# Supporting information

**A Spatial Life Cycle Cost Comparison of Residential Greywater and Rainwater Harvesting Systems**

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# 1. Study Site Description – Cities

## 1.1 Geographic Distribution

For this Study, 12 Cities were chosen from the 10 EPA regions to obtain a good representation of the socio-economic and environmental characteristics of the U.S. cities (Figure S1).

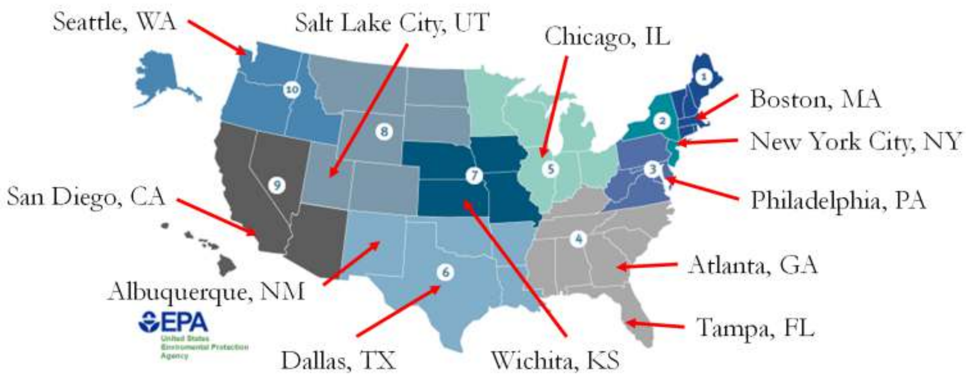


Figure S1 City spatial locations throughout the U.S.

## 1.2 Current Utility Rates

For each city that was selected for this study, water and electrical utility rates were collected from municipality websites for each city and the U.S. Energy Information Administration (EIA, 2018) (Table S1).

Table S1 Sources of current utility rates in cities investigated

| **City, State (Abbrev.)** | **Sources** |
|---|---|
| Boston, MA (BOS) | https://www.bwsc.org/residential-customers/rates |
| New York (NYC) | https://www1.nyc.gov/nyc-resources/categories.page |
| Philadelphia, PA (PHIL) | https://www.phila.gov/water/PDF/RatesCharges_effective_7-1-2016.pdf |
| Atlanta, GA (ATL) | https://drive.google.com/file/d/1KdbW1uTS5iHjwtp4Vr3dYGyvy4v7DTTm/view |

| | |
|---|---|
| Tampa, FL (TPA) | https://www.tampagov.net/info/utilities |
| Chicago, IL (CHI) | https://www.chicago.gov/city/en/depts/fin/provdrs/utility_billing.html |
| Dallas, TX (DAL) | https://dallascityhall.com/Pages/default.aspx |
| Albuquerque, NM (ABQ) | http://www.abcwua.org/ |
| Wichita, KS (ICT) | https://www.wichita.gov/PWU/Pages/default.aspx |
| Salt Lake City, UT (SLC) | https://www.slc.gov/utilities/pay-my-bill/current-rates/ |
| San Diego, CA (SD) | https://www.sandiego.gov/public-utilities/customer-service/water-and-sewer-rates/water |
| Seattle, WA (SEA) | http://www.seattle.gov/utilities/businesses-and-key-accounts/drainage-and-sewer/drainage-rates/rate-schedule |

## 2. Building Description

According to real-estate trends, U.S. Census data, Open Data Network populations densities, the average single-family and multi-family (apartment style) occupants, building size, and lawn size can be estimated (Table S2). For demand of potable water and estimated residential indoor water consumption, the Alliance for Water Efficiency and the U.S. Geological Survey (HWW, 2018; USGS, 2016) were utilized. For GWR, it is assumed that for daily water use per person is about 2.2 loads of laundry per week (0.057 $m^3$/ load), 0.65 $m^3$ of water (approximate 10-15 min. shower), and sink washing is about 0.023 $m^3$ of water. Toilet flushing contributes to 0.072 $m^3$ per person.

Table S2 Building characteristics for single-family and multi-family households

| Variable | Single-family | Multi-family | Sources |
|---|---|---|---|
| Number of tenants per building | 3 | 15 | https://www.opendatanetwork.com/dataset/data.wa.gov/xv4y-f2k2 |

| | | | |
|---|---|---|---|
| Lawn Size ($m^2$) | 526 | 162 | http://eyeonhousing.org/2016/07/lots-in-2015-are-smallest-on-record/ https://www.planning.org/pas/reports/report165.htm |
| Roof Size ($m^2$) | 116 | 427 | https://www.rentcafe.com/blog/rental-market/real-estate-news/us-apartment-size-2016/ |
| Number of Units | | 5 | |
| building height (m) | 6 | 6 | http://www.ctbuh.org/HighRiseInfo/TallestDatabase/Criteria/HeightCalculator/tabid/1007/language/en-GB/Default.aspx/m/ |
| | | | https://www.rentcafe.com/blog/rental-market/us-average-apartment-size-trends-downward/ |

# 3. Water Balance Simulation

## 3.1 System Dynamic Model

Using daily precipitation records over a ten-year period, a system dynamic model was developed using Vensim® software. Yield-after-spill (Fewkes & Butler, 2000) operating rules were incorporated to determine the volume collected, stored, spilled, and used throughout the simulation. Evaporation of water from the tank was not considered in this study.

$$O_t = \begin{cases} V_{t-1} + I_t - T \\ 0 \end{cases}$$

$$Y_t = \begin{cases} D_t \\ V_{t-1} \end{cases}$$

$$V_t = V_{t-1} + I_t - O_t - Y_t$$

Where $O_t$ is overflow from the tank storage, $m^3$/day; $I_t$ is the inflow of water collected from the current day, $m^3$; $V_{t-1}$ is the storage tank volume from the previous day, $m^3$; $T$ is the tank storage capacity, $m^3$; $Y_t$ is is total yield for the current day, $m^3$; and $D_t$ is the demand for the current day, $m^3$.

## 3.2 Daily Precipitation Records

Daily Precipitations records were downloaded from NOAA (NOAA, 2018) Global Historic Climatology Network-Daily (GHCND) database. Airport observation stations were selected for consistency among the cities (Table S3). Daily precipitation was incorporated in both GWR and RWH models utilized for this study. Annual precipitation data is shown for all cities investigated in Table S4.

Table S3: List of observation stations utilized for precipitation records for the cities selected

| Region | Observed Stations |
|---|---|
| R1- BOS | GHCND:USW00014739: BOSTON, MA US |
| R2- NYC | GHCND:USW00094789: JFK INTERNATIONAL AIRPORT, NY US |
| R3- PHIL | GHCND:USW00013739: PHILADELPHIA INTERNATIONAL AIRPORT, PA US |
| R4- ATL | GHCND:USW00053863: ATLANTA DEKALB PEACHTREE AIRPORT, GA US |
| R4- TPA | GHCND:USC00088782: TAMPA BAY AREA WEATHER FORECAST OFFICE, FL US |
| R5- CHI | GHCND:USW00014819: CHICAGO MIDWAY AIRPORT, IL US |
| R6- DAL | GHCND:USW00013960: DALLAS FAA AIRPORT, TX US |
| R6- ABQ | GHCND:USW00023050: ALBUQUERQUE INTERNATIONAL AIRPORT, NM US |
| R7- ICT | GHCND:USW00003928: WICHITA DWIGHT D. EISENHOWER NATIONAL AIRPORT, KS US |
| R8- SLC | GHCND:USW00024127: SALT LAKE CITY INTERNATIONAL AIRPORT, UT US |
| R9- SD | GHCND:USW00023188: SAN DIEGO INTERNATIONAL AIRPORT, CA US |
| R10-SEA | GHCND:USW00094290: SEATTLE SAND POINT WEATHER FORECAST OFFICE, WA US |

Table S4: Annual precipitation and irrigation periods for each city investigated in this study.

| City, State (Abbrev.) | Annual Precipitation *cm/yr* | irrigation periods (°C) |
|---|---|---|
| Boston, MA (BOS) | 109.15 | June - September |
| New York (NYC) | 111.17 | May - September |
| Philadelphia, PA (PHIL) | 118.23 | May - September |
| Atlanta, GA (ATL) | 118.11 | April - October |
| Tampa, FL (TPA) | 129.03 | All Year |
| Chicago, IL (CHI) | 92.85 | May - September |
| Dallas, TX (DAL) | 96.60 | April - October |

| | | |
|---|---|---|
| Albuquerque, NM (ABQ) | 20.49 | May - September |
| Wichita, KS (ICT) | 93.27 | May - September |
| Salt Lake City, UT (SLC) | 37.72 | May - September |
| San Diego, CA (SD) | 21.95 | April - November |
| Seattle, WA (SEA) | 97.21 | June - August |

## 3.3 Irrigation Periods and Landscape Water Requirement (LWR)

Average monthly temperatures and monthly evapotranspiration data (ET) were utilized to determine the irrigation periods for each city investigated (Table S5 and Table S6). Based on the average monthly temperatures and the ideal growing season for lawn maintenance (16 and 32 degrees Celsius).  WaterSense Water Budget Tool v1.02 (EPA, 2018) form the EPA was incorporated to determine the LWR for each household in each city.

- Average Monthly Temperatures: https://www.usclimatedata.com/
- Average Monthly ET values: http://wcatlas.iwmi.org/
- Lawn care maintenance
  - http://fescue.com/info/whentoplant.html#.WgoB9GhSxaQ
  - https://www.pennington.com/resources/grass-seed/lawn-maintenance/month-by-month-care-calendar-for-warm-season-lawns
  - http://www.american-lawns.com/grasses/grasses.html
  - https://www.todayshomeowner.com/spring-lawn-care-guide/
  - http://www.landscapedevco.com/Practices_for_Watering_Lawns.pdf

Table S5: Average monthly temperatures for each city investigated. Red text identifies the months in which irrigation occurs for that given location.

| **City, State (Abbrev.)** | **AVERAGE MONTHLY TEMPS (F)** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan. | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Boston, MA (BOS) | -1.6 | 0 | 3.3 | 9.4 | 14.4 | **20** | **22.8** | **22.8** | **18.3** | 10 | 7.2 | 1.7 |
| New York (NYC) | 0.5 | 2.2 | 6.1 | 11.1 | **17.2** | **22.2** | **25.6** | **24.4** | **20.5** | 14.4 | 8.8 | 3.3 |
| Philadelphia, PA (PHIL) | 0.5 | 2.2 | 6.7 | 12.2 | **17.8** | **23.3** | **25.6** | **25** | **20.5** | 14.4 | 8.8 | 3.3 |
| Atlanta, GA (ATL) | 6.1 | 7.8 | 11.7 | **16.1** | **21.1** | **25** | **26.1** | **25.6** | **22.8** | **17.2** | 11.1 | 7.2 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tampa, FL (TPA) | **16.1** | **16.7** | **19.4** | **22.2** | **26.1** | **28.3** | **28.3** | **28.3** | **27.8** | **24.4** | **20.5** | **17.2** |
| Chicago, IL (CHI) | -3.9 | -1.6 | 3.3 | 10 | **16.1** | **22.2** | **24.4** | **23.3** | **18.9** | 12.8 | 5 | -1.1 |
| Dallas, TX (DAL) | 6.7 | 8.9 | 13.3 | **17.8** | **22.2** | **26.1** | **28.3** | **28.3** | **25** | **18.9** | 13.3 | -13.8 |
| Albuquerque, NM (ABQ) | 2.8 | 5.6 | 8.9 | 13.3 | **18.9** | **23.9** | **25.6** | **24.4** | **21.1** | 14.4 | -13.8 | 2.2 |
| Wichita, KS (ICT) | 0 | 2.8 | 8.3 | 13.8 | **18.3** | **23.9** | **26.6** | **26.7** | **21.7** | 15 | -13.8 | 1.1 |
| Salt Lake City, UT (SLC) | 0 | 3.3 | 7.8 | 11.1 | **16.7** | **22.2** | **26.6** | **25.6** | **20** | 13.3 | 6.1 | 1.1 |
| San Diego, CA (SD) | 13.8 | 14.4 | 15.5 | **16.7** | **17.8** | **19.4** | **21.1** | **21.7** | **21.7** | **19.4** | **16.7** | 13.9 |
| Seattle, WA (SEA) | -15.5 | 6.1 | 7.8 | 10.5 | 13.3 | **16.1** | **17.2** | **17.8** | 15.6 | 11.7 | 7.8 | 6.1 |

Table S6: Average ET values for each city investigated

| **City, State (Abbrev.)** | **AVERAGE ET VALUES (in/month)** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan. | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Boston, MA (BOS) | 1.31 | 1.44 | 2.49 | 3.67 | 4.82 | 5.59 | 6.27 | 5.33 | 3.76 | 2.71 | 1.85 | 1.37 |
| New York (NYC) | 1.48 | 1.71 | 2.97 | 4.24 | 5.36 | 6.27 | 6.92 | 6.15 | 4.49 | 3.27 | 2.20 | 1.62 |
| Philadelphia, PA (PHIL) | 1.38 | 1.63 | 2.97 | 4.22 | 5.36 | 6.19 | 6.55 | 5.81 | 4.23 | 2.93 | 2.03 | 1.48 |
| Atlanta, GA (ATL) | 1.90 | 2.45 | 3.94 | 5.19 | 5.97 | 6.41 | 6.36 | 5.79 | 4.50 | 3.59 | 2.48 | 1.98 |
| Tampa, FL (TPA) | 2.93 | 3.31 | 4.86 | 6.08 | 7.04 | 6.59 | 6.42 | 6.04 | 5.23 | 4.72 | 3.39 | 2.89 |
| Chicago, IL (CHI) | 0.88 | 1.06 | 2.17 | 3.59 | 5.31 | 6.40 | 6.51 | 5.52 | 4.00 | 2.81 | 1.51 | 0.88 |
| Dallas, TX (DAL) | 2.27 | 2.73 | 4.52 | 5.60 | 6.48 | 7.81 | 9.17 | 8.49 | 5.98 | 4.63 | 3.12 | 2.37 |
| Albuquerque, NM (ABQ) | 2.09 | 2.83 | 4.99 | 7.06 | 9.17 | 10.51 | 9.80 | 8.34 | 6.60 | 4.99 | 2.95 | 1.99 |
| Wichita, KS (ICT) | 1.42 | 1.82 | 3.45 | 4.97 | 6.15 | 7.55 | 9.08 | 8.09 | 5.43 | 4.02 | 2.15 | 1.40 |
| Salt Lake City, UT (SLC) | 0.98 | 1.46 | 2.97 | 4.57 | 6.52 | 8.56 | 10.50 | 9.17 | 6.24 | 3.65 | 1.72 | 0.98 |
| San Diego, CA (SD) | 2.79 | 3.04 | 3.99 | 4.72 | 5.00 | 4.98 | 5.74 | 5.58 | 4.67 | 3.94 | 3.06 | 2.66 |
| Seattle, WA (SEA) | 0.92 | 1.23 | 2.09 | 2.95 | 4.11 | 4.75 | 5.49 | 4.74 | 3.06 | 1.66 | 1.00 | 0.83 |

## 3.4 System Dynamics Simulation

Based on YAS, water balance of the RWH and GWR systems' simplified structure are illustrated in Figure S2. Each model is broken down into three part: Water balance (YAS), Demand of water supply, and cost-benefit.

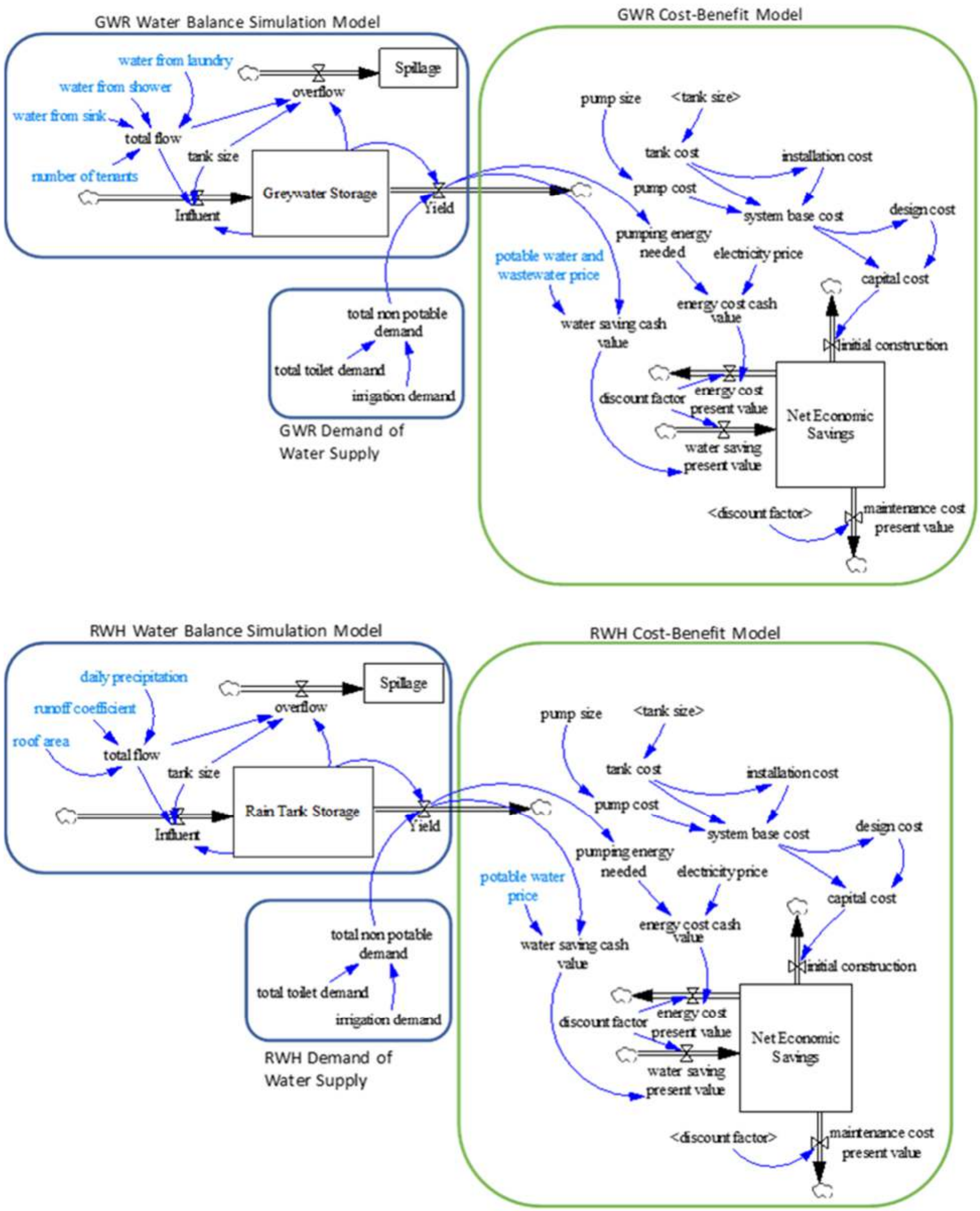


Figure S2: A simplified diagram of the stock and flow components that contribute to the SDM of GWR (top) and RWH (bottom). Aspects of the model that are in boxes are stocks, while the arrows valves are flows. Variables without boxes are auxiliary variables, and blue arrows that connect to other auxiliary variables are connectors. The light blue variables are components that are involved in both the cost-benefit model and the water balance simulation model.

# 4. System Life Cycle Inventory

## 4.1 Tank size

Cost estimates for storage tanks were obtained from an inventory provided by Rain Harvest Systems (Rain Harvest Systems, 2017; Supplies, 2017)(https://www.rainharvest.com/shop/). Above ground tanks were considered for both plastic and steel material. Only plastic tanks were used in this study. Figure S3 was used to plot the tank capacity versus the cost. The linear correlation between the varying tank sizes was used to assume an average cost for any size tank.

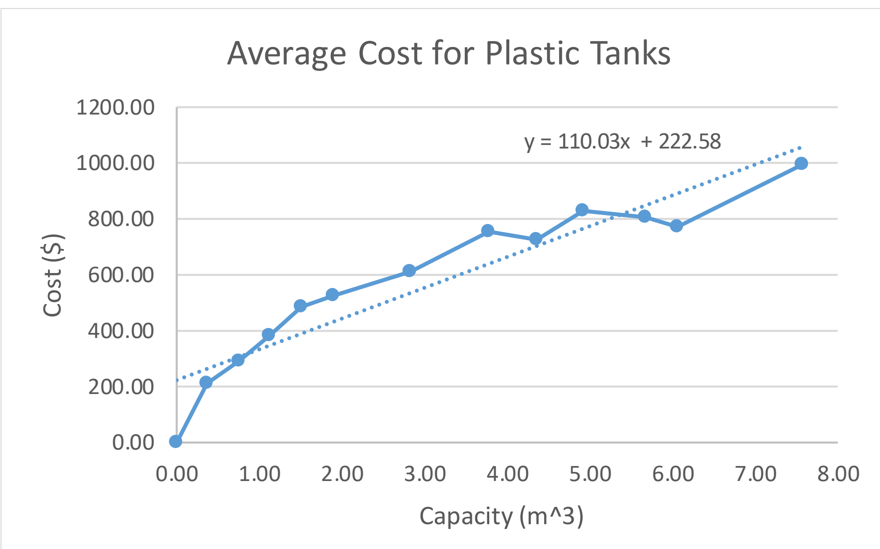


Figure S3 Graph of cost estimates for a range of tank sizes for plastic tanks

## 4.1 Pump Size

Similar approach to the analysis of tank size, cost estimates were collected from RS Means and EPA Best Management Practices Tool for cistern sizing (WRF, 2018) and extrapolated to determine the correlation between pump size and cost. Figure S4 was used to plot the pump size versus the cost. The linear correlation between the varying tank sizes was used to assume an average cost for any pump size based on power.

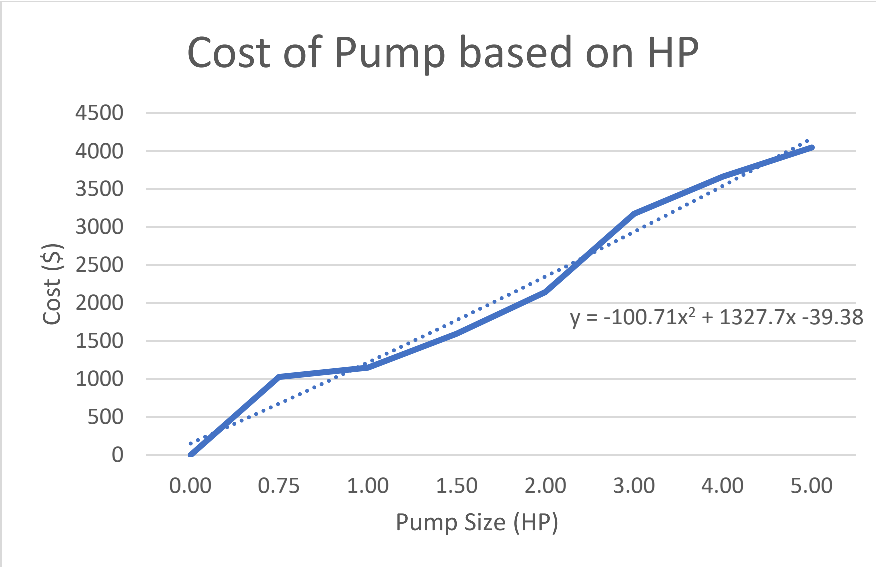


Figure S4 Graph of cost estimates for a range of pump sizes.

## 4.2 Operation and Maintenance Cost

Costing information for annual maintenance on GWR and RWH systems had a wide range of costs from a variety of sources. Based on information from WERF (WRF, 2018) (https://www.waterrf.org/) and EPA (EPA, 2018) (https://www.epa.gov/sites/production/files/2015-11/documents/rainharvesting.pdf ), for RWH the costs associated with maintenance primarily involves keeping gutters and roof free of debris and inspection/replacement of filters, an average of $100/year for maintenance (CTCN, 2018; Fewkes & Butler, 2000; IWMI, 2018; Rahman et al., 2012). For GWR system with household size MBR treatment, inspection/replacement of filters and tank inspection/disinfection were the major aspects considered for maintenance costing. The annual maintenance cost for this technology varies greatly between previous studies and an average of the previously reported values, $200/year was used in this study (EPA, 2016; GWA, n.d.; Marteleira & Niza, 2018).

## 4.3 Construction, Installation, and Design Cost

WERF LID Cistern tool was utilized to calculate the costs for design and installation phases of RWH and GWR systems. Table S7 provides a summary of allocations of costs.

Table S7 Summary of components that make up the capital costs for initial construction

| Variable | Cost equation |
|---|---|
| Tank Cost | - |
| Installation Cost | 60% of Tank Cost |
| System Base Cost | Sum of Tank Cost, Pump Cost, and Installation Cost |
| Design Cost | 8% of System Base Cost |
| Capital Cost | Sum of Design Cost and System Base Cost |

## 5. Sensitivity Analysis

We conducted a sensitivity analysis to investigate the influence of each individual variable on the life cycle cost of the RWH and GWR systems. The same test ranges as those used in the Monte Carlo analysis were adopted for the sensitivity analysis. A sensitivity index was calculated for each input change using Equation 14 (Song et al., 2019).

$$S = \frac{\frac{O_i - O_b}{O_b}}{\frac{I_i - I_b}{I_b}} \qquad \textit{Equation 14}$$

where $O_i$ is the output value after the input was changed; $O_b$ is the base output value; $I_i$ is the altered input value; and $I_b$ is the original input value. Inputs were considered “highly sensitive” if $|S| > 1.00$.

The tested model is sensitive to wastewater fee, potable water fees, discount rate, flushing water demand, runoff coefficient (RWH only), roof area (RWH only), and number of tenants under a 20% increase/decrease in variable range for both GWR and RWH (Table 5). It is not sensitive to factors such as energy fee, building height, lawn size, irrigation efficiency, pumping efficiency, number of loads per day (GWR only), laundry volume (GWR only), shower volume (GWR only), and sink volume (GWR only). This indicates that more accurate data and estimations need to be obtained and investigated for variables that are more sensitive: number of tenants, potable water fee, wastewater fee, runoff coefficient, roof area, and flushing water demand.

**Table 5** Sensitivity analysis results for each variable included in Monte Carlo simulation for GWR model at 2 $m^3$ tank size for the city of Boston, MA over a 10-year period for a multi-family household. Discount rate was analyzed with the base value as 0.008%, differing from the originally analysis that set the discount rate as 0%.

| Variable | Base Value | Test Range | Sensitivity Index | | | |
|---|---|---|---|---|---|---|
| | | | GWR | | RWH | |
| | | | Minimum | Maximum | Minimum | Maximum |
| **Building height (m)** | 5.0 | [4.0, 6.0] | 0.00 | 0.00 | 0.00 | 0.00 |
| **Energy fee ($/kWh)** | 0.199 | [0.159, 0.239] | 0.00 | 0.00 | 0.00 | 0.00 |
| **Irrigation efficiency** | 0.75 | [0.600, 0.900] | 0.00 | 0.00 | 0.00 | 0.00 |
| **Lawn size ($m^2$)** | 152 | [122, 182] | 0.00 | 0.00 | 0.00 | 0.00 |
| **Flushing water demand ($m^3$/person/day)** | 0.072 | [0.057, 0.086] | 0.65 | 0.00 | 0.86 | 0.49 |
| **Number of loads per day ($m^3$/person/day)** | 0.32 | [0.256, 0.384] | 0.00 | 0.00 | - | - |
| **Laundry volume per day ($m^3$/person/day)** | 0.056 | [0.045, 0.068] | 0.00 | 0.00 | - | - |
| **Shower volume per day ($m^3$/person/day)** | 0.065 | [0.052, 0.078] | 0.00 | 0.00 | - | - |
| **Sink volume per day ($m^3$/person/day)** | 0.022 | [0.018, 0.027] | 0.00 | 0.00 | - | - |
| **Pump Efficiency** | 0.5 | [0.400, 0.600] | 0.00 | 0.00 | 0.00 | 0.00 |
| **Roof Area ($m^2$)** | 427 | [342,512] | - | - | 1.49 | 1.11 |
| **Potable Water fee ($/$m^3$)** | 2.19 | [1.75, 2.63] | 0.52 | 0.51 | 2.75 | 2.75 |
| **Wastewater fee (($/$m^3$)** | 2.97 | [2.38, 3.56] | 0.69 | 0.69 | - | - |
| **Number of Tenants** | 15 | [12, 18] | 0.61 | 0.00 | 0.81 | 0.50 |
| **Runoff Coefficient** | 0.8 | [0.640, 0.960] | - | - | 1.49 | 1.11 |
| **Discount Rate** | 0.008% | [0.000%, 0.016%] | 0.87 | 0.68 | 2.14 | 1.79 |

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