University of Twente

Performance assessment of citywide rainwater harvesting strategies in New York City

SUPPLEMENTARY INFORMATION

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Contents

1 Research Framework

1.1 Objective

This research aims to provide a systematic analysis on implementing RWH at a city scale. By modeling and simulating RWH for each building, the water services and economic implications of a city-wide RWH deployment will be assessed given different managerial goals. The research will use New York City (NYC), United States as a case study. More specifically, it is asked, if implemented citywide:

(1) What are the water services and life-cycle economic implications of RWH if each RWH system is engineered (i.e., cistern size and pump choice) towards the cost-effectiveness for each building vs. cost effectiveness on the city scale?

(2) How do the above RWH deployments economically compare with the alternative of expanding and/or enhancing existing centralized infrastructure system that would be otherwise necessary to meet the rising water demand and more stringent water regulations in NYC?

1.2 Scope

Geographically, this research considers rooftop RWH at all buildings within the city boundary of NYC. The operation of each RWH system will be simulated on a temporal resolution of one hour, which has been proved to simulate RWH with sufficient accuracy. The simulation spans over the last 18 years using historical precipitation records.

Three main water services of RWH are modeled and simulated. They are: 1) the volume of non-potable water supply for toilet flushing, laundry and air conditioning, 2) the volume of wastewater load reduction when wastewater and stormwater sewers are combined, and 3) the volume of stormwater runoff abatement. It is beyond the scope of this research to simulate the hydrologic effect of runoff reduction in the streets, which can be pursued in a future study using detailed hydrologic modeling and spatial information.

The lifecycle economic costs of RWH include the capital investment, operation costs (for electricity use), and maintenance costs throughout a typical lifespan of RWH systems. For comparison, life-cycle economic impacts are assessed for operating, expanding and/or enhancing centralized water infrastructures that offer equivalent water services as the city-wide RWH deployment.

1.3 Case study

1.3.1 Intense socioeconomic activities

New York City has a population of over 8 million people, who reside in 3.4 million housing units divided over approximately 1 million different structures. The city is spanning a total area of 780km^2[51], resulting in both the highest population and population density of all cities in the U.S[52]. NYC is famous for being the economic hot spot of the world. The city is tightly packed with over 50 million square meters of office space, offering 1.5 million office-based jobs, a third of the city's total job amount (4.3 million) [53]. The metropolitan district has a gross domestic product (GDP) of 1657 billion dollars, which is the highest in the U.S. (Los Angeles-Long-Beach-Santa Ana; 1001 billion, Chicago-Joliet-Naperville; 651 billion)[54], and enough to surpass multiple nations, e.g. it is double the GDP of the entire Netherlands (824 billion), which ranks 18th in the highest national GDP's worldwide (in 2017)[55]. The combination of intense activity, dense population, and high economic value show the importance and difficulty in supplying and protecting NYC.

1.3.2 Water infrastructure development under pressure

NYC has a vast water management system to cope with high water demand. The potable water demand is supplied by 19 reservoirs and three controlled lakes that spread over a 5200km^2 watershed[56]. In 2010, a total of 3.8MCM(million cubic meter) of potable water was supplied every day, which was the main contribution to the 4.2MCM of daily wastewater production[56]. The immense amount of wastewater is treated in 14 different treatment plants[46,57], spread across the city.

Protecting, monitoring and extending the watershed area is critical for New York to be able to live up to water quality standards whilst simultaneously avoiding energy-intensive and costly water filtration[56]. In contrast to general U.S. city water supply systems[58], only 10% of the water supply is filtered, and the distribution is mainly gravity fed[56]. New York is working hard to avoid having their filtration waiver revoked[59]. Filtration is expensive, installing a treatment plant would cost more than \$10 billion to construct, upwards of \$100 million to operate each year, and would be the largest public works project in the history of the city[60]. The sewer system has problems coping with the water load, New York is 72% impervious area, trigging combined sewer overflows, sending pollution into the river and causing inundations[61–63]. Decreasing the pressure on the water system could be a major cost reduction (due to the reduction of future water filtration needed), an environmental improvement, and increase the safety.

In spite of the reduced costs due to the avoidance of filtration, New York charges 1.35$/m^3 on potable water, and 2.14$/m^3 on sewer usage[64], the 3rd highest water rates of the 50 biggest U.S. cities[65]. Typical monthly bills are in the range of 80$, which is high compared to the U.S. average of 45$[65], but only a third of the average European water rates [66,67].

NYC invest billions in repairing, maintaining and extending the transport tunnels and water catchments[56]. A necessary and complex tunnel repair is scheduled in October 2022. 1.5 billion dollars is set aside to repair the Delaware Aqueduct, one of the main water supply tunnels used[56]. Developments in repairing leaks and implementing improved water systems, decreased the daily water demand per capita from 800 liters in 1979, to 440 liters in 2016[68]. Still, NYC has the highest water consumption of the world's megacities[69]. High investments are continually required, in order to maintain the current water supply system, support the high-water demand, and avoid the need for water filtration.

1.3.3 Sustainable energy goals

With an energy consumption of 300TWh a year[70], NYC is the megacity with the highest energy consumption worldwide[69]. Efforts over the past decade have made their energy use cleaner and efficient. NYC is placed 2nd on energy efficiency in the U.S, still, U.S. cities have significant room for improvement[71]. Approximately 60% of the city's energy consumption is related to buildings, of which most energy is used in space temperature regulation and water heating[72]. The water system demands energy as well, with treatment being the main consumer, since the energy use of water supply, due to filtration avoidance and gravity fed distribution, is relatively low[46,56]. The State of New York uses 1.5 TWh a year for treating wastewater and managing sludge, 60% of which is used by the total 75 wastewater treatment plants located in the New York metropolitan area and Long Island (14 of which are located within NYC limits)[73]. To decrease their environmental impact, NYC aims to reduce energy consumption with 23% and greenhouse gas emissions with 80% by 2050 (reference year 2005)[74], making energy needs and CO2 emissions critical metrics in evaluating alternatives of infrastructure development.

1.3.4 Impacts of climate change

The climate of New York has changed a lot over the last decennia. Since the 1970's the average state temperature has increased with 1.33°C overall, and 2.44°C in the winter[75,76]. The precipitation, affected by the change in air temperature, shows increased year-to-year variability. Since 1958, precipitation during heavy rainfall events has increased by 70%[75,76] This observed change of climate is predicted to continue at an accelerated pace[77]. Temperatures are predicted to rise by 1.7-2.2 degrees every 30 years, and total precipitation will have increased with 12% in 2050[75]. Also, the number of hurricanes like Sandy, which left a devastating amount of damage to NYC[51], are more likely to increase[78]. The combination of all these climate effects increases the chance on city flooding, and the amount of runoff volume in the streets[62].

2 Methods

The methods section follows a sequence of steps. Firstly, the creation of the building dataset is discussed (0). Secondly, the mass balance model equations and the calculations of the in- and outflows are explained (0). Thirdly, the method of analyzing cost effectivity, from both the owner and government perspective is given (0 & 0). Finally, the methods chapter ends with an explanation of how the appropriate tank sizes were calculated (2.4.1.1).

2.1 The Building Dataset

The building dataset contains for every New York City building, dimensions, type, and occupation. Chapter 2.1.1 discusses the conjunction of two big NYC datasets, into one building dataset. Chapter 0 continues with the pretext for classifying and the classification method. It also contains a table containing the created Building Classes. Chapter 0 explains how the building occupancy rates were estimated.

2.1.1 PLUTO & Building Footprint Dataset

The Building Dataset is built from a conjunction of two big datasets. The Building Footprint dataset (BF) contains the height and roof area for every building in NYC. However, in order to know more about the use of the buildings, building area and the number of floors, the PLUTO dataset is required. For detailed information on the available data from both the PLUTO and BF dataset, see Appendix I.

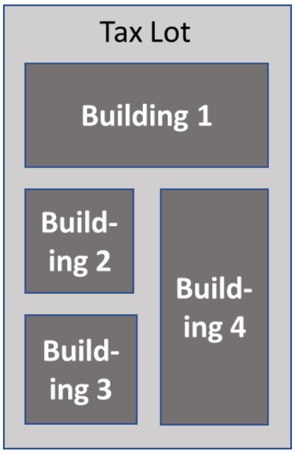

Figure 1: Lot system in NYC, the tax lot information is contained within the PLUTO set, the building information in the Building Footprint dataset.

The PLUTO dataset consists of detailed building data on all of NYC's financial tax lot's. A tax lot is a parcel of real property meant to be owned by one or multiple owners (Figure 1). 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.

In order to get the building area and number of floors of all buildings in the lot, different methods were used. The building area is distributed according to a buildings relative volume to all buildings on the lot, which was estimated by using the roof area and height from the BF dataset. The number of floors is estimated using median floor heights calculated for different types of buildings. For detailed information on the exact methods used to get all available building dimensions, see Appendix II.

After joining the two datasets and supplementing the dataset by filling up for missing data, a complete picture of the buildings in NYC is created, with information for over a million buildings. Figure 2 shows that buildings with a height higher than 16m are relatively rare. Although NYC is famous for its high buildings, they only make up for a small part of the city. Regarding roof areas, 90% are within a range of 25-175m, with a small peak in the higher building area zones, which leads to 20,000 buildings with a very high capacity for harvesting rainwater.

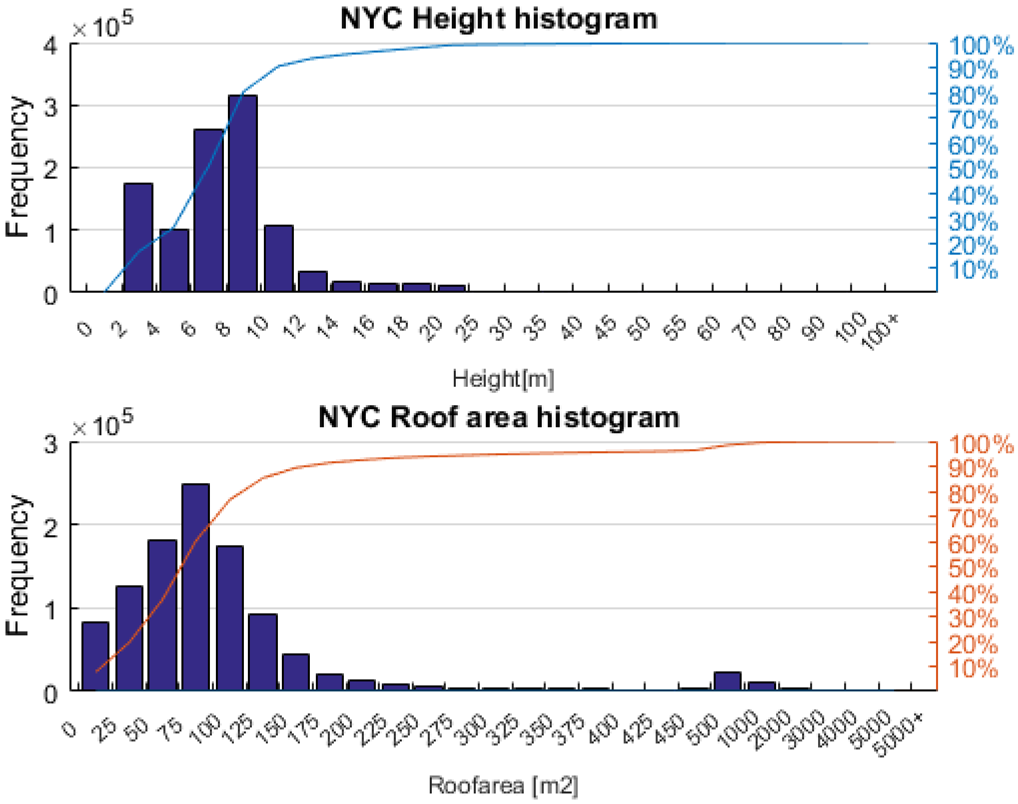

Figure 2: Distribution of both the height (top), and roof area(bottom) of buildings in NYC.

2.1.2 The Building Classes

New York City's buildings vary greatly in purpose, which results in variation in water demand patterns. For instance, theatres mainly use non-potable water at the end of the day, and only to flush toilets. Residential buildings non-potable water use peaks in the morning, and consist of both demand for toilets and washing machines.

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 2.2.3).

The PLUTO dataset already has over 270 different building classes, which are aggravated into 12 Building Classes.

The Building Classes are additionally used in estimating occupation, gaining information on median floor heights and are used in linking smaller parameters, including energy cost. For an oversight of the different building classes, see Table 1, and for further explanation Appendix III.

*Table 1: Building Classification; *The numbers relate to water demand specified in Table 4; **Diurnal Patterns are further explained in chapter Diurnal Patterns2.2.3.2 ; *** Small buildings also use 1.5 kWh/m3, see chapter 2.2.4.2.*

Building Class	**Class info**	**TF***	**CW**	**AC**	**Diurnal pattern ** **	**Energy Use [kWh/m^3] *** **	**Energy Rates [$/kWh]**
1. Multi-Family Residential	apartment complexes, dorms	Yes (1)	Yes (6)	Yes (8)	Toilet, Laundry	3	0.18
2. Single Family Residential	1 and 2 family housing	Yes (1)	Yes (6)	No	Toilet, Laundry	1.5	0.18
3. Mixed Residential & Commercial	buildings with use besides residential	Yes (1) (2) (3)	Yes (6)	Yes (8)	Toilet, Laundry, Office/ Retail	3	0.18
4. Office	Offices	Yes (2)	No	Yes (8)	Office	3	0.15
5. Public Offices	Courtrooms, post offices, law, and order	Yes (2) (3)	No	Yes (8)	Office/ Retail	3	0.15
6. Entertainment	Theatres, Cinema's, Malls	Yes (2) (3)	No	Yes (8)	Entertainment	3	0.15
7. Healthcare	Hospitals	No	No	Yes (8)	Healthcare	3	0.15
8. Lodging	Hotels	Yes (2) (4)	Yes (6)	Yes (8)	Hotel	3	0.15
9. Residential Care Facilities	Homes, Prisons, Asylums	Yes (1) (2)	Yes (6)	Yes (8)	Health-care	3	0.15
10. Industry	Warehouses, Factories	Yes (2)	No	Yes (8)	Industry	3	0.06
11. Education	Schools, Universities	Yes (2) (5)	No	Yes (8)	Education	3	0.15
12. Retail	Small shops	Yes (2)	No	Yes (8)	Office/ Retail	3	0.15

2.1.3 Occupation Estimation

Occupation estimates are important in calculating the water demand of buildings and estimating the required pump power (See 0). The occupation is calculated using occupation rates from different sources, and there are three distinguishable types of occupants: residents, employees, and visitors.

Table 2: Average household sizes in NYC boroughs [82]

Borough	Average Household Size [persons]
Manhattan	2.12
Bronx	2.82
Brooklyn	2.75
Queens	3.03
State Island	2.86

The number of residents in a building is estimated using the number of residential units in a building, and multiplying this with the average household size. The average household size varies per borough (See Table 2). For estimating employees, occupation estimates from the Commercial Buildings Energy Consumption Survey (CBECS) were used[79]. For every type of building not covered by the CBECS, estimates from the Engineering Toolbox were used[80]. Besides employees, buildings with a public function (e.g. Buildings in Building Classes: Entertainment and Public Offices), have customers and visitors passing by. The number of visitors is estimated using occupation rates from LEEDuser[81] and the Engineering Toolbox[80].

2.1.4 Fixture & Pumping Power Estimation

The Building Table also contains the amount of water using fixtures per building floor, which is required in order to calculate the pump power required, and which will be used in estimating the pump costs (See 2.3.3.3).

2.1.4.1 Fixtures

The amount of fixtures per floor is estimated using the International Building Code[83], the fixtures are calculated differently for every class (see Table 3).

Table 3: Estimated Fixtures according to the International Building Code[83]

Building Class Nr	Occupants & Fixtures per floor	Fixture Choice						
1;2;3;6;9	People	1-25	26 - 75	76 -125	126 - 200	201 - 300	301 - 400	400+
	Fixtures	2	4	6	8	10	12	+2 for every 175
8	Fixtures	visitors *0.5						
11	Workers	1-20	16 - 35	36-55	55+			
	Fixtures	2	4	6	+1 for every 50			
	Students	1-15	21 - 50	50+: every 50				
	Fixtures	2	4	1				
4;5	People	1-15	16-35	36-55	55+			
	Fixtures	2	4	6	+1 for every 50			
7	Fixtures	1						
12	People	1-50	51 - 100	101 - 200	201 -300	301 - 400	400+	
	Fixtures	2	4	6	7	8	+1.3 for every 150	
10	People	1-10	11-25	26 - 50	51 - 75	76 - 100	100+	
	Fixtures	2	4	6	8	10	+2 for every 300	

Most fixture methods are directly based on the International Building Code[83], except for the method used for Building Classes: Healthcare and Lodging (nr 7 & 8). Healthcare RWH systems are only allowed to be used for cooling the air conditioning system. Therefore, the number of fixtures is reduced to 1 per floor. Lodging assumes to have a fixture for every two visitors since every hotel guestroom has its own toilet.

2.1.4.2 Pumping Power

Estimation of the required horsepower the RWH pump needs to deliver, an equation from the Water Environment Research Foundation's Life Costing Model(WERF)[84] is used. The equation relates to the number of floors in the building, and the amount of water demanding fixtures per floor.

$$P = 62.4 * N_{floors} * 10 * \left(N_{fixtures} * N_{floors}\right) * \frac{0.00891}{1100} \quad (1)$$

Where P is the required horsepower; N_{floors} is the number of floors in the building, $N_{fixtures}$ the amount of water demanding fixtures.

2.2 The Mass Balance Model

This chapter introduces the Mass Balance Equations (2.2.1), followed by an elaboration on the water in-and outflows (0 & 2.2.3). The chapter ends with a description of important model outputs (2.2.4).

2.2.1 The Mass Balance Equations

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

$$\Delta V_{i,t} = V_{i,t} - V_{i,t-1} = Q_{i,t} - Y_{i,t} - O_{i,t} \tag{2}$$

Where $\Delta V_{i,t}$ is the volumetric change of rainwater in the tank between time t $(V_{i,t})$and time *t-1* $(V_{i,t-1})$[m³/h]; $Q_{i,t}$ is the inflow of rainwater to the tank[m³/h]; $Y_{i,t}$ the rainwater yield used for non-potable water purposes [m³/h]; and $O_{i,t}$ the tank overflow, i.e. spillage [m³/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:

$$O_{i,t} = max\begin{cases} V_{i,t-1} + Q_{i,t} - S_i \\ 0 \end{cases} \tag{3}$$

$$Y_{i,t} = min\begin{cases} D_{i,t} \\ V_{i,t-1} + Q_{i,t} - O_{i,t} \end{cases} \tag{4}$$

$$V_{i,t} = min\begin{cases} V_{i,t-1} + Q_{i,t} - Y_{i,t} \\ S_i - Y_{i,t} \end{cases} \tag{5}$$

Where S_i the storage capacity of the rainwater tank for building i [m³]. The inflow $Q_{i,t}$ consists of the rainfall entering the tank:

$$Q_{i,t} = R_{i,t} * A_{i,cr} * \varphi * \theta \tag{6}$$

$R_{i,t}$ describes the precipitation inflow at time t [m/h], $A_{i,cr}$ is the contributing roof area (which dimensions are based on design choices, but initially uses a value of 100% of the total area A_i [m²], 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 non-potable water demand $(D_{i,t})$[m³/h] is a sum of various non-potable water demands for laundry, toilet flushing and air conditioning. Based on the daily non-potable water demand obtained (see *2.2.3.1*), the hourly demand is further specified using toilet and laundry specific hourly patterns for residential housing[85]. A different daily distribution graph is used for commercial and office buildings[86]. Further explanation of these patterns is found in chapter 2.2.3.2.

The volume of the non-potable water demand unmet by the RWH system of Building Class i [m^3/h] is given by:

$$M_{i,t} = D_{i,t} - Y_{i,t} \tag{7}$$

The total volume of potable water substituted for a building over time period T is described by:

$$Y_{i,total} = \sum_{t}^{T} Y_{i,t} \tag{8}$$

The total substituted volume of an RWH strategy over period T (a combination of all buildings), is expressed as:

$$Y_{total} = \sum Y_{i,total} \tag{9}$$

Class specific totals are also calculated, by summing all buildings within the same Building Class.

2.2.2 Rainfall

The water inflow for the RWH Mass-Balance Model is rainfall which is harvested by the roof and directed to the cistern using gutters.

The rainfall series were 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.

Monthly rainfall is highest in June and lowest in February, with a median of 120mm and 73mm respectively (See Figure 3). Annual rainfall shows wet years in 2009 and 2010, with a total annual rainfall of approximately 1800mm. Dry years occurred in 2001 and 2012 with total rainfall to be around 900mm.

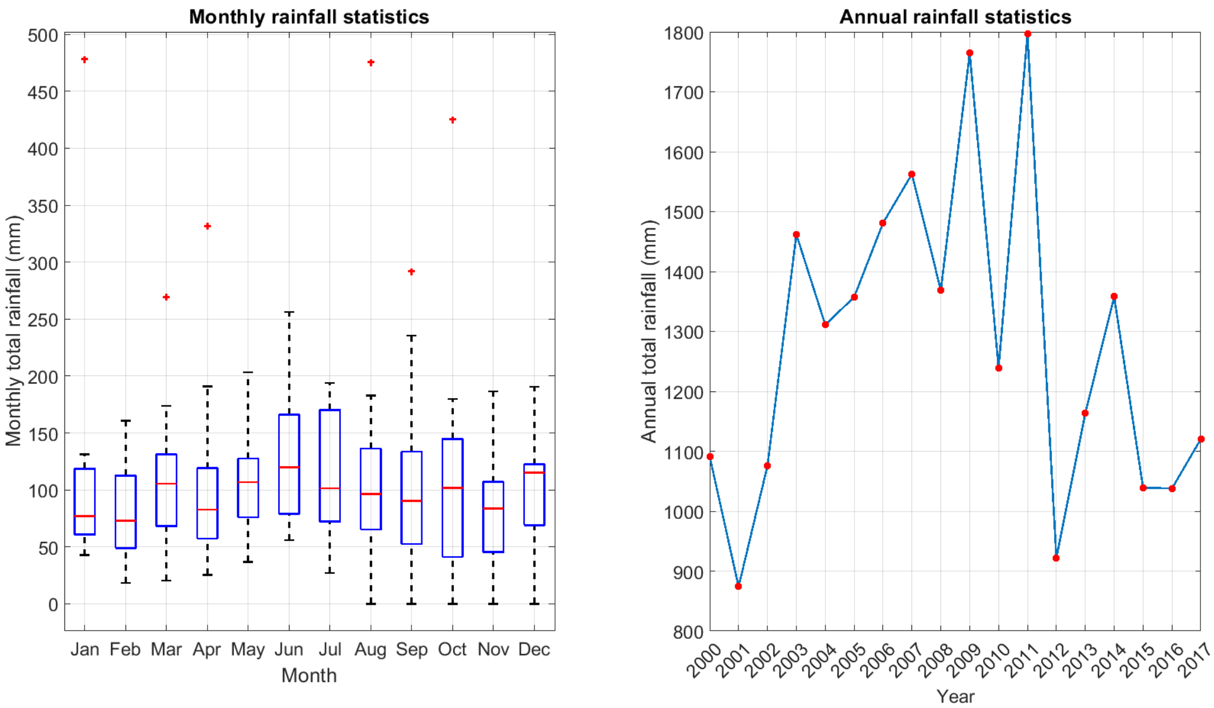

Figure 3: the monthly variation in total NYC rainfall over 18 years (left), and the annual rainfall over the last 18 years (right).

It is assumed that RWH has the best performance in the wetter years and months, so the month of June, and the years 2001 and 2012 show the most potential.

2.2.3 Non-potable Water Demand

The hourly precision used in water inflows has to be applied to the non-potable water demand. However, since water demand data is normally recorded on a daily basis, an extra step is required to get to hourly estimates. First, the choices and data for daily demands are described (2.2.3.1), followed by an explanation of diurnal patterns (2.2.3.2), the information used to get to an hourly scale.

2.2.3.1 Demand Types

The water demand is based on the type of use. Every class has different water use types. The Building Class Table (Table 1), and Water Type Table (Table 4) are connected. The numbers described in Table 1 relate to these water demand types. For washing machines, a water use of 85L is used, which is slightly smaller than the normal estimate of +- 100l. This way, if the washing machine runs three times a week, it simulates the temporal mismatch between water availability and water demand, whilst simultaneously getting the average daily water consumption to 36.4L, which is the reported average water use per capita.

*Table 4: Water demand per water use type. *this number relates to the water use numbers in Table 1.*

Nr *	Type	Daily Usage Per Capita	Water required per use [L]	Average water use per occupant per active day [l/c/d]	Frequency
1	Toilet Flushing – Housing	5	9,8	49	Every day
2	Toilet Flushing – Employee Male	Urinal: 3 Toilet: 1	Urinal: 3.785 Toilet: 9.8	21.2	Every working day
	Toilet Flushing – Employee Female	Toilet: 3	9,8	29,4	Every working day
3	Toilet Flushing – Visitor	0.2	9,8	1,96	Every working day
4	Toilet Flushing – Lodging	3	9,8	29,4	Every day
5	Toilet Flushing – Student	3	9,8	29,4	Every working day
6	Washing machine	1	85	85	3 times a week
7	AC	Constant	0,6l/m2/day	_	Every hour with temperature >22° C

2.2.3.2 Diurnal Patterns

The step from daily to hourly water demand is made using diurnal patterns. Diurnal patterns show the distribution of water use for different building types along the day[87–89]. Nine different diurnal patterns are used, each linking to one or more Building Classes as seen in Table 1. These diurnal patterns were taken from reports by the city of Ann Arbor[89], a case study on Melbourne[90] and research on smart meters for residential toilet and washing machine demand.

Nine out of twelve Building Classes use one specific diurnal pattern which describes the pattern of all water use during the day since more accurate data is not available[89,90]. Residential buildings (Class 1,2 and 3) use more accurate water demand patterns specific to toilet use and laundry[91]. The diurnal patterns show the variation of water demand over the entire week, except for the patterns: Toilet, Laundry and Industry, these have daily diurnal patterns.

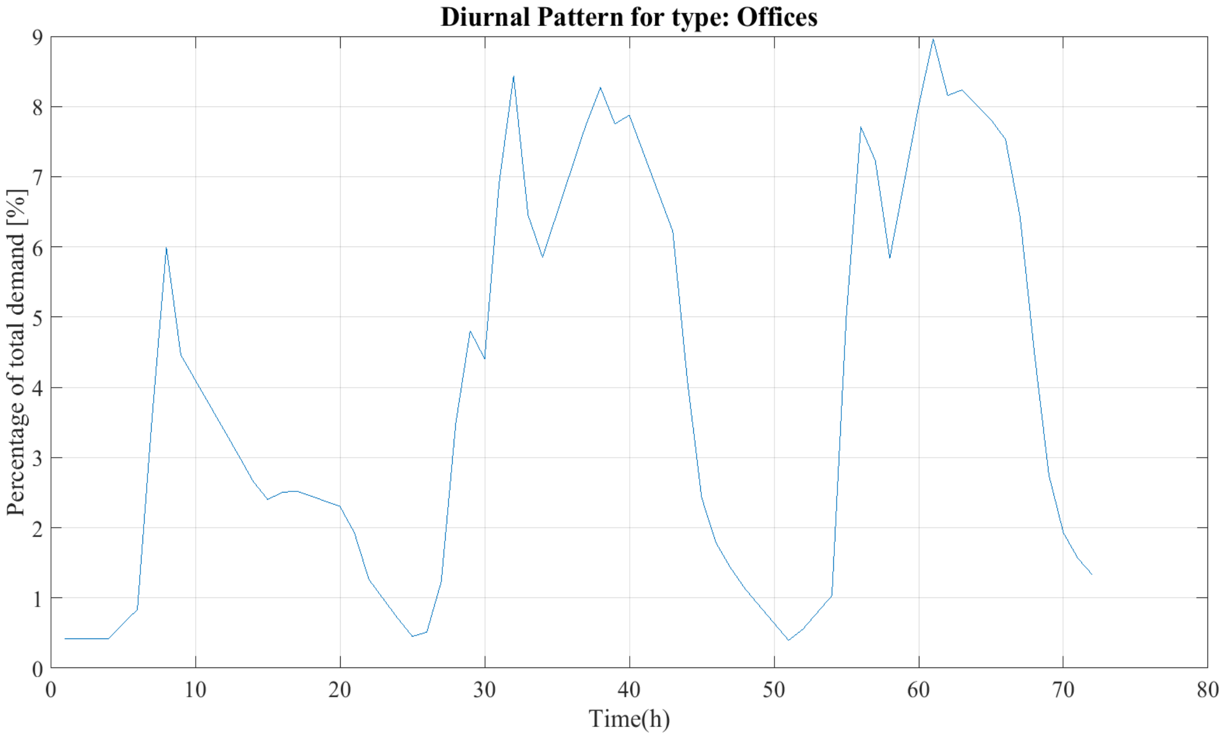

Figure 4: The first three days (Mon-Wed) of the weekly diurnal pattern for office use. Showing an increase of water demand during the week.

Figure 4 shows an example of a diurnal pattern for the office Building Class. It shows an increase in water demand from Monday to Wednesday, with a clear pattern of low water usage from 11 pm to 7 am, and a small dimple after 10 o'clock.

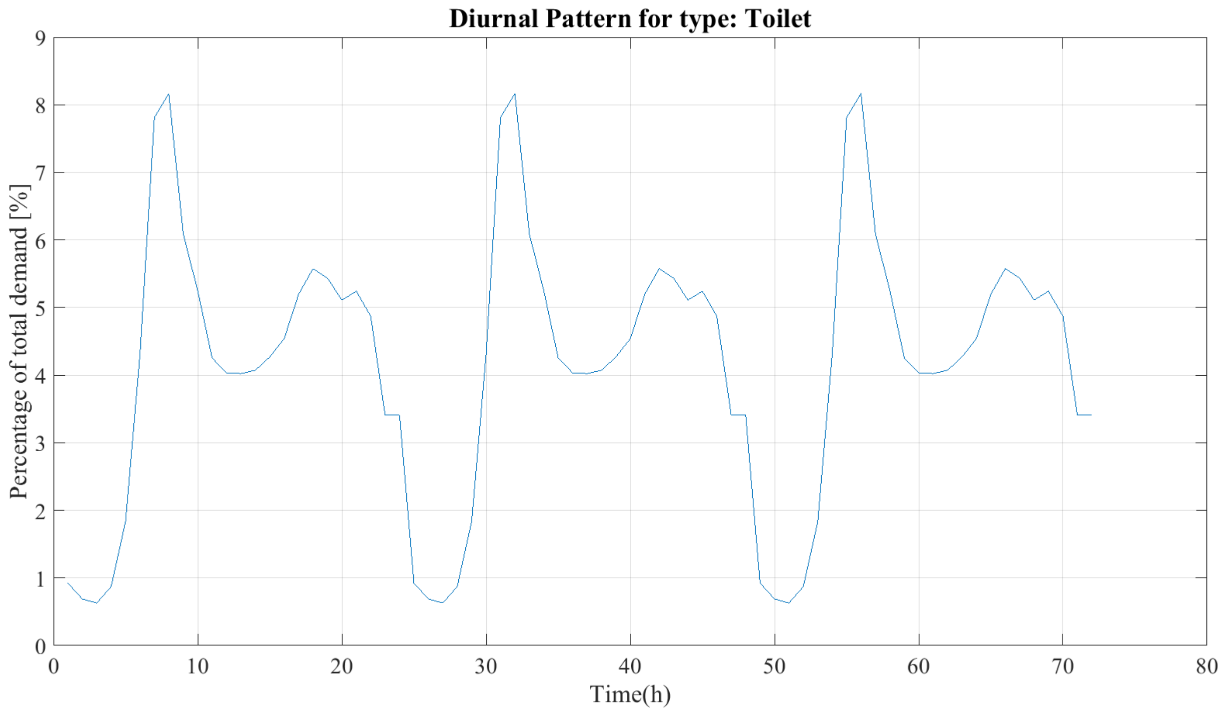

Figure 5: The first three days (Mon-Wed) of the diurnal pattern for toilet use. With clearly visible the recurring daily pattern due to the available data.

Figure 5 is an example of a daily diurnal pattern which is repeated in order to get the weekly demand. The diurnal pattern 'toilet' is used for all residential buildings, and shows high usage in the morning and evening, with a peak use at 9 am.

2.2.4 Model Output

The model is built to release outputs which are later used in choosing appropriate tank sizes and checking the performance of the tanks. Two types of output are discussed: Water performance, and energy performance.

2.2.4.1 Water Performance

The water-related performance of the RWH systems is assessed using the water efficiency and roof runoff reduction[9]:

$$\eta_i = \frac{\sum_t^T Y_{i,t}}{\sum_t^T D_{i,t}} \tag{10}$$

$$R_{i,reduction} = \frac{\sum_t^T Y_{i,t}}{\sum_t^T Q_{i,t}} \tag{11}$$

Where η_i is the water efficiency, the percentage of non-potable water demand supplied by the RWH system. The water efficiency is crucial in choosing the right tank size, as explained in chapter 0. $R_{i,reduction}$ is the percentage of inflow water that is subtracted from the direct runoff. This is used to look at the effect of RWH from the government perspective of increasing safety.

Equation 19 and 20 can be used to assess every Building Class RWH system separately. The entire RHW city application or specific Building Classes can also be assessed as whole, by summation of total yield over total demand supplied, for all in the dataset, or all belonging to a specific Building Class, over time period T.

2.2.4.2 Energy Performance

A pump directs the rainwater towards the toilets and washing machines. The energy performance is an indicator of how much energy is used, which is mainly important for the cost estimation (See 2.3.4). It can also be used to assess how it conflicts with NYC's other sustainable goals, like energy reduction and carbon challenges[11][12]. The total energy use in kWh is calculated using the following equation:

$$E_{i,total} = EI * \sum_t^T Y_{i,t} \tag{12}$$

Where EI is the energy intensity[kWh/m^3], and $Y_{i,t}$ the total yield. The energy intensities are values taken from multiple research projects on RWH pumping cost[40,93–95]. Pumping energy is not calculated using a theoretical approach because theoretical studies underestimate energy use[93].

For single-family residential buildings, and buildings with a height lower than 4m, in combination with an amount of water using fixtures per floor lower than 3, an energy intensity of 1.5 kWh/m^3 is used. These buildings are relatively small, which let them use different and less energy intensive RWH systems[40,93]. Other buildings have an intensity of 3 kWh/m^3[40,96]. New research suggests using tanks on every building floor, in order to reduce pumping cost, however, this is not yet assumed to be practiced in this research[96].

2.3 Benefit-Cost Analysis I: Owner

Assessing the benefits and cost of RWH is done using a different method for both the owner and government perspective. This chapter analyses the owner perspective, chapter 2.4 describes the government perspective.

First, the benefit-cost ratio is introduced as a tool with which the cost analysis is executed (2.3.1). Secondly, the methods for calculating the benefits (2.3.2) and costs (2.3.3) are discussed.

Note, the cost estimates have been retrieved from multiple sources, and have been adjusted to current prices using 2017 CPI values for the US. Costs for maintenance, which are locally determined are adjusted using the 2017 CPI values for NYC.

Table 5: CPI values for the United States and New York City

CPI	US	NYC
2017	245,1	268,5

2.3.1 The Benefit-Cost Ratio

The benefit-cost ratio is the total profits of an RWH project divided by the total costs (See equation 23). It shows if, over a certain lifespan T, the benefits outweigh the profits. The calculation can be performed for a building, a Building Class, or an entire strategy.

$$BCR_i = \frac{\sum_t^T CW_{i,t}}{C_{i,investment} + C_{i,maintenance} + +C_{i,energy}} \tag{13}$$

Where BCR_i is the Benefit Cost Ratio for building i; $CW_{i,t}$ the cost of water services over period t; And the lower C_i values as the cost for the investment, maintenance and energy.

Owner perspective sized RWH systems are designed (i.e., for tank size and contributing roof area) to reach a positive benefit-cost ratio (BCR). Reaching a BCR of 1.0 is seen as a feasible goal, based on existing literature [4,9,28,38,43] considering the current utility fees and annual precipitation patterns in NYC. Building Classes for which the sum of all buildings costs and benefits, lead to a benefit-costs ratio lower than 1, will not be considered for RWH.

2.3.2 RWH Profits

The benefits in equation 30 are the profits made on potable water demand reduction.

NYC uses 159% of the potable water price as wastewater charge[97], thus reducing potable water reduces the cost of wastewater treatment. To determine the cost reduction for Building Class i, the following equation is used:

$$CW_{i,t} = Y_{i,t} * \left(\epsilon_i * (1.59 + 1)\right) \tag{14}$$

Where $CW_{i,t}$ is the water related cost reduction at time t[$/h], $Y_{i,t}$ the demand supplied by rainwater [m^3/h], and ϵ_i the cost of water [$/$m^3$].

2.3.3 Capital Cost

For each RWH system, the investment costs cover the costs of a rainwater cistern, installation, and an electronic pump. These costs depend on the RWH design, specifically:

2.3.3.1 Cistern

Due to the wide price ranges leading to uncertainty in cost estimation, simple equations are used:

$$C_{i,cistern} = S_i * \psi_{cistern} + \beta_{cistern} \tag{15}$$

Where $C_{i,cistern}$ is the cost of each cistern in $, S_i is the storage volume of the cistern, $\psi_{cistern}$ the cost per volume [$/$m^3$] and $\beta_{cistern}$ the initial cost [$]. Different cistern sizes and their related costs are acquired, plotted size over cost, and using a simple linear regression technique, a linear relation between cost and size is determined, leading to the volume related cost factor $\psi_{cistern}$ and initial cost $\beta_{cistern}$ [1].

The factors $\psi_{cistern}$ and $\beta_{cistern}$ change, depending on the tank size. This is because when a tank size reaches a certain limit, the material or location has to change. Plastic tanks reach volumes of around 10m^3, and if the tank volume gets too big, the tank is placed underground, which leads to higher costs. Tank volumes of more than 20m^3 are only reached by big non-residential buildings, so fibreglass tanks smaller than 35m^3 are placed aboveground.

Table 6: Tank Cost Parameters

Volume	Material	Location	$\psi_{cistern}$	$\beta_{cistern}$
1-4	Plastic	Aboveground	154	0
4-20		Underground	340	148
20-35	Fiberglass	Aboveground	155	155
35+		Underground	717	2450

2.3.3.2 Installation

The installation costs are calculated using a method used by a lifecycle costing model created by the Water Environment Research Foundation [84]:

$$C_{i,installation} = C_{i,cistern} * 0.6$$

It assumes that installation of the system is approximately 60% of the cistern cost.

2.3.3.3 Pump

For the choice of pump, the required pumping power is used, which is determined by Equation 24. The equation for the cost is described by an equation from WERF[84]:

$$C_{i,pump} = -100.71 * P_i^2 + 1330.* P_i \tag{16}$$

Where within Building Class i, $C_{i,pump}$ is the cost of each pump in dollars [$] and P_i the required power [HP] (Equation 24).

This function is only applicable for pumps up to 5HP. If the pump power requirement surpasses 5HP, an additional pump is used. This is not only due to the limitation of the cost function. High buildings which require a lot of pumping power, use multiple pumps instead of one strong pump, in order to limit the pressure and avoid bursting [98].

Note, every system part has a specific lifespan, if that lifespan is shorter than the lifespan of the system strategy (30 years), the system is replaced leading to increasing maintenance cost (see 2.3.5). The three cost functions combined lead to the total investment cost $C_{i,investment}$:

$$C_{i,investment} = C_{i,pump} + C_{i,pipe} + C_{i,cistern} \tag{17}$$

2.3.4 Operational Cost

The equations related to energy costs use the energy consumption equations as input (see *2.2.4.2).* The energy costs are described by:

$$CE_{i,t} = E_{i,t} * \zeta_i \tag{18}$$

Where within Building Class i, $CE_{i,t}$ is the total reduction of energy costs at time t[$]; $E_{i,t}$ the energy saved [kWh]; and ζ_i the cost factor [$/kWh], ζ_i is variable depending on the building class i, with different Building Classes having different energy rates (See Table 1)[99].

2.3.5 Maintenance Cost

Maintenance cost is divisible in two parts: routine and corrective maintenance. Routine maintenance is the cost of inspections and keeping the tank and roof collection system clean. Costs of these routine checks are low, but due to the high frequency, the annual cost is high.

Table 7: Routine maintenance cost estimates

PART I Routine Maintenance	Frequency	Occurrence in lifespan T [years]	Average annual cost [US$]	Average Monthly cost [US$]
Inspection, Reporting & Information	Every 0.5 years	36	325	27
Roof Washing & Cleaning inflow filters	Every 0.5 years	36	601	50
Tank inspection and disinfection	Every year	18	300	25

Corrective maintenance is the estimated cost of replacing and repairing the RWH system. These operations have higher costs, yet happen infrequently, leading to lower annual costs.

Table 8: Corrective maintenance cost estimates

PART II Corrective Maintenance	frequency	Occurrence in lifespan T [years]	Average annual cost [US$]	Average Monthly cost [US$]
Intermittent System maintenance (system flush, debris/sediment removal from tank)	Every 3 years	6	163	14
Pump replacement labor	Every 10 years	2	50	4
Pump Replacement				
Minor fittings replacement			38	3
Filter replacement	Every 15 years	1	29	2

The aforementioned maintenance costs are very conservative. These costs are made when all repairs, inspections, and cleaning is outsourced. Australian research reports maintenance costs for residential buildings to be between 1-100$ a year[100]. Assuming that residential home-owners and small shop owners will not outsource their RWH maintenance, the small residential building classes, and retail classes will use an annual maintenance cost of 50$.

2.4 Benefit-Cost Analysis II: Government

2.4.1.1 Water supply and treatment

The operation costs of NYC's MWS for the last few years (2013-2017)[97,101–103] are approximately 2800 million dollars. The predicted cost of the MWS improvement program for 2016 – 2025 are 16767.4 million dollars, which is 1676 million dollars annually, leading to a total annual expenditure of 4476 million dollars. With the MWS of NYC producing 1 billion gallons of water today[97] (the only available, but often cited approximation), this leads to the water cost of 3.24$/m^3$:

$$CW_{mws} = Y_{total} * 3.24 \tag{19}$$

Where CW_{mws} is the total water cost of all Building Classes combined. And Y_{total} the total yield of water (see Equation 9).

2.4.1.2 Energy consumption of water deliverance

Besides the energy consumption of the RWH system inside the building, which is paid for by the building owner, there is energy consumption in the deliverance of water from the upstream watershed towards the building. The energy added to the total consumption by treating and pumping water in NY state (EE_{mws}) is approximately 0.37kWh/m3 [104]. Also, the cost ζ_i is different for the government.

2.4.1.3 Filtration

NYC government pays for water filtration, the estimation of cost saved due to RWH, is based on the cost of a filtration plant. The total cost of filtration is converted to a cost per cubic meter of water filtered. This value is used as an estimate of the costs saved by substituting one cubic meter of potable water using RWH.

$$\frac{Total\ lifetime\ Filtration\ plant\ costs}{Total\ lifetime\ Filtration\ plant\ capacity} * Y_{i,t} = CWF_{i,mws,t} \tag{20}$$

2.5 Tank Selection

2.5.1 Owner perspective

For the owner, the choice of the tank is based on the cost efficiency of the tank. The cost efficiency is described using benefit-cost ratios, where the profits of installing RWH, are divided by the capital cost of installing the RWH system. For further explanations of the benefit-cost ratios see Chapter 2.3.1

Choosing the right tank size is crucial in reaching a cost-efficient RWH system. With over-dimensioned tanks the cost becomes too high; small tanks do not create enough benefits. In order to get the right tank size, thirty different tank sizes are tested for every building. The range of tank sizes is chosen to represent a good impression of the cost efficiencies of all feasible tank options. Cost efficient tanks are expected to be relatively small due to the high increase in price with increased volume. Therefore the thirty tank sizes will not be equally spaced between the limits; the thirty tank sizes will have a higher concentration in the lower volume region.

The functions that distribute the optional tank sizes are described by:

$$S(i) = b + a * e^{i} \tag{21}$$

With

$$a = \frac{(S_{maximum} - S_{minimum})}{(e^{\max(i)} - e^{\min(i)})} \tag{22}$$

And

$$b = S_{minimum} - a * e^{\min(i)} \tag{23}$$

Where $S_{minimum}$ & $S_{maximum}$ are respectively the minimum and maximum tank size choice for a building. a, b and e are parameter variables to get a right skewed distribution of tank sizes in a tank range between the minimum and maximum tank. e decides the amount that the distribution is skewed, with e close to 1 showing an almost equal distribution, and e values upward from 1 showing a more and more skewed distribution to the right, with a high precision in the lower region of tank volumes, and lower accuracy in the higher tank volumes.

The maximum tank size is related to the roof area and the number of occupants. The minimum tank size changes per building class, for the Healthcare class, it is 1, as Healthcare buildings can only use non-potable water for air conditioning cooling, due to health restrictions. For other classes, it is the maximum tank size, divided by 8, which leads to a reasonable tank size.

The model runs all these different tank sizes and chooses the tank size resulting in the highest benefit-cost ratio.

2.5.2 Government perspective

For the government perspective tank size, the same algorithm (See equations 21,22 & 23) is used to calculate the different tank sizes, however, this time the e value is selected closer to one, to get a less skewed distribution, since it is predicted that government tanks are bigger.

Government tanks are selected to get a high-water efficiency, without having over-dimensioned tanks. In order to do this, again thirty tank sizes are generated. The model evaluates the different tank sizes on water saving potential. Using the different water efficiency outcomes of the 30 different tank sizes, a function is created that describes the relationship between tank size and water efficiency. The function is structured as follows:

$$f(S) = \alpha_1 * \frac{S}{(\alpha_2 + S)} \qquad (24)$$

Where S is the volume of the tank [m^3]; α_1 and α_2 are fitted parameter values based on the generated tank sizes and resulting water efficiencies.

Using this function, the tank size that reaches 90% of the maximum water saving potential is estimated, and this is the tank size used for the government perspective.

3 Results

3.1 Building Classification Results

The classification of New York City buildings shows that over 90% of all buildings in the city belong to the residential classes. The residential classes contain the single family, multifamily and the mixed class, which contains buildings with office and residential floor area.

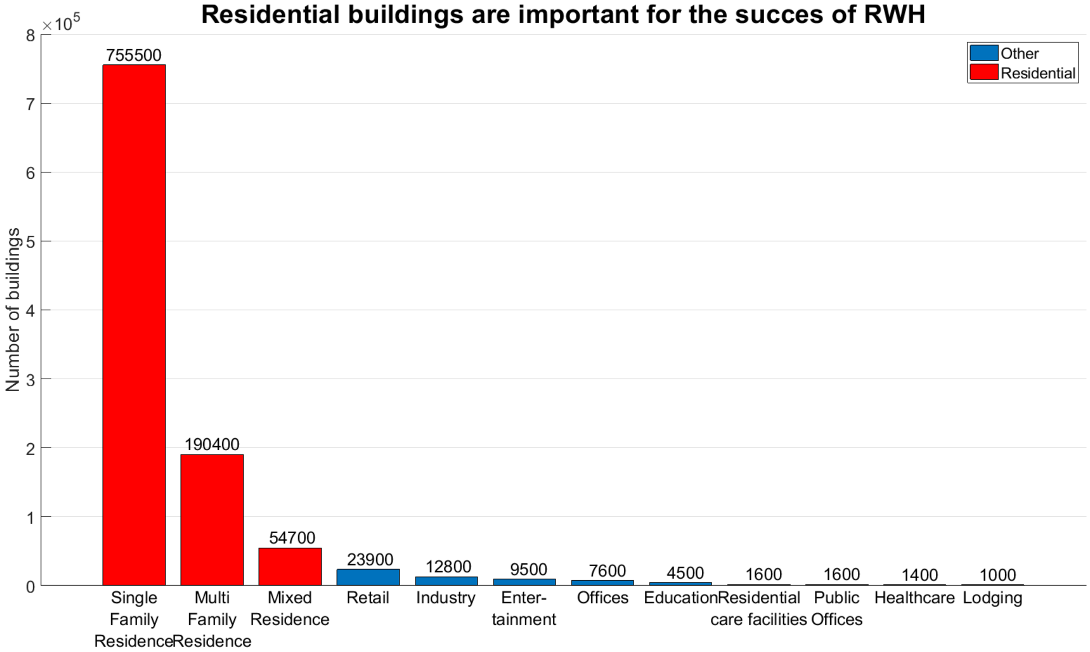

Figure 6: Distribution of buildings across the building classes.

Most potential for subtracting rainwater lays within the residential building classes.

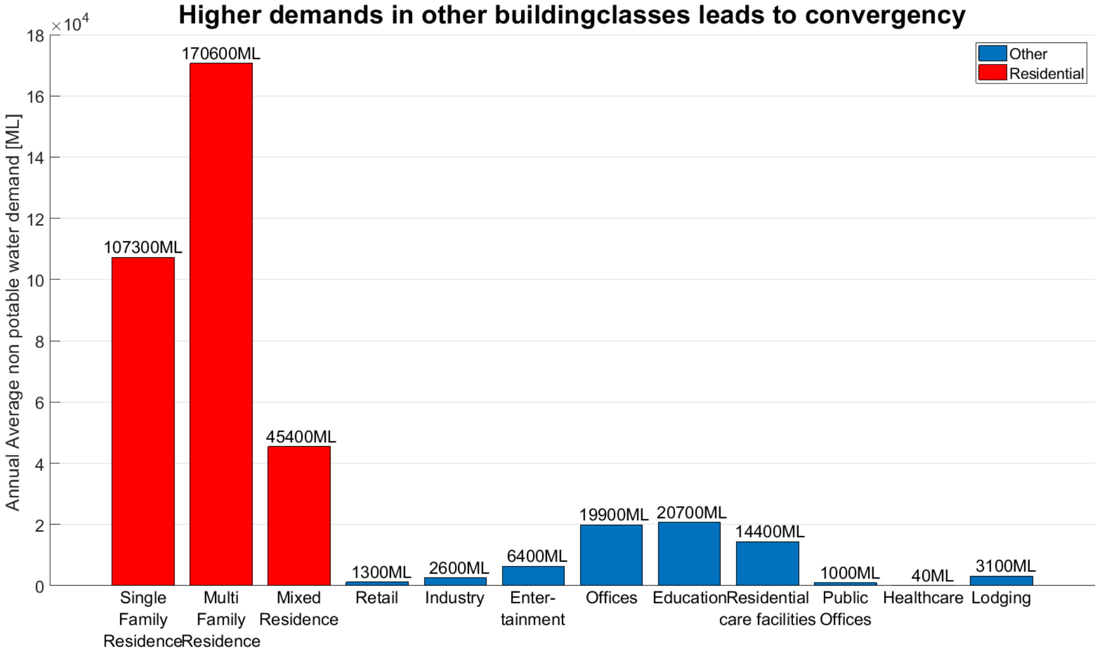

Figure 7:Total Building class non-potable water demand

3.2 Cost Distribution

3.2.1 Average Costs

3.2.1.1 Owner perspective

Average cost for the RWH systems is highest in the Lodging class and lowest in Retail. For the owner perspective, the cost of maintenance is the biggest contribution to the total average cost. As maintenance cost was chosen differently in the Retail, Mixed, and Single Family Classes, they show the least cost, averaging an approximate 5000$. Healthcare shows the weirdest distribution, due to the small sizes of the tank, and pump, combined with the high maintenance costs.

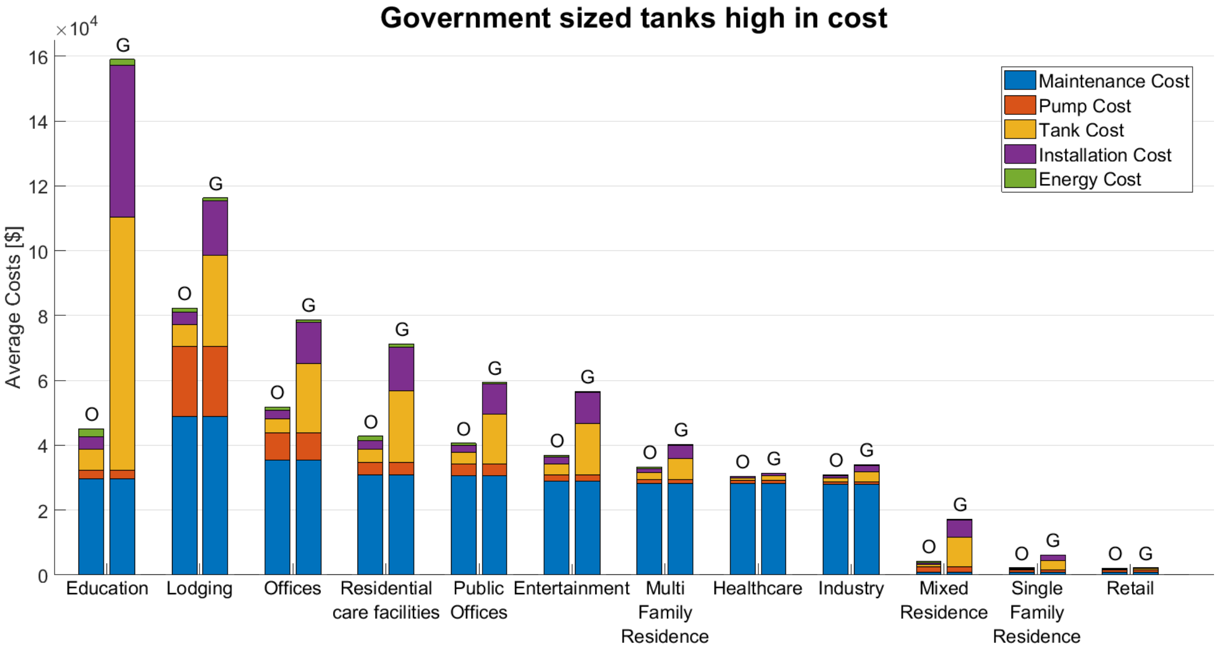

Figure 8: Average Cost of an RWH system per Building Class, for different configurations.

Pump costs are highest in the Lodging class, due to the height of hotels in combination with the number of water demanding fixtures (every guest room is connected to the water system).

3.2.1.2 Government Perspective

The government tank sizes are higher than the owners, resulting in a higher tank cost, clearly visible in figure… Education, due to the sheer size, and roof area, of these buildings, has great potential for harvesting rainwater. Therefore, the model simulates high tank sizes, which results in Education having the highest average tank costs. Entertainment, Public Offices and Residential Care facilities show similar behavior, with Government tank costs being tripled.

3.2.2 Total Building Class Costs

3.2.2.1 Owner perspective

Summing the costs of all buildings within a class, it is no surprise that the residential buildings are highest in cost. 70% of all costs lay with the residential buildings, costing approximately 13 billion dollars. Education and lodging, although high in average cost does not contribute much to the total costs.

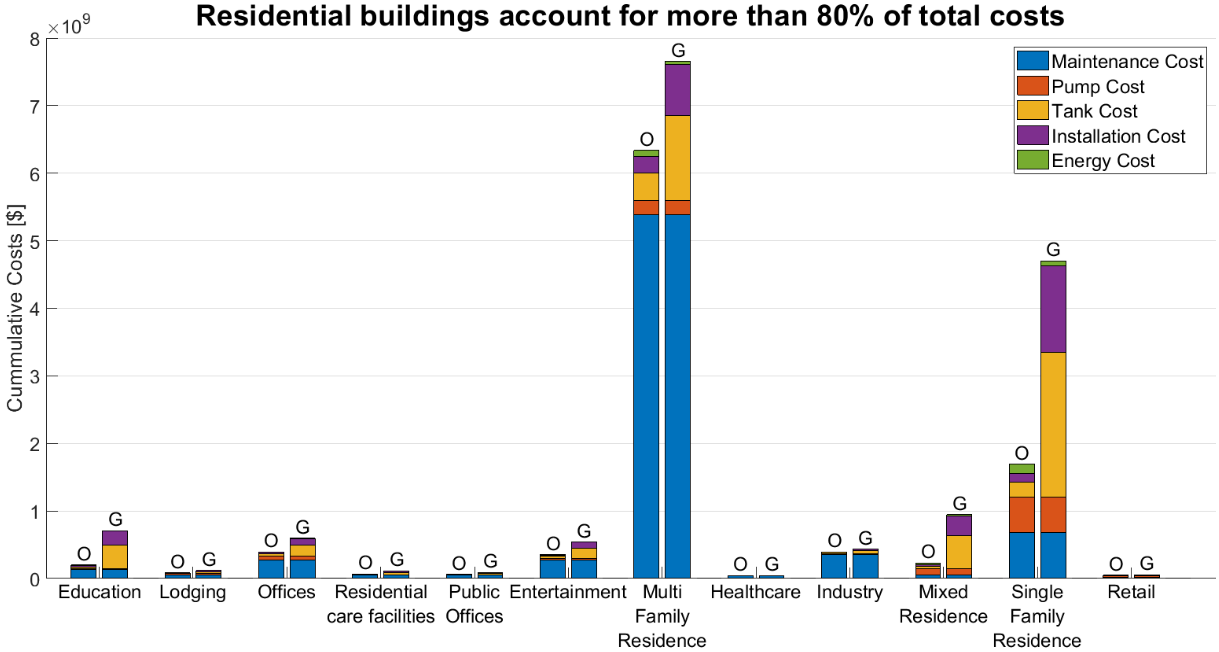

Figure 9: Total cost of implementing RWH per Building Class, for different configurations

3.2.2.2 Government perspective

Government sized tanks increase with 20% in the Multifamily buildings and up to 230% in the Single-family building class. Maintenance costs are a huge portion of the total costs. If the NYC's government would decide on implementing RWH systems, the real maintenance costs would be much lower.

3.3 Water Services

3.3.1 Water Saving Efficiency

The water saving efficiencies show that between 10% and 90% of the non-potable water demand can be supplied. Highest efficiencies are Healthcare, Industry, and Retail. However, this is due to low demands, especially for Healthcare. Residential buildings show a water saving efficiency between 20 and 70%.

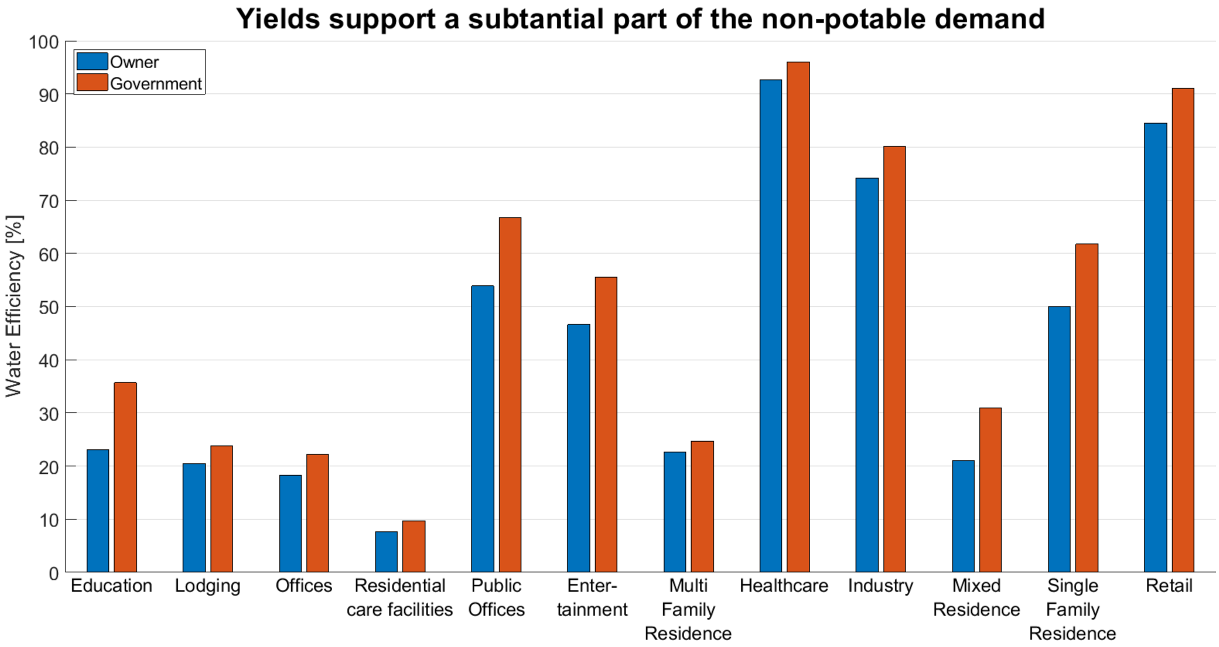

Figure 10:Building Class water saving efficiencies for different RWH configurations

3.3.2 Total Water Saving Potential

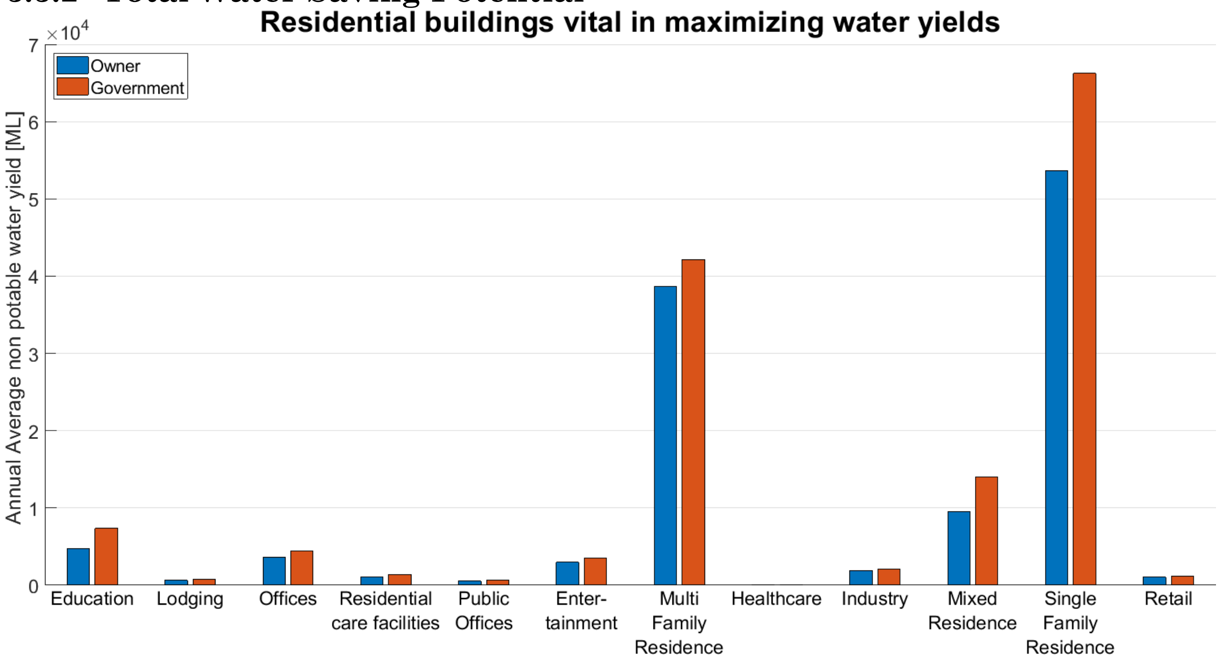

Figure 11: Building Class Water saving potentials, for different configurations

3.4 Cost Analysis

3.4.1 Cost Analysis Owner

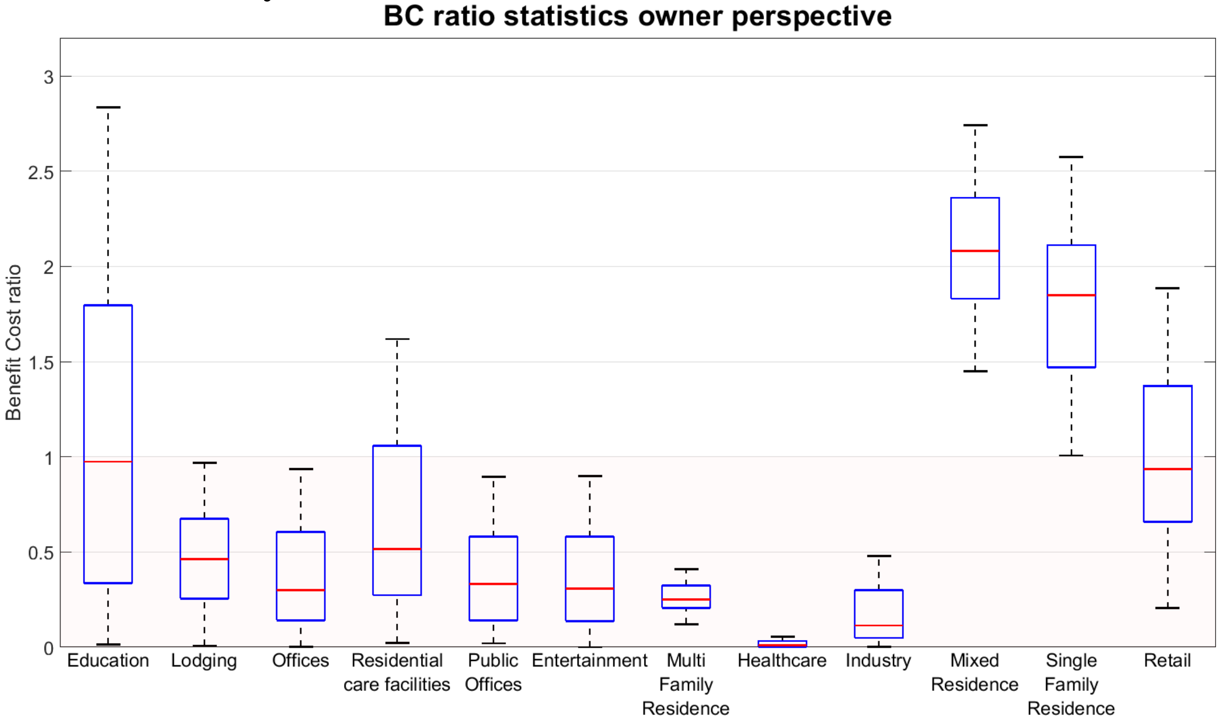

Figure 12: BC ratio boxplots, from owner perspective. Only two classes have a median above 1.

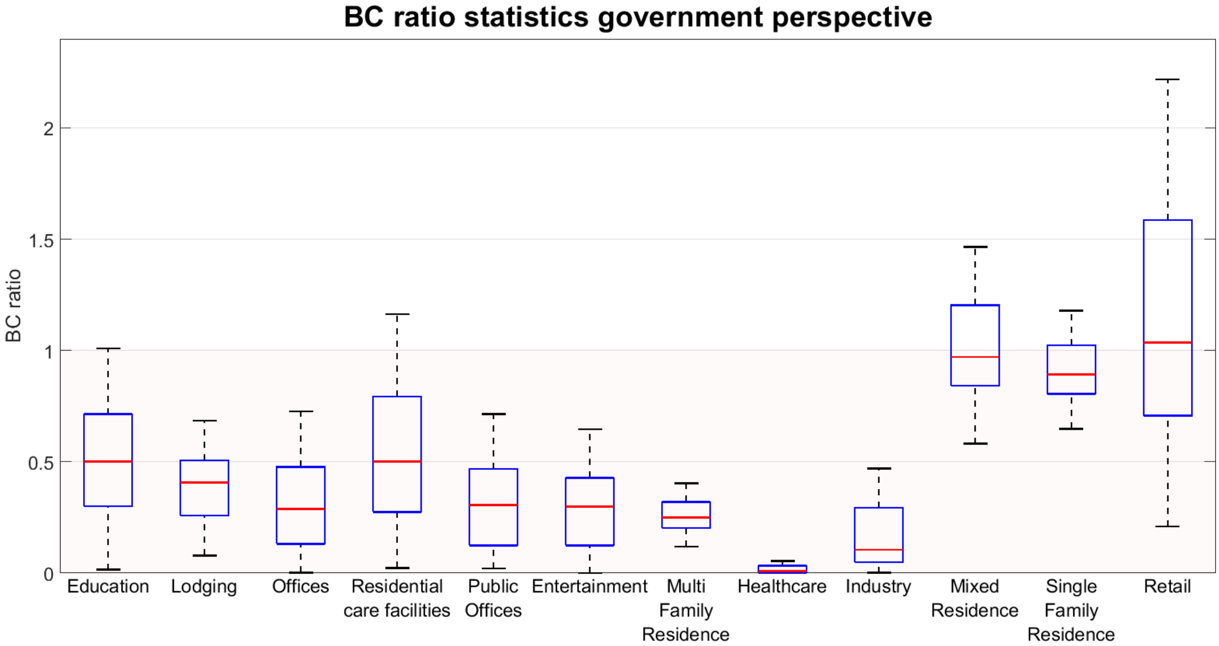

Figure 13: BC ratio boxplots, from city perspective. Only one class has a median above 1.

4 Scenario Table

Table 9: Scenario Information

Scenarios	City water savings [Mm3]	Owner water savings [Mm3]	Total water savings [Mm3]	City cost [B$]	Owner Cost [B$]	Total Cost [$]	city buildings [x100,000]	owner buildings [x100,000]	Total buildings	City m3/$
1. City pays all	2836	0	2836	18	0	18	11	0	11	0.16
2. City pays [BCR <1.5] owner pays [BCR >=1.5]	1122	1290	2412	11	2	13	4	6	11	0.22
3. City pays [BCR <1.0] owner pays [BCR >=1.0]	788	1590	2378	9	3	12	3	7	11	0.26
4. City pays [BCR <1.5&CE>0.1] owner pays [BCR >=1.5]	699	1290	1989	4	2	6	3	6	9	0.51
5. City pays [BCR <1.0&CE>0.1] owner pays [BCR >=1.0]	365	1590	1955	2	3	5	1	7	9	0.84
6. City pays [BCR <1.5&CE>0.2] 7. owner pays [BCR >=1.5]	291	1290	1581	1	2	3	2	6	8	1.38
8. CROTON	2780	0	2780	4	0	4	0	0	0	0.65
9. City pays [BCR <1.0&CE>0.2] owner pays [BCR >=1.0]	106	1590	1695	0	0	4	1	7	8	3.93
10. Owner pays all	0	2335	2335	0	11	11	0	11	11	0.20
11. Owner pays [BCR > 1]	0	1590	1590	0	3	3	0	7	7	0.52

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