Life cycle cost assessment of a rain water harvesting system for toilet flushing
S. R. Ghimire, D. W. Watkins Jr. and K. Li

ABSTRACT
Rain water harvesting (RWH) has gained popularity as a way of supplementing water supplies for various purposes, including drinking, sanitation and irrigation. This paper presents a methodology of life cycle cost assessment (LCCA) of a unit RWH system (hereafter RWH system) for toilet flushing in an industrial site. The life cycle cost and net present value benefits (NPVB) were estimated for the RWH system and compared with those of a conventional system. For the current system design, the analysis of the life cycle cost of the RWH system indicates negative NPVB for all plausible service lives up to 55 years, mainly because of the initial infrastructure investment costs, operation and maintenance (O&M) costs, and pumping costs for the system. However, sensitivity analysis concluded that an alternative design with no pump, low O&M costs (5%) and 1% tank refill volume may be economically viable given 7 years of service life. The sensitivity analysis also revealed that higher hypothetical water prices ($5/m^3) may lead to positive NPVB after only 5 years of service. Full cost pricing for rainwater harvesting is important for the promotion of sustainable practices and life cycle based system design is critical to make RWH systems economically attractive.

Key words | energy, life cycle cost, rainwater harvesting, water use

INTRODUCTION
Rain water harvesting (RWH) is a technique of capturing rain water for beneficial use before it becomes runoff. In many locations it provides water supplies mostly during the rainy seasons, although sufficient storage could allow use during dry seasons as well. RWH has recently become more popular as a way of supplementing water supplies for drinking, agriculture (Boers & Ben-Asher 1982), and sanitation such as toilet flushing. Small-scale RWH systems have been successfully used to supplement multiple water uses in many industrialized countries including USA, Japan, Singapore and Hong Kong (Thomas 1998; Hatibu & Mahoo 1999; Li et al. 2000; Su et al. 2009), France, Australia and Germany (Gires & Gouvello 2009), the UK (Ward et al. 2010), Korea (Han & Ki 2010), as well as to supplement drinking water in developing countries (Meera & Ahammed 2006). In many industrial applications, an efficient RWH system may not only save water (Hermann & Schmida 1999), but may also save energy and money over its entire life cycle.

The major RWH techniques include in-situ, external, and domestic rainwater harvesting (DRWH). The in-situ technique collects rainwater and stores it directly in the soil on-site, whereas the external technique involves transmission of collected rainwater offsite. Both of these methods are primarily used for agricultural purposes. DRWH involves capturing rain from roof tops, streets and courtyards and storing it in tanks or cisterns (Helmreich & Horn 2009), with potential use for drinking, washing, or sanitation, such as toilet flushing. In general, a DRWH system includes three or four major components: a roof collection system, a storage tank, pipes and fittings, and in some cases a pump.

Although rainwater harvesting has been in practice in one form or another since as early as 4,500 B.C. (Frasier
The definition of rainwater harvesting originates from Geddes (1965), at the University of Sydney (Myers 1975; Boers & Ben-Asher 1982; Sharma et al. 1984). A vast amount of literature has addressed various aspects of RWH systems. Cowden et al. (2008) presented an assessment of DRWH in West African cities using multiple stochastic rainfall models and found DRWH as a potential source of water supply in the region. Kahinda et al. (2007) reviewed the current status of DRWH and suggested a few recommendations for sustainable DRWH achievement in South Africa. Ward et al. (2010) evaluated RWH systems using a mass balance method (Jenkins et al. 1978) and a simple user-defined precipitation/demand method developed by the British Environmental Agency (UEKA 2008), finding that the tank size based on the mass balance method was significantly smaller (and thus had a shorter payback period) than indicated by the simple approach. Memon et al. (2009) presented an analysis of the impact of rainwater harvesting in reducing combined and separate sewer flows, and indicated that the flow reduction was a function of many variables such as storm event, water demand patterns and tank size. Hanson et al. (2009) presented a regression model for estimating the RWH potential as a function of storage capacity in the USA. Others have addressed the application of RWH in stormwater (DeBusk et al. 2010; Forasté & Hirschman 2010; Jensen et al. 2010) and agricultural (Srivastava 2000) best management practices, as well as the quality of harvested rainwater (Nicholson et al. 2010).

Despite growing interest in rainwater harvesting, relatively few studies have addressed life cycle cost analysis (LCCA) of RWH systems. Roebuck & Ashley (2007) proposed a computer-based whole life cycle cost (WLC) modeling tool for domestic, commercial and industrial buildings, including alternative water supply systems. They used the ‘Yield After Storage’ model (Jenkins et al. 1978), and analyzed a UK-based RWH system. Our method is a more site-specific and hydrologically relevant methodology for the LCCA of an industrial RWH system, following US federal guidelines for LCCA (Federal Register 1999, Section 707/Page 30860). Rather than estimating water availability using gross average estimates of rainfall (e.g., annual or monthly), the analysis uses hourly rainfall data over an extended period, combined with estimates of hourly water use obtained from the research site, to simulate water savings and energy use. The step-wise methodology is illustrated for a case study site, where life cycle costs of the RWH system are compared with a conventional water supply for toilet flushing. The method is applicable to other sites where sufficient data are available or may be reasonably estimated.

**System description**

The case study site (Payment & Watkins 2007) is located in Midwestern USA, with an average annual precipitation of 32 in (81.28 cm). The total area of roof collection for the entire industrial site, which hosts approximately 1,160 employees throughout the year, was estimated to be 5 acres (20,234 m²). However, in the current analysis, the total roof area for RWH was considered to be equally distributed to 10 unit RWH systems (i.e., area = 2,023 m² per system).

The RWH system was designed similar to a DRWH system, in which rainwater is captured from the roof area, channelized to a gutter and collected in a storage tank. The sizes of the cylindrical polyethylene storage tanks throughout the site are slightly different, yet a radius of 6.4 ft (2 m) with the volume of 3,500 gallons (13 m³) was assumed for all tanks in this analysis. Despite the different piping and fittings of the tanks, a standard set of appurtenances was assumed based on studies by Solarhaven (2001) and the Texas Water Development Board (2010) (as shown in Table 1).

| Table 1 | Investment cost estimation for a unit RWH system based on Solarhaven (2001), Texas Water Development Board (2010). Total investment cost shown is 2008 equivalent values |

<table>
<thead>
<tr>
<th>Item</th>
<th>Details</th>
<th>Cost($) / unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene storage tank</td>
<td>2,500 Gallons (9,450 L)</td>
<td>970</td>
</tr>
<tr>
<td>Catchment gutters</td>
<td>Materials</td>
<td>350</td>
</tr>
<tr>
<td>All fittings, valves, and pipe</td>
<td>Labor</td>
<td>650</td>
</tr>
<tr>
<td>Install pipes and gutters</td>
<td></td>
<td>600</td>
</tr>
<tr>
<td>Pump</td>
<td>1 unit 0.5 hp (373 Watts)</td>
<td>325</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>2,900</td>
</tr>
<tr>
<td>Adjusted total</td>
<td>Tank of 13,230 L and roof area of 2,023 m²</td>
<td>4,060</td>
</tr>
<tr>
<td>Total investment costs</td>
<td>2008 value</td>
<td>5,700</td>
</tr>
</tbody>
</table>
The entire system consists of 10 separate unit rainwater harvesting systems at 10 different locations. Presented here is the LCCA of a unit RWH system. Each unit system consists of piping, a valve, a storage tank and a pump, and is assumed to collect runoff from an area of 2,023 m² (total area was equally divided among the 10 units). The pump activates to refill the tank from the conventional water supply when a specified refill level is reached (see Figure 1). A total dynamic head of 45 ft (13.7 m) and discharge capacity of 0.5 gpm (0.03 l/s) was assumed for the analysis, based on water demands for toilet flushing and typical operating characteristics of a 0.5-hp pump (RainHarvest Systems 2009). An overall pump efficiency of 75%, which incorporates the pump efficiency and motor efficiency (wire-to-water), was assumed (Ghimire & Barkdoll 2010).

METHOD

A methodology of life cycle cost assessment (LCCA) of a unit RWH system for toilet flushing is demonstrated in a case study in conjunction with a rainwater harvesting model called the Precipitation-Storage Water Budget (PSWB) model (described later). The conventional water cost for toilet flushing for the case analyzed was obtained from analysis of water bills and was utilized to estimate the net present value benefit (NPVB) of the RWH system. The methodology applied herein follows US federal guidelines for LCCA, as discussed below.

Life cycle cost analysis

As defined by Norris (2001), LCCA helps make decisions based upon the comparison of the ‘cost-effectiveness of alternative investments’. The timeline for the comparison for such a decision is normally the economic lifetime of the investment (Fuller & Petersen 1996; Norris 2001). Section 707 of the US President Executive Order 13123 defines life cycle costs as (Federal Register 1999, Section 707/Page 30860):

‘Life-cycle costs’ means the sum of the present values of investment costs, capital costs, installation costs, energy costs, operating costs, maintenance costs, and disposal costs, over the lifetime of the project, product, or measure.’

Moreover, 10 C.F.R. Subpart A, § 436.19, provides the guidelines for LCCA as follows (Justia US Laws 2010, Section 436.19):

‘Life cycle costs are the sum of the present values of:
1. Investment costs, less salvage values at the end of the study period;
2. Non-fuel operation and maintenance (O&M) costs;
3. Replacement costs less salvage costs of replaced building systems; and
4. Energy and/or water costs.’

The investment costs were one-time costs, whereas other costs such as pumping energy costs and O&M costs were annual costs.

As several costs associated with the RWH system were difficult to ascertain, the following key assumptions were made in this analysis:

1. Zero salvage value for all items used.
2. Water use at the industrial site is based on average daily demand for toilet flushing, assuming each worker uses the system 365 days/year.
3. An inflation rate of 3% was used (annual US inflation rates were between 2 and 4% from 2003 to 2009) (USDOL 2010).
4. An investment rate of 8% (effective interest rate of 5%) was assumed to compute the present worth value.
5. A 20-year lifetime for the RWH system components was assumed (based on Gould & Petersen 1999) in a baseline analysis. However, longer service lives are also analyzed in a sensitivity analysis.

![Figure 1](https://iwaponline.com/ws/article-pdf/12/3/309/416829/309.pdf)
Cost equations

The life cycle cost of an RWH system is estimated as the sum of total investment costs, energy costs and non-fuel O&M costs. No replacement cost is considered in this analysis, assumed to be conducted over the system’s service life, at the end of which the salvage value is zero. Total investment cost for the RWH system is specified as follows:

$$IC = TC + GC + FC + LC + PC$$  \hspace{1cm} (1)

where, $IC =$ total investment cost, $TC =$ tank cost, $GC =$ gutter cost, $FC =$ all fittings costs, $LC =$ labor cost, $PC =$ pump cost.

Investment costs for the analyzed site were based on representative literature values, given in Table 1 for the base year of 2008 (Solarhaven 2001; Texas Water Development Board 2010). The tank cost, $TC$, was based on a storage tank of size 2,500 gallons (9,450 L) and a catchment area of 3,000 ft² (279 m²), which was linearly scaled to the actual tank size of 3,500 gallons (13,230 L) for the actual total catchment area of the case study system (2,023 m²). Likewise, the gutter cost, $GC$, all fittings costs, $FC$, labor cost, $LC$, and 0.5-hp (373 Watts) pump cost, $PC$, were also adjusted to the scale of the system. As shown, the total investment cost of the unit RWH system was estimated as $5,700. It is recognized that the costs of an RWH system, particularly labor costs, may vary significantly from location to location. Costs used in this analysis were selected as representative of the Midwestern USA.

The cost of maintenance and non-fuel operation costs also vary greatly from site to site. Cunliffe (1998) suggested a low maintenance cost instead of no maintenance for a general RWH system. A minimal maintenance cost of approximately 10% of total initial investment cost is assumed for this analysis. However, a range of O&M costs (5%, 20%) were also analyzed. Some of the maintenance costs of an RWH system for toilet flushing are for tank de-sludging and cleaning, disposal management, and possibly other maintenance such as mosquito control (Cunliffe 1998).

The primary energy cost associated with the RWH system is for pumping water to refill the tanks. In some cases, city water could supply enough pressure to refill the tank but the studied case included a pump for tank refill. A separate analysis with no pump, in combination with lower refill volume, was also conducted (described later).

The total energy cost for pumping was calculated based on the amount of water pumped for the purpose of toilet flushing (calculated below using a water budget model). Energy cost was calculated using the following equation (Haestad Methods 2003):

$$C = C_i \times Q \times h_p \times p \times t / e_p \times e_m \times e_d$$  \hspace{1cm} (2)

where, $C =$ annual operating cost ($), $Q =$ flow rate (gpm, l/s), $h_p =$ total dynamic head of pump (ft, m), $p =$ price of energy ($/kWh), $t =$ duration that pump is operating at this operating point (hrs), $e_p =$ pump efficiency, %, $e_m =$ motor efficiency, %, $e_d =$ variable-speed device efficiency, (%), $C_i =$ unit conversion factor (1.89 English, 101.9 SI).

Note that the Haestad Equation (2) may be derived directly from the fundamental power equation (Finnemore & Franzini 2002) by incorporating pump efficiency and a unit conversion factor that includes the specific weight of water.

In Equation (2), the flow rate, $Q$, of 0.5 gpm (0.03 l/s) was estimated using the water budget model. The total dynamic head, $h_p$, of 45 ft (13.7 m) was assumed based on a typical efficiency curve for a 0.5-hp pump (RainHarvest Systems 2009) and approximately 20 psi (14 m head) of pressure, as recommended for toilet flushing (Jones & Hunt 2006). The price of energy, $p$, for Michigan commercial use was 9.49 cents per kilowatt hour (based on EIA 2010). The ratio of total pumped water use to the total water use for flushing, 0.7, was used to estimate the duration, $t$, 2,035 h (i.e., 70% of 8 h/day x 365 work days) of pump operation in one year. The ratio was obtained from the PSWB model. Finally, the overall wire-water efficiency of 75% (Ghimire & Barkdoll 2010) incorporated the pump efficiency, $e_p$, and motor efficiency, $e_m$. No variable speed pump was used in this analysis.

Precipitation-storage water budget (PSWB) model

A rainwater harvesting spreadsheet model called the PSWB model was developed to quantify the amount of conventional water use, harvested rainwater use and water volume spilled, which was necessary to estimate the energy cost of
the RWH system. The model is a basic ‘yield after spill’ model (Hanson et al. 2009), with the exception that the tank is filled by pumping water from the conventional water supply whenever the tank reaches a threshold level, initially assumed to be 42% full. In the model, annual rain-water use, $R_w$, for toilet flushing is defined as follows:

$$R_w = \sum_{i=1}^{365} D_i - Q_{\text{pump}}$$

(3)

where, $\sum_{i=1}^{365} D_i = \text{Annual water demand for toilet flushing}$, $Q_{\text{pump}} = \text{Total water pumped annually for toilet flushing}$.

The values of $D_i$ are obtained from field water use data collection and analysis. The total water use in the site was further analyzed based on the number of people working at the site and an average water demand for toilet flushing of 10 gallons per capita per day (pcpd) (Linsley et al. 1992).

$Q_{\text{pump}}$ is calculated by the RWH water budget model as follows:

$$Q_{\text{pump}} = \begin{cases} \sum_{i=1}^{365} (S_{\text{max}} - R_0), & \text{if } P_i < R_0 \\ 0, & \text{if } P_i \geq R_0 \end{cases}$$

(4)

where, $P_i = \text{preliminary storage per hour (ft}^3,$ m$^3)$, defined as:

$$P_i = S_{\text{max}} + Q - D_i$$

(5)

$R_0 = \text{refill volume of tank (ft}^3, \text{m}^3)$ and, $S_{\text{max}} = \text{storage capacity of tank, (ft}^3, \text{m}^3)$, $Q = \text{runoff volume per hour (ft}^3, \text{m}^3)$, defined as:

$$Q = CiA$$

(6)

where, $C = \text{runoff coefficient} = 0.95$, $i = \text{hourly precipitation (ft, m)}$, $A = \text{roof area (ft}^2, \text{m}^2)$ (0.5 acres).

Storage capacity $S_{\text{max}}$ and refill volume $R_0$ are computed from tank dimensions, and hourly precipitation data are obtained from the National Oceanic and Atmospheric Administration database (NOAA 2010). The PSWB model considers a representative annual precipitation pattern for the research area. A 30-year precipitation record (1971–2000) was analyzed to estimate the representative hydrologic year for hourly model input. Based on the analysis, it was found that the mean precipitation for the location was 80.1 cm (31.55 in.) (MSU 2010). The year of 2000, with an annual rainfall of 32.2 in., was selected as representative of the 30-year precipitation record, and hourly values for this year were input to the water budget model.

The PSWB model thus computes the following parameters needed for energy cost estimation: (i) total water used, (ii) total water pumped, (iii) total rainwater used, and (iv) total overflow. The model requires water use for the purpose of toilet flushing, which was estimated based on the number of employees using water from the RWH system and field measurements of total water use (for all purposes) at the industrial site. Approximately 1,160 people used the RWH system at the site, on average, throughout the year. A typical water requirement for reduced toilet flush devices in the USA is 10 gallons per capita per day (pcpd) (Linsley et al. 1992). Thus, the total water use for toilet flushing was estimated as 1,160 person $\times$ 10 (gallons/person-day) = 11,600 gallons/day = 44 m$^3$ day, or 1,320 m$^3$/month. The monthly average total water use at the site, obtained from water utility bills, was 54,800 m$^3$, meaning that about 2% of water use was for toilet flushing.

The monthly water price for the site for the year 2008 was in the range of $68,000 to $141,000, and monthly water use was between 33,490 and 74,869 m$^3$. The average water price for higher consumption ($1.89/m^3$) is lower than for the lower consumption ($2.03/m^3$), conforming to decreasing block water pricing in southeastern Michigan (Walton 2010). Based on the water use and cost data obtained from water bills at the site, a price of $2/m^3$ was used in the analysis.

The NPVB is presented as the metric of decision for selecting an RWH system over a conventional water supply for toilet flushing. The NPVB of an RWH system is estimated as follows:

$$\text{NPVB of RWH system} = \text{NPV of water savings} - \text{NPV of energy for pumping} - \text{Investment cost for RWH} - \text{NPV of operation maintenance}$$

(7)

For energy costs, O&M costs and water cost savings, present values are computed as follows (e.g., ACIPCO 2010):

$$\text{PV} = \frac{(1+i)^n - 1}{i(1+i)^n}$$

(8)
where, $PV = \text{Present value per } \$1 \text{ of annual cost}$, $i = \text{Effective interest (discount) rate (}/100)$, $n = \text{Number of compounding periods (years)}$.

We estimated the effective interest rate (discount rate) (i.e., 5%) based on the inflation rate of 3% and investment rate of 8% (USDOL 2010), which also agrees with suggested discount rate by Lampe et al. (2005). Effective interest (discount) rates, $i$, of 5 to 10% for water utilities are recommended by Lampe et al. (2005) as cited by Roebuck (2007). Applying a methodology called the Capital Asset Pricing Model (CAPM) with recommended parameter values resulted in $i = 9.8\%$ (The New South Wales Government 2007; Fernandez et al. 2011). For details on CAPM, readers are referred to Arditti (1973), The New South Wales Government (2007), Roebuck et al. (2010), and Investopedia (2011).

### RESULTS AND DISCUSSION

We first evaluated the base case scenario (including a pump, a 42% tank refill level and 10% O&M costs), followed by sensitivity analyses corresponding to the following scenarios: (i) no pump, along with the reduced O&M costs; (ii) range of water prices; (iii) range of tank refill levels; and (iv) a combination of no pump, reduced O&M costs and reduced tank refill level.

From the PSWB model, the volume of rainwater use in the unit system in a typical year was estimated to be 400 m³, giving a total annual water cost savings of $800 (at the rate of $2/m³). Thus, it was estimated that the RWH system operated with 70% pumped water and only 30% harvested rainwater (i.e., the ratio of rainwater use to total water use for flushing was 0.30).

Assuming the annual water savings from the RWH system may be estimated as ($2/m³) × annual volume of rainwater use, the total life cycle cost and the NPVB of the RWH system for a service life of 20 years are summarized in Table 2 for the base case, and NPVB values for a range of service life are shown in Figure 2. Note that the replacement costs were set to zero assuming alternatives have the same service life, or equivalent, ignoring the salvage value of each alternative.

From Figure 2, it can be seen that the LCCA of the analyzed RWH system for toilet flushing results in negative net present values for all plausible service lives due to the sunken investment costs, O&M costs and pumping costs. The estimated annual energy cost for the unit RWH system is $100, which is approximately one-eighth of the annual water cost savings ($800) (Table 2). As can be seen from Equation (7), the net water savings for the system is not able to offset the total investment, energy and O&M costs, thereby resulting in the negative NPVBs.

#### Sensitivity analysis

To evaluate the effect of RWH system configuration on NPVB, we first analyzed the system with no pump, assuming that the municipal water supply system provides enough pressure to refill the tank of the RWH system. This scenario was analyzed along with a range of annual O&M costs (5, 10 and 20% of total investment costs). Results showed that elimination of pump investment costs significantly impacted the NPVB of the system. However, the O&M costs did not impact NPVB as much, as depicted in Figure 3. From Figure 3 it can be seen that the system with no pump produced positive NPVB in 10 years for 20% of O&M costs, whereas it took approximately 7 and 8 years of service life for 10 and 5% O&M costs, respectively.

Several other factors, such as social and economic factors (including water price, effective interest rates and salvage value of the system) and system characteristics (such as storage tank refill-volume, pump efficiency and non-uniform toilet flushing rates), may influence the NPVB of the analyzed system. Sensitivity analysis of over-all

### Table 2 | Life cycle cost of the unit RWH system

<table>
<thead>
<tr>
<th>Unit RWH system</th>
<th>Cost ($ (2008 value)</th>
<th>Present value ($ (20 yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment cost</td>
<td>$-5,700</td>
<td>$-5,700</td>
</tr>
<tr>
<td>O&amp;M cost/year</td>
<td>$-600</td>
<td>$-7,200</td>
</tr>
<tr>
<td>Replacement cost</td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>Energy cost/year</td>
<td>$-100</td>
<td>$-1,300</td>
</tr>
<tr>
<td>Water savings</td>
<td>$800</td>
<td>$10,100</td>
</tr>
<tr>
<td>NPV benefit of unit RWH</td>
<td></td>
<td>$-4,100</td>
</tr>
</tbody>
</table>
pump efficiency (for the range of 65 to 85%) was carried out, and results (not presented in this paper) showed that the impact of overall pump efficiency was small for the analyzed RWH system. Toilet flushing rates vary throughout the day, week and year; however, this impact is expected to be minimal for an industrial site that operates year-round and with multiple daily shifts and was not included in the analysis due to a lack of data. The salvage value or residual, i.e., the expected value of a system at the end of its useful life may impact the NPVB of the RWH system. The residual value (salvage value) may be estimated assuming a linear depreciation of total investment costs over the life time. The service life and replacement cost for certain system components such as pump may differ and impact the NPVB of the system. However, it was not presented in this analysis.

Water use rates in residential, commercial and industrial sectors vary considerably by location but generally have been rising faster than inflation due to trends such as privatization and reduction in government subsidies. In the USA, according to a recent survey conducted by the *Circle of Blue* (Walton 2010), a family of four members in Atlanta, GA, pays $72.95/month for a water use rate of 100 gallons per capita per day, while the same size family pays $32.93/month in Las Vegas, NV. Water rate structures such as increasing block, decreasing block, day pricing, water surcharges and other conservation pricing strategies (USEPA 2010) could also influence the economic viability of RWH systems. For example, in Phoenix, AZ, residential water prices for a family of four were $0.5/m³, $0.8/m³, and $0.9/m³ for 50, 100, and 150 gallon per capita per day (gpcpd) water consumption, respectively; whereas the rates in Santa Fe, NM were $1.9/m³, $2.7/m³, and $3.3/m³ respectively, for the same water consumption (based on Walton 2010).

Considering these published water rates from around the USA, along with a hypothetical high water price of $5/m³, the impact of water prices on NPVB of the rainwater harvesting system for toilet flushing were analyzed. From the analysis, it was found that the lower water price ranges for the cities did not have any positive impact on the

![Figure 2](https://iwaponline.com/ws/article-pdf/12/3/309/416829/309.pdf)

*Figure 2* | The net present value benefit (NPVB) of the unit RWH for toilet flushing for the base case with a range of service life.

![Figure 3](https://iwaponline.com/ws/article-pdf/12/3/309/416829/309.pdf)

*Figure 3* | The net present value benefit (NPVB) of RWH for toilet flushing for a range of service life, assuming reduced O&M costs (5, 10, 20% O&M) and no pump (comparison with base case).
NPVB of the analyzed RWH system. However, it was found that higher water prices such as in Santa Fe, NM, and a hypothetical water rate of $5/m^3, would result in positive net benefits after 15 years and 5 years of service life, respectively (Figure 4). This simple analysis indicates that the RWH system studied would have a potential economic benefit in other US cities or in a future with higher water prices.

A sensitivity analysis was done to check whether a specific system characteristic, tank refill-volume, could...
have a significant effect on the NPVB of the analyzed system. It was found that lowering the storage tank refill volume to 1% could improve the NPVB of the system significantly; however, it was not enough of an improvement to result in positive net benefits when pumping costs were included. Further, a sensitivity analysis was conducted to check the impact of effective interest rates (1, 3, 5, 7, 8, and 10%) on NPVB of the RWH system. Lower effective interest rates showed higher rates of improvement in NPVB, mainly after 20 years of service life (Figure 5). Results shown were based on minimal O&M costs (5% of total costs) and optimal refill volume (i.e., 1%).

Finally, a combination of no pump, 5% O&M costs and 1% refill volume was analyzed to identify the combined impact on the NPVB of the analyzed RWH system. The results were based on 5% effective interest rates, the lower limit recommended for water utilities (Lampe et al. 2005 as cited by Roebuck 2007). It was found that the combined scenario would generate positive NPVB after 7 years of service life of the analyzed system (Figure 6).

CONCLUSIONS

The life cycle cost analysis (LCCA) of the analyzed unit RWH system for toilet flushing resulted in negative net present values for all plausible service lives, mainly because the high system investment cost is not recouped through sufficient water savings. Since several factors such as social and economic factors (water use rate and effective interest rate) and system characteristics (storage refill volume, pump characteristics and O&M costs) may have some influence on the NPVB of RWH systems, this paper illustrated a sensitivity analysis on an independent factor from each group (water price and storage tank refill volume). Moreover, we analyzed the system with no pump and reduced O&M costs, finding that this scenario would generate positive NPVB after 7 years of service life. A 1% refill volume was found to be optimal for the analyzed RWH system, revealing that minimum overflow design exists in a RWH system. Finally, a best-case scenario consisting of no pump, 5% O&M costs and 1% tank refill level was analyzed, and results showed that the combined scenario would generate positive NPVB in 7 years of service life of the analyzed system.

The impacts of effective interest rates and pump efficiency on NPVB were illustrated through sensitivity analysis, with the latter factor having insignificant impacts. We also considered inflation rate to estimate the effective interest rate. Sensitivity analysis further revealed that the lower water price range for select US cities does not produce a positive NPVB for the analyzed site; however, higher water prices such as those in Santa Fe, New Mexico, let to positive net benefits. A hypothetical higher water price of $5/m$\textsuperscript{3}$ was found to result in a positive NPVB for the analyzed unit RWH system after a service life of only 5 years.

This analysis should prove useful for planning at similar sites where RWH systems are being considered as alternatives to conventional water systems. Key design recommendations are to develop RWH system to utilize as much rainwater as possible while minimizing the initial investment and annual operating costs (eliminating or at least reducing pumping, and reducing the O&M costs). One recommendation is not to completely refill the tank with pumped water each time it reaches a low level but to maintain a minimum reserve level through pumping, so that pumping is minimized and space is reserved to capture rainwater. Additional analysis would be needed to determine the optimal reserve level, considering pump characteristics in greater detail.

It needs to be acknowledged that the RWH system provides benefits not captured in this LCCA analysis. For instance, the system may contribute to the Leadership in Energy and Environmental Design (LEED) certification, and serve as an example of (potentially) sustainable building design. The RWH system may also provide benefits through mitigation of stormwater runoff, although these are probably small for the case study presented herein. A separate study on life cycle assessment (LCA) would provide an estimate of environmental benefits; however, this was beyond the scope of this paper. Finally, the costs and benefits of the RWH system are site-specific; in other locations, particularly in arid regions, the benefits of a similar system may be significantly higher due to water scarcity and potential ecosystem benefits of water savings. It is also acknowledged that the residual (and terminal/scrap/salvage) value of the system would also impact the accuracy of the estimates, although it was not included in the current analysis. However,
a linear depreciation of total costs may be used to estimate the residual costs, when desired (RICS 2011). Moreover, the costs including the salvage value and O&M costs may easily be altered to estimate the LCC of similar RWH site to evaluate the economic viability of the system. The O&M cost of the system was based on literature, which also agrees with the guideline suggested by RICS (2011). The RICS provides the sources of costs-related data for whole life costing (WLC), including the data available from manufacturers, suppliers and specialist contractors, structured and unstructured historical data. The analysis presented herein was based on the costs of an RWH system located in a US city, but the analysis procedure is recommended for preliminary design of any RWH system being considered as an alternative to conventional water systems.

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REFERENCES


Norris, G. A. 2001 Integrating life cycle cost analysis and LCA. Int. J. LCA 6 (2), 118–120.


Sharma, P. N., Neto, F. B. A., Porto, E. R. & Silva, A. D. S. 1984 Runoff induction for agriculture in very arid zones of the
Northeast of Brazil. Pesquisa Agropecuária Brasileira 19 (8), 1011–1019.


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