \frac{T}{f} + (3ft \times #floors \times \frac{T}{f}) \]

Where,
LP = length of piping required (ft)
Ht = height of building
T/f = number of toilets per floor
# floors = number of floors in building

Equation 10. Energy required by pump

\[ E = \left( P \times 365 \text{ days} \times 24 \text{ hours} \times 0.001 \text{ kWh/w} \right) / e \]

Where,
E = Energy required by pump (kWh)
P = Power delivered to pump (W)
e = efficiency of pump (65%)

Equation 11. Power delivered to pump

\[ P = Q \times \gamma \times (h_e + h_p) \times \frac{1 + \alpha}{\eta} \]

Where,
P = Power delivered to pump (W)
Q = Flow rate (m³/s)
\( \gamma \) = Specific weight of water (N/m³)
h_e = Elevation head provided by pump (m)
h_p = Pressure head provided by pump (m)
\alpha = Percentage of energy lost to friction (0.3%)^{34}
\eta = Combined mechanical and hydraulic efficiency of the pump (0.65)^{35}
Equation 12. Flow rate

\[ Q = V_T \times \frac{0.00379 \text{m}^3}{\text{gallon}} \times \frac{12 \text{ months}}{1 \text{ year}} \times \frac{1 \text{ year}}{3.2 \times 10^7 \text{ seconds}} \]

Where,

\( Q = \) Flow rate = toilet flushing demand (m\(^3\)/s)

\( V_T = \) Volume of water required to flush toilets (gallons/month)

Equation 13. Elevation head provided by pump

\[ h_e = \left( \frac{H \times \frac{1 \text{ m}}{3.28 \text{ ft}}}{\alpha} \right) \]

Where,

\( h_e = \) Elevation head provided by pump (m)

\( H = \) building height (ft)

\( \alpha = \) Percentage of energy lost to friction (0.3 %)

Equation 14. Pressure head provided by pump

\[ h_p = \frac{P_c \left( \frac{1.21 \text{ ft}}{1 \text{ psi}} \times \frac{1 \text{ m}}{3.28 \text{ ft}} \right)}{\alpha} \]

Where,

\( P_c = \) pressure provided by city to building (assumed 30 psi)

\( h_p = \) Pressure head provided by pump (m)

\( \alpha = \) Percentage of energy lost to friction (0.3 %)

2.3.3 Economic Calculations

Economic calculations performed by the model encompass net present value (Equation 15) and payback period (Equation 16) functions. Unit costs for each item comprising the different scenarios were determined and are listed in table 2.1. The discount rate needed
for the net present value calculation will vary depending on user input and can range from 0%-12%.

Table 2.1 Cost/unit for each item considered in model

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost/Unit (USD)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wastewater treatment</td>
<td>$0.0042/gal</td>
<td>27</td>
</tr>
<tr>
<td>Potable water treatment</td>
<td>$0.0014/gal</td>
<td>38</td>
</tr>
<tr>
<td>Steel Cistern</td>
<td>$0.7078/gal</td>
<td>26</td>
</tr>
<tr>
<td>Pump</td>
<td>$165.00/each (avg)</td>
<td>43</td>
</tr>
<tr>
<td>Floating tank filter</td>
<td>$425.00/each (avg)</td>
<td>44</td>
</tr>
<tr>
<td>Pipes</td>
<td>$0.97/LF</td>
<td>45</td>
</tr>
<tr>
<td>Concrete pad</td>
<td>$70.00/CY</td>
<td>46</td>
</tr>
<tr>
<td>Energy use by pump</td>
<td>$0.07/kWh</td>
<td>47</td>
</tr>
<tr>
<td>Composting toilet fixtures</td>
<td>$100.00/each*</td>
<td>48</td>
</tr>
<tr>
<td>Central composting units</td>
<td>$2,295.00/each</td>
<td>49</td>
</tr>
<tr>
<td>Power generation and supply (Heat associated with composting system)</td>
<td>$0.07/kWh</td>
<td>47</td>
</tr>
<tr>
<td>Power generation and supply (Fan used in composting system)</td>
<td>$0.07/kWh</td>
<td>47</td>
</tr>
</tbody>
</table>

*Cost of composting toilets is represented as difference between composting and standard toilets.

Equation 15. Net present value

\[
NPV = \sum_{t=1}^{T} \frac{\text{cash flow}_t}{(1 + i)^t} - \text{initial investment}
\]

Where,
NPV = net present value ($),
t=cash flow period (years),
i= Discount rate assumed (2.7%)
Equation 16. Payback period

\[ PP = \frac{Initial \, investment}{Annual \, Cash \, inflow} \]

Where,
PP = Payback period (years)
Annual cash inflow = annual savings

EEAST also calculates return on investment if loans are required to execute the project. The user will select whether or not a loan is required on the input worksheet. The user can then elect to assume the default loan parameters or choose to input specific loan parameters on the financial assessment worksheet (figure 2-3). The user may input the annual interest rate, the loan period, number of payments per year and the start date. The default setting includes a 5% annual interest rate, a loan period of 5 years, 12 payments per year and uses the current date as the start date. Building owners often consider investing their money elsewhere and neglecting to implement sustainable technologies. Owners may also opt to invest the money that they are saving on operational expenses in order to reduce their payback time. EEAST models investing the manufacturing and operational costs in a U.S. treasury bond with a 5% annual return rate (Equation 17).
Equation 17. Future value of investment

\[ FV = P(1 + i)^n \]

Where,

\( FV \) = future value of investment
\( P \) = Principal investment
\( i \) = interest rate (5%)
\( n \) = number of years (1-75)

2.4 Life Cycle Analysis

Life cycle assessment (LCA) methodologies are used in EEAST to determine the energy consumption and Global Warming Potential (GWP) for each scenario. Both manufacturing and operational phases are modeled for each scenario. End of life is not modeled because many of the materials lifetimes exceed the estimated building life of 75 years. Specific items modeled by EEAST are listed in table 2.2. Economic Input Output
Life Cycle Assessment (EIO-LCA) was used to obtain the energy consumption and CO$_2$ emissions resulting from each item associated with the five scenarios. Costs/unit for each item was entered into EIO-LCA (2002 database)$^{20}$. Energy per unit as well as CO$_2$ emissions per unit were pulled from the software and incorporated into EEAST (see Table 2.2). Total emissions and total energy consumption are analyzed by EEAST. Initial values in relation to manufacturing products and implementing the system as well as operational values with respect to operation of each scenario (water/wastewater treatment and power generation) were considered. The environmental impact based on the energy consumption and GWP of the entire lifecycle associated with each scenario is modeled by EEAST. It was assumed that filters, pumps and toilets would need to be replaced every 5, 20 and 35 years respectively.

<table>
<thead>
<tr>
<th>Item</th>
<th>Energy/Unit (kWh)</th>
<th>GWP/Unit (MT CO$_2$e)</th>
<th>EIO-LCA Sector (# and description)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wastewater treatment</td>
<td>3.05</td>
<td>0.00782</td>
<td>221300 Water Sewage and other systems</td>
</tr>
<tr>
<td>Potable water treatment</td>
<td>3.05</td>
<td>0.00782</td>
<td>221300 Water Sewage and other systems</td>
</tr>
<tr>
<td>Steel Cistern</td>
<td>3.61</td>
<td>0.00095</td>
<td>332400 Metal tank heavy gauge manufacturing</td>
</tr>
<tr>
<td>Pump</td>
<td>2.22</td>
<td>0.00056</td>
<td>333911 Pump and pumping equipment manufacturing</td>
</tr>
<tr>
<td>Floating tank filter</td>
<td>1.38</td>
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2.5 Output/Results
EEAST provides a means to strategically choose optimum sanitation technologies for specific buildings based on cost, energy and CO₂ payback consideration. The model will present the user with the year in which each scenario pays for itself in terms of cost, energy consumption and CO₂ emissions (figure 2-4). Payoff years are determined by calculating the initial values for year 0 (the year in which the scenario is implemented) and subtracting cost, energy and CO₂ savings in relation to operational savings for the next year(s). Operational savings include reduced water bills that are in direct correlation with energy and emissions savings by not treating the water. Replacement costs are discounted to present day value based on the user’s discount rate that is inputted. EEAST displays the financial tradeoff of each scenario in a cost-benefit analysis figure which allows users to maximize return on investment.

Figure 2-4 EEAST results showing energy, CO₂ and cost benefit analysis figures
Conclusions

The objective of this research was to determine the economic and environmental impacts of a rainwater harvesting system at a dormitory. The goal was to compare the impacts of rainwater used for toilet flushing and irrigating in an existing and new construction building with current occupancy as well as fewer occupants. The effects of tradeoff based on a building scale and per person basis was also sought. A comparison of tradeoff associated with combined vs. separate sewer systems was the final objective.

It was determined that cost requires the longest payback followed by energy and then CO$_2$ emissions. If rainwater is to be utilized for toilet flushing it is both economically and environmentally advantageous to install the system when the building is initially constructed to avoid construction associated with retrofitting the existing structure. The optimum end use at Crossings based on cost, energy and CO$_2$ payback is irrigation. It was observed that an increase in roof area per occupant will result in shorter energy and CO$_2$ paybacks when analyzing a building. When considering emissions per person an increased roof area will however result in longer paybacks. It was observed that sites with combined sewer systems correlate to shorter paybacks of rainwater harvesting systems due to the elimination of treatment of the rainwater at the wastewater treatment facility.
EEAST, an excel based decision model, was developed based on this research. EEAST compares alternative sanitation technologies including, standard and low flush toilets, rainwater used to flush toilets, composting toilets and also looks at rainwater used to irrigate. EEAST provides the necessary information to support budget and planning decisions, identify environmental and economic tradeoffs for each technology and determine the optimum choice for a specific building and site.
References


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http://www.ohiolawncarecompany.com/sections/residential/lawn/irrigation.asp

http://www.rainwaterharvesting.co.uk/calculator.php accessed January 2009


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[30] GaBi 4.0, GaBi software, Software solution by PE international, August , 2010


http://www.whitehouse.gov/omb/circulars_a094_a94_appx-c/


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Appendix A

Crossings Supplemental Information

Figure A-1 Plan view of Crossings. Total roof area is 4,093 m².
Figure A-2 Irrigation area surrounding crossings. Google area calculator was used to determine total irrigation area of 11,660 m².

Table A.1 Items included in construction estimate. WinEstimating Software was used.

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Appendix B

EEAST Supplemental Figures

Figure B-1 Operations performed by EEAST.