Maximizing the Benefits of Rainwater Harvesting Systems: Review and Analysis of Selected Case Study Examples

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Abstract Rainwater harvesting systems are decentralized water solutions that involve capturing rainwater, typically from an impervious surface such as a rooftop, and storing it for selected uses. Rainwater harvesting systems can be used to meet water conservation and stormwater management objectives and may also represent a less energy intensive water source. This chapter includes an analysis of the available literature to identify key features such as frequency and consistency of water use and appropriate tank sizing that maximize the potable water use reduction, financial savings, and environmental benefits of rainwater harvesting systems. Case studies of rainwater harvesting systems, such as a commercial system where rainwater is used for potable purposes, a residential community which incorporates rainwater harvesting and on-site wastewater treatment, and rainwater use on a university campus are presented to highlight key features of rainwater harvesting systems. The review of the literature and the case studies reveal that to realize the full benefits of these systems, one must: maximize and diversify water uses, optimize the design, integrate RWH into an overall sustainable water management plan, and ensure that rainwater harvesting is compared to *viable* site options as opposed to idealized alternatives.

Keywords Rainwater harvesting · Water supply · Stormwater management · Green infrastructure · Payback period

1 Introduction

Rainwater harvesting (RWH) is an ancient practice that is used across the world today. In Africa, RWH, particularly for rural and low-income areas, is supported

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by RWH associations with many people adopting RWH due to economic inability to obtain water in another way [1]. In Australia, RWH has seen significant growth with household rainwater storage system capacity almost doubling from 6.0 to 11.2 Gl from 2000 to 2015 [2]. Across humid and sub-humid areas of China, more than 10 million RWH systems supplying domestic water for 22 million people had been constructed by 2007, many because of governmental and non-profit initiatives [3]. In Brazil, the "One Million Cisterns Program" led to a $600,000,000 USD investment in 400,000 household cisterns for rural areas [4]. Given the widespread adoption of RWH around the world and the significant financial investment in it, an analysis of the benefits of RWH is important. RWH, broadly, is the capturing of runoff for some benefit. RWH is often split into passive RWH, in which the runoff is directed toward landscape features for watering and infiltration, and active RWH, in which the runoff is directed to a storage tank and later used for potable or non-potable uses. This chapter focuses on active RWH, specifically active RWH systems designed to collect roof runoff. These systems consist of the roof catchment, a conveyance system, an aboveground or below ground storage tank and pumps, and additional filtration/water treatment to meet the end use requirements. Some systems also include additional tanks and controls. Filtration and water treatment can include filters and other devices both before and after a storage tank. Non-potable uses, such as toilet flushing, laundry, and irrigation, are the most common uses in industrialized countries and require less treatment than when the water is used for potable purposes.

The objective of this chapter is to perform an analysis of the benefits of RWH and identify strategies to maximize RWH benefits, and to present case studies demonstrating how these strategies can be used and to what extent these benefits are realized. Topics discussed in this chapter include water supply benefits, stormwater mitigation benefits, financial benefits, and other, less commonly identified benefits, of rainwater harvesting. The subheadings under each of these topics describe strategies distilled from a review of the literature for maximizing these potential benefits.

2 Water Supply Benefits

One of the primary drivers for the installation of RWH systems is reducing reliance on other water sources, particularly potable water sources. Understanding how to maximize the water supply benefits of RWH systems requires understanding how this benefit is evaluated. To facilitate comparisons, water supply benefits are often characterized based on the ability of harvested rainwater to satisfy a specified demand. For example, water savings efficiency is one of the most commonly used metrics and is the percent of the overall water demand for a specific end use (for example, irrigation) that is replaced by rainwater [5, 6]. Other studies, such as Ghisi et al. [7], report total potable water savings, which compares the quantity of rainwater used to the total water demand in the building(s). Estimates of potable water use reduction and water saving efficiency vary widely for RWH systems. Some examples of these studies are listed below.

- Ghisi [8] estimated that harvested rainwater could supply 48–100% of domestic water demand in Brazil, with the variability attributable to the region of the country. The approach assumed that all rainfall could be captured and used; however, some water is lost to overflow, splash, and evaporation in all RWH systems, which was not considered by the author.
- Ghisi and Ferreira [9] found that RWH systems alone could supply 14.7–17.7% of total water demand (37.5–41.5% of toilet flushing, laundry, and cleaning water demand) in a sample multi-story residential building in Brazil but could replace 36.7–42.0% of potable water use when combined with greywater.
- Zhang et al. [10] modeled RWH use for toilet flushing in hypothetical office buildings in four Australian cities, with two levels of water efficient appliances. With the less efficient appliances, the RWH systems could supply 7–10.4% of total water demand, while with more efficient appliances, they could supply 29.9–32.3% of the demand.
- Domènech and Saurí [11] found that RWH could supply 16% of the total household water demand for a town in Spain. When examining individual buildings and specific water uses, they found that harvested rainwater could supply 100% of irrigation demand at single-family and multi-family dwellings or 100% of toilet flushing, or 80% of toilet flushing and laundry washing demand for single family dwelling and 44% of toilet demand and 73% of laundry demand at a multi-family dwelling.
- Belmeziti et al. [12] modeled the impact of RWH in Paris, France and found that harvested rainwater could replace 11% of the total water demand, with residential areas accounting for 2/3 of this savings.
- Campisano et al. [13] examined water saving efficiency for all domestic buildings in an area of a city in southern Italy. They found that for most buildings, harvested rainwater could replace 30–50% of toilet flushing water demand.
- Ghisi et al. [7] found, in a study of two buildings (called blocks in the paper) in Brazil, RWH was able to supply between 39.74 and 64.70% of the potable water demand. This percentage increases with larger tanks and increased demand placed on the rainwater harvesting system (i.e., a greater percentage of the total potable water demand is modeled as being drawn from the rainwater harvesting system).
- Leong et al. [14] found that domestic RWH systems in Malaysia could supply more than 90% of non-potable demands while commercial systems supplied less than 43% of the total demand. This study also demonstrated that combining RWH systems and greywater systems can significantly increase the yield and water saving efficiency.
- Sousa et al. [15] described a RWH system installed to supply cooling towers (a high demand water use) at a shopping center in Lisbon, Portugal and found that the system only supplied 9.4% of the total cooling tower water demand (6,500 m^3 out of 70,000 m^3 annually).

These studies demonstrate the substantial but variable impacts of RWH systems on potable water use reduction. Because the ability of RWH systems to supply potable and non-potable water is one of the most widely studied aspects of RWH, the literature provides insights on how to maximize this benefit.

2.1 Focus on the Volume of Water Supplied, not Demand Met

Percent of potable water demand met with rainwater and water saving efficiency are metrics frequently utilized in the literature, but they often do not effectively represent water supply benefits of RWH systems. Because they represent the overall benefit as a percent of the demand, systems with lower designated uses/demands will often yield higher values (indicating greater benefit) than systems with higher demands, even when the latter replace a larger volume of potable water. Alternatively, a metric that expresses benefit relative to the total volume of water better depicts the true water supply benefits provided by a RWH system.

An example of this is demonstrated in a study performed by Lúcio et al. [16] who examined RWH in multiple zones in the City of Lisbon, and concluded that a combination of fewer occupants in the building and a larger roof area led to more water savings. This water saving efficiency value represents the percent of a 0.041 m^3 per capita demand for toilet flushing and laundry that is met by harvested rainwater and was presented as non-potable water saving calculated using the following formula:

$$Non - potable\ water\ savings = \frac{Consumed\ rainwater}{Non - potable\ water\ consumption}$$

However, a more in-depth analysis of the data reveals that when the total volume of water replaced per day (V_{RWH}, which is also equivalent to the average volume of water supplied by the rainwater harvesting system per day) is calculated as

$$V_{RWH} = \%WS * O * D_{PC}$$

where, *%WS* is the percent of the non-potable demand met by harvested rainwater, *0* the number of occupants, and D_{PC} is the daily per capita demand of 0.041 m^3 for toilet flushing and laundry, the buildings with more occupants in each zone have higher *volumetric* water savings (Table 1). Thus, because water saving efficiency (i.e., a RWH system demand-based metric), as opposed to a volume -based metric, was used to characterize water savings, systems that supplied a lower volume of water were presented as having greater water saving benefits. This emphasis on water saving efficiency (or percent of potable water demand met), instead of the volume of water saved, is common throughout RWH research [6, 17].

A closer examination of the literature further implies that water saving efficiency and potable water use reduction metrics are inadequate tools to accurately represent water supply benefits. Both Domènech and Saurí [11] and Ghisi et al. [7] examined water supply from RWH systems by modeling the effect of varying rainwater

Table 1 City zone, building characteristics, non-potable water savings, and volumetric water savings for modeled RWH systems on buildings in Lisbon, Portugal. Table created by the authors with data from Lúcio et al. [16]

Zone	Number of occupants (O)	Number of floors	Tank capacity (m^3)	Non-potable water savings (%) (%WS)	Roof area (m^2) (RA)	Volume of water replaced per day (m^3) (V_{RWH})
A	3	1	3	34	32	0.04
A	9	2	30	53	159	0.20
B	12	3	15	34	126	0.17
B	16	4	30	44	229	0.29
C	18	4	15	29	152	0.21
C	36	8	15	22	228	0.32
D	14	3	15	31	127	0.18
D	18	4	50	46	265	0.34
E.1	3	2	3	29	25	0.04
E.1	44	9	7.5	16	199	0.29
E.2	3	2	7.5	54	55	0.07
E.2	58	8	30	26	421	0.62
F	3	1	15	57	55	0.07
F	3	2	30	86	103	0.11

harvesting demand for a single structure. Domènech and Saurí [11] examined both a single-family residence with a 107 m^2 roof area and 3 residents and a multi-family residence with a 625 m^2 roof area and 42 residents. They modeled the RWH systems and optimized tank sizes for irrigation, toilet flushing, and laundry as single end uses and in combination. Domènech and Saurí [11] present the water saving efficiency for ten scenarios representing combinations of building type (single or multi-family), water use, and tank size.

Ghisi et al. [7] modeled water supply for an educational building with a total catchment area of 526 m^2 and evaluated supply when the demand on the RWH system varied from 50 to 80% of the total water demand for the building and total water demand varied from 15 to 50 L $person^{-1}$ day^{-1} for 103 people. Ghisi et al. [7] reported the percent of total potable water demand replaced by the rainwater harvesting system. From the data in the paper, the water saving efficiency can be calculated by dividing the total potable water demand replaced by the percent of the total demand that was estimated as demand on the rainwater harvesting system.

For all of the data, the annual volume of water supplied by the RWH system was either reported or calculated from the water saving efficiency and the annual water demand on the RWH system. For example, in Domènech and Saurí [11] the water demand for toilet flushing and laundry is 43 L $person^{-1}$ day^{-1}, so the daily demand for the single-family residence (given 3 residents) is 129 L day^{-1} or 47,085 L annually (using 365 days per year). When necessary, annual water volume supplied was then calculated by multiplying the water saving efficiency by the annual demand. For example, in Domènech and Saurí [11] the single-family residential system supplying toilet flushing and laundry had a water saving efficiency of 80% so the volume of water supplied was calculated by multiplying this water saving efficiency by the annual demand on the rainwater harvesting system (47,085 L).

A graphical representation of these results (Fig. 1) demonstrates that the volume of harvested rainwater supplied by the system decreases as the water saving efficiency increases (Fig. 1a) and increases as the annual demand on the system increases (Fig. 1b). This demonstrates that maximizing water saving efficiency can decrease the total volumetric water supply benefits, but that increasing demand on the RWH system increases volumetric water supply benefits. Similarly, using the percent of total potable demand met can lead to lower volumetric water supply benefits when comparing multiple projects. For example, the data from Ghisi et al. [7] includes a system supplying 29.76% of a 50 L person^{-1} day^{-1} demand and a system supplying 64.70% of a 15 L person^{-1} day^{-1}. While the first RWH system replaces a lower percent of potable water demand, it supplies 559 m^{3} of harvested rainwater annually while the second system only supplies 365 m^{3} (the volumes are calculated as described above).

Farreny et al. [18], Mun and Han [19], and Chilton [20] include a measure of how effectively the RWH system catches the water from the roof, presented as a percent of the available roof runoff water that is used by the system. This metric better captures the overall response of a RWH system to changes in demand because it normalizes the potable water reduction to the water available and avoids the appearance of greater gains by reducing demand. This approach also has the advantage of aligning with

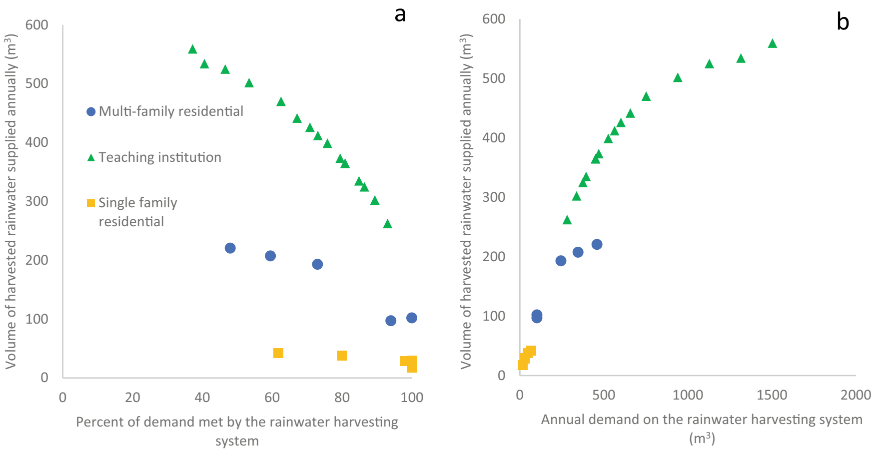

Fig. 1 The relationship between volume of water supplied by rainwater harvesting systems **a** the percent of demand met by the system (water saving efficiency) and **b** the annual volumetric demand on the system. *Source* created by the authors using data from [7, 11]

stormwater management goals, discussed later in this chapter. While available roof area and precipitation will both affect the total water available, and therefore the potable water savings, these factors are generally unchangeable in a single project.

2.2 Optimize the Tank Size

In addition to roof areas and precipitation rates, storage tank size is one of the primary factors controlling the amount of water that a RWH system can supply. In general, increasing storage capacity increases the amount of water supplied by a RWH system; however, increasing the tank size represents both an economic and an environmental cost. Numerous studies have demonstrated that increases in tank size initially provide significant improvements in the volume of water supplied from RWH systems but beyond a certain volume, further increasing the tank size has a negligible effect on the quantity of water supplied (e.g., [11, 13, 21]). When Domènech and Saurí [11] modeled a RWH system at a multi-family residential building, a 70 m^3 storage tank was needed to meet 100% of irrigation demand, but a much smaller, 45 m^3 storage tank could meet 94% of the irrigation demand. Similarly, a 17 m^3 storage tank could supply all of the toilet flushing needs for a single-family home, but a much smaller 11 m^3 storage tank could supply 97.9% of the demand [11]. This aligns with the common finding that tank size is the controlling factor for the quantity of water supplied up to a critical tank size beyond which the total available water becomes the controlling factor [17]. Numerous studies have demonstrated that the effectiveness of a RWH system varies with both roof area and tank size (i.e., [14]), but tank size is likely easier to manipulate at most sites. Optimizing the tank size before installing a RWH system is therefore the key to maximizing the potable water reduction benefit of a RWH system without unnecessarily increasing the cost or materials needed for the system.

2.3 Use the Harvested Rainwater for Multiple Uses

For a RWH system to effectively reduce potable water use and supply the greatest volume of water, multiple uses of harvested rainwater should be considered. Domènech and Saurí [11] found that the most efficient use of harvested rainwater in a multi-family building in Barcelona was irrigation and laundry, for which an appropriately sized RWH system could meet 59.5% of demand and save 207.3 m^3/year potable water. Overall, efficiency and the total volume of water saved were higher when multiple water uses were combined in the simulations [11]. The total volume of rainwater supplied generally increases with the number of uses due to increased demand emptying the tank more frequently and reducing the amount of tank overflow [14]. As discussed later in this chapter, using harvested rainwater for multiple uses also makes RWH systems more effective for stormwater management.

2.4 Consider the Impacts of Climate Change

The water available for a RWH system depends on the local climate and RWH potential will be altered with climate change. Zhang et al. [22] simulated RWH systems designed for irrigation, toilet flushing, or both, in multiple regions of China to examine the impacts of climate change. They separated long rainfall records (>50 years) into baseline and "changed" periods to examine current impacts of climate change on RWH systems. For example, in Beijing, China, a 22.3% reduction in annual rainfall resulted in lower water supply for all combinations of storage capacity and water use. In Urumqi, where annual average precipitation increased, water supply for all scenarios increased. Importantly, this study demonstrated that changes in storage tank size are not sufficient to counteract the effects of climate change. Changes in water supply generally mirrored the changes in precipitation, with water supply increasing in areas with increased precipitation and decreasing in areas with decreased precipitation. In addition, RWH systems with larger water demands show a greater response to changes in annual precipitation [22]. Imteaz et al. [23] examined the impacts of climate change on RWH tanks in Adelaide, Australia and found that while climate change will generally decrease the water savings potential from RWH systems, in some scenarios, the water savings potential may actually increase, particularly in the near future and under lower carbon emission scenarios. The studies demonstrate that while climate change will affect the potable water savings from RWH systems, generalizations about the nature of these impacts are rather difficult to make. Because of this, local predictions of climate change should be used when designing RWH systems.

2.5 Consider the Interaction of Factors

All of the factors affecting water saving efficiency work simultaneously. For example, Sousa et al. [15] found that below a threshold value of tank size, changes in precipitation due to climate change had little effect on water savings, but as tank size increased, the availability of precipitation—not the tank size—became the limiting factor. The tank size at which this transition occurred varied directly with average annual rainfall [15]. Similarly, at some point, continuing to increase demand will not increase the total volume of water supplied. Maximizing the water supply benefits of RWH systems thus requires optimization across all of these factors. Finally, when considering the water supply benefits due to RWH, RWH may also be a way to increase overall water availability in an area, not just reduce demand on available potable water sources. While most of the papers reviewed in this section have focused on replacing available potable water, RWH may be even more valuable where it is needed to supplement the available water to meet multiple water needs.

3 Stormwater Management Benefits

While the water supply benefits of RWH have been the historical driver of RWH installations in the past two decades, RWH has been increasingly recognized and utilized as a stormwater management practice to mitigate stormwater runoff [1]. At the site level, these systems can significantly reduce the volume and peak flow rate of runoff leaving the site [24–26]. At the neighborhood or watershed scale, widespread implementation of RWH tanks in urban areas can decrease the need for downstream infrastructure expansion, increase performance of downstream stormwater networks, reduce the risks of downstream drainage system failures, mitigate the impacts of urbanization on local streams, and decrease downstream flooding frequency and magnitude [27–31].

When the primary objective for a RWH system is stormwater management, an empty storage tank is ideal, as this provides the maximum amount of detention space (and, thus, mitigation) for the next runoff event. This is often seen as counter to water conservation goals, which focus on retaining water in the tank for use. However, with careful and appropriate system design, systems can successfully achieve both objectives. Examples of the stormwater runoff mitigation benefits provided via RWH abound worldwide:

- Gilroy and McCuen [32] created a spatio-temporal model to evaluate the effects of RWH systems on stormwater peak runoff rates and volumes leaving single-family, townhome, and commercial lots in Baltimore, Maryland. They found that cisterns could effectively reduce peak rates and volumes from the single-family lot for a 1-year storm; however, they provided less than 10% reduction for a 2-year event. Effectiveness with respect to runoff mitigation decreased as the storm size increased and as the density of development increased.
- Campisano and Modica [33] used a water balance modeling approach for a representative household system used for toilet flushing. They found that RWH systems can potentially provide significant reduction of runoff peak flow rates—and even complete capture of the peak for a large number of rain events—so long as the tank size and water usage patterns are appropriately selected and implemented.
- Araujo et al. [31] found that for a semi-arid region in Brazil, the widespread adoption of RWH systems in a densely-developed residential area could reduce runoff by approximately 28%. They concluded that the adoption of any RWH system—even those that are simple or under-designed—is beneficial to mitigating urban stormwater flows.
- van der Sterren et al. [34] monitored two RWH systems in Western Sydney, Australia for a 1-year period. They found that the reduction in stormwater volume provided by a system was highly dependent upon the usage patterns of harvested water with more designated water uses providing greater runoff volume reduction. In their study, the site with higher water demands provided a 97.5% reduction in roof runoff volume, whereas the site with fewer water demands provided a reduction of 91%.

- Steffen et al. [27] modeled daily precipitation and water demand for 23 different cities representing 7 regions of the U.S. to determine the effect of widespread implementation of RWH systems on single family residential buildings in an 11-ha, 100-parcel neighborhood. This modeled scenario had high potential for stormwater benefits; more than 17 of the 23 cities could capture at least 25% in rooftop runoff volume at the parcel scale by installing a 190-L rain barrel on each dwelling. At the region level, the amount of stormwater mitigation possible is dependent upon precipitation and water usage patterns; semi-arid regions have the greatest potential for stormwater mitigation via widespread implementation of RWH systems at the neighborhood scale.
- Wilson et al. [35] found that RWH systems can also provide stormwater quality mitigation, as well. A cistern installed as part of a low-impact development (see Sect. 6.3 for the Market at Colonnade Case Study) was found to reduce total suspended solids concentration by 67%, but did not reduce nutrient concentrations, though this may have been due to the low influent concentrations in this system. These results indicate that RWH systems can be used to mitigate nutrient and total suspended solids in stormwater runoff.

Research on RWH systems has demonstrated how design and environmental factors can influence the stormwater mitigation performance of a given system. Being aware of these factors and incorporating them into the design of a system is essential to ensuring the system meets the established goals and objectives. DeBusk et al. [26] found that the drivers and objectives of RWH systems implemented in arid and semi-arid regions differ greatly from those located in humid regions. Thus, it is important to accurately assess the drivers and objectives to effectively match designated uses to accomplish the system's overall goals.

3.1 Account for Location

The hydrologic performance of RWH systems is primarily controlled by two factors: the precipitation entering the storage tank and the water demands extracting water from the storage tank. Thus, understanding the precipitation patterns of a given location is essential to designing a system that provides maximum stormwater mitigation.

In general, locations with greater annual precipitation (i.e., humid regions) have a lower potential for stormwater volume and peak flow reduction than areas with lower annual precipitation (i.e., semi-arid and arid regions) for systems of the same size; thus, in wetter regions a larger storage volume may be needed to achieve the same amount of stormwater mitigation than in (semi-)arid regions [27, 36]. Additionally, the larger variations in annual rainfall in arid regions may result in less consistent performance of RWH systems with respect to stormwater mitigation when compared to more humid regions [36].

The stormwater mitigation potential of RWH systems is strongly influenced by the magnitude of a storm event; numerous studies have found that the runoff volume and peak flow reduction provided by a system decreases as the depth of the storm increases [29, 32, 34, 37]. Thus, RWH systems can rather consistently provide effective flood volume reduction for small and medium storm events, but rarely for large storm events. For example, Freni and Liuzzo [29] found that the widespread implementation of 5 m^3 RWH systems in a 1.6 km^2 residential neighborhood could reduce flooded areas by up to 100% for small rainfall events (<34 mm), and up to 35% for rain events between 34 and 50 mm. However, they found that flood reduction for severe events was negligible. This does not necessarily mean that these systems should not be considered for urban water management; in many areas it is flooding produced by the small- and medium-sized storms that contributes the greatest flood risk, as was the case in the study performed by Jamali et al. [30]. Additionally, Palla et al. [37] concluded that even though the runoff reduction provided by RWH systems for larger storms was not as high as it was for smaller storm events, it still contributed to increased hydrologic performance of the receiving stormwater network for the design storm (return period of 10 years). It may be possible to increase stormwater mitigation for these larger events by increasing the system's storage tank volume [38]; however, a review of the overall project objectives should be conducted, as well as a cost–benefit analysis. It is possible that adding another stormwater practice in series with the RWH system(s) could achieve the same benefit at a lower cost [29].

To increase the mitigation of peak flow rates, Gilroy and McCuen [32] recommend coordinating the storage volume with the volume of runoff that occurs at the time of maximum rainfall intensity. In other words, one should ensure that the storage tank is large enough to have ample space remaining to capture the portion of the storm event with the highest rainfall intensity. Jamali et al. [30] reported the same to be true for maximizing runoff volume reduction: "Maximum flood reduction could be expected if the available storage is used to capture the peak of a storm" p. 10. Because of this, achieving peak flow reduction may be more difficult in areas where the predominant storm type includes a large fraction of high-intensity rainfall and may require larger storage volumes to achieve the desired reduction [25].

Research suggests that the benefits of RWH may be more prominent in more densely developed (i.e., urban) areas. Deitch and Feirer [39] suggest that the potential for RWH to mitigate peak flow rates is greater in more densely developed areas—but only if there is comprehensive implementation at the neighborhood scale; thus, it may not be feasible to achieve a desired peak flow reduction rate in rural areas with less-dense development. However, it is important to note that the runoff volume reduction a system can be expected to achieve will be limited by the amount of impervious area (e.g., rooftop area) draining to a RWH system [37].

3.2 Maximize and Optimize Water Demand

As mentioned previously, the water usage patterns of a system strongly influence the system's hydrologic performance. In fact, some studies suggest that the stormwater mitigation potential of a system is more sensitive to the water demand patterns than the precipitation patterns [31]. All evidence unequivocally indicates that higher water usage demands from a RWH system will yield better performance with respect to stormwater mitigation, as it avails more space in the storage tank for the runoff produced by the next rain event [1, 27, 28, 31, 34, 40, 41]. Thus, it is recommended to establish as many uses for harvested rainwater as possible to maximize runoff volume reduction [31, 34, 40]. While optimizing systems for water supply and stormwater management are often seen as conflicting goals, both water supply and runoff reduction are optimized when RWH systems are used for multiple uses.

DeBusk et al. [26] found that systems employing consistent, frequent, year-round withdrawals of harvested rainwater provide superior stormwater mitigation benefits compared to systems with infrequent withdrawals. In humid regions, where RWH systems are frequently used for seasonal irrigation purposes, this likely means adding additional uses, though excess irrigation is also an option. Gee and Hunt [42] found that in areas with highly permeable soils, harvested rainwater could be used to irrigate Bermuda turfgrass in excess of the minimum water requirements without deleterious effects to turf health or groundwater quality. The Market at Colonnade Case Study (see Sect. 6.3 of this chapter) is another example where harvested water was used to irrigate an area that did not require supplemental irrigation to thrive.

Identifying designated water uses that are required on a regular basis, as opposed to seasonal or weather-dependent demands, can also help ensure consistent usage. Jones and Hunt [43] and DeBusk et al. [26] found that RWH systems in humid regions often go unused for periods of time because the perception of the relative abundance of rainfall can lead to less impetus to use the system. For example, a system user may manually switch to a backup source of water and forget to return to the RWH system when it fills or use the municipal water supply instead of the RWH system because the faucet for the RWH system is in a less convenient location. These types of scenarios can result in underutilization of RWH systems. Thus, DeBusk et al. [26] recommends incorporating design modifications to make water usage from a system as convenient and automated as possible to maximize usage and, consequently, stormwater mitigation. This could include automating irrigation with an irrigation timer or soil moisture sensor, automatically incorporating a backup water supply so the user does not have to manually operate it, or placing a lock on the municipal water supply spigot to discourage its use when rainwater is available.

3.3 Consider Active or Passive Release

When it is not feasible to incorporate enough water demands to ensure a consistent, year-round usage that is large enough to facilitate sufficient stormwater mitigation, an option is to "create" a demand by slowly releasing water from the storage tank between rainfall events. Gee et al. [24] presents the idea of a passive release mechanism in which the storage tank is divided into two sections—the detention portion and the *re*tention portion—which are separated by a small orifice. Harvested rainwater contained below the orifice is retained for meeting water demands while the volume above the orifice is slowly released via the orifice. The orifice should be sized appropriately to release the detention volume within a specified length of time (e.g., the average antecedent dry period for the location, or the timeframe required by applicable stormwater regulations). Ideally, this released water would be conveyed to an area where it could infiltrate, thus providing volume reduction. In the study performed by Gee et al. [24], the inclusion of a passive release mechanism increased the stormwater volume and peak flow reduction provided by a RWH system from 20 to 74% and from 64 to 90%, respectively. Other published studies have also identified the passive release mechanism as a feasible method of increasing the stormwater mitigation provided by a RWH system [28, 41]. A downside to this approach, however, is that it decreases the volume of harvested rainwater available to meet designated water uses.

Another option that can be implemented to maximize stormwater mitigation without compromising the system's ability to fulfill the designated uses is called an active release mechanism. With this approach, a smart controller accesses future rainfall forecasts and converts the anticipated depth of rain to a volume based upon the contributing drainage area characteristics. The controller then determines if there is enough storage space in the RWH system to fully capture the forecasted volume; if there is not enough space, the controller opens an automated valve to release enough water so that the forecasted event can be fully captured [24]. If there is enough space within the RWH system to capture the full volume, the controller takes no action. Gee and Hunt [24] found that incorporating the active release mechanism into the design of a RWH system increased the runoff volume and peak flow reduction from 21% to 85% and 38% to 93%, respectively. Because this extra release of harvested rainwater only occurs in anticipation of another rainfall event, the impact on the water supply should be minimal. While this mechanism resulted in increased stormwater mitigation performance in studies performed by Gee and Hunt [24] and Braga et al. [44], Quinn et al. [41] found that the active release mechanism actually increased flow rates for the 30 largest storm events due to the size of the release pipe, which was designed to quickly dewater a system in preparation for a forecasted event. Thus, careful design of the drawdown orifice is recommended to ensure water is not released at a rate detrimental to receiving water bodies. Compared with the passive release mechanism, the active release mechanism is substantially more expensive, requires oversight and maintenance from a knowledgeable company, and requires internet and electricity, making it most appropriate for larger, commercial RWH systems [24].

3.4 Combine RWH with Other Stormwater Management Practices

To some extent, increasing the volume of the storage tank can increase the stormwater mitigation performance of a RWH system; however, because the mitigation that can physically be provided by a system will ultimately be determined by the size of the drainage area, there is a maximum effective volume beyond which there will be minimal improvement realized [32]. The *optimal* volume, where the costs of further increase outweigh the benefits provided, is likely much lower than the maximum *effective* volume. When the cost–benefit analysis of a system does not warrant a larger storage tank volume but additional stormwater mitigation is needed or desired, additional stormwater practices can be added in series to improve the hydrologic performance. For example, the overflow from the RWH system can be directed to another practice, such as a bioretention area, to provide additional water quality improvement and volume reduction via infiltration [28]. The Market at Colonnade Case Study (Sect. 6.3 of this chapter) is an excellent real-world example in which RWH is combined with several other green infrastructures practices to meet (and exceed) stormwater regulatory requirements while also providing ancillary benefits such as potable water conservation, groundwater recharge, and increased profitability for the developer.

4 Financial Benefits

Saving money is often a motivator for installation of a rainwater harvesting system. RWH systems represent a significant upfront investment and most research on the financial viability of RWH systems is based on assessing the return on this original investment. One of the most common metrics is the payback period, or the time it takes for the financial savings from the RWH system to equal the initial investment plus any expenses (such as maintenance) that have occurred. Net present value is also commonly used. It begins with the cost of the system as a negative value and adds financial savings each year, then subtracts any expenses. In general, a payback period less than the life of the system or a positive net present value during the life of the system indicates a financially viable system. Other researchers use metrics such as benefit–cost ratio (e.g., [45]), which considers all of the financial benefits and costs of the system during its life, making a benefit–cost ratio >1 indicative of a financially viable system. Still others, such as Faragò et al. [46] use total value added, which calculates the economic value of a RWH system based on the total benefits and total losses to the community, not just costs and benefits to the system owner. All of these metrics of financial viability rely on the anticipated lifespan of the system.

The results on the financial viability of RWH systems are widely varied, with most research showing that RWH systems are not financially viable. For example:

- Zhang et al. [10] studied payback periods in commercial buildings in four Australian cities for RWH systems used to supply toilet flushing. They found that in all cases, the payback period was less than 30 years. Payback periods were shorter (8.6–13.7 years) when overall building demand was higher than when overall water demand was reduced by using more water-efficient fixtures (10.4–21.9 years). It was noted that the water-efficient fixtures and RWH system combined to create substantial potable water savings for the buildings.
- Roebuck et al. [47] studied the whole life cycle cost of a range of domestic RWH configurations in England and found that none of the systems recouped their initial investment, and many recovered little to none of the upfront capital cost because of maintenance costs, particularly the replacement of parts.
- Sousa et al. [15] compared the payback periods of two RWH systems to be installed in shopping centers, one in Portugal and one in Brazil. The system in Portugal could reduce potable water use by 60% but would have a 19 year payback. The system in Brazil would meet 20–50% of demand (depending on storage capacity) but would have a <2 year payback period. This difference was due to a combination of lower upfront costs and higher water fees in Brazil.
- Faragò et al. [46] compared decentralized rooftop RWH systems with three centralized stormwater and RWH systems, and a conventional drinking water supply system for a planned community in Denmark. While the three centralized stormwater and RWH systems all had a positive economic impact (measured as total value added), with two out of the three options performing better financially than the conventional drinking water system, the decentralized RWH system was a negative total value added and was not a financially viable option.

In some cases, the differences between these results may lie in oversimplification or omission of some costs. For example, Roebuck et al. [21] used a range of overly simplistic calculations and more detailed simulation modeling of RWH systems (whole life costing as described in Roebuck et al. [47]) to estimate the payback period for a single-family dwelling in the UK. While the systems modeled with the simplistic calculations showed payback periods of 27–35 years and a net financial gain, a more realistic modeling approach showed that these simplistic calculations overestimated the amount of water supplied and, therefore, the amount of financial savings. The simplified approaches also neglected some maintenance and operational costs [21]. However, as will be illustrated later in this chapter, many studies also overlook potential benefits of rainwater harvesting systems. As in previous sections, guidelines to maximize the financial benefits of RWH systems are further described in this section.

4.1 Maximize Water Supply Benefits

Similar to what was seen in discussion on water supply benefits, the percent of demand met is not always a direct indicator of the financial viability of a system.

Domènech and Saurí [11] calculated payback periods for RWH systems for single-family and multi-family residences, which ranged from 19 years to >200 years depending upon the type of building, water uses, storage tank size, water price, and discount rate. The need to consider total volume of water supplied, not just percent demand met, when developing RWH systems is clear from this payback analysis. While using harvested rainwater for irrigation at a multi-family building could meet 100% of demand, this approach has a payback period of 61 years under the most favorable conditions. Other uses, for which RWH will meet a lower percent of demand but provide a greater volume of water, have payback periods between 21 and 26 years for the same financial assumptions [11].

Simply, the payback period for a RWH system is dependent upon the extent of water use, with greater water use corresponding to shorter payback periods [11]. Ghisi and Ferreira [9] calculated payback periods for theoretical RWH and greywater systems installed at a multi-story residential building and found a slightly shorter payback period for the greywater system, but that both RWH and greywater systems had payback periods of under 6 years when the full savings from potable water use reduction were realized. In one studied block of buildings, the RWH systems were never able to achieve payback because the water use was below the minimum amount billed by the utility, so no financial savings were achieved. Interestingly, this study did not include any costs for water treatment in the RWH system.

4.2 Prioritize Replacing High-Cost Water

The financial outlook for a rainwater harvesting system is highly dependent on the cost of water. Farreny et al. [18] studied the economic benefits of four RWH configurations in a dense neighborhood of Barcelona consisting of all combinations of new construction/retrofit and single building scale/neighborhood scale. The harvested rainwater was used for laundry in these hypothetical systems with washing machines located in individual apartments for the retrofit single-building scenario and in communal laundry rooms for all other scenarios. They found that none of the strategies had a payback period lower than the lifespan of the systems, thus none were financially viable, even with an expected 60-year life span, given the current water rate. However, when they considered an arbitrary higher water price (4 Euros per m^3), the neighborhood scale systems became economically viable, an indication of the benefits of economies of scale and the impact of water cost. The authors also noted that their analysis leaves out a number of benefits of RWH, such as stormwater abatement, that would make the overall financial picture of these systems more positive [18]. Campisano et al. [13] compared RWH to hauled water and desalination, the two water supply approaches on the small Mediterranean island for which they simulated RWH, and found that after 10–13 years, the RWH system represented a net savings. The water rate in this study (4.17 Euros/m^3) was higher than in many other studies examining the financial viability of RWH (e.g., [18, 48]). In this case, the high cost of other water alternatives contributed to the financial viability of RWH.

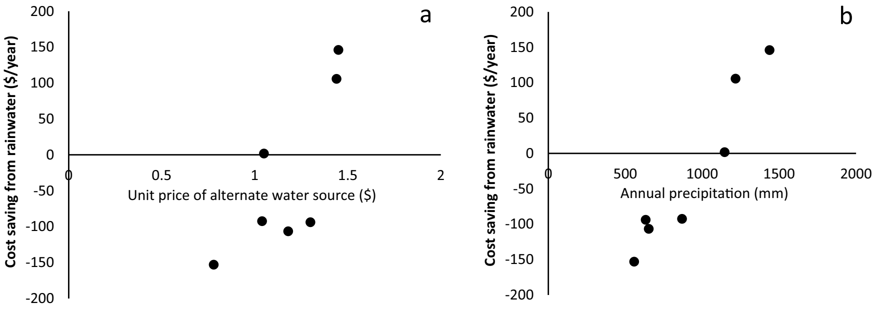

Fig. 2 Lifecycle costs of rainwater harvesting systems in seven cities in Australia with varying **a** water costs and **b** precipitation. *Source* created by the authors with data from [49]

The nature of the water to be replaced is also important to consider. When Amos et al. [45] conducted a financial analysis of a residential RWH system in Kenya, they found that no system configuration considered was financially viable when compared to the cost of water from the centralized water supply, but when the cost of purchasing additional water at a much higher cost from a street vendor was considered, almost all scenarios became financially viable. Because purchasing additional water is common practice in this area because of limited central supply, this higher cost water should be considered in determining the financial viability of RWH systems.

While the cost of water is important, the total volume of water supplied is likely more important. A single study comparing cost effectiveness across a range of water prices, rainfall, tank sizes, and demand scenarios gives insight into the factors that control the economic benefits of RWH systems based on potable water use reduction. Tam et al. [49] compared the cost of RWH systems with the cost of other alternative water sources in seven cities in Australia. This study provides an opportunity to look at the relative impacts of multiple factors on the payback period (Fig. 2). The annualized net financial benefits of the RWH systems increased with both water cost and precipitation but were more closely related to precipitation, indicating that the total availability of water is a stronger control on the financial viability of a RWH system. Both roof area and tank size also affected the financial performance of the systems.

4.3 Consider RWH as a Tool to Expand the Water Supply System

RWH is often used to supplement available, existing water sources, but incorporating RWH in plans to expand the overall system supply can improve financial viability. Wurthmann [50] examined the cost-effectiveness of using residential RWH systems for irrigation in two counties in Florida with growing populations as a way to expand the available water supply. The proposed RWH systems were more cost effective than a proposed desalination project or a proposed reclaimed water project but may be more expensive and less effective than a proposed reservoir project. The authors did note that the reservoir project's estimated cost is likely an underestimate due to infrastructure omitted from the estimate. The RWH system also had the benefit of incremental implementation [50]. This analysis does not consider that, with the centralized water supply systems, the utility would be able to recoup some of the costs of the water through billing. Similarly, van Dijk et al. [51] examined installation of RWH systems on all 1.06 million buildings in New York City (USA). They examined a range of public and private funding for the systems, often with private funding used for systems deemed profitable (a benefit–cost ratio > 1, 64% of systems using a tank sizing approach to maximize financial benefit). With this approach, for 3 out of 4 scenarios involving a mix of public and private funding, the water supplied by the RWH systems was a more cost-effective use of public funds than a planned expansion of capacity for the existing drinking water system [51].

4.4 Incorporate RWH into the Stormwater Management Plan

While RWH clearly has stormwater management benefits, many analyses of the financial benefits of RWH overlook the financial impacts of the stormwater management benefits of RWH. This may be because the impact of RWH systems for stormwater management is often downplayed. For example, Joksimovic and Alam [52] found that the cost and impact of RWH systems compared to other low-impact development practices in a neighborhood were negligible. However, they only considered installation of RWH systems on single-family residences, a small portion of the impervious area in this mixed-use community, and gave no information on the design and sizing of the system. In contrast, Braga et al. [44] compared the cost and space requirements of advanced RWH systems, which included automated release of water in anticipation of storm events, traditional cisterns, permeable pavers, and bioretention. In this study, RWH technologies were generally, though not always, less expensive than bioretention areas and used a smaller footprint. The RWH systems were typically more expensive than permeable pavement systems but also used a smaller footprint, though the permeable pavement areas are obviously dual use. The authors also noted that the maintenance costs for permeable pavers may make them a more expensive option over long time periods [44]. In this case, the RWH system may represent a financial benefit even without considering potable water savings. If RWH is included in the stormwater management plan, some of the cost of the RWH system can be considered a necessary expense to meet stormwater management goals rather than an added expense that must be repaid through water savings.

The financial benefits of RWH for stormwater management are even more evident at the catchment level. Jamali et al. [30] modeled the flood reduction impact of RWH systems implemented on all buildings in a suburban catchment in Melbourne, Australia. RWH systems reduced the expected annual damage from flooding by 18–31%, a savings of $ 1.9–3.2 million AUD annually, depending on the demand scenario. The RWH systems were more effective at reducing small and medium flooding events, but because of the greater frequency, these smaller events account for a large share of the annual flood damage. All economic analyses showed a positive net present value (based on the flood reduction and water saving benefits). The financial benefits from flood reduction were enough to offset the costs of the RWH systems in all demand scenarios with a discount rate >6%, demonstrating the financial viability of this approach [30]. While this study used a very long time period for simulation (85 years) and did not include replacement or maintenance costs, the study does demonstrate the potential large financial benefits of RWH systems for flood reduction. Similarly, Tavakol-Davani et al. [53] modeled the incorporation of RWH into the gray infrastructure approach to reduce combined sewer overflows in Toledo, Ohio (USA) and found that this combined approach could improve cost-effectiveness by 48%. When Wang and Zimmerman [54] did lifecycle costing of hypothetical RWH systems in 14 US cities, they found that the only city for which RWH provided a financial benefit was Seattle, the city with the highest stormwater fees. This demonstrates that the stormwater management benefits of RWH systems are true financial benefits as well.

4.5 Consider Ancillary Benefits

Much of the research on the economic viability of RWH systems has focused on using harvested rainwater to replace available potable water. Alim et al. [55] considered a scenario in which harvested rainwater was used to produce drinking water in a rural area in Australia without an available centralized water supply. The RWH system was designed to store water in a large tank and then gravity-feed the water through a filter system to a smaller tank before use. In addition to supplying the water demands in the hypothetical house, the system would also provide drinking water to sell in the wetter months. When the system was optimized to only provide drinking water for the family, the system was highly reliable (91–99%) but not economically feasible because of a long payback period. However, when the system was designed to both supply water for the family and water to sell, the payback period was 1–6 years, depending on the price of the water [55]. While selling water in this way may not be a viable option in many areas due to regulations, this study demonstrates the importance of thinking more broadly about the potential financial benefits of RWH. In particular, comparing the benefits of a RWH system to the cost of centralized water may not be appropriate as the water may be replacing bottled water, hauled water, or a new well. This broader perspective must also be considered when examining centralized water systems.

In addition, financial benefits beyond stormwater mitigation and potable water use reduction should be considered. Vargas-Parra et al. [56] found that 80% of the financial savings in residential RWH systems could come from a reduction in detergent and fabric softener use (due to the water softness from RWH systems). When Amos et al. [45] considered the increase in property value associated with having a RWH system, many modeled residential RWH systems in Sydney, Australia that were not initially financially viable without this hedonic pricing became financially viable. The increase in property value was established by a hedonic pricing method by Zhang et al. [57] who established that a RWH system increased the value of a house by $ 18,000 AUD in Perth, Western Australia. Dallman et al. [58] examined the overall economic value of widespread RWH adoption in a watershed in southern California (50% of residential and commercial buildings) and included economic benefits from energy savings and carbon reduction as well as potable water savings, but did not include economic benefits from stormwater management. The analysis included two water use scenarios: outdoor irrigation only and outdoor irrigation plus toilet flushing and laundry use. The difference in water savings between these two scenarios was minimal, likely due to the high irrigation demand in the region, but the costs of the systems that included indoor use was much higher. When water prices were held constant for the analysis, only the smallest outdoor cistern was financially viable. Including increasing water prices makes most combinations of indoor and outdoor use and cistern size financially viable with potential lifetime (30 year) benefits in excess of 100 million US dollars for some outdoor use scenarios. The water supply system in this region is energy intensive and involves long distance transport of water, but the majority of the savings were still from potable water use reduction, which are savings that would be directly realized by the end user [58].

5 Additional Benefits of RWH Systems

Water supply, stormwater mitigation and financial savings are the primary benefits of RWH systems. However, these are not the only benefits. Two additional, and less-studied, benefits, or potential benefits, of RWH systems deserve attention.

5.1 Reduction of Combined Sewer Overflows

A benefit of RWH systems that is in concert with stormwater volume reduction is the potential for reducing combined sewer overflow (CSO) frequency and occurrence in urban areas. Combined sewers use one piping network to transport both stormwater and sanitary sewer discharges to the wastewater treatment plant. However, during rain events, these systems are often overwhelmed due to the enormous volume of stormwater generated in highly-urban areas, resulting in the system overflowing and dumping a mixture of stormwater and raw sewage into a nearby receiving water body. Combined sewer systems service over 700 communities in the U.S. and discharge over 3000 million cubic meters of partially treated wastewater into surface water bodies each year [53]. Reducing the volume of stormwater entering these combined sewer systems can decrease the magnitude and frequency of these CSO events, and RWH is a mechanism by which stormwater runoff volumes can be lessened.

Tavakol-Davani et al. [59] used continuous hydrologic and hydraulic modeling to determine how the widespread implementation of RWH systems throughout the city of Toledo, Ohio USA would impact CSOs. Their results showed that installing RWH systems with toilet flushing as the sole water demand (“Green” scenario) slightly decreased the volume of CSO released annually compared to the “business as usual (BAU)” scenario, but was the least effective scenario considered—likely due to the relatively low water demand volume. This approach did, however, have the lowest life-cycle cost. When the scenario was modified to simulate the dewatering of the storage volume via a passive release mechanism, CSO volumes were still not substantially reduced compared to the BAU scenario. The scenario that yielded the lowest annual CSO volumes, but the highest life cycle costs, was the combination of the RWH approach and the gray infrastructure approach (which includes sewer separation, storage pipeline implementation, wastewater treatment plant improvement, storage basin implementation, storage tunnel construction, and existing storage tunnel extension), referred to as the “Green + Gray” scenario. A scenario in which the RWH approach was applied to the eastern half of the city and a gray infrastructure approach was applied to the western half of the city produced substantially lower CSO volumes compared to the BAU scenario; it also yielded a lower life cost when compared to the “Green” scenario but a higher cost when compared to the “Green + Gray” scenario. Thus, it would likely be considered the ideal scenario if life cycle costs were considered.

Tavakol-Davani et al. [53] utilized the same approach as Tavakol-Davani et al. [59], except they used future projected rainfall data scaled to the daily time step to model the impact of climate change on CSOs. Their results showed that the number of CSOs will increase due to climate change if no mitigation practices are implemented. They then analyzed the impact of installing 6 different sizes (0.757, 1.892, 3.785, 6.813, 11.356, 15.141, and 18.927 m^3) of RWH systems on 50% of the buildings in the city to be used for toilet flushing demands. They concluded that installing the smallest RWH system (0.76 m^3) on 50% of the buildings in the city would fully mitigate the projected impacts of climate change, reducing the number, duration, and volume of CSO events by 40%, 15%, and 28%, respectively, compared to the baseline condition (no RWH system implementation) [53].

Previous findings published in primary literature indicate that RWH systems can be considered an effective tool to reduce stormwater flows in urban areas, in turn reducing contributions to the combined sewer network. Incorporating any methods to maximize stormwater volume and flow rate mitigation will result in increased benefits. For example, adding an active release mechanism to these systems could provide increased mitigation of stormwater, further aiding in the reduction of CSO events (Braga et al. 2018). Based on these results, as well as those from other studies, widespread implementation of RWH has great potential as a tool to be used to decrease the number, magnitude, and duration of CSO events; however, its combination with other green and gray source-control strategies will likely yield the most effective results [53, 59–61].

5.2 Energy Consumption

As RWH implementation is considered a means of mitigating stormwater, augmenting potable water supplies, and mitigating climate change, energy use should be considered. Current research is ambiguous as to how the energy intensity of RWH systems compares to traditional municipal supply systems; empirical studies tend to conclude that the energy intensity of RWH systems is larger than that of a traditional municipal supply system, while theoretical studies suggest otherwise [62, 63]. Collectively, they indicate that the actual energy intensity of different system types can vary greatly and is highly dependent on system-specific factors, such as location, the source of potable water, types of pump(s) employed, height of the building, and water demand patterns, among others. Perhaps most importantly, they have identified design elements that can be modified to reduce the energy intensity of a given RWH system, and potentially make a RWH system less energy-intensive than the public water system.

Many RWH systems consume more energy than necessary due to inefficiencies associated with the pump(s) used to extract harvested water. Oftentimes, pumps are larger than necessary for the systems' designated water uses, resulting in excess energy usage by the system [62, 64]. For maximum energy efficiency, a pump should be selected such that the best efficiency point aligns with the most prevalent flow rate and pressure needed for designated water uses [62]. This is especially true for fixed-speed pumps. Choosing a variable-speed pump can result in significant energy savings, though these are often more expensive [64]. Additionally, choosing a pump model that requires minimal energy when in standby mode can contribute to energy savings as well [62].

The inclusion of ultraviolet (UV) disinfection in the design of a RWH system can be a key driver in the total energy consumption of a RWH system, as UV lights require significant energy to operate [62]. UV disinfection is often the most practical solution for disinfection of harvested rainwater due to relatively low cost, minimal maintenance, and safety; thus, it should not be discounted due to energy consumption. Instead, design modifications can be employed to maximize energy efficiency. To optimize the energy intensity of UV disinfection components, Vieira et al. [62] recommends:

- Choosing a product/model that most efficiently converts electricity to UV radiation,
- Minimizing the number of startup cycles (UV lamps are fluorescent and need to warm up for a period of time before they become effective),
- Consider standby energy usage when selecting a product/model, and
- Design the system so that UV disinfection is applied as the water is used so that re-treatment of water is not required.

For maximum energy efficiency, Vieira et al. [62] recommends a design in which a designated volume of water undergoes UV disinfection every six hours and is pumped into a header tank, from which it is extracted to meet water demands. This approach minimizes the number of startup cycles, thereby reducing energy consumption; however, the volume of treated water should be carefully selected so that water is used within the required timeframe before re-treatment is necessary [64].

The end use for which a RWH system supplies water can also influence the energy intensity of the system. Uses that utilize low flow rates, such as drip/trickle irrigation or indoor demands employing low-flow fixtures, are generally associated with high energy consumption, whereas higher flow rates result in lower energy consumption [65]. Thus, designated water uses and their associated flow rates and pressure requirements should be carefully considered when designing a system in order to minimize energy intensities; over the lifetime of the system these decisions can affect the economic viability of the entire system with respect to energy and electricity costs [65].

A study performed by Siems and Sahin [65] identified a surprising source of energy consumption for RWH systems: plumbing leaks. They found that out of 19 systems studied, 8 exhibited minor plumbing leaks that led to substantially larger energy intensities for the system as a whole. In this case, the leaks were due to leaky toilets that were unnoticed by property owners. The continuous re-pressurization of water lines due to the leaks resulted in substantially higher energy consumption compared to systems without leaks and can significantly reduce the lifespan of the pump [65]. Hence, a thorough inspection of the system to identify and repair small leaks can reduce energy consumption and prolong the life of system components.

Vieira et al. [62] concluded that the most energy efficient design of a RWH system utilizes a header tank as opposed to the direct supply of harvested rainwater. In this scenario, water is pumped from a primary storage tank to a header tank at a flow rate that minimizes energy consumption, and then gravity supplies the pressure and flow needed from the header tank to meet water demands. This setup minimizes the number of pump startups and allows the pump to operate at its most efficient point [62]. Even if a booster pump is necessary to achieve requisite flow rates for water demands, this will still yield lower energy intensities compared to a system without a header tank, as the header tank provides positive pressure and assists with pump startup [62]. Finally, the method by which a backup water supply is provided can affect energy intensity; an automated switch requires constant energy, as does an electronic float switch (which is more energy intensive than the automated switch), whereas a mechanical float switch or a manual switch require no additional energy [62].

Incorporating as many of these design modifications as possible into a RWH system will increase its energy efficiency, making it more comparable to other sources of water. Vieira et al. [62] states that simply optimizing pump operation may reduce the energy intensity of a RWH system enough that it is equal to or lower than other alternative water supply systems (e.g. reclaimed water or desalination). Future research and innovations may be able to reduce the energy intensity of RWH systems even further to favorably compare with traditional sources of potable water, such as municipal systems.

5.3 Climate Change Adaptation

Climate change is significantly altering precipitation patterns around the world, and will continue to do so [23]. The result will be an increased need for stormwater mitigation during rain events of higher magnitude and intensity and/or augmentation of traditional potable water supplies whose capacity may be diminished or compromised due to climate change. In some locations, these needs may occur simultaneously. Fortunately, RWH is a unique practice that can accomplish both of these objectives and can be used to mitigate the consequences of climate change [66, 67]. One of the greatest consequences of future climate change is expected to be a decrease in water security. Currently, over 2 billion people around the world lack access to a reliable, safe water supply at their home, requiring them to travel significant distances to acquire water for their daily needs [68]. Climate change will increasingly threaten water security, especially in low-income regions, and it is expected that by 2050, 70% of the world's population will be living in urban areas experiencing increased water stress due to climate change [69, 70]. Widespread adoption of RWH can improve water sustainability and increase water security [66, 67].

6 Case Studies

The preceding discussion of maximizing the benefits of rainwater harvesting focused on strategies to maximize individual benefits and often relied on simulated estimates of system performance and manipulation of individual system design features. This section presents case studies of existing rainwater harvesting systems that demonstrate real world application of the strategies.

6.1 Case Study: University of North Carolina at Chapel Hill, USA

The University of North Carolina at Chapel Hill (UNC-Chapel Hill) is a public university located in Chapel Hill, North Carolina, USA whose main campus spans approximately 300 hectares. In its 2001 Development Plan, UNC-Chapel Hill announced their commitment to mitigating stormwater runoff impacts from development on campus. Specifically, the University committed to:

- *No increase in the volume of runoff (2-year, 24-h storm) leaving main campus for all future development projects.*
- *No increase in the rate of runoff (2-year, 25-year, and 50-year, 24-h storms) or the quantity of non-point source pollutants as a result of new development.*

- *An overall decrease in the volume of stormwater runoff, the rate of runoff, and the amount of non-point source pollutants leaving campus as compared to existing conditions* [71].

As part of the Development Plan process, the University entered into an agreement with the Town of Chapel Hill regarding stormwater management performance standards, and then commenced a stormwater improvement plan to implement projects to mitigate the volume and peak flow rates of stormwater from existing campus development [72]. UNC-Chapel Hill made a conscious decision to include rainwater harvesting in their approach to mitigating stormwater impacts throughout campus, in part due to a historical drought that occurred in 2001–2002, but also in efforts to maximize the retention of stormwater on-site. This is an especially challenging task, as much of UNC-Chapel Hill's campus is underlain by tight clay soils which limit the use of traditional stormwater infiltration practices. When the University was evaluating methods to truly retain stormwater on campus, rainwater harvesting was identified as a preferred method when and where feasible.

Rainwater harvesting is one of the few non-infiltration practices in which stormwater can be truly retained on-site—that is, it is not released at any time; other stormwater practices that do not utilize infiltration release the collected stormwater at a controlled rate or through evapotranspiration. Not only does this retention help to meet volume reduction requirements, but it also facilitates nutrient reduction by retaining the nutrients on site with the stormwater. To this end, the state of North Carolina allows nutrient reduction credit for rainwater harvesting systems so long as they meet certain design requirements [73]. This is especially beneficial for UNC-Chapel Hill, as they are not only bound by their agreement with the Town of Chapel Hill, but also by state stormwater regulations, including the Jordan Lake Nutrient Strategy Rules [74].

As a result of UNC-Chapel Hill's commitment to rainwater harvesting, 10 RWH systems were installed on campus between 2002 and 2017 (Table 2). The majority of these systems are underground due to space constraints typical of an urban campus and are used for landscape irrigation or toilet flushing. Three of the 10 systems include a backup supply comprised of reclaimed water. All of the toilet flushing systems have a potable water backup in the building.

While an obvious benefit of these systems is the contribution to stormwater volume, peak flow, and nutrient reductions required by various stormwater regulations, there have been other benefits realized as well:

> *In my opinion, the biggest benefit has been the ability to irrigate about one acre of garden beds (perennials, shrubs and small trees) and a tiny bit of lawn around our Education Center without having to pull from the town's potable water supply or the aquifer that supplies local well water. In the 11 years that we have been using our cisterns, that has added up to over 600,000 gallons [2.27 million L]!*
>
> *We have seven above ground storage tanks that look like grain silos and one underground vault. All together they hold 54,400 gallons [206,000 L] which has been enough capacity to keep up with the irrigation needs of one acre of densely planted garden beds even when we have gone 3-4 weeks without rain.*

Table 2 Summary of rainwater harvesting systems installed on UNC-Chapel Hill Campus (*Source* table provided by UNC-Chapel Hill)

Building	Designated water use	Cistern size (L)
Bell Tower Amphitheater & Genome Sciences Building	Irrigation, Toilet Flushing	1,325,000
Boshamer Stadium	Irrigation	302,800
Hooker Fields	Irrigation	1,325,000
Edible Landscape Garden	Irrigation	19,300
Koury Oral Health Sciences Building	Irrigation	219,550
FedEx Global Education Center	Toilet Flushing	163,900
Hanes Hall	Irrigation	151,400
Marsico Hall	Irrigation, Toilet Flushing	217,300
NC Botanical Garden	Irrigation	206,000
Rams Head Plaza	Irrigation	203,650

> *During really heavy rains (which we frequently have in the summer) collecting the rainwater right off our downspouts also reduces the erosion of paths within our garden and the transport of sediment to the creek just below us; so yes, [there are] stormwater management and water quality benefits as well.*
>
> —Daniel Stern, Director of Horticulture, North Carolina Botanical Garden.

Components of this system are shown in Fig. 3.

Fig. 3 (Left) One of the seven cisterns used to collect rainwater at the NC Botanical Garden at UNC-Chapel Hill (the one pictured is approximately 18,000 L). (Right) The sprinkler system connected to the RWH system that is used to irrigate the gardens. Photo courtesy of UNC-Chapel Hill

The installation, operation, and maintenance of these systems over the past 16 years has naturally led to lessons learned. When asked what they would recommend to others considering RWH systems, Meg Holton, Water Resources Manager for UNC-Chapel Hill, says: "Keep it as simple as possible for what you are trying to achieve." Holton acknowledges that simplifying a system can actually be challenging, but stresses that the more complex a system is, the more likely it is that something may go wrong (M. Holton, personal communication, July 14, 2021). This advice extends not only to overall system design, but to control systems as well; it is preferable to have control systems that are simple enough to be understood and repaired by resident tradespeople, as opposed to relying on external vendors, which can delay response times (M. Holton, personal communication, July 14, 2021).

Holton also suggests incorporating some form of redundancy in system design to ensure water demands can be met when the system is not operating (M. Holton, personal communication, July 14, 2021). This goes beyond simply incorporating a backup supply that's internal to the system. Many systems include a backup water supply but, due to regulatory requirements designed to prevent cross contamination with the potable supply system, that backup supply is discharged into an air gapped storage tank. With that configuration, the system pump is still required to withdraw the backup water; if the pump is not working or the system needs to be repaired or maintained, there is no way to meet the water demand. UNC-Chapel Hill, working with the North Carolina Department of Environmental Quality, Division of Water Resources, has come up with an innovative way of addressing this issue:

> *What we've done is in those cases, especially for toilet flushing, is to provide the air gap by having a piece of removable pipe that can be on one supply or the other supply but cannot be on both supplies; that creates an air gap (break in pipe) so you can't have a cross connection with back pressure of contaminated water against the other system. The spool piece has to be physically moved by plumbers and, at the same time, they have to check the backflow preventers to make sure they're functioning properly. This is located on the non-potable side of the backflow preventer so that the potable water is protected.*
>
> —Meg Holton, Water Resources Manager, UNC-Chapel Hill.

Making small changes to the construction process can improve the outcome of a RWH system. Oftentimes, external system components are installed by a different subcontractor than internal system components; optimizing communication and coordination among these contractors is essential to avoiding problems (J. Smedsmo, personal communication, July 14, 2021). Additionally, with large, complex systems there are many pieces to the puzzle, and it is ideal to have the system fully vetted and troubleshot before the system is considered complete and turned over (M. Holton, personal communication, July 14, 2021). Finally, it is always beneficial to negotiate longer warranties and support than the typical one year from project completion that is in the standard state construction contract, if possible—especially since it is often unclear, with beneficial occupancy, when the project is deemed "complete" (M. Holton, personal communication, July 14, 2021).

Because of a higher-level decision at UNC-Chapel Hill to make rainwater harvesting part of the University's commitment to stormwater management and overall sustainability, over 4.1 million liters of harvested rainwater storage is available for capturing runoff and reusing it across campus. Not only are these systems used to reduce the environmental impact of the University's campus, but they are also used to educate students about responsible water management. "We do tours of some of our innovative stormwater control measures and talk to students about how stormwater is managed to help them think about their water—where it comes from and how they use it," says Jamie Smedsmo, Water Resources Engineer for UNC-Chapel Hill. Hopefully, these future generations of citizens will embrace rainwater harvesting as well now that they see how it can be used to reduce stormwater impacts and conserve potable water on their beloved campus.

6.2 Case Study: Warrenton-Fauquier Airport, USA

In January 2020, an expansion of the Warrenton-Fauquier Airport in Fauquier County, Virginia, USA opened. The airport, which started as a simple grass strip in the 1960s, serves as a reliever airport for Dulles International Airport, one of three large airports that serve Washington D.C. The airport has a single asphalt runway which serves both aviation companies housed at the airport and transient smaller aircraft, allowing more space for larger, faster aircraft at Dulles International for a total of 55,000–60,000 take-offs and landings per year [75].

The airport terminal is designed to be an environmentally sensitive building with 79 solar panels, 28 geothermal wells and a 76 m^3 rainwater harvesting system [76]. However, the inclusion of rainwater harvesting in this system was equal parts necessity and environmental consciousness. The airport lies in a service district without a local public water system, and groundwater did not seem like an appropriate long-term option because of concerns about both the available quantity and quality. The airport is intended to anchor a large commercial and industrial expansion area and the local water and sewer authority is planning to provide centralized service, but also needs to expand capacity in many of its service districts [75]. The region primarily uses groundwater resources and the need to protect these resources has led to adoption of a policy that states "Rainwater harvesting has become a realistic, environmentally sound and practical option to groundwater for future large-scale public facilities with expansive roofs. This alternative should be explored with new public facilities" [75]. Because of this, a potable rainwater harvesting system was identified as the best water supply option for the airport terminal.

The rainwater harvesting system includes both pre-tank and post-tank treatment to protect the water quality. The system is designed so that water is collected from the roof and passes through a self-cleaning filter before entering the tank. This filter prevents the buildup and then decay of leaves and other organic material in the tank. The harvested rainwater is then taken from just below the surface of tank water by one of two variable frequency drive pumps. The two pumps are provided for redundancy and the variable frequency drives and large pressure tank reduce pump starts and stops and allow the pump to operate at lower capacities, therefore higher energy efficiency, when needed. The water is pumped through a 50-micron sediment filter, then a 1 micron sediment filter and a carbon filter before ultraviolet and chlorine disinfection. The chlorine disinfection is used to provide a testable disinfection residual. The system is designed for a water demand of 1.3 m^3 per day based on typical staff, flight training center personnel and students and average private plane traffic with potential growth figured in for the next five years. Rainwater Management Solutions, a rainwater harvesting company involved in the project, modelled the rainwater harvesting system using a daily time step and historical rainfall data and found that the system should meet 95% of overall demand. The system is designed with an alarm when the storage tank level drops to 25% and a water hauler can be called to deliver supplemental water for the system. When the airport hosts large events, such as air shows which happen about once per year, portable toilets are brought to the site and used to avoid exceeding the capacity of the system.

Unfortunately, regulations have not kept pace with this demand for rainwater harvesting. The state of Virginia does not have guidelines for potable use of harvested rainwater in commercial/public facilities. The Virginia Department of Health was charged with developing regulations for use of harvested rainwater in the Virginia Administrative Code (32.1–248.2) but this charge, as amended in 2018, specifically excludes developing requirements for potable use. In response, House Bill 1949 was introduced in the 2019 legislative session to amend this section of the administrative code and require development of guidelines for potable consumption of harvested rainwater in commercial facilities [77]. While this legislation was tabled, the Virginia Department of Health is working to develop the appropriate guidelines. This regulatory hurdle led Warrenton-Fauquier Airport to temporarily use groundwater to supply its potable needs. This project demonstrates the potential for harvested rainwater to provide a reliable water source in areas where water resources are strained and/or public water is not available. It also includes design elements, such as the pre-tank filtration and variable frequency drive pumps, which decrease the maintenance and operational costs, both economic and environmental, of the system. Finally, it demonstrates the potential, pending regulation, to use harvested rainwater for all uses in a building. As described earlier in this chapter, increasing the demand on a rainwater harvesting system maximizes the stormwater reduction and water supply benefits of the system and this move towards using harvested rainwater for all end uses in public buildings can make full realization of these benefits easier.

6.3 Case Study: Market at Colonnade

From 2010 to 2019, Raleigh, North Carolina, USA was recorded as the second fastest-growing large metro area in the United States, with a growth rate of 23% (Ordoñez 2020) [78]. This is no surprise, as the region was ranked the #1 performing metro area in the country in 2020 (WCED 2020) [79]. Likewise, it is no surprise that developers are attracted to the area and want to acquire property within it. This was the case for Regency Centers, a national owner, operator, and developer of shopping centers (Regency Centers 2021) [80], that took interest in a 2.53-ha site in an area of Raleigh that was densely developed with high-end residential neighborhoods.

For stormwater quantity and quality mitigation, the City of Raleigh requires commercial developments to treat the runoff from a 1-in. storm event to meet water quality standards and to detain development runoff and release it at a rate that does not exceed the pre-development discharge for the 2-year and 10-year 24-h storm events to meet water quantity standards (City of Raleigh 2002) [81]. While numerous developers had previously considered the site, all had passed on it due to a major challenge—the area and density of development necessary for a profitable retail center did not allow enough room for traditional stormwater control measures (e.g., detention pond or stormwater wetland) to meet the applicable stormwater regulations. After consulting with Soil & Environmental Consultants, PA (S&EC), who performed extensive soil and hydrologic analyses on the site, Regency Centers felt confident that they could accomplish their goals with an amalgamation of green infrastructure components—of which rainwater harvesting was a primary component.

Their final approach to stormwater management on the site was a treatment train of practices, the layout of which is shown in Fig. 4. Runoff from the Whole Foods Market rooftop drains to a 44,300 L aboveground cistern (Fig. 5), where it is used for indoor toilet flushing, and also to a 57,900 L underground cistern, where it is used for surface irrigation of the preserved wooded area during the growing season (April-September) (Wilson et al. 2015) [82]. Surface runoff from the “Shops Building” is collected in a 60,560-L underground cistern from which the harvested water is used for irrigating site landscaping and parking area plantings. The underground cisterns

Fig. 4 Layout of green infrastructure practices used to mitigate the quantity and quality of stormwater for the Market at Colonnade development (Aerial image procured from Google Maps; photos taken by Soil & Environmental Consultants, PA and Regency Centers)

Fig. 5 The aboveground cistern, which is used for indoor toilet flushing, is prominently displayed at the entrance of the Whole Foods Market—the anchor store for the Market at Colonnade development (Photo courtesy of Regency Centers)

are equipped with a 10 mm-diameter drawdown orifice that dewaters the cisterns within 5 days; this water is piped to the underground detention chamber (Wilson et al. 2015) [82]. Runoff from 0.25 ha and 0.08 ha of parking lot drains into 140 m of grassed bioswales and a 60m^2 bioretention cell, respectively (Wilson et al. 2015) [82]. Overflow from all three cisterns, drain water from the two underground cisterns, the overflow from the bioswales and bioretention cell, as well as runoff from 1.37 ha of parking lot all drain to the 1,325 m^3 underground detention chamber. Incoming water flows through the detention chamber and into the underground infiltration chamber—a gravel-filled trench system providing approximately 435 m^3 of storage capacity overlying minimally disturbed soils of hydrologic soil group B (Wilson et al. 2015) [82]. Once the infiltration system reaches maximum volume capacity, incoming water backs-up and is temporarily stored in the detention chamber which is equipped with a 10 mm-diameter drawdown orifice designed to drain the chamber within 5 days or less (Wilson et al. 2015) [82]. If the detention chamber reaches capacity, it overflows an internal weir in an outlet control box and into the existing municipal stormwater network via a single 38 cm-diameter pipe. Remaining water continues to drawdown via the orifice, also discharging to the municipal stormwater network.

A unique aspect of this project was that it included hydrologic and water quality monitoring for a 1-year period after construction completion to assess the performance of the stormwater management infrastructure. The monitoring revealed that despite being comprised of 84% directly connected impervious area, the site reduced runoff by 98.3%, meaning that "all but 1.7% of the stormwater was detained onsite and infiltrated into the underlying soils or harvested for use" (Wilson et al. 2015) [82]. Of the 777 mm of rainfall that fell on the site during the monitoring period, only 15 mm left the site (Wilson et al. 2015) [82]. When compared to an immediately adjacent commercial site of comparable size that utilizes conventional stormwater control measures (grassed pre-treatment swales and a dry detention basin), the outflow volume for the conventional site was 28 times higher than that of the Market at Colonnade site (Wilson et al. 2015) [82]. The site also significantly reduced peak flow rates of stormwater. While the concentrations of nutrients in stormwater leaving the conventional site and the Market at Colonnade site were similar, the latter "discharged significantly lower pollutant loads, by factors ranging from 23 to 85" due to the substantial volume reduction achieved on site (Wilson et al. 2015) [82].

The incredible mitigation of stormwater quantity and quality provided via the green infrastructure treatment train is attributed predominantly to (1) the amount of stormwater storage provided onsite (1950 m^3 total, 163 m^3 of which is rainwater harvesting system storage), and (2) the relatively high infiltration capacity of the in-situ soils, which allowed the infiltration of large volumes of stormwater (Wilson et al. 2015) [82]. Thus, the benefits of including rainwater harvesting in this scenario was the provision of additional storage capacity for holding runoff, thus giving it time to infiltrate, as well as providing additional means of true volume reduction via the use of harvested rainwater for indoor toilet flushing, landscape irrigation, and irrigation of the tree protection area. While the tree protection area was an established wooded area and did not need supplemental irrigation to thrive, irrigating this area did not serve as a detriment to the vegetation and provided stormwater volume reduction via the infiltration of irrigated water. Similar results were reported by Gee et al. (2020) [82], who demonstrated that excessive irrigation of turf with harvested rainwater can facilitate additional stormwater volume mitigation without detrimental impacts to the turf or groundwater quality.

In addition to soils with significant infiltration capacity, another aspect that made this project feasible was a grant from the North Carolina Land and Water Fund (formally known as the Clean Water Management Trust Fund). Due to the extensive underground infrastructure required for this green infrastructure treatment train approach, the cost was significant; so significant, in fact, that without financial assistance this approach likely would not have been feasible, thus requiring the developer to use surface treatment practices for stormwater mitigation and develop at a lower density, resulting in a lower profit margin (P. Smith, personal communication, July 14, 2021). Fortunately, Regency Centers was able to procure an innovative stormwater management grant from the North Carolina Land and Water Fund totaling $727,000 USD that was used for the design process, construction oversight, and implementation of the green infrastructure components of the stormwater network. Funding also provided for the site monitoring. This highlights how public and private financial assistance programs can make environmentally friendly development more cost-effective and attainable.

Remarkably, this system has been in place for over 10 years now and has not had any problems or malfunctions. Patrick Smith, P.E. of Soil & Environmental Consultants, PA (S&EC) attributes this to the fact that the system is *simple* (which concurs with the advice given by Meg Holton of UNC-Chapel Hill). The only mechanical components exterior to the Whole Foods Market building consists of 2 pumps to facilitate site irrigation; the rest of the system uses gravity to move water through the system and expedite infiltration. This approach minimizes problems that can arise from mechanical failures or malfunctions and relies on natural principles—gravity—to drive system operation.

In addition to simplicity, a consistent and frequent maintenance plan also wards off problems with the system. Regency Centers has contracted with S&EC to perform quarterly inspections to ensure all aspects of the system are functioning properly. They also provide maintenance recommendations to the landscape contractor based upon their findings (most of the actual maintenance work is performed by the landscape contractors) (P. Smith, personal communication, July 14, 2021). S&EC also performs a more comprehensive annual inspection and oversees subcontracted maintenance activities such as the dewatering of cisterns and the removal of accumulated sediments, pipe and outfall inspections, the cleaning of pretreatment devices so that contaminants do not migrate to the infiltration system, and other tasks all in an effort to ensure the system maintains optimal functionality (P. Smith, personal communication, July 14, 2021). This scheduled, contracted maintenance plan ensures that one entity is responsible for keeping the system maintained and arranging necessary repairs, thus alleviating communication issues that may arise from multiple entities managing different parts of the system. No doubt, this approach has contributed to trouble-free operation of the system for over a decade.

This precedent-setting development exemplifies how multiple types of green infrastructure—including rainwater harvesting—can be incorporated into a site development plan to meet applicable stormwater regulations. In this case, this approach yielded greater stormwater quantity and quality mitigation when compared to a conventional development. However, the benefits of this approach are not limited to stormwater—they also include a higher profit margin for the developer due to a greater area of developed space, increased attraction for tenants who value sustainability; public education opportunities via onsite signage, potable water conservation via the usage of harvested rainwater for non-potable applications, and groundwater recharge via the infiltration of the majority of stormwater runoff produced by the site.

6.4 Case Study: Ecovillage at Currumbin

The Ecovillage at Currumbin, Queensland, Australia is a widely studied example of a green housing development. The development includes 144 lots for 1–3-bedroom homes and a Village Center. All houses are built in accordance with the Ecovillage Architectural and Landscape Code that requires green, sustainable features on each home, such as RWH systems and solar panels, and excludes energy intensive appliances such as air conditioning. The development is 80% open space and 20% developed and even includes a stipulation disallowing dogs and cats in deference to local wildlife. The sustainable features add an additional 15,000–20,000 Australian dollars to the cost of each house, with 4,100–6,100 Australian dollars for the RWH system and 3,400 for a household water and energy use monitoring platform called Ecovision [83]. The development was guided by a set of Desired Environmental Outcomes which included ecological, social, and economic objectives. RWH is seen as beneficial in all of these categories because it reduces impacts on streams and runoff (ecological), provides safe drinking water (social) and has long replacement periods for system components (economic) [83].

The community is thought to be the first in Australia that is not connected to an external water supply or sewer system [83]. Each house is required to have a RWH system to meet all of the potable water needs while recycled wastewater is used to meet indoor non-potable needs and irrigation demand. The minimum storage sizes for the RWH systems are based on the house size and range from 20 to 45 m^3 with each tank including a small stormwater detention volume (10% of the storage tank size) [84]. To minimize site disturbance, all of the tanks are aboveground. During times of drought, homeowners can bring in additional water from water haulers to fill their tanks. The recycled wastewater is supplemented with water from an on-site borehole. The recycled wastewater is the primary source for firefighting in the community, but each household water tank system also includes 5 m^3 of storage for firefighting.

The overall effectiveness of the green features in the Ecovillage were studied by Hood et al. [84]. Staff from the Queensland Department of Environment and Resource Management read meters for water and energy use monthly and recorded at least 90 days of data for each house included in the study (houses were added to the study as they were completed and occupied). The average household water use (196 L/person/day) was higher than local averages (185 L/person/day for the Gold Coast, 134 L/person/day for Central South East Queensland and 121 L/person/day for a comparison decentralized development in Brisbane). However, this difference may be largely due to the availability of water for outdoor use in Currumbin, which did not have any watering restrictions during the study period, unlike many of the comparison areas (excluding the Gold Coast, which did not have restrictions). The outdoor water use in Currumbin was more than double other local comparisons. This recycled water for irrigation both supports the growth of vegetable gardens at most residences and prevents the introduction of nutrients in the treated wastewater to the local waterways. Construction activities, establishment of gardens and leaks (which were fixed) may have contributed to the high use of recycled water during this study [84]. Interestingly, the Body Corporate (the community governance body) can shut off irrigation water to users that are exceeding acceptable use levels [83]. While overall water use was high, Hood et al. [84] found that the indoor water use at Currumbin (115 L/person/day) is lower than many local comparisons that the authors found in the literature (133–169 L/person/day), but higher than the comparison decentralized development in Brisbane (89 L/person/day). The low water use at the development in Brisbane may have been due to water restrictions during the study period. Overall, the RWH system provided 48% of household water [84].

Hood et al. [84] also assessed the energy intensity of the RWH systems and found pumping energy to be 1.4 kWh m^{-3}. When comparing this to other decentralized systems, the RWH systems at Currumbin were generally lower energy use, but were higher energy use than the current centralized system and the projected energy intensity of the centralized system when new alternative water sources, desalination and recycled water, were included. However, the RWH system was less energy intensive than either of these new additional water sources (Hood et al. 2010) [83]. While the Hood et al. [84] paper did not include any energy used to treat the harvested rainwater and therefore is likely an underestimation of the true energy use of the RWH systems (UV disinfection at all houses per Tanner [83]), the comparison does illustrate the need to assess the environmental impact of RWH systems against other options to increase water supply, not just against the existing supply.

The RWH system at the Currumbin ecovillages represent a RWH success story for a number of reasons. First, all water management systems were designed together, instead of designing potable water, sewer and stormwater systems separately. For example, because RWH systems are required at each house, they could be considered in the overall stormwater management plan for the site [83]. This holistic planning also allowed the entire site to be water independent. In addition, the water independence allowed homeowners to continue to irrigate gardens, even when water restrictions were required in other areas. While the water supply system is more energy intensive than the local potable water system (1.1 kWh m^{-3} for the reclaimed water system, 1.4 kWh m^{-3} for the RWH systems and 1.0 kWh m^{-3} for local potable water system), the water supply system is less energy intensive than local alternatives planned to increase the available water supply. If the water system at Currumbin is considered a means of increasing local water availability, it is less energy intensive than other recycled water or desalination systems. The ecovillage at Currumbin has received numerous awards for its overall sustainable design (see https://ecovillageatcurrumbin.files.wordpress.com/2013/04/awards-list-v12_50511.pdf for a complete list) and the efficient use of water in the development is a major contributor to these achievements.

7 Conclusion

While the water supply benefits of RWH systems are generally the most lauded, the benefits of RWH systems extend far beyond water supply. RWH systems can provide a substantial volume of water that can either replace water available from a centralized system or create an additional water source. RWH systems can also reduce flooding and reduce stormwater flows to waterways and downstream stormwater infrastructure. These water supply and stormwater reduction benefits of rainwater harvesting, as well as ancillary benefits such as impacts on housing prices, can combine to make RWH a financially viable and even profitable solution. However, as reviewed in this chapter, the extent to which these benefits are attained (e.g., the amount of water supplied or the net present value of a RWH system) varies widely across RWH systems. While strategies for achieving each type of benefit (e.g., financial benefits) are presented throughout the chapter, the review of the literature and the case studies provided illustrate a simple set of best management practices to maximize all of the benefits of RWH systems.

(1) *Look for a variety of uses*—More demand on a RWH system leads to more use of the harvested rainwater and therefore more space in the tank for stormwater management. While these two objectives, water supply and stormwater management, have often been seen as conflicting, both are maximized when the harvested rainwater is used frequently, consistently and for a variety of uses.
(2) *Optimize design*—Careful modeling of the system can allow right-sizing of the pump, storage tank and treatment systems to minimize the cost while maximizing the benefits.
(3) *Incorporate other technologies*—While RWH is a powerful tool, it is most effective when combined with other water-saving technologies and other stormwater management practices.
(4) *Consider the alternatives*—To determine the costs and benefits of RWH systems, a realistic alternative, perhaps a new water supply system or other stormwater management practices, should be considered. In some cases, harvested rainwater may simply replace readily available public water, but the benefits are likely greater when it can be incorporated into overall infrastructure planning.

In this time of changing climate, the need for the types of benefits provided by RWH systems will increase and employing the best management practices illustrated here will be necessary to fully realize these benefits. RWH may move from a supplementary water source to a key tool in overall water management and infrastructure and clear guidelines on how best to maximize the potential of these systems will facilitate this transition. These strategies are essential for maximizing the benefits of RWH systems now and in the future. The analysis of literature and case studies provided in this chapter can serve as a guide for successful strategic implementation of RWH systems.

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