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# Development and application of EEAST: A life cycle based model for use of harvested rainwater and composting toilets in buildings

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ABSTRACT

Harvested rainwater systems and composting toilets are expected to be an important part of sustainable solutions in buildings. Yet, to this date, a model evaluating their economic and environmental impact has been missing. To address this need, a life cycle based model, EEAST was developed. EEAST was designed to compare the business as usual (BAU) case of using potable water for toilet flushing and irrigation to alternative scenarios of rainwater harvesting and composting toilet based technologies. In EEAST, building characteristics, occupancy, and precipitation are used to size the harvested rainwater and composting toilet systems. Then, life cycle costing and life cycle assessment methods are used to estimate cost, energy, and greenhouse gas (GHG) emission payback periods (PPs) for five alternative scenarios. The scenarios modeled include use of harvested rainwater for toilet flushing, for irrigation, or both; and use of composting toilets with or without harvested rainwater use for irrigation. A sample simulation using EEAST showed that for the office building modeled, the cost PPs were greater than energy PPs which in turn were greater than GHG emission PPs. This was primarily due to energy and emission intensive nature of the centralized water and wastewater infrastructure. The sample simulation also suggested that the composting toilets may have the best performance in all criteria. However, EEAST does not explicitly model solids management and as such may give composting toilets an unfair advantage compared to flush based toilets. EEAST results were found to be very sensitive to cost values used in the model. With the availability of EEAST, life cycle cost, energy, and GHG emissions can now be performed fairly easily by building designers and researchers. Future work is recommended to further improve EEAST and evaluate it for different types of buildings and climates so as to better understand when composting toilets and harvested rainwater systems outperform the BAU case in building design.



## 1. Introduction

The general objective of wastewater management is to protect the public health and environment while reducing the pressure in the existing water resources (Massoud et al., 2009). Towards achieving this goal, a centralized approach is used in developed countries where human excreta are received in a toilet, flushed with municipally supplied potable water, and conveyed away via pipes to a wastewater treatment plant. Large volumes of potable water are used to help with conveying of this waste. In the United States, the estimated indoor water use per person per day is 45–100 L and 27% of this water is used just for toilet flushing (Mayer and William, 1999; Gleick, 1996). As the municipal water supply is to be carried from freshwater resources over large distances in underground pipes, the chances of leakage are high. On average, 20% of drinking water is typically lost due to the leakage in the distribution system from the source to the tap (Mehta, 2009; CBO, 2002). Considering that the quantity and quality of available freshwater resources are limited and decreasing regionally, nationally, and globally (Gleick, 1996), the use of high quality water to flush human waste is an inefficient and unsustainable approach to resource and sanitation management. High energy use and lack of funding are other problems facing today's centralized water and wastewater infrastructure. In the United States, 3% of total national energy demand is used for water and wastewater treatment and conveyance and there is a $11 billion per year funding gap to maintain this infrastructure (EPRI, 2002; USEPA, 2002). Solutions developed with sustainability in mind are necessary for addressing these water and sanitation management challenges.

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One alternative to flushed toilets are composting toilets that disconnect the toilet from the centralized water and wastewater infrastructure since they require little to no flushing (Redlinger et al., 2001). Composting toilets are an emerging technology that have infiltrated mainly into the rural areas that may not have water and wastewater infrastructure connections. By saving water and decentralizing the sanitation management, composting toilets appear to have some sustainability benefits over flushed toilets; however, the science and technology of composting toilets is fairly immature and their environmental and economic evaluation is an emerging topic of research with only limited available information (Anand and Apul, 2010; Anand and Apul, 2013a).

Another alternative is to disconnect only the water infrastructure from the toilet and use a decentralized approach to provide water for flushing toilets. One such system is rainwater harvesting; a free and easily available water source for many regions. Decentralized rainwater harvesting systems are designed to capture the rainwater from the roof (catchment) for either immediate use or for storage and use in the future. Since the water captured from the rainwater harvesting system may not be enough to fulfill the total demand, the connection to municipal water supply can be retained as a supplemental or backup source (Anand and Apul, 2010). Use of rainwater for toilet flushing not only reduces the potable water supply demand but also reduces the stormwater runoff, downstream drainage infrastructure needs, and ultimately the stress on water and (combined sewer) wastewater infrastructure.

Use of rainwater for non-potable purposes such as for irrigation and toilet flushing are most convenient since there is no need to significantly improve the water quality for these end uses. The first flush of rainwater containing most of the solids and pollutants is typically discarded allowing cleaner rainwater to enter the cistern. The solids settle to the bottom once in the tank and the remainder of suspended solids is further removed by use of a submerged filter that withdraws water from the cistern. The microbiological quality in toilets supplied with rainwater is approximately the same as in toilets supplied with potable water (Albrechtsen, 2002); so disinfection of the harvested rainwater is not recommended for non-potable purposes such as use in toilet flushing (Herrmann and Schimida, 2010; Coombes et al., 2002). Rainwater supplied toilets may have some pathogens that are not found in toilets supplied with potable water (Albrechtsen, 2002; Jordan et al., 2008); however, human health risks may nevertheless be minimal since humans would not have any direct contact with toilet water.

Rainwater harvesting systems have been used for centuries to meet urban water supply needs (Reid, 1982) and there is a rapidly growing body of literature on rainwater harvesting. Therefore, the knowledge base, acceptance, and implementation of rainwater harvesting systems are further along than composting toilets. Yet, the high initial cost due to addition of rainwater tank and pipes as well as the very limited knowledge on economic and environmental performance for the life cycle of the system pose barriers for their more widespread implementation. If these barriers could be overcome, more informed decisions can be made and rainwater harvesting systems would likely be more widely practiced especially in green construction projects where water efficiency and sustainable sites credits can be earned towards a green certified building (e.g. LEED, Green Globes certifications) (LEED, 2005; Green Building Initiative, 2012). The construction and operational costs of rainwater harvesting systems have been reported in some recent studies (Ghisi and Oliviera, 2007; Zhang et al., 2009; Anand and Apul, 2010; Rahman et al., 2010; Tam et al., 2010; Ward et al., 2010; Khastagir and Jayasuriya, 2011; Liang and Van Dijk, 2011) but very limited research has been done to quantify the energy use and greenhouse gas (GHG) emission rates during the life cycle stages of the rainwater harvesting systems (Anand and Apul, 2010;

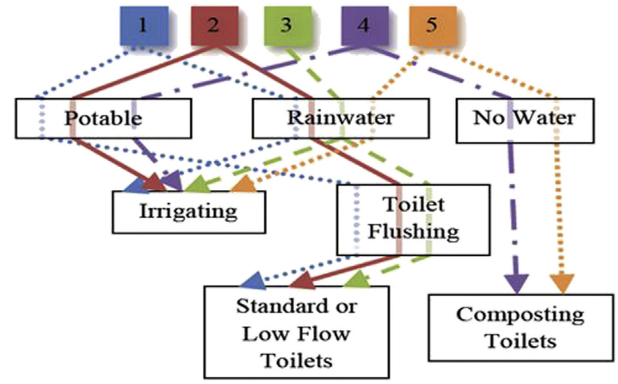


**Fig. 1.** Five different scenarios modeled by EEAST.

Racoviceanu and Karney, 2010; Crettaz et al., 1999; Angrill et al., 2012). In addition, the findings from these prior studies are applicable to the specific building and regional parameters modeled and cannot be extrapolated directly to studying other types of buildings in other regions.

To our knowledge, there exist no robust tool for modeling the life cycle economic and environmental implications of rainwater harvesting systems or composting toilets that can be used with different building designs, climates, and regional parameters. Such a tool can especially be valuable in decision making in the design phase of the construction of a new building. The goal of this study was to develop a model that can address both the practical needs of building designers and research needs of the building and infrastructure community for better understanding the potential role of composting toilets and rainwater harvesting systems in today's urban environment. A spreadsheet model, EEAST, was developed that compares potable water use in toilets to alternative systems based on water saving, cost, energy, and GHG emission criteria. The tool name EEAST is an abbreviation of Economic and Environmental Analysis of Sanitation Technologies. It is available for free from this website: http://eeast.wikispaces.com/home. In this paper, we present the EEAST model by first discussing its methodology and then illustrating its capabilities with a sample simulation.

## 2. Methodology

### 2.1. Scope of EEAST

EEAST models the business as usual (BAU) case of using potable water for both toilet flushing and lawn irrigation in a building. It then compares this option to decentralized technologies of composting toilets that require no water and toilets flushed with harvested rainwater. The flush-based toilets modeled are defined as being standard (1.6 gal/flush) or high efficiency (1.28 gal/flush). EEAST also models lawn irrigation with potable water or rainwater as the water source. All modeling is done with the assumption of new construction; retrofitting existing buildings are not currently coded in EEAST but can be added in future versions. Being a spreadsheet model, the parameters used in EEAST can be changed by the user. However, certain default values are embedded to help with a novice modeler. The criteria that EEAST calculates for decision-making are water savings, Net Present Value (NPV), and payback periods (PP) for energy, GHG emissions, and (discounted) cost.

### 2.2. Modeled scenarios

EEAST models five alternative scenarios whereby source water (harvested rainwater versus potable water) for toilet flushing and irrigation are varied (Fig. 1). The main target of developing these five different scenarios was to determine the most sustainable way of using rainwater for indoor and outdoor end uses. In EEAST, each of these five scenarios is compared to the BAU case in which a conventionally constructed building would be using only potable water for all end uses. The five alternative scenarios are:

**Scenario 1**. Potable water for toilet flushing and harvested rainwater for irrigation

**Scenario 2**. Harvested rainwater for toilet flushing and city supplied potable water for irrigation.

**Scenario 3**. Harvested rainwater for both toilets flushing and irrigation.

**Scenario 4**. Composting toilets instead of standard toilets and municipal potable water for irrigation.

**Scenario 5**. Composting toilets instead of standard toilets and harvested rainwater for irrigation.

Each of the five different scenarios is modeled at the same time within EEAST and for Scenarios 1 to 3, the option to select between high and low efficiency fixtures are provided. Output data for all scenarios are plotted in a comparative bar graph that displays the NPV and payback periods for cost, energy, and GHG emissions for each scenario with respect to the BAU case.

### 2.3. Conceptual structure of EEAST

A schematic representation of how EEAST model works is shown in steps A–F of Fig. 2. First, the input data on precipitation, building characteristics, and occupancy are used to design and size the rainwater harvesting system for the building (Steps A and B). The building characteristics used in the design include building height, width, length, and number of toilets per floor, number of floors, irrigation area, and building type. Building type affects the number of flushes per person per day (4 for office, 3 for educational, and 5.1 for residential) (Vickers, 2001). The composting toilet design is modeled after centralized composting toilets by Sun-Mar company. Each centralized composting tank is connected to four toilet fixtures. System sizing including energy requirements for harvested rainwater pumping is further explained in supporting information. Once the systems are sized, the cost, energy, and emissions inventory for construction and operation of the building water system (rainwater and potable water) are determined using life cycle costing (LCC) and life cycle assessment (LCA) methods (steps C, D, and E). Cost, energy, and emissions associated with manufacturing of cistern, cistern support structure, pump, conveying pipe, and composting toilets are modeled. Cost, energy and emissions from transportation and installation of the materials are not modeled for simplicity and also because these phases are expected to have negligible impacts (Racoviceanu et al., 2007). The inventory of the operation phase includes replacement of filter, pumps, and toilets every 5, 20, and 35 years, respectively (Kirk and Dell'Isola, 1995). The energy (and associated cost and greenhouse gas emissions) associated with annual potable water production, harvested rainwater pumping, and stormwater treatments (if applicable) are modeled as part of the operation phase. Lastly, the results are presented in terms of PPs of cost, energy, and GHG emissions (Step F). EEAST performs all calculations for the life cycle of the building (assumed 75 years) but results are graphed in terms of PPs so as to more easily compare the alternative systems to the BAU case.

### 2.4. Economic analysis

Once the required size of the rainwater harvesting system is designed, the costs associated with those items are estimated from vendor prices. These items include cistern, pump, floating tank filter, pipes, concrete pad, wastewater treatment, potable water treatment, and energy used by pump. For composting toilet system design, the costs of composting toilet fixtures, central composting units and power requirement (heat and fan used in composting

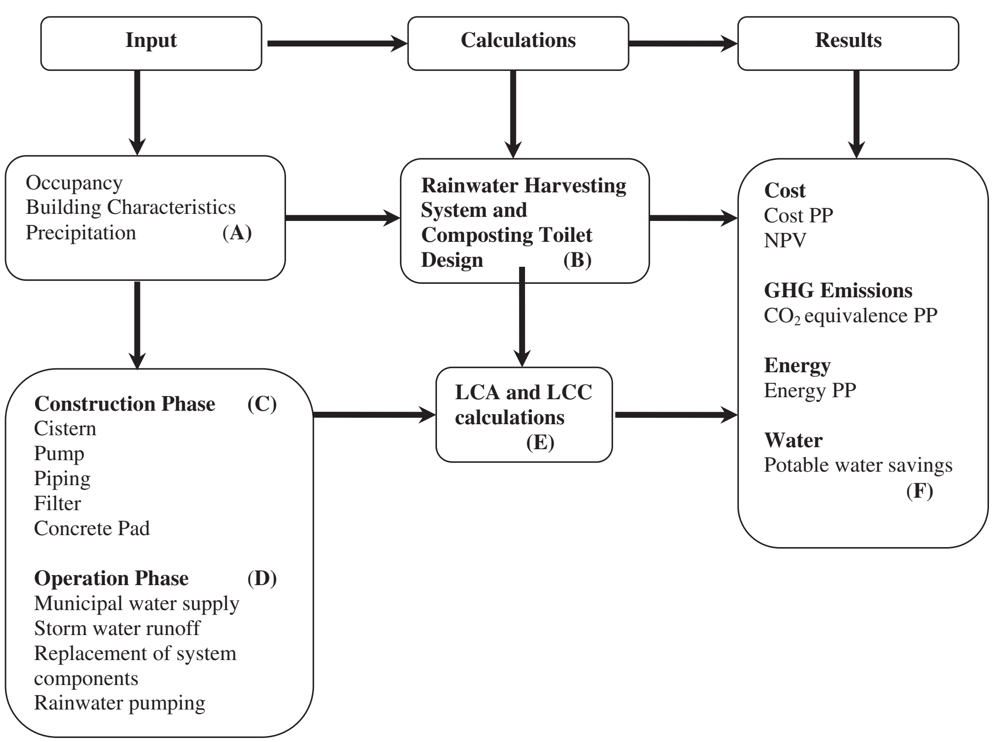


**Fig. 2.** Conceptual model structure of EEAST.

**Table 1**
EIO-LCA energy and greenhouse gas emission data incorporated in EEAST.

| Item | Energy/Unit (kWh per $ spent) | GWP/Unit (MT $CO_2$e per $ spent) | EIO-LCA sector (# and description) |
|---|---|---|---|
| Wastewater treatment | 5.17 | 0.00178 | 221300 Water sewage and other systems |
| Potable water treatment | 5.17 | 0.00178 | 221300 Water sewage and other systems |
| Energy use by pump, composting tank fan and heater | – | 0.00937 | 221100 Power generation and supply |
| Composting toilet fixtures | 4.72 | 0.00108 | 32711 Pottery, ceramics, and plumbing fixture manufacturing |
| Composting tank | 4.17 | 0.000904 | 32619 Plastic plumbing fixtures and all other plastic products |
| Steel cistern | 3.61 | 0.00095 | 332400 Metal tank heavy gauge manufacturing |
| Pump | 2.22 | 0.00056 | 333911 Pump and pumping equipment manufacturing |
| Floating tank filter | 1.38 | 0.00053 | 333319 Other commercial and service industry machinery |
| Pipes | 6.67 | 0.00142 | 326120 Plastic pipe, fittings and profile shapes |
| Concrete pad | 6.67 | 0.00274 | 230103 Other non residential structures |

system) are also used. The cost values are used in calculating two different economic criteria; NPV and discounted PP.

A positive NPV value for a scenario indicates a project that is worth pursuing. It can be preferred over the discounted PP information since the PP ignores the cash flows for the years beyond the PP. On the other hand, most institutions cannot plan for 75 year budgets and the PP becomes an equally important criterion to determine whether to invest in a project. Discounted PP values are determined by checking the year at which a particular scenario's cumulative cash flow equaled that of the BAU case. NPV is calculated as follows:

$$\mathrm{NPV} = \sum_{t=0}^{75} \frac{C_t}{(1+i)^t} - \Pi \tag{1}$$

where,

$i$ = Discount rate.
$t$ = Cash flow period (years).
II = initial capital cost required for rainwater or composting system as compared to initial cost required for BAU
$C_t$ = cash flow of evaluated scenario minus the cash flow of BAU scenario for year $t$

## 2.5. *Energy and greenhouse gas emission analysis*

EEAST uses EIO-LCA (Economic Input-Output Life Cycle Assessment) method (Hendrickson et al., 1998) to estimate the life cycle energy and greenhouse gas emissions from each scenario. EIO-LCA model was run for unit price (1$) for all inventory items. The energy and emission values output from EIO-LCA were coded in EEAST (Table 1). These values were multiplied by the total price of the item to obtain the energy and emission for that inventory item. For energy use in the operation phase, EIO-LCA was run only for GHG emission estimation. The energy required by the pump, by the composting tank fan and heater are directly coded in EEAST and are not obtained from EIO-LCA output.

A major limitation of the use of EIO-LCA data is the aggregated sectors. For example, wastewater treatment has greater greenhouse gas emissions than water treatment on a per gallon water treated. However, both of these treatment processes are lumped into one sector in EIO-LCA. Despite its shortcomings, EIO-LCA data are used in EEAST so as to be consistent with its data source and to avoid arbitrary selection of process data. This shortcoming can be overcome by the user since EEAST has the option to over-ride any default values; other data with site specific or more comprehensive datasets can be entered in by the user.

EEAST's calculation of energy and GHG emission PPs were adopted from renewable energy literature. For photovoltaic systems, the calculation of these two terms are given as (Cucchiella and D'adamo, 2012):

$$\text{Energy PP} = E_{\text{in}}/E_{\text{out}} \tag{2}$$

$$\text{GHG PP} = \text{GHG}_{\text{em}}/\text{GHG}_{\text{sv}} \tag{3}$$

where

$E_{in}$ = embodied energy of the system
$E_{out}$ = annual energy output of the system
$GHG_{em}$ = emissions associated with the life cycle PV electricity production
$GHG_{sv}$ = the annual GHGs produced by the local power plant for the power generated by the PV system.

Since there is no energy output from harvested rainwater or composting toilet technologies equation 2 is not applicable to EEAST. Equation 3 is based on the concept of GHG emission 'savings' compared to a BAU technology. (For PV systems the BAU technology is the local power plant.) In EEAST, this concept of 'savings' is applied to both the energy and GHG emission PP calculation. The cumulative (manufacturing and operational energy) energy required (or GHG emitted) by each scenario are calculated for each year and compared to the BAU case. The PP is set equal to the year the cumulative GHG emission or energy demand equals that of the BAU case. A simple division by annual savings (as in equation 2 and 3) was not possible because system components (e.g. filter, tank, toilet) are replaced in different time intervals.

# 3. Sample simulation

## 3.1. *Building description*

A three-story office building housing 100 employees was simulated to illustrate EEAST modeling capabilities. The building is modeled after an existing building in Ohio. The complete input data sheet for the simulated building is shown in Fig. 3. Yellow cells are where the user provides information whereas orange cells are EEAST calculated values. Ohio's average electricity rate and Columbus, Ohio's water and wastewater utility rates were used in operational cost calculations (Table 2).

# 4. Results and discussion

## 4.1. *System design and water use*

For the office building modeled, the toilet water demand ($V_t$ = 19,467 gal/month) was slightly greater than the available

| Possible Scenarios | |
|---|---|
| 1 | Rainwater used to flush toilets, potable water to irrigate |
| 2 | Potable water used to flush toilets, rainwater used to Irrigate |
| 3 | Rainwater used to flush toilets and irrigate |
| 4 | Composting toilets used, potable water used to irrigate |
| 5 | Composting toilets used, rainwater water used to irrigate |

| Expected Collection Data | |
|---|---|
| Precipitation Data | |
| Month | Average Rainfall (in) |
| January | 1.8 |
| February | 1.7 |
| March | 2.7 |
| April | 3 |
| May | 2.9 |
| June | 3.8 |
| July | 3.3 |
| August | 3.3 |
| September | 2.9 |
| October | 2.1 |
| November | 2.8 |
| December | 2.9 |
| Average/month | 2.77 |

http://countrystudies.us/united-states/weather/

| Proposed Building Characteristics | | Units |
|---|---|---|
| Length | 150 | ft |
| Width | 100 | ft |
| Height | 60 | ft |
| Roof Area | 15,000 | sq. ft |
| Stories | 3 | |
| Number of toilets per floor | 10 | |
| Total Toilets | 30 | |

| Anticipated Total Cost of Implementation | |
|---|---|
| Rainwater used to flush toilets | $10,934 |
| Rainwater used to irrigate | $2,539 |
| Rainwater used to flush toilets and irrigate | $22,202 |
| Composting toilets used | $23,210 |

| End Use Data | |
|---|---|
| Outdoor Use | |
| Irrigation Area | Square Feet |
| | 1,000 |
| Indoor Use | |
| Building Type | flushes/person/day |
| | Office |
| Expected Occupancy | Persons/day |
| | 100 |
| Toilet Data | gallons/flush |
| | Standard Toilets |

| Expected City Pressure at Building | |
|---|---|
| Pressure Provided by city to building | psi |
| | 50 |

| Discount Rate | |
|---|---|
| Variable Discount Rate (%) | 3 |

| Summary | | |
|---|---|---|
| Rainfall available for capture | **19,400** | gallons/month |
| Volume required to flush toilets/urinals | 19,467 | gallons/month |
| Volume required to irrigate | 4,052 | gallons/month |
| Total Demand | **23,518** | gallons/month |

| Cistern Specifications | | | | |
|---|---|---|---|---|
| End Use | Volume (gallons) | Height (ft) | Diameter (ft) | Cost |
| Flush Toilets | 19,400 | 10 | 18 | $9,764.13 |
| Irrigate | 4,052 | 10 | 8 | $2,039.20 |
| Both | 19,400 | 10 | 18 | $9,764.13 |

**Fig. 3.** Screenshot of input sheet of EEAST model.

rainwater ($V_r$ = 19,400 gal/month) and much greater than the irrigation water demand ($V_i$ = 4,052 gal/month). Therefore, for scenarios using rainwater to flush toilets, the cistern size ($V_c$ = 19,400 gal for Scenarios 1 and 3) and water savings (Fig. 4) were driven by the available rainwater. For scenarios using rainwater to irrigate, the cistern volume was driven by the irrigation water demand ($V_c$ = 4,052 gal for Scenarios 2 and 5). Since the irrigation water demand was less than the water demand for toilet flushing, the lowest water savings were observed for the use of rainwater for irrigation (Scenario 2, Fig. 4). Using composting toilets and irrigating the lawn with rainwater resulted in the highest water saving.

For the office building modeled, the harvested rainwater could fulfill 100% of the non-potable water demand when the harvested rainwater was used for toilet flushing or irrigation and 82% when used for both. These numbers are higher than what has been reported in the literature. For example, Ward et al. (2010) noted that the water collected from rainwater harvesting systems could fulfill 36% (residential development) and 46% (office building) of the total water supply demand in the U.K.. Racoviceanu and Karney (2010) reported potable water savings of 54% for toilet flushing and lawn irrigation end uses for residential buildings in Toronto, Canada.

**Table 2**
Utility rates used in the sample simulation.

| Utility | Rate ($) |
|---|---|
| Electricity | $0.116 per kWh |
| Potable water | $3.369 per 1000 gal |
| Wastewater treatment | $4.920 per 1000 gal |

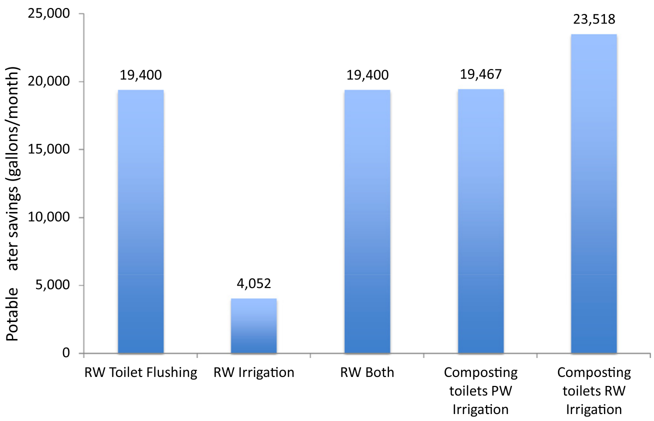


**Fig. 4.** Potable water savings in gallons per month for different scenarios.

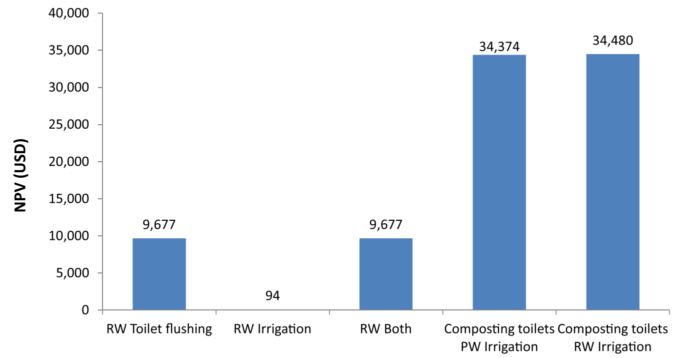


**Fig. 5.** Net present values in dollars for different scenarios.

Proenca et al. (2011) found that the average water savings of 60% could be obtained in public buildings if harvested rainwater was used for toilet flushing purpose in Fluorianopolis, Brazil. A large variation in water saving percentages is found in different studies because of the differences in building type, roof area, water demand, precipitation, and end uses modeled.

### 4.2. Cost

All scenarios had a positive NPV (Fig. 5). Scenarios 1 and 3 had the same NPV values because there was only enough rainwater to flush toilets and not for both toilet and irrigation end uses. As such, for this particular building, scenarios 1 and 3 are essentially the same. The composting toilet scenarios had much higher NPVs than toilet flushing scenarios primarily due to composting toilets using no water. A similar observation was noted by Anand and Apul (2010) who also modeled rainwater harvesting and composting toilet scenarios. However, in that study, the NPV values were much higher (about $250,000 for composting toilets) since that study modeled a different type and a much bigger building with 2,200 occupants.

The cost PPs were quite high for all scenarios because the initial costs of composting toilets and the cistern were very high compared to the utility savings that can be realized from reduced potable water use (Fig. 6). Composting toilets had lower payback periods than rainwater scenarios because they require no water for flushing which reduced their operational cost. The highest payback period was observed when harvested rainwater is used for irrigation (Scenario 2). This is because water savings were minimal in this case and even though a small cistern was used, the percentage contributions from ancillaries such as floating filter and dual piping to the total impact were more compared to other harvested rainwater scenarios.

A large range of payback periods (16–64 years) was observed in this study for this particular building. Prior studies also reported a large range of payback periods (7–61 years) as well (Ward et al., 2010; Zhang et al., 2009; Ghisi and Oliviera, 2007; Khastagir and Jayasuriya, 2011). However, since the objectives and data sources of the other studies and the scenarios they modeled were different, the payback periods reported in the literature cannot be compared directly with our research.

The problem of not being able to compare results is a common issue in LCA. Working to overcome this problem, the methods and assumptions for energy LCA studies were recently harmonized to evaluate the variability observed in energy LCA studies (Sathaye et al., 2011). Many studies had to be excluded in the analysis when assumptions, data sources, and calculation approaches could not be discerned from the papers. Availability of a tool specific for a certain type of analysis (i.e. rainwater harvesting in this case) can help overcome this problem by providing a common platform that researchers can use. EEAST provides a foundational framework for doing harvested rainwater LCA studies. Being an Excel model, it is easy to use and is adjustable to different situations. It accommodates variations in parameters that affect the ultimate payback period. If it can serve as the foundation for future harvested rainwater LCA studies, it will be easier to compare the payback periods from different studies and situations.

### 4.3. Energy and GHG emissions

The energy (10–12 years) and GHG (7–10 years) PPs did not show much variation among scenarios (Fig. 6). Yet, for all scenarios, the cost PP was greater than the energy PP which was greater than the GHG emission PP. When discount rate is set to zero the cost PPs are reduced but are still higher than energy and GHG emission PPs. Anand and Apul (2010) also reported the same finding with respect to cost PPs being highest and GHG emission PPs being lowest. This trend is observed because saving water does not save much in cost due to low utility rates; yet it does save a lot in energy and even more in GHG emissions since water supply and treatment are energy and GHG emission intensive processes. Utility rates can be higher in other locations; and in general, the rates are expected to increase so as to meet the increasing needs of maintaining the infrastructure. When higher utility rates are used, the cost PPs will be lower. In contrast, the energy PPs are expected to be higher in many instances because energy use per liter of water/wastewater treated may be lower. Our review of 36 water and wastewater treatment LCA papers found three (2.8E-06 to 4.8E-03 kWh per L for water treated) and seven (2.83E-09 to 1.32E-02 kWh per L of wastewater treated) orders of magnitude of variation in energy used per liter of water or wastewater treated respectively (Anand and Apul, 2013b). This high variation is due to differences in system boundaries and treatment methods. Since price based EIO-LCA values used in EEAST (4.6E-3 kWh/L water treated; 6.7E-3 kWhr/L wastewater treated) are in the upper part of the range of energy data reported from water and wastewater treatment LCA studies, the energy PPs for scenarios modeled in EEAST will be higher when everything else in the model is kept the same but site specific or process based data are used for energy requirements of the water and wastewater infrastructure.

### 4.4. Comparison among different sanitation alternatives

Ranking of the scenarios based on NPV, water savings, cost PP, energy PP, and GHG emission PP criteria is shown in Table 3. For this

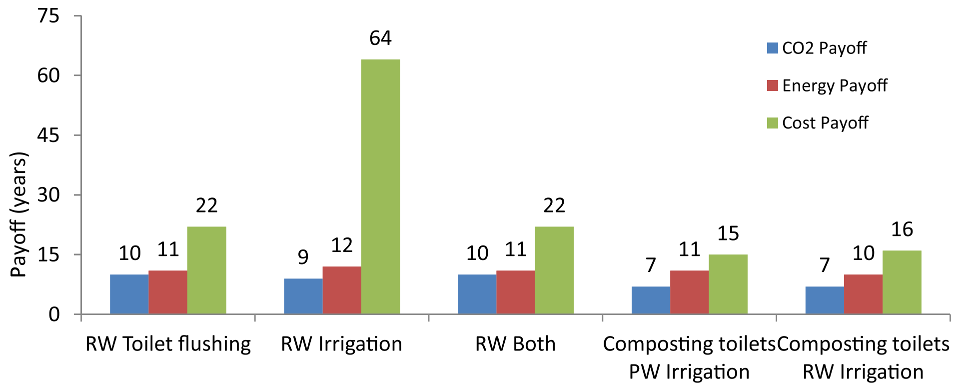


**Fig. 6.** $CO_2$, energy and cost PPs for different scenarios.

particular building with the specific utility rates used in the simulation, the ranking was similar for many of the criteria. The composting toilets performed well in all criteria and Scenario 2 performed worst except in GHG emission PP. However, the GHG emission PP values were quite similar among scenarios. So, in general, it can be said that the use of rainwater for irrigation is the least preferred scenario for this particular building and this scenario should not be a part of the building design. The composting scenarios were most preferable followed by Scenarios 1 and 3. Since there was not enough water for use in both irrigation and toilet flushing and collected rainwater can only meet the need of toilet flushing, Scenarios 1 and 3 were essentially the same for this particular building.

It is interesting to note that there was not a big difference in absolute values but the ranking of Scenarios 4 and 5 were switched off within NPV and cost PP criteria. In cost PP, Scenario 4 (composting toilets, PW irrigation) ranked better than Scenario 5 (composting toilets RW irrigation) because there was no cistern required and the upfront cost was less. However, in the long run, Scenario 5 saved more potable water and led to a smaller NPV. In other buildings the absolute values of cost PP and NPV may show greater differences among scenarios and the decision might need to be made based on cost PP or NPV.

Since many of the EEAST calculations are based on cost, all results except water savings were very sensitive to water, wastewater, and energy utility rates used in the model. When higher utility rates are used in EEAST, the range of PPs observed among scenarios is reduced. In contrast, using smaller utility rates increases both the absolute values and the differences in PPs among scenarios. For example, at 3% discount rate, reducing the water and wastewater utility rates by 30% increased the cost PPs of Scenarios 1 and 3 from 22 to 44 years and the cost PPs of Scenarios 4 and 5 from 15 to 16 to 24 and 26, respectively. The energy and GHG emission PPs are also affected by utility rates in EEAST since EIO-LCA data were used in their estimation. A 30% reduction in water and wastewater utility

**Table 3**
Ranking of scenarios based on different performance criteria.

| Scenarios | NPV | Cost PP | Water savings | Energy PP | GHG emission PP |
|---|---|---|---|---|---|
| Scenario 1 (RW toilet flushing) | 3 (tie) | 3 (tie) | 3 (tie) | 2 (tie) | Last (tie) |
| Scenario 2 (RW irrigation) | Last | Last | Last | Last | 2 |
| Scenario 3 (RW both) | 3 (tie) | 3 (tie) | 3 (tie) | 2 (tie) | Last (tie) |
| Scenario 4 (Composting toilet, PW irrigation) | 2 | 1 | 2 | 2 | 1 (tie) |
| Scenario 5 (Composting toilet, RW irrigation) | 1 | 2 | 1 | 1 | 1 (tie) |

rates increased the energy PPs from a range of 10–12 years to a range of 14–18 years. Similarly, the GHG emission PPs increased from 7 to 10 years to 10–17 years. Of course when utility prices are reduced, the amount of water used can remain the same. However, from an EIO-LCA perspective a reduced cost on any inventory item results in reduced energy and emissions. Users need to understand the limitations of EIO-LCA in running the EEAST model. In addition, since all results are very sensitive to utility rates, it is important to be as exact as possible in cost input to EEAST and particularly the input of local utility rates.

## 5. Conclusions, limitations and future recommendations

Harvested rainwater systems and composting toilets are expected to be an important part of sustainable solutions in buildings. Yet, to this date, a model evaluating their economic and environmental impact has been missing. To address this need, a life cycle based model, EEAST was developed. EEAST compares the BAU case to rainwater harvesting and composting toilet based technologies in buildings using water savings, cost, energy, and GHG emission criteria. The EEAST model can appeal to building designers and owners who may use the model to evaluate different sanitation technologies at the design stage. EEAST can also appeal to researchers since it provides the first available tool for life cycle cost, energy, and emission calculations for harvested rainwater and composting toilet use in buildings.

Since EEAST uses economic input output for the basis of energy and emission calculations, all results are very sensitive to cost data used in EEAST. The limitations of EIO-LCA such as linear output (i.e. lower cost resulting in lower energy and emissions) and aggregated sectors (e.g. water and wastewater treatment modeled as one single sector) are carried over to EEAST model. However, the use of EIO-LCA data prevents the arbitrary selection of process based life cycle inventory data that can vary many orders of magnitude depending on data sources and boundaries selected. The size of the cistern influences the PPs. EEAST uses a monthly rainwater tank sizing method which may overestimate the size and therefore the PPs compared to daily sizing methods.

A sample simulation was presented to illustrate the capabilities of EEAST. For the office building modeled, the cost PPs were greater than energy PPs that were greater than GHG emission PPs. This is primarily due to energy and emission intensive nature of the centralized water and wastewater infrastructure. The sample simulation suggested that the composting toilets may have the best performance in all criteria. However, EEAST does not explicitly model solids management and as such gives composting toilets an unfair advantage compared to flush based toilets.

Future work is recommended for evaluating EEAST for different types of buildings and climates so we better understand how the different scenarios perform in different situations. A sensitivity analysis is also recommended so as to determine how the decision criteria may vary based on both the model input parameters and the modeling approach itself. EEAST could not be verified against other models since no other similar model exists. However, the effect of using other methods such as cistern sizing using daily time step method (instead of monthly average rainfall) and using process based life cycle inventory data (instead of EIOLCA data) can be studied. In addition, the modeling of composting toilets can be improved by considering solids management. Understanding the effects of these different modeling approaches will be helpful in making more informed decisions on when to use harvested rainwater systems and composting toilets in buildings.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2013.09.015.

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