

Strategic design and finance of rainwater harvesting to cost-effectively meet large-scale urban water infrastructure needs

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ABSTRACT

Many cities are confronted with both water scarcity and urban flooding as centralized water infrastructures becoming increasingly inadequate in a changing climate. Decentralized infrastructures like rainwater harvesting (RWH) can ease both issues. Yet, most studies find RWH offers limited infrastructure capacity at high cost. Previous assessments, however, fail to consider two critical advantages: multi-functionality and high adaptability. By improving the incorporation of these advantages in our analysis of 1.06 million buildings with distinct design and water demand characteristics and 20-year hourly precipitation records in New York City (NYC), we demonstrate, contrary to existing studies, that strategically designed, financed and implemented rooftop RWH systems in all or a subset of the buildings can meet large-scale infrastructure development needs for water supply and stormwater management. RWH implementation featuring public-private partnerships (PPP) in 43–96% of the buildings can serve 17–29% of the city's non-drinking water demands while reducing the public expenditure per unit of water supply by 13–85%. The distributed citywide RWH implementations prevent 35–56% of rooftop runoff from entering the sewage system, rivers, and/or waterways per month, with observed rooftop runoff reductions as high as 90% for a single rain event.

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1. Introduction

Global urbanization and climate change present an urgent need to develop more efficient and sustainable urban water systems worldwide (Nations, 2019). By 2050, due to increases in urban population and wealth, global urban water demand is expected to grow by 80% (Florke et al., 2018). Additionally, climate change will lead to more extreme events such as floods and droughts across the world thereby further stressing current water and non-water infrastructure (Stott, 2016). Sustainable urban water system research concentrates on low- and middle-income countries, yet, cities in high-income countries also face analogous, albeit different, challenges. In most high-income countries, drinking water treatment and delivery systems are aging and decaying while critical maintenance and repairs are backlogged or neglected, posing great health risks, comparable to the 2004 surprise lead contamination in

Washington D.C.'s water supply (Renner, 2004), and more recently, problems of dilapidated water infrastructure exacerbated by climate change and population growth in London (Cooper, 2019). Moreover, drinking water systems are under pressure to comply with more stringent water quality standards and newly identified contaminants of concern to safeguard human health (Cañedo-Argüelles et al., 2016; Rosario-Ortiz et al., 2016). As an example, the European Parliament regularly reviews and updates the EU Water Directives like the enforced EU water quality standards applicable to surface water that recently added pharmaceuticals to a new watch list (European Union, 2018).

Rainwater harvesting (RWH) is a viable but contested strategy for simultaneously addressing various water-related challenges. Unlike existing urban water infrastructures that are centralized and single-purpose, a RWH system is a decentralized multifunctional infrastructure that augments water supplies, substitutes high-quality drinking water used for non-drinking purposes, and reduces stormwater runoff – a major source of flooding and water pollution in cities worldwide (Campisano et al., 2017). RWH's positive performance measured against various water supply and

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runoff reduction indicators is well supported (Basinger et al., 2010; Ennenbach et al., 2018; Jones and Hunt, 2010; Rostad et al., 2016; Ward et al., 2012; Zhang et al., 2009). Some studies also highlight RWH's ability to abate water quality impairments in cities serviced by a combined sewer system (CSS), where untreated runoff-sewage mixtures overflow into rivers or waterways during periods of high precipitation (Basinger et al., 2010; Gwenzi and Nyamadzawo, 2014; Wang and Zimmerman, 2015). Still, most existing studies find that RWH promises low water supply potential with unit costs higher than centralized water supply (Basinger et al., 2010; Farreny et al., 2011; Roebuck et al., 2011). As a result, RWH's ability to improve urban water systems has been challenged.

The unfavorable assessments of RWH, however, are derived without fairly incorporating the critical advantages of decentralized infrastructure: multi-functionality and adaptability. Most economic assessments of water-related infrastructures implicitly assume a single 'utility', such as water provision (Boers and Benasher, 1982; Farreny et al., 2011; Roebuck et al., 2011; Vieira et al., 2014). This single 'utility' approach works well for conventional one-purpose infrastructure but underestimates the benefits realized by alternatives serving more than one infrastructure need, such as RWH. The neglect of RWH's high adaptability is more nuanced. First, existing large-scale RWH studies are based on a one-size RWH configuration and assume non-discriminative all-building implementation in a city (Rostad et al., 2016) or country (Ennenbach et al., 2018). However, RWH system performance is contingent on the sizing of rainwater tanks (Imteaz et al., 2011; Jones and Hunt, 2010; Wang and Zimmerman, 2015) and water demand patterns in buildings (Basinger et al., 2010; Environment Agency, 2010; Retamal et al., 2009). That is, the performance of citywide RWH implementation can be improved by strategically sizing the rainwater tanks by building class and by targeting the buildings with good RWH performances. RWH's customizability of size, cost and design for individual buildings is not possible for centralized infrastructure systems. Further, the high customizability and its decentralized nature allow RWH systems with different design and cost characteristics to be flexibly bundled to meet impending infrastructure expansion needs at a range of scales. The advantages also enable RWH implementations to be highly adaptable to the different priorities of public funds (e.g. societal benefits) and private funds (e.g. return on investment), maximizing the socio-economic value of capital investment.

Against this background, we examine the performance of large-scale RWH implementation by more fairly incorporating its critical advantages of multi-functionality and high adaptability. To do so, our research improves existing literature in a few respects. We model citywide RWH with unprecedented spatial detail, considering 1.06 million buildings with distinct design and water demand characteristics in New York City (NYC). Based on the large and diverse building stock, we present, to the best of our knowledge, the most consistent assessment of RWH's water saving efficiency and financial aspects by building class. More crucially, with the building-level results, we are able to identify precise implementation and funding strategies that lift the financial performance of large-scale RWH implementations, potentially beyond that of the centralized alternative. For the first time, we reveal the potential and the importance of public-private partnerships (PPP) in improving the cost-effectiveness of large-scale RWH implementations.

The paper proceeds as follows. First, we introduce the method and data sources in detail. Next, we present the assessments based on RWH implementation in all 1.06 million buildings under two primary design criteria: each RWH system is sized to achieve maximum rainwater yield (Scenario 1, S1) or maximum benefit-cost ratio (Scenario 2, S2). Then, we present a range of strategic

implementation scenarios, in which RWH in a subset of buildings is implemented under different PPP funding schemes.

2. Material and methods

2.1. Research context

2.1.1. Study area

This RWH research was conducted in New York City (NYC) because of the complexity of the area, the dedication of NYC to urban sustainability specifically in stormwater management practices (NYC, 2010), and the availability of data, especially a rich building dataset.

NYC's intense economic activity, dense population, and high imperviousness show the necessity and difficulty of water management. NYC comprises 1.06 million buildings (Fig. 1, left) and a population of over 8 million people within a 780 km² area. As such, NYC has the highest population and population density of all cities in the United States, with the population only expected to grow. A vast water infrastructure system thus exists to manage the city's high water demand. While a total of 3.8 Mm³ (million cubic meter) of drinking water is supplied every day to meet both drinking and non-drinking purposes (NYC, 2019), a large portion likely goes to non-drinking purposes, since an estimated 46% of the residential water use in the United States goes to toilet flushing and laundry (DeOreo et al.).

Even though, about 60% of the city has CSSs, the CSSs struggles to cope with the urban runoff load as over 70% of the city's land is paved. As a result, combined sewer overflows (CSOs) occur frequently, with untreated runoff-sewage mixtures discharged into rivers and waterways and causing inundations every other rain event (Fig. 1, right).

2.1.2. Simulation and assessment period

The RWH simulation and assessment period spans 20 years (January 4, 2000 to May 21, 2019). Our simulation is based on an hourly time-step, given previous proof that this is sufficient resolution for RWH calculations (Ward et al., 2010, 2012). Results are reported as 20-year annual averages, annual time series, monthly averages, or for one single rain event, depending on the purpose of the results.

2.2. Mass balance of rooftop RWH modelling

For a RWH system implemented on the rooftop of building i at time t , we model the water flows using mass-balance equation (1):

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

$\Delta V_{i,t}$ is the volumetric change of rainwater in the tank between time t and time $t-1$. $Q_{i,t}$ is the inflow of rainwater to the tank, $Y_{i,t}$ is rainwater yield, i.e. rainwater utilized for non-drinking water purposes, and $O_{i,t}$ is the tank overflow, i.e. spillage from the rainwater tank at time t . All variables are measured in cubic meters (m³) on an hourly time-step.

$Q_{i,t}$ is calculated as follows in equation (2):

$$Q_{i,t} = h_{i,t} * A_i * e \quad (2)$$

$h_{i,t}$ is the depth of rainfall at time t (in m). A_i is the contributing roof area of building i (in m²), e is the yield coefficient for which a value of 0.9 is assumed for all building classes (Ward et al., 2010), representing losses from the rainwater filter and from the roof material.

We simulate the mass balance using the Yield After Spillage

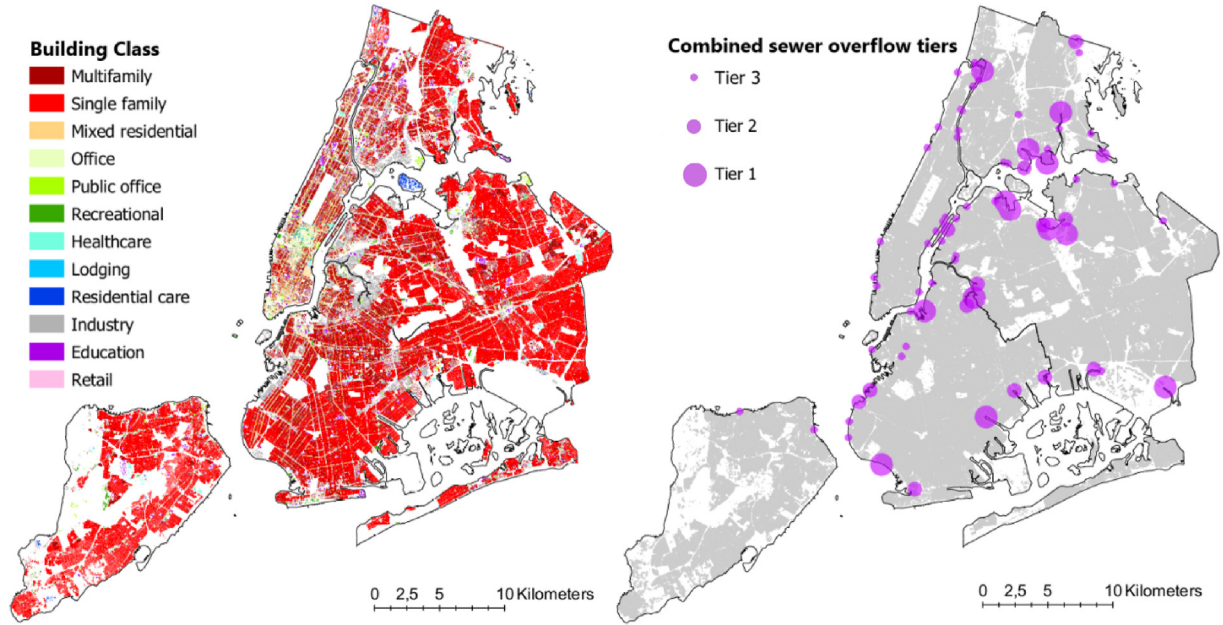


Fig. 1. Spatial distribution of building classes in NYC (left) and main combined sewer overflow (CSO) occurrences observed historically (right). Tier 1 CSO discharges over 500 million gallons per year (mgy) or 1.9 million cubic meter per year (Mm^3/y), Tier 2 CSO discharges between 250 and 500 mgy, or 0.9–1.9 Mm^3/y , and Tier 3 CSO discharges between 50.7 and 250 mgy, or 0.2–0.9 Mm^3/y .

(YAS) rule to obtain a conservative yield estimation. According to the YAS rule, rainwater yields are determined *after* the tank overflow is subtracted, specifically:

$$O_{i,t} = \max \left\{ \begin{array}{l} V_{i,t-1} + Q_{i,t} - S_i \\ 0 \end{array} \right. \quad (3)$$

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

$$V_{i,t} = \min \left\{ \begin{array}{l} V_{i,t-1} + Q_{i,t} - Y_{i,t} \\ S_i - Y_{i,t} \end{array} \right. \quad (5)$$

where S_i (in m^3) the storage capacity of the rainwater tank for building i and $D_{i,t}$ is non-drinking water demand at time t (m^3/hour).

2.3. Modelling water demand by building class

2.3.1. Building classes

We divide the 1.06 million buildings into 12 building classes based on the main usage and water use types of the building (Table 1). Distinct water use types and diurnal patterns are then modelled by building class. The spatial distribution of the building classes in NYC are presented in Fig. 1 (left).

2.3.2. Non-drinking water demand

Non-drinking water demand is modelled as either toilet flushing (TF) or laundry (Table 2). For every building, both the non-drinking water demand type and the temporal distribution of non-drinking water demand are determined by the building class it belongs to, e.g. residents use non-drinking water for toilet flushing and laundry; office employees use non-drinking water for toilets only. To quantify the magnitude of non-drinking water demand, we estimate occupancy rates for each building: the number of residents, employees, and visitors in a building per day. The number of residents per building are estimated as the product of the number of

residential units in a building and the average household size of each borough in NYC. We estimate the number of employees and visitors based on building floor area and occupancy density. More detailed explanations are available in the Appendix.

Further, nine different diurnal patterns are developed based on (Bahl et al., 2006, DeOreo et al., Gurung et al., 2014), each linking to one or more building classes (see Appendix). The diurnal non-drinking water demand patterns are used to distribute daily water demand by hour (e.g. restaurants have a high water demand at dinner time). For the three residential classes, we apply detailed diurnal patterns of non-drinking water demand. For other buildings classes, we model the demand patterns based on total water demand (including both drinking and non-drinking) due to the lack of data.

2.4. Sizing rainwater storage tanks

We model each RWH system under two design criteria: 1) maximum rainwater yield (**S1**) and 2) maximum benefit-cost ratio (BCR, **S2**). For **S1**, each rainwater tank is sized to 90% of its theoretical maximum rainwater yield potential since any additional capacity is achieved at extremely high marginal costs. **S2** is based on earlier research (Belmeziti et al., 2013; Fewkes, 2000). For each building, we identify the tank sizes that meet the two criteria, respectively, based on 30 possible sizes that are linearly distributed from the lower to the upper limits. To do so, we first determine potential ranges of tank sizes by building class: minimum 1 m^3 to maximum 40–400 m^3 based on the literature and our own judgements, especially when the existing literature is scarce (e.g. RWH in residential care facilities, factories, and warehouses). For each building, we then narrow the range of possible tank sizes based on the building class, building occupancy, and roof area. With the 30 tank sizes identified for each building, we then quantify the 20-year-average water yield and BCR of the corresponding RWH system designs. Moreover, if the maximum BCR is reached at the lower/upper limits of the 30 tank sizes, we extend the tank size within the broader tank size ranges by building class, until

Table 1

An overview of the 12 building classes of the 1.06 million buildings in NYC.

Building class	Class examples	Occurrence in the building stock	
		(thousands)	(% of total)
1. Multi-family residential	apartment complexes, dorms	190.4	17.9%
2. Single family residential	one- or two-family houses	755.5	71.0%
3. Mixed residential & commercial	market units on the first floor	54.7	5.1%
4. Office	financial office	7.6	0.7%
5. Public offices	courts, police stations	1.6	0.2%
6. Recreational	theatres, cinemas, malls	9.5	0.9%
7. Healthcare	hospitals	1.4	0.1%
8. Lodging	hotels	1.0	0.1%
9. Residential care	nursing homes, prisons	1.6	0.2%
10. Industry	warehouses, factories	12.8	1.2%
11. Education	schools, universities	4.5	0.4%
12. Retail	shops	23.9	2.2%

Table 2

Non-drinking water demand types modelled by building class.

Water demand type	Daily usage per occupant (times/p)	Water demand per use (L/time)	Water use per occupant per day [l/p/d]	Weekly frequency	Applicable building classes
A TF – Housing	5.0	9.8	49.0	Daily	1-3, 9
B TF – Worker Male	Urinal: 3.0 Toilet: 1.0	Urinal: 3.8 Toilet: 9.8	21.2	Work days	3-6, 8, 9-11
TF – Worker Female	Toilet: 3.0	9.8	29.5	Work days	
C TF – Visitor	0.2	9.8	2.0	Work days	3, 5-6
D TF – Lodging	3.0	9.8	29.5	Daily	8
E TF – Student	3.0	9.8	29.5	Work days	11
F Laundry	1.0	84.8	84.8	3 times/week	1-3, 8-9

decreasing/increasing the tank sizes do not improve *BCR* anymore. The procedures are explained in detailed in the *Appendix*.

2.5. Assessing RWH performance

2.5.1. Performance metrics

To assess RWH's ability in providing urban water infrastructure services and the economic feasibility of RWH implementation the following metrics are used:

Water saving efficiency (E_T), also known as volumetric reliability, is defined as water supplied by the RWH system divided by the sum of the water demand requested from the RWH system for the period under consideration. In this research, E_T is calculated as the percentage of rainwater yield in relation to the non-drinking water demand, for each building or the city as a whole, over a time period T .

$$E_{T,i} = 100 \times \left(\frac{\sum Y_{i,t}}{\sum D_{i,t}} \right) \quad (6)$$

Runoff reduction (RR_T) measures the amount of rainwater captured by the tank, i.e. rainwater yield, in relation to the rainwater falling on the contributing roof surface over a time period T .

$$RR_{T,i} = 100 \times \left(\frac{\sum Y_{i,t}}{\sum h_{i,t} \cdot A_i} \right) \quad (7)$$

Benefit-cost ratio for each building (BCR_i). The *BCR* quantifies the expected balance of, in monetary terms, benefits and costs over the 20-year life span of a RWH system from a building owner's perspective expressed in 2017 U.S. dollars (equation (8)). Note, we did not consider inflation and assumed a 0% discount rate to reflect the social time value of money. Implications of the assumptions are illustrated and discussed in the *Appendix*. t_1 to t_2 spans 19 years and

5 months, the period when the hourly precipitation records in NYC are obtained. We then linearly extrapolate the results calculated from equation (8) to the service life of the RWH systems (20 years).

$$BCR_i = \frac{\sum_{t_1}^{t_2} CW_{i,t}}{C_{i,inv} + \sum_{t_1}^{t_2} C_{i,maint,t} + \sum_{t_1}^{t_2} C_{i,nrg,t}} \quad (8)$$

$CW_{i,t}$ is the water utility fees avoided. $C_{i,inv}$ is the upfront capital cost of a rainwater tank and electric pump(s). The cost of a rainwater tank is related to the size of the tank. As the size of a tank increases, different materials are required. Each material has a specific cost function, obtained from retailers of RWH systems, creating a cascading effect as certain size thresholds are crossed. $C_{i,maint,t}$ consists of the cost of regular and intermittent maintenance activities, including inspection, cleaning, repairing, and replacements of the RWH system and its components. $C_{i,nrg,t}$ is the operational electricity cost of pumping the rainwater to users. Electricity use per volume of rainwater pumped is estimated as a function of building height, occupancy rate, and water use types. More details including information on the empirical cost functions, water- and energy-related utility fees, and the maintenance cost factors are available in the *Appendix*.

It is crucial to note that the *BCR* analyses are formulated from the perspective of individual building owners, thus there are public benefits that are not accounted for in the *BCR* analyses. For example, by reducing drinking water supply demand, RWH mitigates a city's need for constructing, operating and maintaining additional facilities for drinking water treatment and delivery. Besides, prior studies attributed RWH's poor financial performance to the fact that water is supplied at a subsidized rate in most places (Farreny et al., 2011), hence not reflecting the real public expenditures required for water provision.

As such, we conduct a cost-effectiveness analysis where the 'effectiveness' (i.e. water infrastructure service) does not have to be

monetized. The *cost effectiveness ratio* (*CER*) is thus defined as the cost per volume of water supplied for each building *i*.

$$CER_i = \frac{\sum_{t=1}^{t_2} C_{i,inv} + \sum_{t=1}^{t_2} C_{i,maint,t} + \sum_{t=1}^{t_2} C_{i,nrg,t}}{\sum_{t=1}^{t_2} Y_{i,t}} \quad (9)$$

2.5.2. Strategic implementation scenarios

We assess strategic implementation of RWH systems in a subset of buildings under various public-private financing schemes (S3–S7, Table 3). To match the RWH systems with the funding schemes, the two tank sizes estimated in section 2.4 are used. We first check the applicability of private funds based on the maximum *BCR* of RWH in each building. If the private funding criteria (e.g. $BCR > 1$ or 1.5) is not met, we then check the public funds applicability. Given that public funds prioritize the provision of public benefits, each publicly-funded RWH system under public-private partnership (PPP) is sized for its maximum rainwater yield. Furthermore, the thresholds of $CER < 4$ and $CER < 3$ are chosen based on the distribution of the simulated cost-effectiveness results of 1.06 billion buildings and the authors' own judgements.

For each scenario *n* presented in Table 3, we assess the overall cost-effectiveness of the RWH implementation in selected buildings, represented by B_n (equation (10)) and compare it against that of a centralized alternative represented by the Croton Water Filtration Plant in NYC. Croton was recently developed to buffer the city's water provision system from problems in the other treatment facilities and to meet the new water treatment needs as the city's source water were increasingly contaminated by stormwater runoff and other pollution incidents (Grolleau and McCann, 2012). It currently supplies 10% of the water demand in NYC, equivalent to 37% of the non-drinking water demand.

$$CER_n = \frac{\sum_{B_n} \sum_{t=1}^{t_2} C_{i,inv} + \sum_{t=1}^{t_2} C_{i,maint,t} + \sum_{t=1}^{t_2} C_{i,nrg,t}}{\sum_{t=1}^{t_2} Y_{i,t}} \quad (10)$$

2.5.3. Spatial presentation

Based on the buildings selected under strategic scenarios, we then visualize the magnitudes and the spatial variations of water saving efficiency and runoff reduction rates achieved by the large-scale RWH. We also distinguish the type of funds, i.e. public or private, that are matched to the RWH system at building scale. The building-specific estimates of E_T and RR_T are spatially presented using ArcGIS 10.7 (Esri, 2019). Buildings are color coded to distinguish low (0–30%), medium (30–60%) and high performance

(60–100%). Runoff reduction can only reach a maximum of 90% as 10% of the rainfall is assumed lost (yield coefficient, equation (2)).

2.6. Data sources

We obtain building properties from two datasets: the Building Footprint Dataset (BFD) (DoITT 2019)–height and roof area of each building, and the Primary Land Use Tax Lot Output (PLUTO) dataset (DCP 2019)–building type, building floor area and the number of floors. Detailed information on the data we obtained from both PLUTO and BFD, and how the data were combined are available in the Appendix. The two datasets are joined using the building identification numbers (BIN). We divide the buildings into 12 building classes based on the 270 building classes specified in PLUTO. The hourly rainfall data used is measured at a weather station in New York City's Central Park from the Northeast Regional Climate Centre (NRCC, 2019). Water and wastewater utility fees and electricity rates are obtained from annual NYC reports and financial government reports (Electricity Local, 2019; NYC Water Board, 2016; U.S. EIA, 2019). The installation and maintenance costs of RWH systems are estimated based on a combination of earlier research estimates (Farreny et al., 2011; Hajani and Rahman, 2014; Roebuck et al., 2011).

3. Results and discussion

3.1. Large urban water supply and runoff reduction potentials of all-building RWH

Our results show that RWH implementation on all 1.06 million buildings' roofs enables considerable substitution of central drinking water supplies and reduction of stormwater runoff (Fig. 2a). With each RWH system sized to achieve maximum rainwater yield (*S1*), an average of 130 million m³ of central drinking water supply can be substituted each year, equivalent to 33% of NYC's total annual non-drinking water demand in recent years (2016–2018). The same amount of runoff is prevented from entering the sewage treatment systems, the rivers or waterways. Over a service life of 20 years, the RWH systems offer 2.5 billion m³ of non-drinking water supply and urban runoff reduction. In comparison, sizing each RWH system for the highest benefit-cost ratio (*BCR*) (*S2*) results in 14% less rainwater yield overall. Still, the RWH implementation meets over 29% of NYC's non-drinking water demand.

For both *S1* and *S2*, nearly 90% of the rainwater harvested is utilized at residential settlements ('Multifamily', 'Single family', and 'Mixed residential') - the most common building classes (1,000,573 or 90% of the 1.06 million buildings). The non-drinking water

Table 3

All-building and strategic RWH implementation scenarios examined in this research. 'PU' and 'PR' indicate that RWH systems under the criteria are financed by public funds and private funds, respectively.

Scenarios	Profitability based on max. <i>BCR</i>			Cost-effectiveness achieved at max. E_T			
	(low high)			(low high)			
	$BCR_i < 1$	$BCR_i > 1$	$BCR_i > 1.5$	$CER_i > 10$	$CER_i < 10$	$CER_i < 4$	$CER_i < 3$
RWH system selection criteria for building <i>i</i>							
S1				PU	PU	PU	PU
S2	PU	PU	PU				
S3		PR	PR		PU	PU	PU
S4			PR		PU	PU	PU
S5			PR			PU	
S6			PR				PU
S7			PR				

substitution rates, i.e. the percentage of non-drinking water demand substituted by rainwater supply, are highest in non-residential buildings. Within the 'Industry' and 'Retail' classes, about 90% of the non-drinking water demands are met by rainwater on average. The substitutions are also high for 'Office' and 'Recreational' facilities, at 70–80% on average. Results for all building classes are presented in the *Appendix*.

The substantial non-drinking water supply and runoff reduction provided by the all-building RWH implementations appear robust during the 20-year simulation period (Fig. 2b and c). The annual non-drinking water substitution rate in NYC as a whole ranges between 26% and 41% under *S1* and 23%–36% under *S2*, with the lower percentages in each range occurring in relatively dry years and the higher percentages occurring in wet years. Similar variations are found on a monthly basis (27%–39% and 24%–33%, respectively). When measured against the runoff reduction rate, the performances appear more positive. Annual and monthly rooftop runoff reduction rates in NYC as a whole range from 46% to 73%; runoff that would otherwise enter the sewage system or the water environments, contributing to urban flooding and non-point source pollution. Given that building roofs constitute a large fraction of the urban land area (11–12% in NYC (DDC, 2007)) and an even greater fraction of the impervious land area, the rooftop runoff reductions indicate great stormwater management potential at the city scale. At a finer temporal scale (hourly and daily), the rates of non-drinking water substitution become more variable. The variations are a result of the fluctuating water demand throughout a day or week (Fig. A1 in the *Appendix*) but are also, predominantly, due to the variable daily and weekly precipitation patterns. In general, rainwater yield spikes during and after rain events and zeros out when the tanks are emptied following a few rainless days. The temporal results thus emphasize RWH as a sizable, dual functional addition to, rather than a replacement of, the existing central urban water infrastructures.

The water services achieved by non-discriminative RWH implementation in all buildings entail considerable financial costs (Fig. 2a), especially when each RWH system is sized for the maximum rainwater yield (*S1*). In this case, the financial costs are estimated to be roughly 9.2 billion U.S. dollars (USD, in 2017 value) over the RWH systems' service life of 20 years. The life-time costs are mainly attributable to upfront capital costs (51%, rainwater

tank, pump and installation) and recurring spending on maintenance (38%, cleaning, repairs, and pump replacement). Operations only account for a small fraction (11%, electricity costs for pumping). When the RWH systems are sized for maximum BCR (*S2*), total costs are reduced by nearly a third (to 6.3 billion USD) while the rainwater yield is reduced by only 14%. Such disproportionate changes highlight a trade-off between achieving the maximum rainwater utilization and having to pay for a much higher marginal cost (e.g. in the case of *S1*).

3.2. Heterogeneous financial performances of RWH within and across building classes

S2 achieves better financial performance than *S1* (sized to maximum rainwater yield) because each RWH is sized to its maximum BCR under *S2*. Yet, even with each RWH system sized to its maximum BCR under *S2*, the financial performances vary significantly both within and across the building classes (Fig. 3). For ease of interpretation, we refer to RWH systems with $BCR > 1$ as profitable and those with $BCR > 1.5$ as highly profitable. Under *S2*, about 64% of the systems are profitable ($BCR > 1$) and 38% are highly profitable ($BCR > 1.5$). In contrast, *S1* leads to 45% profitable and only 6% highly profitable RWH systems. In both scenarios, 'Single family' and 'Education' buildings are two of the best-performing classes: 79% (57%) and 75% (52%) of them are profitable under *S2* (*S1*) and over half turn out highly profitable under *S2*. Moreover, the RWH BCRs in these two building classes are more sensitive to tank sizing than in the case of the other building classes (i.e. showing larger BCR discrepancies between *S1* and *S2*). RWH system designs in these types of buildings thus play a crucial role in the financial prospects of RWH at both building and city scale. Fig. 3 also reveals that profitable and highly profitable RWH may be achieved at almost all building classes, featuring diverse rainwater supply and water demand patterns and can be found in different parts of a city.

3.3. Strategic RWH implementation under public-private funding schemes

The varying BCR estimates justify strategic, rather than all-building, RWH implementations. Profitable or highly profitable RWH systems may appeal to private funding and public funds can

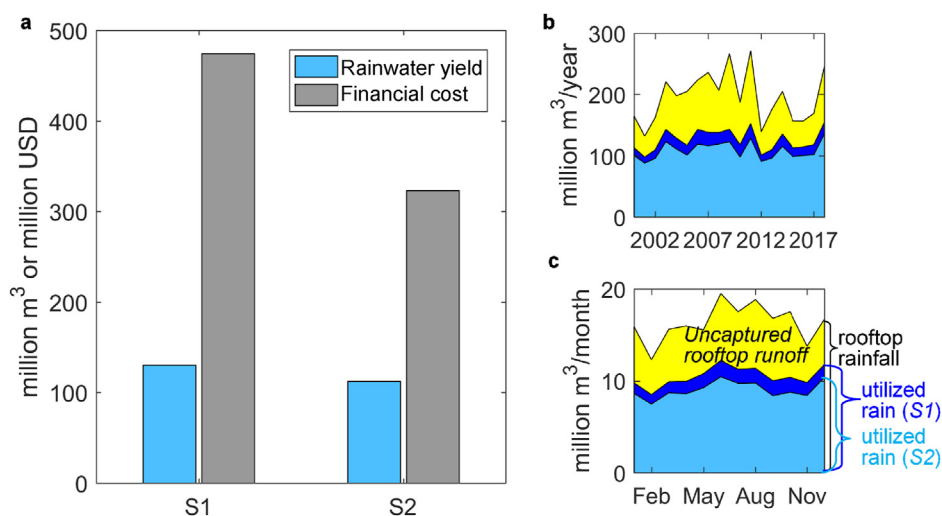


Fig. 2. City-level assessments of all-building RWH implementation when maximizing rainwater yield (*S1*) and maximizing benefit-cost ratio (*S2*) (a). Annual average rainwater yield (i.e., non-drinking water supply or runoff reduction), and annual average financial costs based on 20-year simulations on an hourly basis. (b–c). Inter- and intra-annual variations of the monthly rainwater yield and uncaptured rooftop runoff based on 20-year simulations.

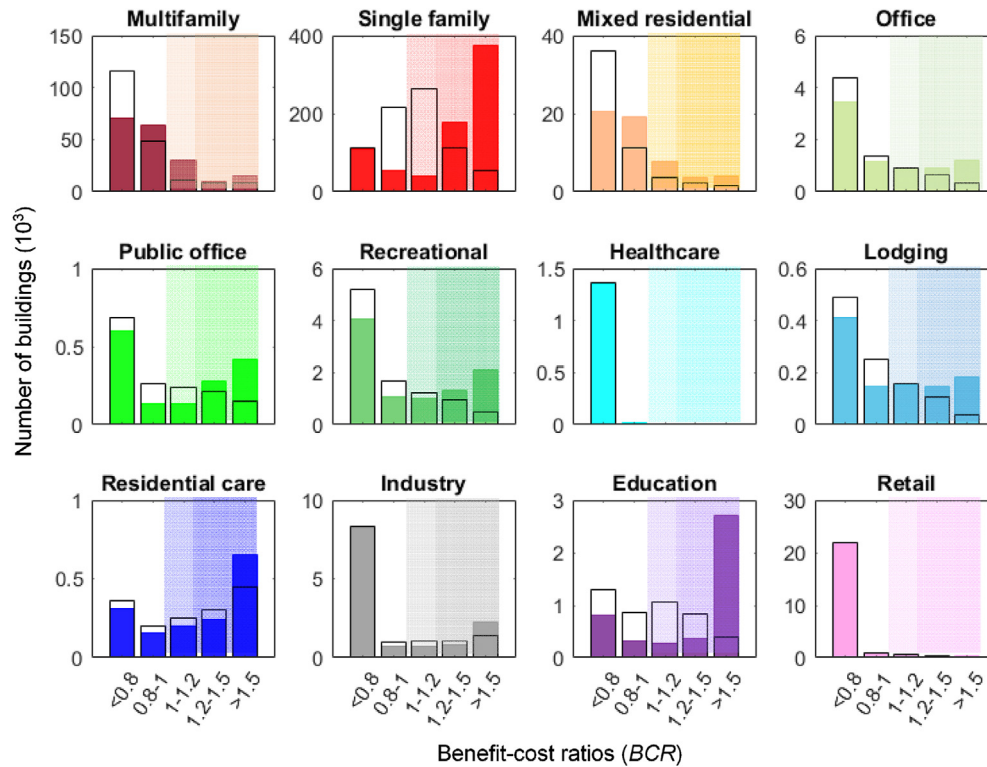


Fig. 3. Distributions of the building-specific benefit-cost ratios (BCRs) under *S1* (hollow bars) and *S2* (colored bars) by building class. In each subplot, buildings equipped with profitable ($BCR > 1$) RWH systems are highlighted with colored shade. The ones with highly profitable ($BCR > 1.5$) systems are further highlighted with a darker shade. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

be applied to the rest of the more optimal cases (*S3*–*S7*, Fig. 4). The discrete nature of RWH and other decentralized infrastructures makes such public-private funding feasible.

The strategic RWH scenarios result in a wide variation of total public expenditure on RWH as well as the public expenditure per unit of rainwater supply (Fig. 4). In comparison to a non-selective all-building RWH implementation financed completely by public funds (*S1*), total public spending is reduced by 49–97% under *S3*–*S6* when public-private partnerships fund RWH in 38%–96% of the buildings or by 100% when only applying private funding on the

38% highly profitable RWH systems (*S7*). The corresponding rainwater yields vary less and remain considerable, accounting for 15% (*S7*) to 30% (*S4*) of the city's non-drinking water demand. Given that the valuation of the trade-off between rainwater yield and financial cost is difficult and context-dependent, we do not attempt to present a simple best scenario, e.g. based on optimization algorithms. Further, we map the 20-year average non-drinking water substitution rate assessed for each of the 650,534 buildings (61% of the 1.1 buildings) under *S5* (Fig. 5a). Consistent with the distributive nature of RWH, a high non-drinking water substitution rate (75–100%) is achieved in different parts of the city. Such building-level estimates highlight the importance of conducting site-specific analysis to incorporate the decentralized feature of RWH and for informing capital investment across large heterogeneous urban landscapes.

Results of the strategic scenarios suggest that RWH is a competitive alternative for large-scale urban water infrastructure development, albeit the comparison with the Croton Water Filtration Plant, i.e. the centralized option, is not straightforward. Croton currently supplies 10% of the water demand in NYC, equivalent to 37% of the non-drinking water demand. At an estimated cost of 1.55 USD/m³, the Croton system provides high-quality drinking water supply with high reliability. In comparison, the strategic RWH implementations under *S3* and *S6* provides 78% and 45% of Croton's current water supply at 77% and 15% the unit cost, respectively. Yet, we did not factor in 'the economies of scale' in accounting for the costs of large-scale RWH implementation. We also neglect the value of RWH for serving stormwater management. The City of New York has set aside \$2.9 billion to reduce combined sewer overflows (CSOs) by 2030 (NYC, 2010) and another \$20 billion in increasing the cities resiliency against inundations (Russ, 2013). The real ecological and human health values of reduced freshwater

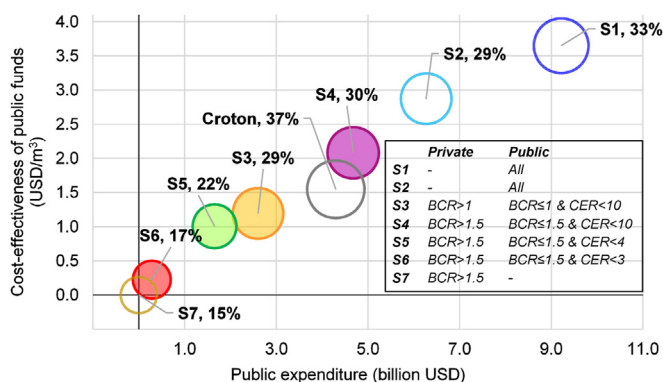


Fig. 4. Strategic large-scale RWH implementation given various private-public funding schemes. Areas of the bubbles and percentages show the new water supply as a fraction of existing non-drinking water demand. The grey bubble refers to the centralized drinking water supply alternative. Bubbles with filled colors represent RWH implementations funded by PPP. More information of the scenarios is provided in the Materials and methods. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

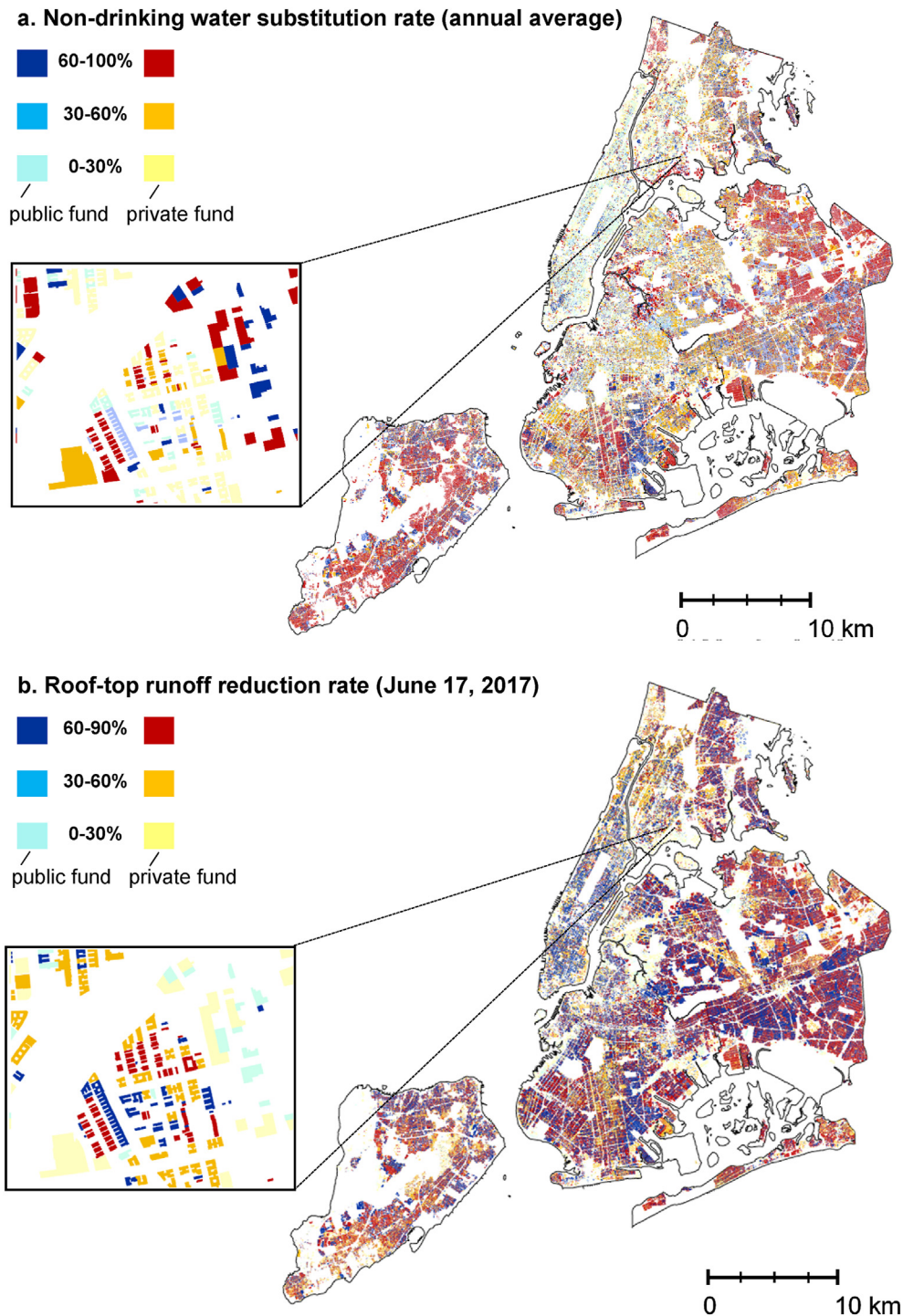


Fig. 5. Citywide building-specific (a) non-drinking water supply and (b) stormwater runoff reduction achieved by RWH under S6. The building-level resolution of the results is illustrated by the zoomed-in inset plots.

extractions and runoff reductions are difficult to quantify in monetary terms.

For a close look at how large-scale RWH implementation could alleviate the flows of urban runoff citywide, we mapped the rooftop runoff reduction rates of RWH achieved in 650,534 (61%) buildings over one big rain event (1.39 inches or 3.53 cm in a 3-hr period on June 17, 2018) under S5 (Fig. 5b). It is highlighted that the RWH implementation leads to high rooftop runoff reductions across the city. High runoff reductions overlap with the main CSO events that

occurred in NYC in the past, suggesting RWH's potential for mitigating the ecological and health consequences of CSOs. We also found that the runoff reduction rates of RWH are especially high in the city's poor neighborhoods which are densely occupied by small residential houses. This is because of a better match between the amount of non-drinking water demand and the amount of rainwater harvestable from the roof area. The results indicate RWH as a profitable climate change adaptation strategy in urban areas that are densely populated with low-rise buildings, which are known to

be more vulnerable to climate change impacts (USGCRP, 2018).

3.4. Improved consideration of RWH's critical advantages

The novel results on the performance of large-scale RWH implementation are enabled by improved incorporation of RWH's multi-functionality and high adaptability. In our analysis, the multi-functionality feature is represented by RWH's ability to provide non-drinking water supply and reduce stormwater runoff from roofs. For building owners, the avoided drinking water demand is modelled as reduced water and wastewater utility fees. From the city's perspective, the water supply and stormwater management services provided by RWH relieve the needs for expanding and/or building new centralized infrastructures. We incorporate RWH's adaptability in three ways. First, we size the rainwater storage tanks for each building, considering its roof catchment area, height and occupation rates, maintenance requirements, and the type of non-drinking water demand and temporal distribution of the water demand function. Second, for each building, we examine two different tank sizes that enable maximum non-drinking water supply and maximum benefit-cost ratios, respectively. While the former design criteria matches individual owners' and private funds' top interests in return on investment (ROI), the latter better fits the city's and public funds' priority in providing urban water services. We hence illustrate that, in comparison to the design of a centralized infrastructure project, RWH systems implemented in each building can be adapted to different financing priorities. Lastly, through scenario analysis, we show that RWH can flexibly meet infrastructure expansion needs at a variety of scales by implementing RWH at all or a subset of buildings across the city. In comparison to the centralized water infrastructures, the capacity of RWH can be more flexibly scaled up or down by adding it to an individual building or a selection of buildings; it can be easily maintained, upgraded, or removed, less dependent on the spatial layout of other infrastructure systems.

3.5. Model limitations and possible future work

Rainwater utilization potentials depend on the trends of water demand, rainfall, and aging of existing infrastructure. The potential of rainwater utilization may decrease as water demand or rainfall decreases, and vice versa. However, when water demand decreases (increases), RWH will enable a higher (lower) water substitution rate and reliability of water provision. The cost-effectiveness from a private perspective will decrease, when more water saving appliances are adopted. Yet from a public perspective, water safety will increase. As an example, to prepare for the Delaware Aqueduct shutdown for leakage repairs in 2022, NYC needs to reduce water consumption by 5%. This gap can be met by implementing a subset of the best-performing RWH systems (NYC, 2018). Hence, we expect a gradual shift from private to public funding.

The costs of RWH systems presented here should be considered a high estimate and thus the cost-effectiveness presented is conservative. Additional work is needed to explore the effect of bulk production and economies of scale on the upfront capital and maintenance costs of RWH systems. Moreover, the costs may be further reduced when RWH systems are shared among multiple adjacent buildings rather than equipping buildings with their own RWH systems. Further, the materials, energy, and environmental implications of implementing large-scale RWH should also be investigated and compared with an equivalent centralized water provision project. Future research is required for simulating and assessing the effects of large-scale RWH implementation on urban runoff drainage. This analysis demonstrates that a variety of large-scale RWH deployments can prevent large amounts of rain

becoming urban runoff, reaching the rivers and waterways, yet, the impacts on the urban drainage networks are not explored directly. The detailed spatial results from our analysis offer crucial inputs for such future research.

4. Conclusion

In this research, we include the crucial yet often neglected advantages of RWH in a big data analysis of 1.06 million buildings in New York City (NYC) that examines building-specific configurations of RWH systems, 20 years' hourly rainfall time series, and distinct water demand patterns. To the best of our knowledge, this research presents the first realistic estimate of rooftop RWH's maximum potential for reducing water abstraction and runoff for a major city. More crucially, based on our analysis, it becomes clear that RWH can be a cost-effective and thus feasible option to improve the urban water system. We show that:

- Strategically designed, financed, and implemented rooftop RWH systems meet multiple infrastructure development needs of a major city with reduced public expenditure as compared to centralized systems.
- RWH can be a profitable climate change adaptation strategy, especially in densely-populated urban areas with low-rise buildings, areas that are known to be more vulnerable to climate change impacts.

The findings highlight a potential solution to the urgent issue of sustainable urban water system transformations given global urbanization and climate change. Our methodological improvement in assessing the sustainability aspect of large-scale RWH implementation will be of interest to scientists and policy makers working on other decentralized water systems.

Author Contribution

S.V. designed the model and performed the computations. All authors analysed the data and discussed the results. R.W. and A.L. wrote the paper with input from all authors. R.W. conceived the study and were in charge of overall direction and planning.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.watres.2020.116063>.

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