

Performance assessment of citywide rainwater harvesting strategies in New York City

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Abstract

Many cities, in both developed and developing countries, are seeking solutions for increased freshwater demands, higher flooding frequencies, uncertain precipitation patterns, and aged water infrastructures. Rainwater harvesting (RWH), a traditional and reviving decentralized infrastructure may address many of these problems simultaneously. Yet, the performance of RWH has mostly been examined from the perspective of the individual building owner, without accounting for the wider implications of a large-scale implementation. Here we provide a systematic analysis of the water service, energy use, and economic costs of city-wide application of RWH in New York City (NYC), from the perspectives of the building owner and the city manager, respectively. Distinct RWH systems for the city's 1.1 million buildings were designed, tailored to the building characteristics based on hourly rainfall data between Jan-01-2000 to April-08-2018. Under various policy scenarios, citywide RWH implementation in NYC can meet 22-40% of the city's non-potable water demand. Strategic public-private partnership that finances cost-beneficial and cost-effective RWH applications in 83% of all buildings in NYC can meet 22% of the city's non-potable water demand while halving the costs estimated for a filtration alternative.

Keywords

Water management, Rainwater harvesting, Green infrastructure, Urban runoff reduction, Urban hydrology, Potable water savings

Introduction

Challenges regarding increased freshwater demand[1–4], inundation problems[5], uncertain precipitation patterns[6,7], and aged water infrastructures[8–10] are faced by cities globally. These issues may be simultaneously mitigated using a traditional[11,12] and reviving technology, rainwater harvesting (RWH)[13–15]. Currently, RWH has been mainly implemented and studied on a small scale, from a single family house[6,16–19] to a neighborhood with several blocks[2,5,20–23]. If implemented on a city scale, RWH may enable additional and greater water and non-water merits, yet this speculation has not been systematically tested[24–26]. As such, this research intends to provide a systematic investigation of the main water and economic effects of a citywide implementation of RWH.

Rooftop rainwater harvesting is the most common form of urban RWH [27–30]. At a sub-city scale (i.e., from a single family house to a neighborhood with several blocks), existing studies suggest RWH systems can reduce non-potable water demand by 2-100%[5,8–10,23,31,32], and roof runoff by 20-100%[4,17,27,31]. The wide ranges are attributable to differences in local precipitation patterns[3,33], the type and magnitude of water demand for substitution [3,9,18,34], building type[34–36], cistern size[1,9,18,37], and contributing roof size[3,9,38]. In a combined sewer system, where rain events can take up the sewer capacity, RWH can abate the treatment needs wastewater influents, mitigating the risks of combined sewer overflows (CSO) [10]. The ability to provide multiple water services makes RWH a plausible infrastructure alternative in cities with different water managerial priorities[1,8,9,15,19,27,39].

Regarding the non-water implications, existing sub-city studies focused on quantifying the energy use[30,40,41] and economic cost-benefit ratios[1,2,9,42] as additional determinants of RWH's performance. Energy use of RWH ranges from 0 to 4.9 kWh/m³, mainly affected by tank location[29], cistern size[14] and the type of pump used[14,40,41]. According to existing studies, RWH systems tend to have a higher energy demand on a unit basis than centralized water supply [13] (0.4 to 2.5 kWh/m³ [40,41,43]). A study comparing RWH to the municipal water supply (MWS) in Washington D.C. included the energy consumption related to wastewater treatment and found RWH consumes 5% less energy than the MWS[14].

The economic cost-effectiveness of RWH is uncertain as well. Most studies reported poor benefit-cost ratios (benefits divided by costs, see Methods)[4,9,39,44], or long payback periods[13,45] of RWH. Design dimensions are critical for RWH's cost-effectiveness[3,42]. Studies found the benefit-cost ratio of RWH could be improved by careful tank size selection [1,3], with one study reporting benefit-cost ratios increasing by 24%[44]. Over and under dimensioning a tank highly influences the BC-ratio[17,44]. Big roof areas[29] and higher occupation rates[3,42,46] affect RWH performance, it is predicted that bigger non-residential buildings with higher occupation rates will be more cost-effective than single-family buildings[13,14,47].

In most of the existing literature, the costs of saved potable water are compared to the costs of installing and maintaining a new RWH system[1,2,13,39]. Accounting for stormwater fees[9] and energy costs[4,9,29] may lift the benefit-cost ratios of RWH to over 1.0[29]. Existing studies also found the water and non-water implications of RWH to vary across different sub-city scales [3,6,8,13,48], suggesting RWH implemented at a city scale may be more cost-effective and deserves further research [5,15,20,39,42].

So far, only a few studies have studied RWH on a city scale[2,8,14,35,49,50]. The rainwater harvesting potential in four major Australian and four major U.S. cities have been assessed. Non-potable water demand reductions of 7-10% were reported in Australia[4], and reductions of 49-81% of the toilet flushing demand in the U.S. Increasing the demand with 100% caused a reduction from 93% to 57% in the toilet water saving efficiency for New York City(NYC)[27], showing the importance of water demand. These studies are based on a single average water demand value and only one RWH system design, leading to a crude assessment. Other studies focused on a single city and determined RWH potentials for cities like New York[8] and Dhaka city (Bangladesh)[22]. They however only considered residential buildings[8,22]. Implementing RWH on all roof types might reduce the pressure on current water infrastructure, as well as affecting the cities hydrology, in line with the new Chinese initiative of sponge cities[51].

Here we performed a systematic RWH analysis on the water services and life-cycle economic implications of RWH in New York City, considering the dimensions, purpose, and occupation of all 1.1 million buildings in the city. Two RWH configurations were engineered for every building, of which the performance was assessed under 18 years of hourly rainfall data. The first RWH configuration, referred to as ‘owner sized RWH’, is designed for favorable benefit-cost ratio over the RWH lifespan, considering the cost of installing the RWH system vs. the decreased water and sewer rates. In the second configuration, ‘city-sized RWH’, tanks are designed for the maximum water saving potential, as water saving is the important benefit from the citywide perspective. NYC is chosen due to the challenges faced with centralized water system expansion[52,53], the risk of flooding and CSO’s (NYC is a coastal city)[54,55], and the highly supportive attitude towards green initiatives[56].

It was revealed that RWH can provide 22-40% of NYC’s non-potable water demand and if strategically implemented, with a cost-effectiveness of more than two times the current filtration alternative. Outsourcing profitable RWH implementation to building owners, and instituting cost-effectiveness thresholds for RWH qualification, have shown to increase the cost-effectiveness of city-wide RWH strategies.

Results

Owner sized RWH shows overall favorable BC ratios, although limited to specific building classes.

Full city, owner sized RWH implementation, leads to an average water saving of 120 million m³ (Mm³) annually and a total non-potable water saving of 2.3 billion m³ (Bm³) over the RWH system lifespan. Residential buildings show the highest potential for water saving. Single-family buildings contribute most, with 54 Mm³ annually. Multifamily buildings come second with 39 Mm³ annually. Together with the remaining residential building class, these three classes make up for 86% of the total water savings. The other classes show lower water savings, ranging between approximately 5 Mm³ and 0.5 Mm³, with one outlier; Healthcare only saves 0,032 Mm³ (32,000 m³) annually. Note, the residential buildings contribute to almost 80% of the total number of buildings (See SI, Fig 6).

Owner sized RWH can support a maximum of 33% of the total non-potable water demand if implemented on all buildings. The water efficiency (i.e. total water saved divided by total water demand), is highest in healthcare, industry, and retail, between 75-90%. The residential buildings show varying results, single-family and multifamily buildings have total water efficiencies of 50% and 22% respectively. Toilet flushing contributes most to the total water demand. 63% of non-potable demand substituted by rainwater is toilet flushing, 37% of the substituted demand is laundry. Water used for AC cooling is negligible at a maximum of 0.6% in hot years (when AC demand is highest).

Results show low annual and high day to day variation in water savings. The water saving potential is at maximum 17% lower from average in dry years, 2001 & 2012, and 20% higher in wet years 2011, 2003 (Fig 3). RWH water saving performance is less variable than rainfall. In wet years 40% more rain can fall, in dry year 32% less. The annual variation is higher than the monthly variation. Wet months show 21% higher than average yields and dry months show 15% lower average yields. From day to day the variation in yields is highest. Demands show consistent behavior, yet rainfall variates highly, leading to high yields during and after rain events. When rainfall is absent the yield decreases to zero as the RWH tank is emptied.

Energy consumption of citywide implementation of owner sized RWH shows an average of 270,000 MWh per year (0.18% of NYC’s estimated annual energy use[57]), leading to an energy intensity of 2.25kWh/m³. NYC’s current water supply and treatment use only 0.70kWh/m³, RWH uses three times as much energy[58].

Variability in annual energy consumption shows fluctuations of +- 20% of the mean energy consumption. The variability corresponds to the variability in water savings in the wet and dry years. This is to be expected as energy consumption comes from pumping rainwater. The cost of energy is \$44 million a year, with a total of \$880 million over the entire lifespan, 8.4% of the total lifecycle cost. CO_{2e} emission is calculated from the energy consumption. Emissions are 68,000 tons of CO_{2e} a year, leading up to lifespan CO_{2e} emission of 1400,000 tons. The annual emission from owner sized city-wide RWH would contribute to 0.13% of the annual CO_{2e} emission of New York City[59]. City-sized RWH strategies show comparable results (See Fig 1).

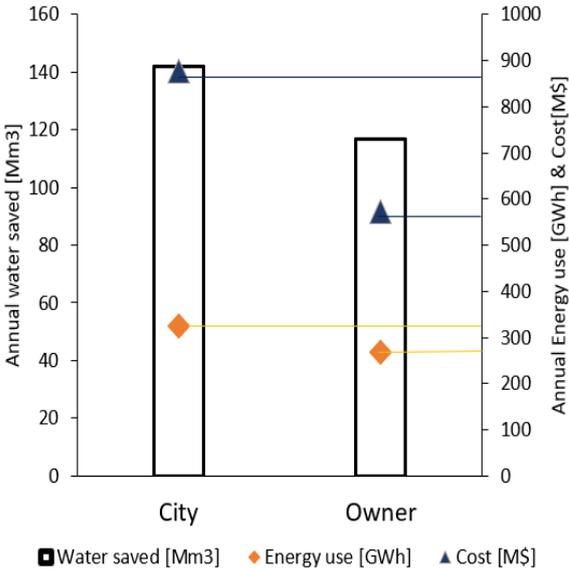


Figure 1: Annual water savings, energy use and cost for the city and owner sized RWH strategies.

If all buildings are equipped with owner sized RWH, the water savings are 2.3 Mm³ in 20 years, with a total cost of \$11.5B. If only the buildings with a BC ratio higher than 1 are equipped, water saving is 1.6 Mm³, for a cost of \$3.1B. Although the non-cost efficient buildings contribute to 30% of all water savings, their cost contributes to 73% of the total cost, showing that investing in these buildings is inadvisable. Increase in rainfall shows higher water savings, for similar costs, as only energy cost (8% of total costs) scales with an increase in water savings. This shows that with increased rainfall, the benefit-cost ratios of owner sized RWH systems would increase.

The single family and mixed residential buildings perform best with median BC ratios of 2.1 and 1.8 respectively. Education and retail follow up at median BC ratios of 1, the costs and profits are equal over 20 years. Two maintenance cost estimates were used, for big or shared buildings a conservative UK estimate was used. For building owners for which maintenance can be done without outsourcing to cleaning companies, a lower cost estimate from an Australian study was used (10% of UK maintenance costs). Only the classes with low maintenance costs showed median profitable BC ratios. Other classes ranged between 0.4 and 0.6 (Fig 1). Multifamily buildings show a low benefit-cost ratio median, however, it has the fourth most buildings with profitable BC ratios, scoring better than education.

RWH from the owner perspective is often beneficial as 70% of all buildings show a profitable BC ratio. Single-family and mixed residential buildings, only 2 of the 12 classes, together cover more than 75% of all buildings and 96% of the cost-beneficial buildings. These residential buildings are important targets for cost-efficient RWH strategies. The relationship between BC ratios and water saving is uncertain. A higher BC ratio does not determine a higher amount of rainwater being caught, 30% of all water savings comes from non-cost efficient buildings(Fig 2).

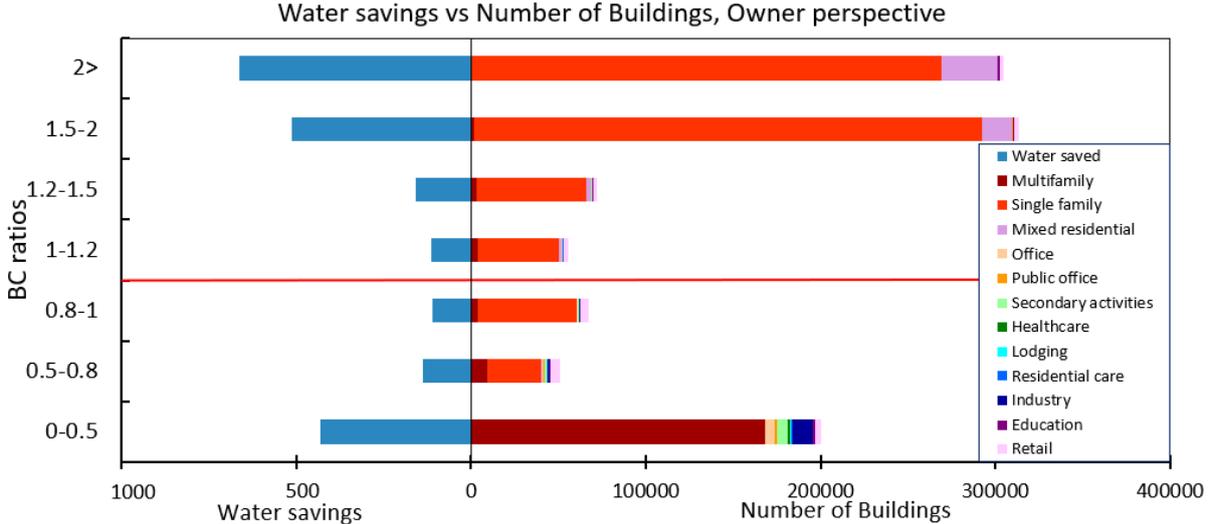


Figure 2: Water saving relative to the number of buildings, for different BC ratio ranges. The colours correspond to the building class colours as seen in the building maps (See SI). Most important are multifamily (maroon), single family (red) and retail (lavender). The number of buildings within a BC ratio range is indicated by the building frequency (blue).

City-sized RWH shows a reduction in cost-effectiveness, in exchange for increased water saving potential.

Full city, city-sized RWH implementation, leads to average water savings of 140 Mm³ annually and total water savings of 2.8 Bm³ over the RWH system lifespan. Residential buildings show the highest potential for water saving. Single-family and multifamily buildings contribute the most, at respectively 66 Mm³ and 42 Mm³ annually. Together with the remaining residential building class, they make up for 85% of the total water savings. The other classes perform less, ranging between 7 Mm³ and 0.7 Mm³, with healthcare facilities again underperforming at 0.035 Mm³ annually.

The water efficiency (i.e. total water saved divided by total water demand), is highest in healthcare, industry, and retail, between 80-95%. The residential buildings show varying results, single-family and multifamily buildings show 60% and 25% respectively. Single-family shows a higher increase in water savings, compared to the owner sized tanks. The total water saving efficiency of all buildings combined is 37%. City-sized RWH is dimensioned to increase water savings to 95% of the maximum. This explains the overall increase in water savings and water efficiency compared to owner sized RWH.

City-sized RWH shows a slight increase in annual and monthly performance variability, compared to owner sized RWH (Fig 3). The water savings are 23% lower from average in dry years 2001 & 2012,(Fig 3) and 22% higher in wet years 2003, 2006 & 2011 (Fig 3). Wet months show higher average yields, 21% higher than normal. Dry months show 16% lower than average yields. From day to day yield is still unpredictable, and dependent on rain events.

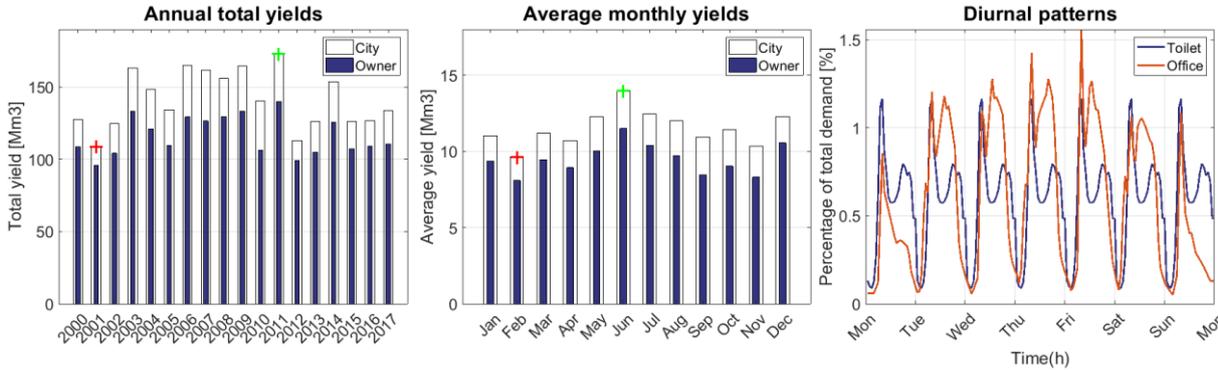


Figure 3: Yearly and monthly variation in yield (water savings), and the diurnal patterns showing variation in demand. The red and green markers indicate the maximum and minimum years respectively. The diurnal demand patterns show the daily consistency of the toilet demand pattern, compared to the office pattern showing a demand increase during the week.

Cost-benefit ratios from city-sized RWH are significantly lower than owner sized RWH (Fig 4). Note, in this paragraph only the benefits of reduced water costs are considered.

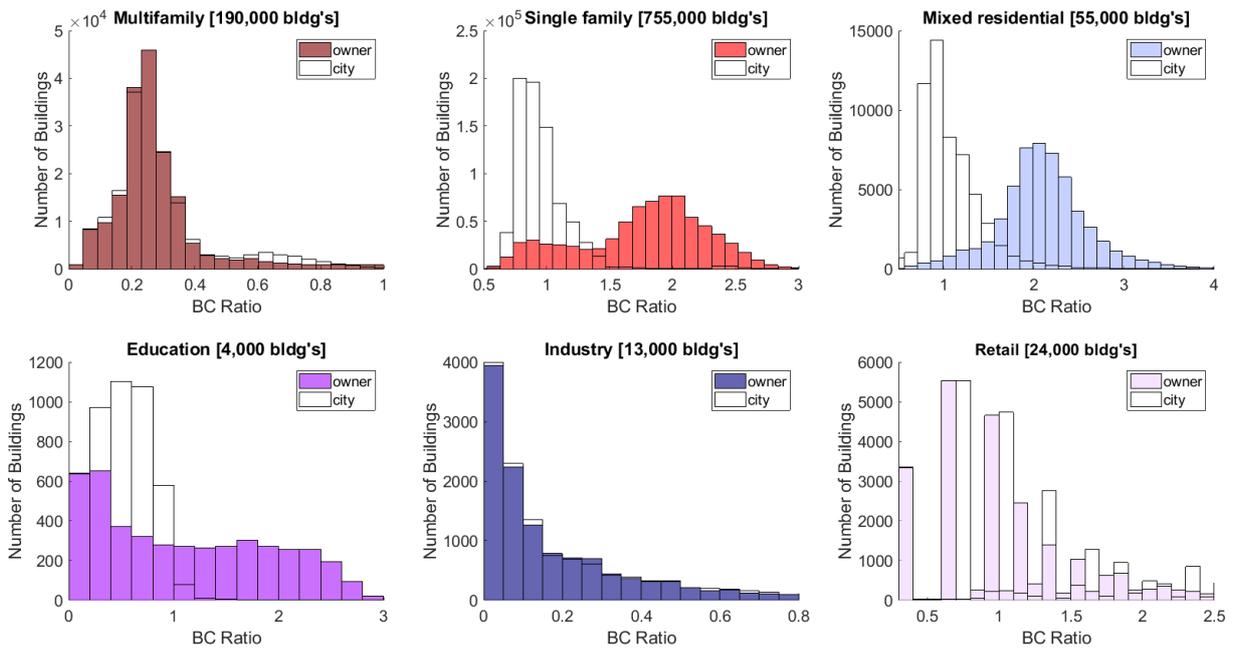


Figure 4: Histograms of building distribution along BC ratios. The classes left out from the figure (i.e. offices, public offices, secondary activities, healthcare & residential care) show distributions similar to the industry class, the lodging class, shows similarities to single family owner.

The mixed residential and single-family buildings have a median below one, showing no return of investment within 20 years. Retail, single family and mixed residential buildings perform best with median BC ratios ranging from 0.9-1.1 (Fig 4). Residential care and educational facilities follow with median BC ratios of 0.5. Maintenance cost showed to be a limiting factor in RWH BC ratio performance. However, even when maintenance cost of the non-residential and mixed buildings are lowered with 50%, BC ratios of the best performing classes only reach 0.7.

Most water savings from city-sized RWH come from buildings with poor BC ratios. The relative water saving is higher in the higher BC ratio ranges, suggesting a relation between BC ratio and water savings.

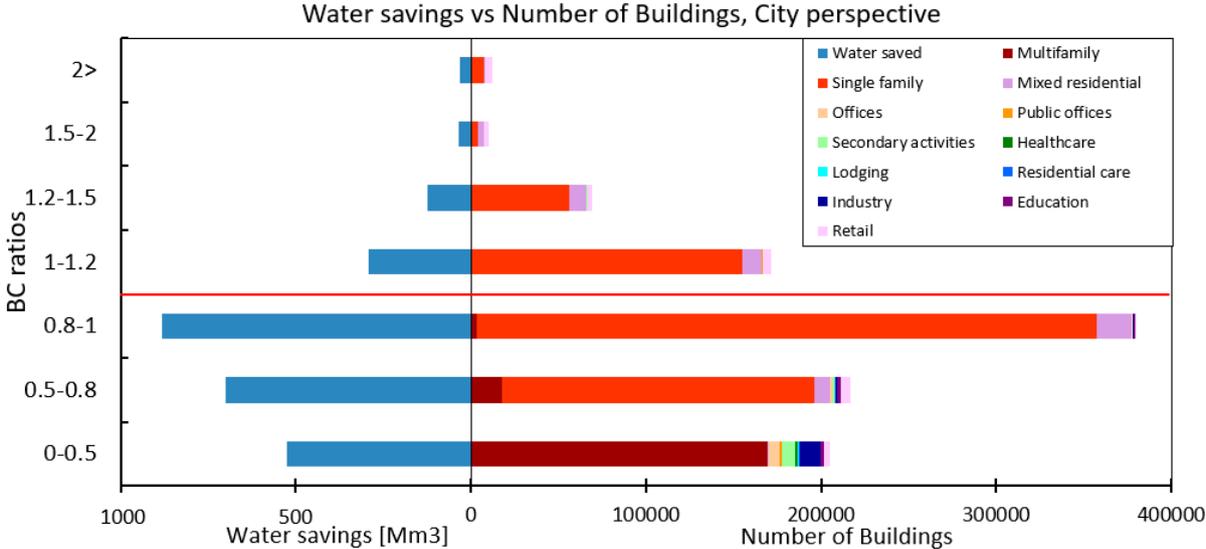


Figure 5: Water saving relative to the number of buildings, for different BC ratio ranges.

The costs and benefits of city-wide employment of RWH should be compared to benefits besides reduced water costs. In contrast to general U.S. city water supply systems[60], due to upstream watershed management, only 10% of the water supply has to be filtered [53]. New York is trying to avoid having to filtrate all water, which is necessary if their waiver is revoked[52]. Filtration is expensive, installing a treatment plant, able to support 90% of the city’s demand, would cost over \$10 B to construct, upwards of \$100 M to operate each year, and would be the largest public works project in the city’s history[61]. A smaller plant, the CROTON filtration plant, has been built in 2015. The expected costs were \$1B for construction, which increased to \$3.7B when it was finished. Maintenance and operation costs are estimated between \$30-150M a year[62,63]. The CROTON plant now supplies 140 Mm³ annually, 10% of the city’s total water demand, which can be increased to 30%.

The New York sewer system has problems coping with the water load, New York is 72% impervious area, triggering combined sewer overflows (CSO), sending pollution into the river and causing inundations[64–66]. New York set aside \$2.9B to reduce CSO’s in the future[56,67], and another \$20B in increasing the cities resiliency against inundations[68]. For cost-effect analysis of citywide RWH employment, different RWH implementation scenarios are created, which are compared to the CROTON filtration plant.

If applied strategically, RWH shows preferable traits compared to centralized water supply alternatives.

The water saving potential of the RWH implementation strategies ranges from 1.6 Mm³ to 2.8 Mm³ over a lifespan of 20 years. Total system life costs range between \$1B and \$18 B. Complete RWH tank implementation, where tanks are designed for maximum water store potential and implemented on all the city’s buildings, shows the highest water supply potential, comparable to alternatives at 2.8 Mm³ (Scenario 1, Fig 5). Yet, the costs of this type of RWH implementation, is costlier than alternatives, with more than four times the cost of water filtration systems like the CROTON facility (Fig 5).

Strategies that outsource part of the RWH implementation and expenditure to building owners, increase cost-effectiveness (Scenario 2,3, Fig 5). Results show a decrease in governmental costs of up to 47%, assuming that owners pay and implement the RWH systems with a guaranteed profit of 50% in 20 years (Scenario 2, Fig 5). Using this method, cost-effectiveness increases from 0.16m³ per \$ to 0.23m³ per \$, which is still a low cost-effectiveness compared to water supply alternatives like the CROTON filtration plant, with 0.64 m³ per \$. Building owner tank design is based on favorable benefit-cost ratios instead of maximizing water saving potential. Hence, the decrease in total water savings of 13% to 2.4 Mm³.

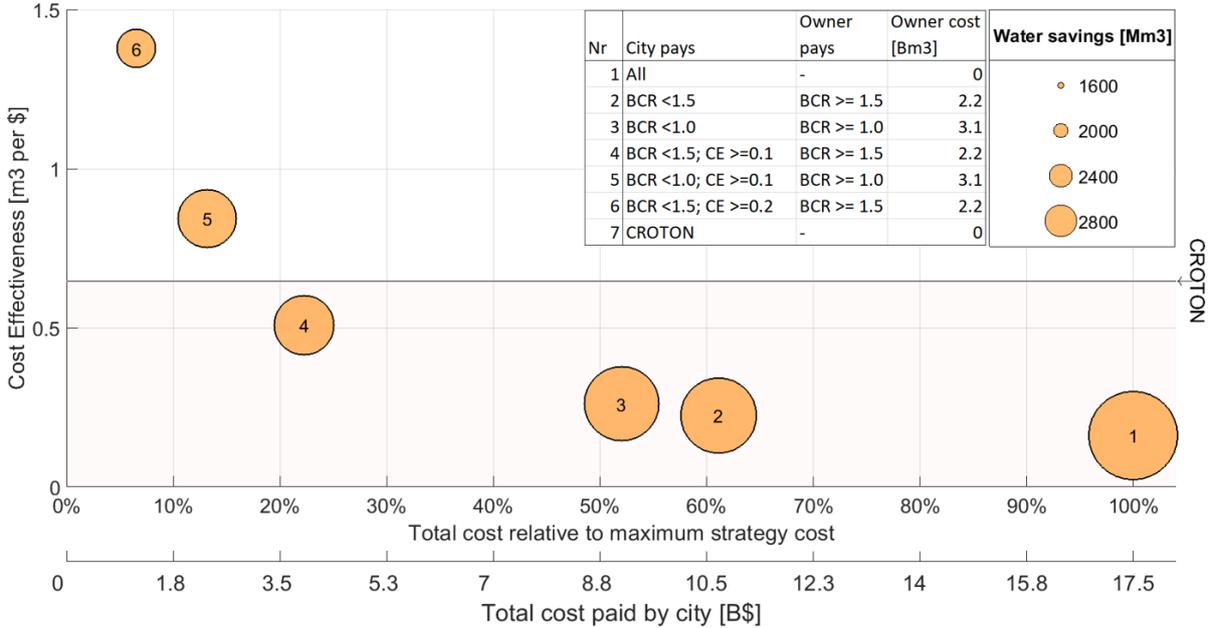


Figure 6: Scatter plot, showing the cost effectiveness, relative and absolute cost of different RWH implementation scenarios. The size of the circle shows the approximate water savings. The table shows the cost of the owner,

Instituting cost-effectiveness thresholds in RWH implementation strategies, further increases the total cost effectiveness (Scenario 4,5 & 6 , Fig 5). A RWH installation needs to returns a minimum amount of water savings for every dollar invested, to be implemented. This method avoids ineffective RWH system implementation. In comparison with full implementation, when raising a threshold of 0.2m³ per invested dollar, costs are reduced by 93% to only \$1.2 B, in exchange for a reduction of water savings by 44% to 1.6 Mm³(Scenario 6, Fig 5). The cost per m³ resulting from this method is 1.38m³/\$, which is more than twice the effectivity of the CROTON filtration plant (0.64 m³ per \$). Using this cost-efficient method, 6% of NYC’s total water demand can be supplied.

City-sized RWH can be implemented at halve the costs of filtration alternatives. Scenario 6 shows the best cost performance due to a higher benchmark for building RWH systems, in combination with outsourcing implementation to building owners when BC ratios are above 1.5. Additionally, Scenario 6 is believable due to the BC ratio restriction of 1.5. BC ratios of 1 (Scenario 3 & 5) would not carry the incentive to actually make owners implement RWH systems. Scenarios where only owners pay show profitable results (See SI, Table 9), although it is unknown if, without government interference, RWH implementation is sufficiently stimulated. For maps showing Scenario 5&6 implemented in NYC, see SI Chapter 5.

Discussion

This research revealed that citywide implementation of RWH, if implemented strategically, is able to support 22% of NYC's non-potable water demand, for a cost-effectiveness [m³/\$] more than two times higher than the currently used filtration alternative.

The performance of RWH was assessed using conservative methods. The costs of the current filtration alternatives are estimated to be low, although recent history suggests filtration cost to be underestimated. Plants like CROTON turned out to cost more than 3 times the original estimated price. And in this study, the same operational costs estimates were used. A new filtration for the entire city is expected to cost \$10 B, which would be more cost effective than RWH, however, there is high uncertainty in the estimations, as illustrated by the CROTON facility.

Previous studies showed that RWH has negative benefit-cost ratios if analyzed from the owner perspective. This research showed that benefit-cost ratios can surpass 1 for the smaller buildings, but only if maintenance is not outsourced (reducing the costs to 10% of the original, see SI). Additional work is needed to explore the effect of bulk production and economies of scale on RWH installation costs. This research did not consider the potential cost reduction if RWH is purchased in bulk, by a government authority. If NYC installed RWH installations connecting multiple adjacent buildings, economies of scale could result in cost reductions.

Future RWH effectivity is negatively influenced by decreased water usage, and positively by increased water costs. The use of water is decreasing, in NYC annual water use per capita decreased from 800L to 400L, which is still far above other cities (e.g. Amsterdam 150L; Shanghai 200L; Paris 190L and London 170L) [69]. As US cities slowly decrease the consumption towards normal standards, the absolute water saving ability of RWH decreases. On the other hand, RWH will show a higher water efficiency and reliability to provide water. The predicted future higher rainfall intensities, together with the increases in water costs could therefore positively affect RWH performance.

More work is required to address the effect of RWH on CSO's. Additionally, Geospatial information can be included to analyze the effect of RWH on street runoff, and the role in water protection. This research, due to scope limitations, could not analyze the CSO reduction effects.

Additionally, an improved lifecycle analysis is required to thoroughly assess the effects of RWH on energy use and greenhouse gas emissions. This study looked at the energy used in pumping systems, without considering the energy embedded in the production and recycling process.

Methods

Mass Balance model

The water flows of an RWH system for building i , at time t are quantified based on the mass-balance equation:

$$\Delta V_{i,t} = V_{i,t} - V_{i,t-1} = Q_{i,t} - Y_{i,t} - O_{i,t} \quad (1)$$

Where $\Delta V_{i,t}$ is the volumetric change of rainwater in the tank between time t ($V_{i,t}$) and time $t-1$ ($V_{i,t-1}$) [m^3/h]; $Q_{i,t}$ is the inflow of rainwater to the tank [m^3/h]; $Y_{i,t}$ the rainwater yield used for non-potable water purposes [m^3/h]; and $O_{i,t}$ the tank overflow, i.e. spillage [m^3/h] at time t . An hourly time-step is used, given it has been proved as a sufficient temporal resolution for RWH calculations. Larger timesteps show inaccuracy in representing RWH system behaviour [7].

Importantly, the mass balance terms are evaluated using the Yield After Spillage (YAS) rule, due to the accuracy with which it simulates RWH system behavior [3]. According to the YAS rule, rainwater yields after the overflow of the tank is subtracted:

$$O_{i,t} = \max \left\{ \begin{array}{l} V_{i,t-1} + Q_{i,t} - S_i \\ 0 \end{array} \right. \quad (2)$$

$$Y_{i,t} = \min \left\{ \begin{array}{l} D_{i,t} \\ V_{i,t-1} + Q_{i,t} - O_{i,t} \end{array} \right. \quad (3)$$

$$V_{i,t} = \min \left\{ \begin{array}{l} V_{i,t-1} + Q_{i,t} - Y_{i,t} \\ S_i - Y_{i,t} \end{array} \right. \quad (4)$$

Where S_i the storage capacity of the rainwater tank for building i [m^3].

Inflow: The inflow $Q_{i,t}$ consists of the rainfall entering the tank:

$$Q_{i,t} = R_t * A_{i,cr} * \varphi * \theta \quad (5)$$

$R_{i,t}$ describes the precipitation inflow at time t [m/h], $A_{i,cr}$ the contributing roof area for building i [m^2], φ is the runoff coefficient for which a value of 0.9 is assumed for all building classes [9], and θ is the system filtration efficiency, for which also 0.9 is assumed [9].

The rainfall input R_t was recorded at a weather station located in New York City's Central Park, supplied by the Northeast Regional Climate Centre (NRCC). The spatial variation of rainfall in the city is neglected, due to the shortage of hourly rainfall data. The dataset consists of over 18 years of rainfall data, from Jan-01-2000 to April-08-2018.

Outflow: The non-potable water demand ($D_{i,t}$)[m³/h] is the sum of various non-potable water demands: laundry, toilet flushing and air conditioning (AC). A buildings occupation and class are used for estimating the daily non-potable water demand of a building (e.g. residents use non-potable water for toilets and laundry; office employees use non-potable water for toilet use and AC).

Diurnal patterns are used to scale the demand estimates from a daily to hourly resolution[70–72]. Nine different diurnal patterns are used, based on different research projects[72–74], each linking to one or more building classes(SI,2).

Nine out of twelve building classes use one specific diurnal pattern which describes the pattern of all water use during the day, as more accurate data is not available[72,73]. Residential buildings (Class 1,2 and 3) use more accurate water demand patterns specific to toilet use and laundry[74].

Tank Selection: The model is initially used to calculate effective tank sizes for two different managerial perspectives. The owner perspective requires RWH system configuration resulting in favorable benefit-cost ratios over 18 years, considering the capital cost and operational cost of owning an RWH system and the profits of decreased water and sewer rates. 30 tanks within a feasible tank range are assessed of which the highest performing tank is selected.

The government perspective assumes the profit to be within increasing water supply, water safety, and CSO reductions. Therefore, the tank is dimensioned to reach 95% of the maximum water saving potential, in order to get high water savings without the exponential growth of cost.

Dataset

Building Data: The Building Dataset is based on a conjunction of two datasets. The Building Footprint Dataset (BFD) contains the height and roof area of NYC buildings. The PLUTO dataset contains building type, building area and the number of floors. For more detailed information on the available data from both the PLUTO and BF dataset, see the SI.

The PLUTO dataset resolution is on financial tax lot level. A tax lot is a parcel of real property meant to be owned by one or multiple owners (Figure 1, SI). However, as multiple buildings can exist on one lot, the PLUTO dataset only gives building information on the largest building on the lot, or in case of building area and the number of residential units, the summation of all buildings on the lot.

Multiple manipulations are executed to get from tax lot to building resolution. The building area is distributed according to a buildings relative volume to the volume of all buildings on the lot, estimated using the roof area and height from the BFD. The number of floors is estimated using building type specific median floor heights. For detailed information on the exact methods used to get all available building dimensions and estimate missing data, see SI.

Classification: In order to capture the differences in water use types and temporal variability, without having to acquire this information for every building separately, buildings are divided into multiple building classes. Every building class i gets a distinct combination of water use types and diurnal patterns (See SI).

The PLUTO dataset originally has 270 different building classes based on building use, these classes are aggravated into 12 building classes based on water characteristics.

Occupation Data: Occupation estimates are important in calculating the water demand for buildings, and estimating the required pump power. There are three distinguishable types of occupants: residents, employees, and visitors.

The number of residents in a building is estimated using the number of residential units in a building, and multiplying this with the borough specific average household size (See Table 2). For estimating employees and customers, occupation estimates from the Commercial Buildings Energy Consumption Survey (CBECS), LEEDuser[81] and Engineering Toolbox[80].

Performance indicators

Water Efficiency: The water-related performance of the RWH systems is assessed using the water saving efficiency:

$$\eta_i = \frac{\sum_t^T Y_{i,t}}{\sum_t^T D_{i,t}} \quad (6)$$

Where η_i is the water efficiency, the percentage of non-potable water demand supplied by the RWH system.

Benefit-Cost Ratio: The benefit-cost ratio (BC ratio) is the total profits of an RWH project divided by the total costs over a time period T, used to see if a system returns the investment costs. The calculation can be performed for a building, a building class, or an entire strategy.

$$BCR_i = \frac{\sum_t^T CW_{i,t}}{C_{i,investment} + C_{i,maintenance} + C_{i,energy}} \quad (7)$$

Where BCR_i is the Benefit Cost Ratio for building i ; $CW_{i,t}$ the cost of water services over period t ; $C_{i,investment}$ is a summation of the tank and pump cost, which are influenced by tank volume and required pump power respectively[\$]; $C_{i,maintenance}$ is the cost of cleaning, repairing and replacements of the RWH system[\$]; $C_{i,energy}$ is the operational energy cost of pumping the saved rainwater through the system. The total 20 years costs and benefits are based on averages from 18 years of data.

Cost Effectiveness: Cost-effectiveness (CE) is used to assess the city-sized RWH performance:

$$CE_i = \frac{\sum_t^T Y_{i,t}}{C_{i,investment} + C_{i,maintenance} + C_{i,energy}} \quad (8)$$

Where CE_i is the cost effectiveness in $m^3/\$$ for building i . $C_{i,investment}$ is a summation of the tank and pump cost, which are influenced by tank volume and required pump power respectively[\$]; $C_{i,maintenance}$ is the cost of cleaning, repairing and replacements of the RWH system[\$]; $C_{i,energy}$ is the operational energy cost of pumping the saved rainwater through the system. For more information on cost factors see the SI (Chapter 2).

Bibliography

- [1] N. Pelak, A. Porporato, Sizing a rainwater harvesting cister by minimizing costs, *J. Hydrol.* 542 (2016) 1340–1347.
- [2] L. Domènech, D. Saurí, A comparative appraisal of the use of rainwater harvesting in single and multi-family buildings of the Metropolitan Area of Barcelona (Spain): Social experience, drinking water savings and economic costs, *J. Clean. Prod.* 19 (2011) 598–608. doi:10.1016/j.jclepro.2010.11.010.
- [3] A. Palla, I. Gnecco, L.G. Lanza, Non-dimensional design parameters and performance assessment of rainwater harvesting systems, *J. Hydrol.* 401 (2011) 65–76. doi:10.1016/j.jhydrol.2011.02.009.
- [4] Y. Zhang, D. Chen, L. Chen, S. Ashbolt, Potential for rainwater use in high-rise buildings in Australian cities, *J. Environ. Manage.* 91 (2009) 222–226. doi:10.1016/j.jenvman.2009.08.008.
- [5] J. Steffen, M. Jensen, C.A. Pomeroy, S.J. Burian, Water supply and stormwater management benefits of residential rainwater harvesting in U.S. cities, *J. Am. Water Resour. Assoc.* 49 (2013) 810–824. doi:10.1111/jawr.12038.
- [6] A.S. Silva, E. Ghisi, Uncertainty analysis of daily potable water demand on the performance evaluation of rainwater harvesting systems in residential buildings, *J. Environ. Manage.* 180 (2016) 82–93. doi:10.1016/j.jenvman.2016.05.028.
- [7] P.J. Coombes, M.E. Barry, The relative efficiency of water supply catchments and rainwater tanks in cities subject to variable climate and the potential for climate change, *Aust. J. Water Resour.* 12 (2008) 85–100. doi:10.1016/S0019-8501(99)00110-8.
- [8] M. Basinger, F. Montalto, U. Lall, A rainwater harvesting system reliability model based on nonparametric stochastic rainfall generator, *J. Hydrol.* 392 (2010) 105–118. doi:10.1016/j.jhydrol.2010.07.039.
- [9] R. Wang, J.B. Zimmerman, Economic and environmental assessment of office building rainwater harvesting systems in various U.S. Cities, *Environ. Sci. Technol.* 49 (2015) 1768–1778. doi:10.1021/es5046887.
- [10] N. Marleni, S. Gray, A. Sharma, S. Burn, N. Muttill, Impact of water source management practices in residential areas on sewer networks - A review, *Water Sci. Technol.* 65 (2012) 624–642. doi:10.2166/wst.2012.902.
- [11] D.N. Pandey, a K. Gupta, D.M. Anderson, B. Pandey, Deep Narayan (Indian Institute of Forest Management); Gupta, Anil K. (Indian Institute of Technology); Anderson, David M. (University of Colorado, Rainwater harvesting as an adaptation to climate change, *Curr. Sci.* 85 (2003) 46–59. wos:000184219200016.
- [12] M.P. Jones, W.F. Hunt, Performance of rainwater harvesting systems in the southeastern United States, *Resour. Conserv. Recycl.* 54 (2010) 623–629.
- [13] S. Ward, F.A. Memon, D. Butler, Performance of a large building rainwater harvesting system, *Water Res.* 46 (2012) 5127–5134.
- [14] S.R. Ghimire, J.M. Johnston, W.W. Ingwersen, S. Sojka, Life cycle assessment of a commercial rainwater harvesting system compared with a municipal water supply system, *J. Clean. Prod.* 151 (2017) 74–86.

- [15] A. Campisano, D. Butler, S. Ward, M.J. Burns, E. Friedler, K. DeBusk, L.N. Fisher-Jeffes, E. Ghisi, A. Rahman, H. Furumai, M. Han, Urban rainwater harvesting systems: Research, implementation and future perspectives, *Water Res.* 115 (2017) 195–209.
- [16] Marsden Jacob Associates, The cost effectiveness of residential rainwater tanks in Perth, *Financ. Econ. Consult. ABN.* 66 (2009) 657–72.
<http://www.marsdenjacob.com.au>.
- [17] D.J. Sample, J. Liu, Optimizing rainwater harvesting systems for the dual purposes of water supply and runoff capture, *J. Clean. Prod.* 75 (2014) 174–194. doi:10.1016/j.jclepro.2014.03.075.
- [18] E.A. Martin, S.G. Buchberger, D. Chakraborty, Reliability of harvested rainfall as an auxiliary source of non-potable water, *Procedia Eng.* 119 (2015) 1119–1128. doi:10.1016/j.proeng.2015.08.954.
- [19] T.C. Walsh, C.A. Pomeroy, S.J. Burian, Hydrologic modeling analysis of a passive, residential rainwater harvesting program in an urbanized, semi-arid watershed, *J. Hydrol.* 508 (2014) 240–253. doi:10.1016/j.jhydrol.2013.10.038.
- [20] V.G. Mitchell, A. Taylor, T.D. Fletcher, A. Deletic, Storm water reuse, Potable water substitution for Melbourne, 2005.
- [21] T.R. Gurung, A. Sharma, S. Umapathi, Economics of Scale Analysis of Communal Rainwater Tanks Urban Water Security Research Alliance Technical Report No . 67, (2012) 1836–5558.
- [22] M.R. Karim, M.Z.I. Bashar, M.A. Imteaz, Reliability and economic analysis of urban rainwater harvesting in a megacity in Bangladesh, *Resour. Conserv. Recycl.* 104 (2015) 61–67. doi:10.1016/j.resconrec.2015.09.010.
- [23] A. Petit-Boix, J. Devkota, R. Phillips, M.V. Vargas-Parra, A. Josa, X. Gabarrell, J. Rieradevall, D. Apul, Life cycle and hydrologic modeling of rainwater harvesting in urban neighborhoods: Implications of urban form and water demand patterns in the US and Spain, *Sci. Total Environ.* 621 (2017) 434–443. doi:10.1016/j.scitotenv.2017.11.206.
- [24] B. Kerkez, C. Gruden, M. Lewis, L. Montestruque, M. Quigley, B. Wong, A. Bedig, R. Kertesz, T. Braun, O. Cadwalader, A. Poresky, C. Pak, Smarter stormwater systems, *Environ. Sci. Technol.* 50 (2016) 7267–7273. doi:10.1021/acs.est.5b05870.
- [25] C.M. Agudelo-Vera, K.J. Keesman, A.R. Mels, H.H.M. Rijnaarts, Evaluating the potential of improving residential water balance at building scale, *Water Res.* 47 (2013) 7287–7299.
- [26] K. Debusk, W.F. Hunt, Rainwater Harvesting : A Comprehensive Review of Literature Prepared By : Biological & Agricultural Engineering North Carolina State University Prepared For : North Carolina Water Resources Research Institute, (2012).
- [27] N. Rostad, R. Foti, F.A. Montalto, Harvesting rooftop runoff to flush toilets: Drawing conclusions from four major U.S. cities, *Resour. Conserv. Recycl.* 108 (2016) 97–106. doi:10.1016/j.resconrec.2016.01.009.
- [28] J.S. Muna, M.Y. Hanb, Design and operational parameters of a rooftop rainwater harvesting system: Definition, sensitivity and verification, *J. Environ. Manage.* 93 (2012) 147–153.

- [29] Y.R. Chiu, C.H. Liaw, L.C. Chen, Optimizing rainwater harvesting systems as an innovative approach to saving energy in hilly communities, *Renew. Energy*. 34 (2009) 492–498. doi:10.1016/j.renene.2008.06.016.
- [30] J.-A. James, S. Sung, H. Jeong, O.A. Broesicke, S. French, D. Li, J.C. Crittenden, Impacts of Combined Cooling, Heating and Power Systems and Rainwater Harvesting on Water Demand, Carbon Dioxide and NO_x Emissions for Atlanta, *Environ. Sci. Technol.* (2017). doi:10.1021/acs.est.7b01115.
- [31] T.D. Fletcher, A. Deletic, V.G. Mitchell, B.E. Hatt, Reuse of Urban Runoff in Australia: A Review of Recent Advances and Remaining Challenges, *J. Environ. Qual.* 37 (2008) S-116. doi:10.2134/jeq2007.0411.
- [32] A. Fewkes, P. Wam, Method of modelling the performance of rainwater collection systems in the United Kingdom, *Build. Serv. Eng. Res. Technol.* 21 (2000) 257–265. doi:10.1177/014362440002100408.
- [33] D. Zhang, R.M. Gersberg, C. Wilhelm, M. Voigt, Decentralized water management: Rainwater harvesting and greywater reuse in an urban area of Beijing, China, *Urban Water J.* 6 (2009) 375–385. doi:10.1080/15730620902934827.
- [34] J. Kim, H. Furumai, Assessment of Rainwater Availability by Building Type and Water Use Through GIS-based Scenario Analysis, *Water Resour. Manag.* 26 (2012) 1499–1511. doi:10.1007/s11269-011-9969-9.
- [35] A. Belmeziti, O. Coutard, B. de Gouvello, A new methodology for evaluating potential for potable water savings (PPWS) by using rainwater harvesting at the urban level: The case of the municipality of colombes (paris region), *Water (Switzerland)*. 5 (2013) 312–326. doi:10.3390/w5010312.
- [36] A.K. Marinoski, R.F. Rupp, E. Ghisi, Environmental benefit analysis of strategies for potable water savings in residential buildings, *J. Environ. Manage.* 206 (2018) 28–39. doi:10.1016/j.jenvman.2017.10.004.
- [37] G. Vaes, J. Berlamont, The effect of rainwater storage tanks on design storms, *Urban Water*. 3 (2001) 303–307. doi:10.1016/S1462-0758(01)00044-9.
- [38] T. Herrmann, U. Schmida, Rainwater utilisation in Germany: efficiency, dimensioning, hydraulic and environmental aspects, *Urban Water*. 1 (2000) 307–316. doi:10.1016/S1462-0758(00)00024-8.
- [39] R.M. Roebuck, C. Oltean-Dumbrava, S. Tait, Whole life cost performance of domestic rainwater harvesting systems in the United Kingdom, *Water Environ. J.* 25 (2011) 355–365. doi:10.1111/j.1747-6593.2010.00230.x.
- [40] B. Kneppers, D. Birchfield, M. Lawton, Energy-water relationships in reticulated water infrastructure systems, *Water Supply (KWh/Capita)*. 76 (2009) 15–75.
- [41] M. Retamal, J. Glassmire, K. Abeysuriya, A. Turner, S. White, The water-energy nexus: Investigation into the energy implications of household rainwater systems, 2009.
- [42] R. Farreny, X. Gabarrell, J. Rieradevall, Cost-efficiency of rainwater harvesting strategies in dense Mediterranean neighbourhoods, *Resour. Conserv. Recycl.* 55 (2011) 686–694. doi:10.1016/j.resconrec.2011.01.008.
- [43] Swiss Federal Institute of Aquatic Science and Technology, Factsheet: Water and energy, (2010) 4.

http://www.eawag.ch/fileadmin/Domain1/Beratung/Beratung_Wissenstransfer/Public_Praxis/Factsheets/fs_water_and_energy_oct2011.pdf.

- [44] A. Rahman, J. Keane, M.A. Imteaz, Rainwater harvesting in Greater Sydney: Water savings, reliability and economic benefits, *Resour. Conserv. Recycl.* 61 (2012) 16–21. doi:10.1016/j.resconrec.2011.12.002.
- [45] K.M. Debusk, W.F. Hunt, J.D. Wright, Characterizing Rainwater Harvesting Performance and Demonstrating Stormwater Management Benefits in the Humid Southeast USA, *J. Am. Water Resour. Assoc.* 49 (2013) 1398–1411. doi:10.1111/jawr.12096.
- [46] V.A.R. Lopes, G.F. Marques, F. Dornelles, J. Medellin-Azuara, Performance of rainwater harvesting systems under scenarios of non-potable water demand and roof area typologies using a stochastic approach, *J. Clean. Prod.* 148 (2017) 304–313. doi:10.1016/j.jclepro.2017.01.132.
- [47] T. Morales-Pinzón, J. Rieradevall, C.M. Gasol, X. Gabarrell, Modelling for economic cost and environmental analysis of rainwater harvesting systems, *J. Clean. Prod.* 87 (2015) 613–626. doi:10.1016/j.jclepro.2014.10.021.
- [48] R.E. Engström, M. Howells, G. Destouni, V. Bhatt, M. Bazilian, H.H. Rogner, Connecting the resource nexus to basic urban service provision – with a focus on water-energy interactions in New York City, *Sustain. Cities Soc.* 31 (2017) 83–94. doi:10.1016/j.scs.2017.02.007.
- [49] F.A. Abdulla, A.W. Al-Shareef, Roof rainwater harvesting systems for household water supply in Jordan, *Desalination.* 243 (2009) 195–207. doi:10.1016/j.desal.2008.05.013.
- [50] J. Lange, S. Husary, A. Gunkel, D. Bastian, T. Grodek, Potentials and limits of urban rainwater harvesting in the Middle East, *Hydrol. Earth Syst. Sci.* 16 (2012) 715–724. doi:10.5194/hess-16-715-2012.
- [51] Y. Jiang, C. Zevenbergen, Y. Ma, Urban pluvial flooding and stormwater management: A contemporary review of China’s challenges and “sponge cities” strategy, *Environ. Sci. Policy.* 80 (2018) 132–143. doi:10.1016/j.envsci.2017.11.016.
- [52] E.A. Goldstein, New Filtration Waiver Poses Challenges for NYC Water Supply, NRCDC. (2017). <https://www.nrcdc.org/experts/eric-goldstein/new-filtration-waiver-poses-challenges-nyc-water-supply> (accessed March 2, 2018).
- [53] B. De Blasio, W. Branch, New York City 2016 Drinking Water Supply and Quality Report, (2016). <http://www.nyc.gov/html/dep/pdf/wsstate13.pdf>.
- [54] The City of New York Mayor Bill de Blasio, A Stronger, More Resilient New York, New York City, 2013.
- [55] R.M. Horton, D.A. Bader, C. Rosenzweig, A.T. DeGaetano, W. Solecki, Climate Change in New York, 18 (2014).
- [56] B. De Blasio, V. Sapienza, NYC Green Infrastructure: 2016 Annual Report, (2017). http://www.nyc.gov/html/dep/pdf/green_infrastructure/gi_annual_report_2017.pdf.
- [57] University of Ontario Institute of Technology, Energy and material flows of megacities, (n.d.) 1–23. <http://sites.uoit.ca/sustainabilitytoday/urban-and-energy-systems/Worlds-largest-cities/energy-and-material-flows-of-megacities/beijing.php>.

- [58] C. Copeland, N.T. Carter, *Energy - Water Nexus : The Water Sector ' s Energy Use*, (2017) 1–10.
- [59] C. Pasion, C. Oyenuga, K. Gouin, C. LLC, *Inventory of New York City greenhouse gas emissions in 2015*, (2017) 1–56.
- [60] J. Batten, *Sustainable cities water index. Which cities are the best placed to harness water for future success?*, 2016. <https://www.arcadis.com/media>.
- [61] NYC Government, *High Quality NYC Tap Water Receives New Filtration Waiver*, (2017). <http://www1.nyc.gov/office-of-the-mayor/news/779-17/high-quality-nyc-tap-water-receives-new-filtration-waiver> (accessed March 2, 2018).
- [62] M. Of, I. On, H. In, *New York City Independent Budget Office*, (2002).
- [63] *CROTON WATER TREATMENT PLANT FINAL SUPPLEMENTAL ENVIRONMENTAL IMPACT STATEMENT*, (n.d.).
- [64] A. Licata, *Innovative & Integrated Stormwater Management*, (n.d.).
- [65] J.D. Miller, M. Hutchins, *The impacts of urbanisation and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom*, *J. Hydrol. Reg. Stud.* 12 (2017) 345–362. doi:10.1016/j.ejrh.2017.06.006.
- [66] B. De Blasio, *Water Demand Management Report*, New York City, 2016.
- [67] New York City Department of Environmental Protection, *NYC Green Infrastructure Plan*, *Vasa.* (2008) 8. doi:10.1017/CBO9781107415324.004.
- [68] The City of New York, *Mayor Announces New Resiliency Guidelines to Prepare City's Infrastructure and Buildings for Effects of Climate Change*, (2017). <https://www1.nyc.gov/office-of-the-mayor/news/271-17/mayor-new-resiliency-guidelines-prepare-city-s-infrastructure-buildings-for> (accessed September 23, 2018).
- [69] *International Statistics for Water Services 2016 Information every water manager should know This report is now in it ' s twelfth edition , and this year contains data from 40 countries and 170 cities . For the first time we have been able to gather data ,* (2016).
- [70] S.A. Lucas, P.J. Coombes, *Residential diurnal water use patterns and peak demands : Implications for integrated water infrastructure planning*, (2009).
- [71] S. Umapathi, M.N. Chong, a K. Sharma, *Assessment of diurnal water demand patterns to determine supply reliability of plumbed rainwater tanks in South East Queensland*, *Water.* (2010) 1–8.
- [72] A.M.R.R. City, *AMR Diurnal Monitoring and Pattern Development Report City of Ann Arbor Distribution System Master Plan Technical Memorandum*, (2010).
- [73] R. Sitzenfrei, J. Zischg, M. Sitzmann, P.M. Bach, *Impact of hybridwater supply on the centralised water system*, *Water (Switzerland).* 9 (2017). doi:10.3390/w9110855.
- [74] T.R. Gurung, R.A. Stewart, C.D. Beal, A.K. Sharma, *Smart meter enabled water end-use demand data: Platform for the enhanced infrastructure planning of contemporary urban water supply networks*, *J. Clean. Prod.* 87 (2015) 642–654. doi:10.1016/j.jclepro.2014.09.054.

