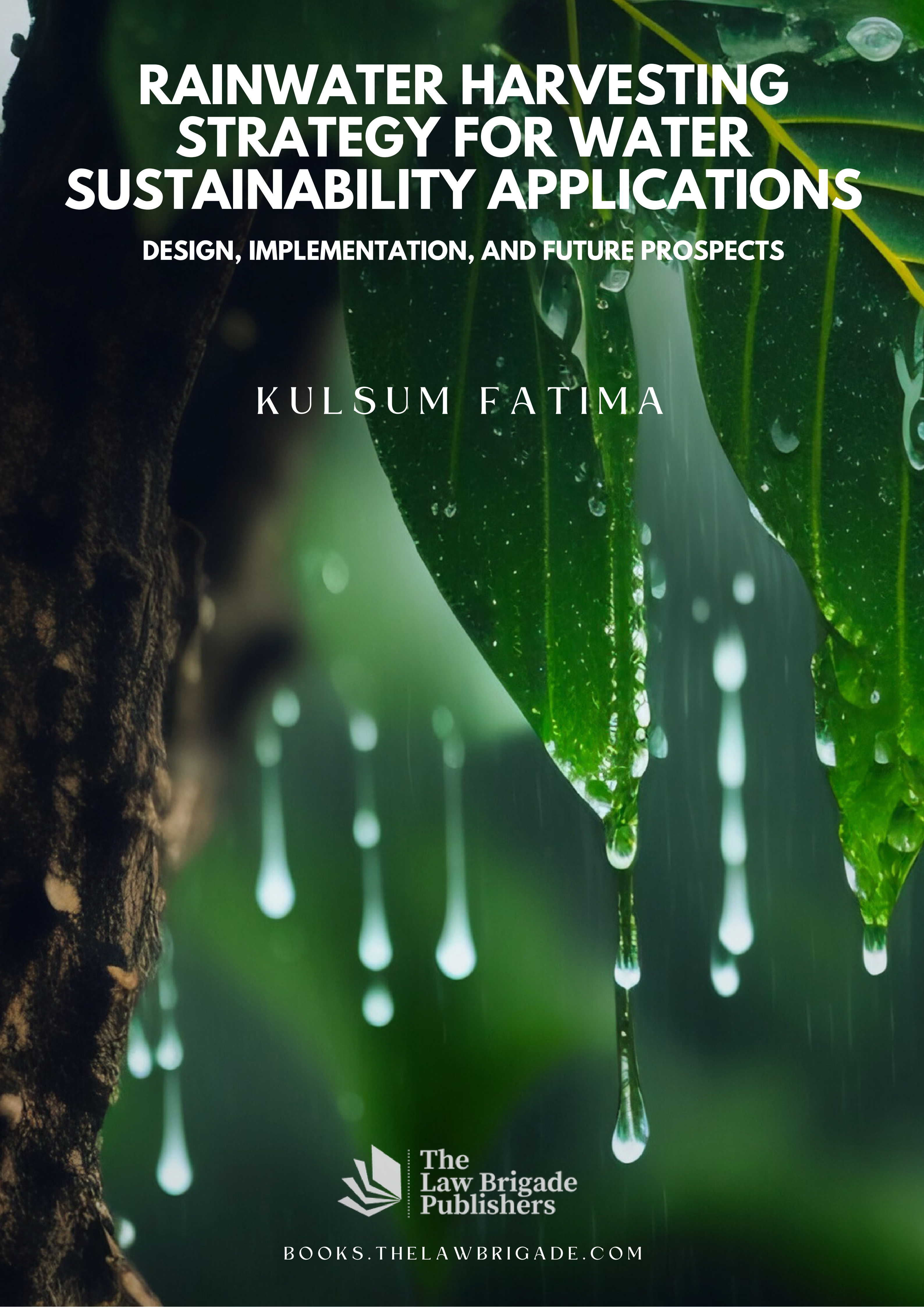

RAINWATER HARVESTING STRATEGY FOR WATER SUSTAINABILITY APPLICATIONS

DESIGN, IMPLEMENTATION, AND FUTURE PROSPECTS

KULSUM FATIMA

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FOREWORD

Sustainable design is the art of developing those elegant solutions that balance the needs of today and challenges of tomorrow. In this quest, sustainability professionals are always looking for opportunities where they can take advantage of natural resources to accomplish project goals. The harvesting of rainwater is one of those rare opportunities, however the simplicity of the concept often belies the surprising complexity of the task. This book will be a valuable resource for sustainability practitioners looking to embark on this journey with the tools and knowledge required to navigate successfully to their destination.

Kulsum and I met during my time stewarding sustainable building practices at the University of Calgary. The University of Calgary provided an interesting jumping off point for the conversation on rainwater. The institution has seen the implementation of a number of different rainwater capture and reuse schemes. The action on rainwater management on this campus was driven by the dual constraints of aging infrastructure limiting stormwater capacity and the campus's location in a drought prone region. Kulsum's research into rainwater harvesting led to a number of conversations between us that went beyond the superficial and dug into the details of these projects. I have been inspired by the creativity and dedication she has demonstrated when exploring this topic and have no doubt that those personal qualities have directly contributed to the valuable insights presented herein.

If you are looking to cultivate awareness, interest, and action on rainwater harvesting in your realm of influence – I consider this text to be required reading. Within this book, the author provides a fantastic overview of the topic covering everything from the introduction of water sustainability, history and trends in rainwater harvesting, design challenges, and the current state of research on the topic. This information is complemented by a practical review of a number of case studies for inspiration and lessons learned. In my opinion, included herein is everything one would need to confidently approach rainwater harvesting in their own pursuit of sustainability.

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SYNOPSIS

This book is a valuable resource for anyone interested in understanding and implementing rainwater harvesting systems from a design perspective. It captures various aspects of rainwater harvesting system design including its historical and legal governance landscape, technical landscape, design landscape, literature landscape and its application landscape. Under each of these landscapes, the book captures the prevailing practices, methods and approaches to inform future decision making and address issues around climate change and water scarcity. As a result, it offers multiple perspectives to examine the dynamics involved in the application and acceptance of rainwater harvesting as a design strategy.

The book underlines the social component using the historical background, current practices, and the legal governance landscape that encourage rainwater harvesting applications globally. It highlights a series of innovative engagement programs and promotions as examples of social change and user empowerment, focused on decision-makers and beneficiaries of RWH strategies. It represents systems that encourage and incentivize rainwater use for a variety of applications and serves as an effective guide for those looking to incorporate rainwater implementation into their local communities.

One of the significant aspects of this book offers practical insights, by comparing the literature landscape and the application landscape existing in the field of rainwater harvesting design. This comparison offers real-world understanding specific to the green building applications at higher education campuses, by offering technical insights into the invention, benefits, barriers and challenges in rainwater harvesting system applications.

The social impact, governance aspect, policy incentives, popular approaches, technical challenges, design limitations, literature restrictions and case study applications, included in this book cover multiple aspects of rainwater harvesting system design making it an essential read for anyone interested in this field. This book is a useful read for information on best practices and methods for rainwater harvesting system design to show how rainwater harvesting systems can help achieve water sustainability. This book is a result of research investigations dedicated to capture aspects of rainwater harvesting design applications for higher education green campuses.

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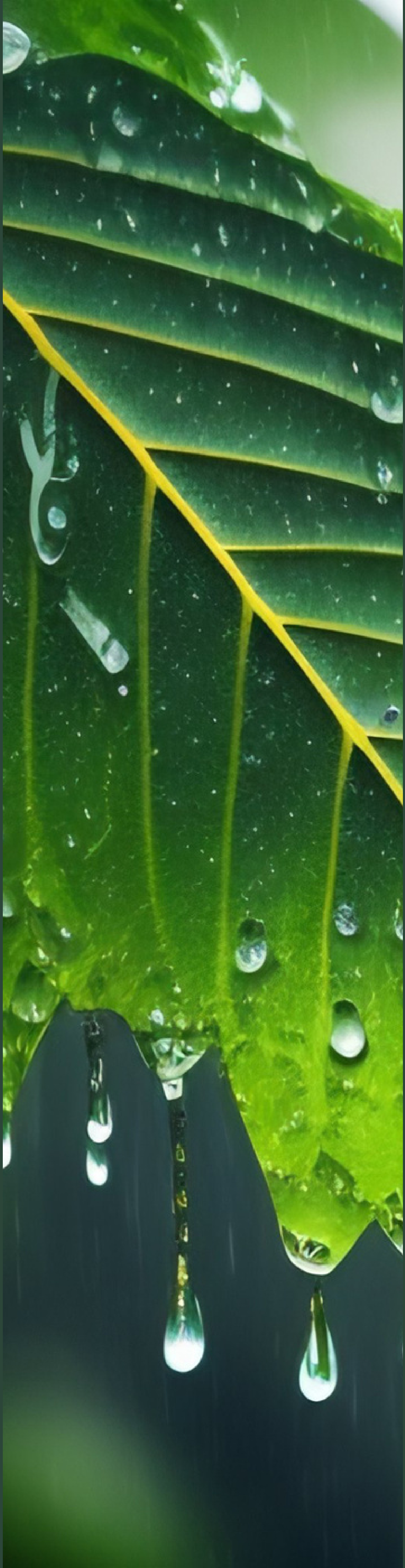


1

INTRODUCTION

This chapter provides a comprehensive introduction to water sustainability and the importance of rainwater harvesting in achieving this goal. It highlights the role of rainwater in minimizing climate change impacts and sets the context for subsequent chapters.

Water scarcity has been predicted for the human future, demanding an urgent exploration of its causes and strategies for better management of global water resources. Globally, it is important to consider its emergence and criticality in urban design and building planning, because it is not only a solution to water shortages, but also a measure to plan for future water demands due to urbanization and population growth. As a result, numerous researches and experiments have been conducted to determine sustainable methods for acquiring and maintaining water. Several approaches towards sustainable design are identified through literature review which primarily emphasises on water resources and their management. Water resources can be mainly divided underground, surface and alternate water sources where ground and surface water are the conventional water sources that exist in their natural conditions offering less opportunities for intervention except for maintenance and monitoring but alternate water sources offer an immense area of design intervention including rain water harvesting, water recycling, water treatment, etc. Alternate water sources are well recognised globally through their implementation ranging between urban to local scales. This includes individual houses, communities, business and university campuses, city wide implementation, and even gaining importance through enforcement of national policies and legislation. Among the available alternate water sources, rainwater harvesting and its applications are mostly used towards water resource management on urban and local scales. As an actual water source alternative, it is most commonly considered as a practical and common on-site solution. According to Aladenola (2016), it is advantageous because it has a "lower cost and lesser risk to public health" (p. 3459). It has gained considerable attention as an alternative source of water and Mahmoud (2015) describes it as a "useful tool for sustainable water management" (p. 8623).

Rainwater is regarded as a free and natural source of water that reduces pressure on the urban water supply system. It is due to this virtue that it has gained prominence among alternative water sources and conservation methods that are in high demand today. This virtue complements the urgent need for appropriate use and source optimization to be implemented and enforced. Yet, the most prevailing RWH harvesting application is identified as a roof top collection system implemented specially to cater for non-potable water uses on sites. This roof top system offers less polluted runoff water than other permeable collection surfaces like the ground, roads, or green areas. The rainwater harvesting strategy is considered "a helpful [and effective] tool for sustainable water management" (p. 8623), which prioritises this strategy in alignment with the United Nations 2019 report. This report advocates "[sustainable] water management to respond to water related challenges" (Nations, The United Nations World Water Development Report 2019, 2019). As result, it is understood that rainwater harvesting can help to reduce water scarcity and ensure water security in many parts of the world. It is an important step towards sustainable water management and can help to conserve water resources.

The trend of greening day-to-day campus practices has gained tremendous momentum globally. This is in response to the social and societal role higher education institutions play in promoting sustainable societies and enforcing the UN SDGs. Ahmed (2016) says “[HEI] campuses are one of the most water consuming projects” (p. 182), and Choi (2016) states that HEI offer a “scaled-down form of an urban system” (p. 1), good enough to replicate and test the effectiveness of design systems for better future applicability. Rainwater being known as the most prevailing design strategy used to offset water demands through freely available water capture using on-site rainfall, carries tremendous potential for application at higher educational campuses. As identified by Cupido (2016), rain water harvesting is one of the most common approaches “used in green building applications at institutional campuses” (p. 170). This idea is further highlighted for campus wide applications by Chaimoon (2009) suggesting "rainwater harvesting and reuse to be applied on campus to promote sustainable campus and water conservation policy” (p. 781). Its primary benefits are boosting green spaces, enhancing quality of physical as well as educational landscape, improving sustainable irrigation practices, and adding water self-sustenance to educational sites and local communities. In addition, it is suitable for water applications including portable & non-portable water supplies for flushing and laundry demands. The secondary benefits of rain water harvesting are the reduction in “greenhouse gas emissions” (Imteaz, Adeboye, Rayb, & Shanableh, 2012, p. 51). This reduction is achieved by eliminating the need and involvement of infrastructure supporting water supply including storage reservoirs, water treatment processes, supply pipelines, etc, whose operation would otherwise contribute significantly towards climate change problems. Other benefits complimenting rain water harvesting strategy relies in its process of collection, percolation and infiltration into the ground as mentioned by Saeedi (2018) for providing benefits “such as maintaining nutrients in the soil and removing pollutants and providing healthier green space” (p. 2). It also effectively recharges our ground water aquifers to compensate for their over extraction due to excessive urbanisation. Jebamalar (2012) states that “the need to implement measures to ensure that the rain falling over a region is tapped as fully as possible through appropriate techniques for recharging ground water aquifers as well as for direct storage of rain water" (p. 625).

As a result of its numerous benefits, rainwater addresses the global issue of groundwater depletion by recharging ground water through freely accessible and locally captured rainwater. It is also estimated to help optimise the water management scenario on site by compensating for water demand and supply on higher education campuses. A scenario like this helps achieve a water balance to mitigate climate change related impacts. It also helps mitigate climate change impacts by reducing water demand, minimizing stormwater runoff, mitigating the heat island effect, supporting sustainable agricultural practices, providing a reliable water supply, etc. The next chapter will explore trends in its applications, benefits and role in promoting sustainable practices to minimize climate change impacts.

2

TRENDS IN RAINWATER HARVESTING IMPLEMENTATIONS

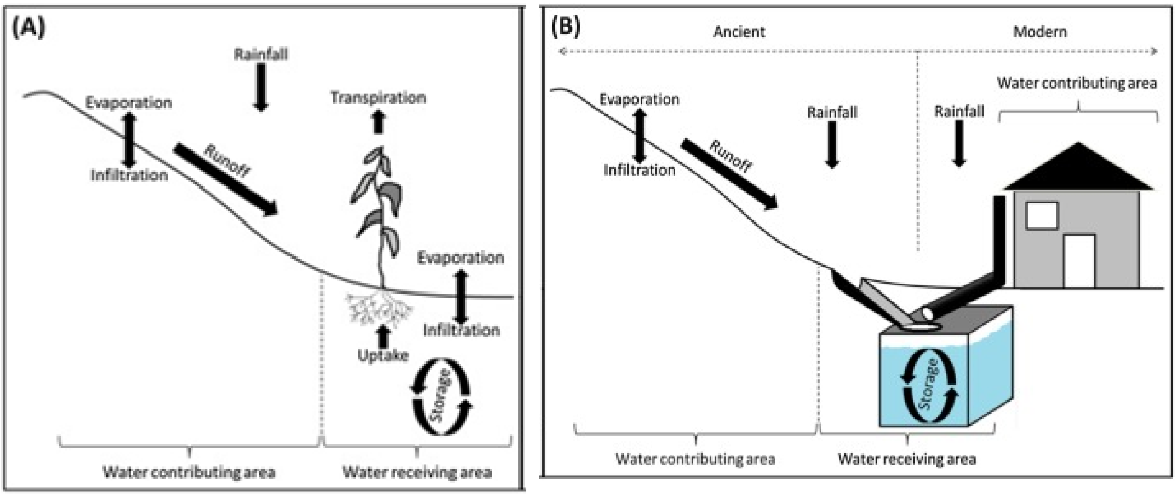
This chapter offers valuable insights into rainwater harvesting trends. It covers the history of rainwater harvesting, current trends, prevailing practices and popular approaches in this field. In addition, it explores various scenarios, including social factors, legal governance, alternative supply sources, and government promotions that prevail to encourage RWH adoption. This chapter is particularly useful for decision-makers, planners and communities.

This chapter presents an overview of rainwater harvesting (RWH) practices from a historical perspective and current practices. These practices identify incentives, promotions and motivations provided in regional context to promote RWH applications. In doing so, it highlights the social component attached with RWH system applications and the legal governance landscape that governs its wider acceptability. This landscape is used to identify popular approaches including centralized vs decentralized systems and RWH incorporation for Alternate supply systems. As a result, it offers insights into how RWH systems can be tailored to the local context and how RWH systems are utilized to mitigate climate change impacts.

2.1. History of Rainwater Harvesting

Rainwater harvesting has been practiced for thousands of years, and is used to provide sustainable water supplies in many parts of the world. The idea of capturing rainwater prevails since centuries as the most fundamental alternative water resource (Reckinger, Bocchino, Jackowitz, & Perry, 2014, p. 121). Rainwater harvesting has its roots traced back to ancient practices concerned with predominantly dry climatic conditions. As per archaeological records the most primitive rainwater harvesting systems are approximately 9000 years old. These systems facilitated increased water collection efficiency and ensured durable availability for longer periods. In agricultural practices where flood water irrigation was used, this was mostly found to be a common application. Even today, man-made collection systems intended for rain water harvesting replicate the natural systems designed to capture rain water. These systems are depicted in *Figure 1*, which represents the relation between rainwater collection through natural process and man-made process.

Primarily used to supply water for agricultural irrigation, rainwater collection systems have been modified through time and ages to provide for purposes other than agriculture. For example, stone structure cisterns used in India to collect and store rainwater, more famously known as ancient water step-wells serving communities and regions in large, or the storage cisterns and rock carved canals built for transporting rainwater found in Petra, Italy. Additionally, the Aqueducts found in Rome were an early example of a centralized water system. It is also found that even until the 1960s, stormwater management practices, intended to dispose of water accumulated on site, quickly to the nearest area for receiving water. As a result, a lot of piping networks were built into a centralized and public water system. Over time, various negative impacts associated with such systems have become evident. As identified by EPA, "aging infrastructure is a top water priority for the United States for the 21st century" (Novak, Giesen, DeBusk, & Geisen, 2014, p. 07). As a result, the need arises to revolutionize the use of water systems in urban environments and shift focus to private water systems and eventually shifting responsibilities from municipal authorities to building owners and individuals. In view of this need, a rainwater strategy empowers people to take control of their water resources and manage it responsibly. As found in the case of Potsdamer Platz, Berlin, Germany, where the natural lake is biologically cleansed, natural drainage is promoted on site and roof top collected water is used to offset irrigation & toilet flushing demands in the building, restoring a vibrant natural area to its original (Novak, Giesen, DeBusk, & Geisen, 2014, p. 15). This serves as an example of promoting integrated rainwater system models involving water conservation, stormwater management and aesthetic appeal in an urban context. In urban contexts, such integrated rainwater system models offer the advantage of a long history of promoting and implementing sustainable water solutions.



Natural Process: Rain events followed by surface run-off was routed into topographical depressions collecting flood water used for irrigation, as shown in the diagram above.

Man-Made Collection: Water directed either form an urban watershed or man-made collection surface was directed into a small storage basin, either underground or above ground or even used directly for irrigation or domestic uses.

Figure 1 Rainwater Harvesting Concept Evolution (Nachshon, Netzer, & Livshitz, 2016, p. 400)

2.2. Current Trends in Rainwater Harvesting

Earlier RWH was considered as a simple method of collecting water for drinking and irrigation purposes until recently, emerging as a global concern with added perspectives in a broader context such as sustainable economic growth, functioning of ecosystems, flood control in urban areas, quality control of surface run-off events, watershed management, mitigation of climate change impacts, building green infrastructure and so on (Fernandes, Terêncio, & Pacheco, 2015, p. 98). Based on a thorough literature review it is identified that RWH studies are mainly focused on the issues concerning payback period analysis, RWH tank evaluation and design criteria, effectiveness under different climate scenarios and regimes (including dry, average and wet years), differences between average annual rainfall and daily rainfall data use in RWH system assessment, impact of climate conditions on RWHS performance, sizing and performance, comparison in its efficiency among different climates, effective integration on urban runoff models, case studies integrating its economics and financial feasibility studies, socio-economic constraints and opportunities in its application, and the impact of RH water over public health.

In recent years, rainwater harvesting has reemerged as a specific implementation and adoption strategy within the water planning and design sector for achieving free water and to cope with climate-linked changes in the future. In view of carrying potential benefits on site and its ability to enhance local ecosystems and “livelihood resilience”, it was identified by Young (2012) for being “overlooked in water planning because countries have relied almost exclusively on conventional sources of rivers and groundwater supplies” (p. 01). This neglect is also supported by Nachshon (2016) stating that "in the modern era water harvesting has been neglected, due to technological advances in the field of water production and transport” (p. 398). Fernandes (2015) identified "the biggest challenge with rainwater harvesting is that it is not included in water policies in many countries” (p. 99).

Due to this continuous neglect over the years, for various reasons, this resource is now declared scarce. The prevailing understanding of water scarcity is expressed through countries classification based on water resources assessment. Sahin (2019) classifies countries as water poor and water rich based on the availability of water reserve resources. For countries having less than 1000m3 per person, countries are defined as water poor. The ones within the range of 1,000-3,000m3 are called water scarce countries, while the ones within the range of 3,000-10,000m3 are identified as water rich countries (p. 367). Sahin & Manioğlu (2019) also note that countries with more than 10,000m3 per person can be considered water abundant. As a result of this classification it is noted that water scarcity is a global problem. Climate change will adversely affect water resources in many water-poor countries, which will likely contribute to the increase of water scarcity in the near future. A number of researches have been initiated with the aim of reducing environmental stress on water systems and subsequently addressing the global water scarcity problem. These researches have demonstrated the value of rainwater harvesting in supplementing water supplies on varying scales of intervention from urban scale to building scale. For example, Hermann (2000) reported "rainwater to promote potable water savings in buildings" (p. 307). Similar to Sahin (2019) stating that "use of rainwater in buildings has been discussed actively in many countries for many years" (p. 368).

Consequently, the economics involved in RWH systems have been identified as a potential barrier to its wider acceptability at building scale. For example, in the case of private residences or building units, it needs user encouragement to implement RWH systems through government rebates and incentive schemes whereas the economics of larger scale building projects like public buildings and institutions offering a shorter payback period has proven to be more feasible examples of building scale intervention. On the other hand, numerous city-scale incentives promote rainwater harvesting systems installations. These include efforts from government and organizations offering encouragement through rebates on water bills, subsidizing initial investment costs for rainwater harvesting system installations and enforcement of laws & regulations that promote wider acceptability. For instance, the city of Victoria offers rebates of up to $500 for those who install new rainwater tanks on their properties (Imteaz, Adeboye, Rayb, & Shanableh, 2012, p. 51). The states and cities in USA for example, provide incentives, tax credits, rebates, or fee reductions through stormwater utilities (Wang & Zimmerman, 2015, p. 1774), for private and public buildings. Rainwater harvesting is also considered crucial in the context of higher education applications based in North America. As a result, the educational campuses based in the North American region provide examples of how RWH can be implemented in higher education practices. One of the most significant rainwater applications outside North America is the Sustainable Campus Project (SCP) in Taiwan where RWHS are included to demonstrate sustainable solutions to the public (Chiu, 2018, p. 213). It has also been discovered as an innovative energy saving approach besides, just being a means of capturing water. Chiu (2009) suggests RWH use over energy generating Solar PV systems, as a "more economical and feasible technology option" to be implemented over building rooftops (p. 492). Moreover, it was demonstrated and established as a water-energy conservation concept at the city scale (p. 6285). Due to this concept, the city of Taipei in Taiwan implemented a city-wide RWH program which delivered an estimated energy saving of 3.7 million kWh per year for households.

2.3 Prevailing Practices and legal governance landscape

Based on the invention, benefits, barriers and challenges identified for rainwater harvesting applications, it is imperative to analyze the global prevailing practices that govern the field of rainwater harvesting implementation. The literature assessed so far identifies that RWH systems and their implementation have a wide range of applicability and acceptability. There is a need to understand its intended purpose and varied applications in various contexts to access its effectiveness. To gain a comprehensive understanding of rainwater harvesting and its potential, it is essential to explore the practical implementations of these systems around the world and evaluate the efficacy of their application. In order to do so, this section presents the implementation for RWH implementation under five categories. Each of these categories has different requirements and challenges, which need to be considered when designing RWH systems. A thorough understanding of these categories is essential for successful RWH system implementation. These five categories are namely rainwater implementation for general practice, for domestic use (reducing non-potable demands), for recharging ground water, to substitute drinking water (potable demands) and examples of addressing climate change and water scarcity issues with localized intervention using RWH strategy. Each country implementing rainwater related incentives is classified under these categories. *Table* 1 below identifies countries and their contribution to the above-mentioned implementation categories. This *Table 1* highlights best practices in promoting rainwater implementation through law enforcement, government promotion and communal practices. This table serves as an effective guide for those looking to incorporate rainwater implementation into their local communities. It represents systems that encourage and incentivize rainwater use for a variety of applications at regional, national and city scales. Each category in this table is discussed in detail to provide a comprehensive understanding of the benefits and barriers associated with RWH systems implementation. It also offers a detailed analysis of the extent and context of RWH legal enforcement and government promotion within regional contexts. As a result, this section offers an insight into the legal governance landscape that prevails to encourage RWH applications.

Table 1 Implementation categories for rainwater harvesting strategy

General Practice	Domestic use	Recharging ground water aquifer	Drinking Water	Addressing climate change and water scarcity
In the USA, water conservation is mainly achieved through demand reduction (Cupido, Steinberg, & Baetz, 2016, p. 164). The RWH is implemented as an additional resource in many regions faced with water shortages.	Among the countries with the most successful implementation of RWH's for domestic purposes and government promotions, Germany is the leading example. As a result of strict	City scale application in Tel-Aviv, Israel is demonstrated by Nascho (2016) claiming RWH increases groundwater recharge by 300% compared to a Non-RWH condition. As a result of direct	In Thailand, RWH is used as a source for drinking water. **Government Promotions:** The government of Thailand has implemented a number of policies to encourage RWH,	In efforts to address drought conditions, El Nino effects and water scarcity problems, the Malaysian government mandated the installation of rain water harvesting systems in its "2012 Building Bye laws for all new buildings with roof areas >100 m2" (Leong, et al., 2018).

Government Promotions: A variety of RWH schemes ranging from "do-it-yourself" rain cisterns for watering food gardens to tanks for fire suppression at the community scale are already implemented and used. For example, the State of Texas financial incentives exempt RWH equipment from sales tax and the City of Austin encourages using rainwater for non-portable uses by offering a rebate of 0.050 per gallon for non-pressurized systems and 1.00 per gallon for pressurized systems (Novak, Giesen, DeBusk, & Geisen, 2014, p. 64). The Shepherd Creek watershed, Cincinnati, implemented a reverse-auction	water regulations in the UK, it can only be used for non-portable purposes such as irrigation, toilet flushing, and laundry (Słyś, 2009, p. 318). **Government Promotions**: A smart regulation program tailored for the German market offers a holistic incentive covering water abstraction fees, water supply, effluent fees and subsidies. This program encourages integration instead of isolated implementations (Campisano, et al., 2017, p. 205). This helps to optimize the water cycle cost structure for businesses and local authorities. It also provides	infiltration, it is boosting local and regional water cycles (Nachshon, Netzer, & Livshitz, 2016).	such as the "Rainwater Harvesting for Domestic Use" program. This provides financial incentives for households to install RWH systems. Additionally, it has also implemented a nationwide program to promote jar tank systems to collect rainwater (Campisano, et al., 2017, p. 198). These jar tank systems are implemented as individual household ***jars*** and community-oriented ***tank jars.***	For instance, the guidelines state that all buildings must be designed to collect and store at least one-third of the total roof area runoff, which is then used for non-potable purposes such as toilet flushing, car washing, and landscape irrigation.

incentive program to encourage citizens to install rain barrels and rain gardens (Campisano, et al., 2017, p. 205).	financial impetus for companies to invest in technologies that improve water consumption and wastewater treatment.			
In the Ethiopian context RWH is mainly focused on irrigational use. The Ethiopian government offers various incentives to encourage rainwater harvesting. These include tax deductions and exemptions for individuals and businesses implementing rainwater harvesting systems. They also provide financial assistance in the form of grants and subsidies to promote the adoption of rainwater harvesting technologies across the country	In 2001, the South American government launched its RWH program called "one million cisterns" in Brazil. This program benefits 2 million households in semi-arid rural settlements with no portable water source. This program is not only recognized for identifying community participation as an essential component of a successful RWH program. But also, by empowering women in the strategic and	As a way to recharge shallow aquifers, Tamil Nadu in India recommended RWH implementation at the city scale with every house. This was a way to conserve and store monsoon rains for sustained water availability throughout the year. The project was successful in recharging over 30,000 shallow aquifers and providing safe drinking water to an estimated 10 million people. As a result of	In Gansu province, China. RWH is used for drinking water and supplemental irrigation needs. This system has been successfully implemented in many villages, providing a reliable source of water and reducing the pressure on existing water resources. The success of this system has been credited to its low cost and ease of maintenance. For instance, the low-cost, shallow-well system in Gansu province was able to provide sufficient water	In South Korea RWH is implemented as an adaptation strategy for coping with climate extremes in urban areas with a special emphasis on large-scale RWH projects. For instance, Seoul implemented the Urban RWH Park Project, which captures rainfall from the city's rooftops in large tanks, which is then used to irrigate nearby parks and green spaces. The project was a success, capturing 14.1 million tons of water in its first three years, and reducing the amount of water pumped from nearby rivers to fill local reservoirs by 8.4%. (Campisano, et al., 2017, p. 198).

Law Enforcement: As part of the Ethiopian water sector strategy (EWSS), RWH is addressed in article 4.1.1 under the topic of water resource development focusing on its use for domestic and irrigation supply needs, as well as for centralized water supply systems. While Ethiopia's Rural Development Policy and Strategies (ERDPS) identifies rainwater collection only for farmers involving labor-intensive techniques (Temesgen , Han , Park, & Kim, 2016, p. 5209).	physical construction of water management, as both "decision-makers and beneficiaries in relation to RWH" (De Moraes and Rocha, 2013). The program has been a success, with over 2 million cisterns built since its inception. This success has been credited to the participatory approach, which has enabled women to become agents of change in their communities. This pioneering program has since been used as a model for similar initiatives around the world.	adopting this policy, water supplies and groundwater levels in water-stressed cities in India have improved since the implementation (Abraham Jebamalar, 2012, p. 624).	to meet the needs of over 2000 households in just two years.	
In African countries, RWH is practiced because	Taiwan enacted a law in 2014, making RWH		In Iran, RWH is used as a remedy to combat	In Mexico, RWH helped alleviate water scarcity and local flood problems.

of economic water scarcity instead of physical scarcity. This is owing to the lack of infrastructure for water storage, treatment and transportation. For instance, in Uganda, most of the rural households rely on RWH to meet their domestic water needs as there is no piped water supply in rural areas. “Small-scale communal RWH applications are the most widely spread application” (Campisano, et al., 2017, p. 198). Despite RWH's importance, there is no significant national policy or strategy to promote RWH in these countries. This has created a knowledge gap and lack of awareness of the	mandatory for domestic purposes. For newly constructed buildings having area <1000m2 RWH is mandated to cover at least a minimum of 5% of their total water consumption (Şahin & Manioğlu, 2019, p. 368). The government provides incentives such as subsidies and tax cuts to encourage RWH adoption. Furthermore, businesses are encouraged to use recycled water to reduce water consumption. **Law Enforcement**: In 2009, the Taiwan Water Resources Agency included RWH in the Taiwanese Water Law as an		drought conditions and to replace portable water resources. For instance, in the city of Isfahan, more than 5,000 rooftop rainwater harvesting systems have been implemented to help alleviate drought conditions.	It was successfully displacing "pipas" (trucks that supply household water) through the Isla Urbana Initiative in Mexico City (Campisano, et al., 2017, p. 200). This initiative created a network of 10,000 rainwater harvesting systems in the city and was a major success in Mexico. The rainwater harvesting systems not only provided a reliable source of water but also improved the quality of life for the local people. This initiative is an example of how RWH can be used to improve access to clean water in water scarcity areas.

potential of RWH among the people.	alternative source of domestic water supply (Campisano, et al., 2017, p. 198). This legal recognition of RWH made it easier for citizens to install RWH systems in their homes with government subsidies. To support RWH projects, the Agency also established a Water Resources Conservation Fund. As a result, RWH systems are now widely used in Taiwan.			
In Delhi, India, the Ministry of Urban Affairs and Poverty Alleviation, mandated rainwater harvesting in all newly constructed buildings with a roof area of more than 100 square meters and in all	Australia has one of the highest degrees of RWH implementation at household scale, reducing portable water demand including toilet flushing, cloth-washing and hot water usage. For			In the Canadian context, the idea is focused primarily on the improvement of water supply rather than the reduction of demand, anticipating future concerns about water supply and climate change in the future (Cupido, Steinberg, & Baetz, 2016, p. 164).

plots with an area of more than 1000 square meters, which are being developed, since June 2001 (Environment, 2019). The aim of this mandate is to reduce the demand for potable water and to recharge groundwater. It is being implemented primarily due to the fact that rainwater harvesting has been mandated in various cities across the nation.	instance, Sydney has seen a reduction of up to 33% in potable water usage due to RWH implementation in households. Compared to households without RWH systems, RWH systems save an average of 29% water in Perth, Australia. **Government Promotions**: The Living Victoria Water Rebate Program provides a rebate for rainwater tanks provided by the government. This "rebate affects water regulations and water pricing factors" (Campisano, et al., 2017, p. 199).			For example, in Canada, the federal government has invested in a number of water-related initiatives to increase water supply, such as the construction of new water storage facilities, the development of water monitoring systems, and the improvement of water treatment and distribution systems.
In Spain, incentives coupled with complementary strategies are	Traditionally RWH has been used for household use (laundry,			In the Caribbean context, RWH is used to meet water demands exacerbated by disasters & climate variability. For

utilized to encourage installation, such as the introduction of local regulations mandating RWH in new buildings and partial subsidies for such new build and retrofit cases, requiring a voluntary contribution (Campisano, et al., 2017, p. 204). For example, in the region of Andalusia, the Water Resources Law provides incentives for RWH by offering a 50% subsidy for the construction of new building with rainwater harvesting systems.	washing and other cleaning operations) in the UK but these days commercial scale systems are gaining prominence due to increased financial viability than house-hold scale systems. For example, a recent study in the UK showed that a commercial scale RWH system is more cost-effective than a house-hold scale system when the initial cost of construction is considered. Companies of all sizes are increasingly recognizing the monetary and environmental benefits of RWH systems, leading them to invest in RWH solutions.			instance, the Bahamas has adopted RWH systems to address water shortages following hurricane damage to potable water infrastructure. Also, on the Caribbean islands of Barbuda and Dominica, the destruction of water infrastructure due to recent hurricanes has resulted in an increased reliance on RWH systems. **Law enforcement**: The law mandates the inclusion of rainwater cisterns in all new constructions under governmental economic support, in the Bahamas, Bermuda, and other Caribbean islands. **Government promotions**: are available on storage tanks, enabling people to capture rainwater for domestic uses. For instance, the government of Bermuda provides a rebate of up to 50% on the cost of a water storage tank, plus an additional 25% for installation costs (Aladenola, Cashman, & Brown, 2016).

	Government Promotions: intended to conserve municipal rainwater supplies, through programs like Rain Share, offering collective sharing of roof runoff from nearby houses and Code for Sustainable Homes, encouraging RWH domestic installations (Wikipedia, 2019)			

Based on *Table 1*, it is understood that RWH implementation for drinking purposes and ground water recharge is limited, with fewer cases compared to the general practice category. Implementations that address climate change and local water shortages while offsetting potable water demands in domestic applications provide maximum examples of intervention. Additionally, this *Table 1* also highlight a series of innovative engagement programs and promotions including the Living Victoria Water Rebate Program operational in Australia, Rain Share in UK, “do-it-yourself” rain cistern program and reverse-auction incentive in USA, the Isla Urbana Initiative in Mexico and “one million cisterns” program in Brazil, as examples of social change and user empowerment, focused on decision-makers and beneficiaries of RWH strategies.

Additionally, cases of law enforcement, local regulations and government promotions encouraging RWH implementation on a communal scale are identified. A number of specialized RWH systems have been identified, including header tanks in Taiwan, rainwater cisterns in the USA and Caribbean, direct infiltration methods in Tel-Aviv, Israel, and tank jar systems in Thailand. These systems demonstrate the extent and context of RWH applications in terms of rainwater availability and intended use, indicating the dynamics involved in RWH strategies. These systems are also useful in understanding the potential for RWH in other regions, and how RWH systems can be tailored to the local context. As a result, these provide useful insight into the challenges and potential benefits of RWH solutions. Based on this analysis, several popular approaches are identified, which are attributed to the implementation of rainwater harvesting into water system designs. Among these, RWH incorporation for centralized vs decentralized systems and RWH incorporation for alternate supply systems are discussed in detail.

2.4 Popular approaches

This book section discusses and analyzes case studies using these popular approaches from a design perspective. These approaches provide guidance on selecting the most appropriate RWH system for a given site. Moreover, they explain how RWH systems can be integrated into existing water supply systems, as well as what kind of RWH practices are used for green building certification. These approaches are discussed as follows:

RWH incorporation for Centralized vs decentralized systems

One of the most debated and discussed approaches to RWH is its inclusion in distribution and delivery systems. As and when compared to the energy sector and its preference for renewable resources over fossil technologies, the water supply sector lacks a similar approach to delivering sustainable water resources. As identified in the literature, decentralized systems are an effective means of renewable water supply. They eliminate the intricacies and hassles involved in a centralized supply system. But despite their contribution to sustainability, centralized infrastructure is still widely given priority compared to decentralized options (GhaffarianHoseini, Tookey, GhaffarianHoseini, Yusoff, & Hassan, 2016, p. 07). Therefore, decentralized systems are not only suggested as the most suitable approach for individual residences but also for systems supporting public buildings and larger infrastructure scales. These decentralized systems, particularly those working with RWH, have played a potential role in complementing centralized systems in addressing the deficit between water supply and demand in many countries. For example, in the case of Ethiopia, where several research studies are implemented to identify the "economic gaps in implementation of decentralized rainwater harvesting and its utilization as an alternative water supply source in urban areas" (Temesgen , Han , Park, & Kim, 2016, p. 5206).

RWH incorporation for Alternate supply systems

Another popular approach is to disconnect toilet flushing supply from the centralized water supply system carrying portable water and use a decentralized water supply system fed by harvested rain water as an alternate supply. Given the volume of water involved in the wastewater conveyance system and the supporting infrastructure investment, this approach is considered specially by the green certification systems to offset water demands. This approach saves potable water wasted on flushing and reduces stress on the supporting conveyance infrastructure. This idea is supported by the argument that RWH can be used as a convenient means to substitute non-portable water applications like toilet flushing since flushing doesn't require any significant improvement in water quality (Devkota, Schlachter, Anand, Phillips, & Apul, 2013, p. 398). Also, identified by Albrechtsen (2002) "the microbiological quality in toilets supplied with rainwater is approximately the same as in toilets supplied with potable water" (p. 315). Both these researches are indicative of the fact that disinfection of harvested water is not recommended before flushing use. Therefore, rainwater is suggested to be used for "non-portable purposes like toilet flushing” (Coombes, Kuczera, & Kalma, 2003, p. 111). Besides these, numerous research studies support the wide acceptance of rainwater harvesting systems as an easy and economical way of flushing toilets. Especially the ones that deal with green building literacy, as they reduce both water bills and water consumption levels. As a result, this approach has been identified as an effective method for reducing the demand for portable water in buildings and campuses contemplating green building certification in order to mitigate climate change impacts.

In view of its wider acceptability, global applicability and potential for green building certification applications the next chapter will offer technical insights into rainwater harvesting system design. This will examine design factors such as rainfall components and system design components and explore how these components influence operational efficiency. Different approaches presented in this chapter provide practical guidance for designing effective rainwater harvesting systems. Consequently, it captures the details of the technical landscape that indicates the need for future technological innovation.

3

RAINWATER HARVESTING SYSTEM DESIGN

This Chapter focuses on rainwater harvesting system design, considering physical factors such as rainfall components and operational efficiency. The different approaches to system design presented in this chapter provide practical guidance for designing effective rainwater harvesting systems. This chapter captures the details of the technical landscape and indicates the need for innovation in smart technologies to support green building applications.

Rainwater harvesting systems are designed to capture, store, and reuse rainwater for various uses including drinking, irrigation, and individual household uses and public water systems. These system designs range from simple rooftop catchment systems to large-scale underground storage systems. This range requires different details and design requirements. Proper design of these systems is essential to ensure their effectiveness and efficiency at capturing and storing rainwater. The process of designing and constructing these systems involves the selection of rainfall components, operational design considerations and operational efficiencies. Rainfall components play a crucial role in deciding rainwater harvesting system design considerations. These components include the intensity, frequency, and duration of rainfall events in a specific region. Knowledge of these factors is essential to determine the size and capacity of the harvesting system to efficiently collect and store rainwater. For instance, rainfall intensity influences the size of the catchment area and the capacity of storage tanks. Higher intensity requires a larger catchment area to capture a lot of water in a shorter period of time. Similarly, rainfall duration determines the system's ability to recharge storage tanks during extended dry spells. System sizing and other design requirements are guided by these requirements. Another vital aspect is operational efficiency, which needs to be considered when designing a system based on rainfall components. Operational efficiency ensures that the system effectively collects and stores rainwater without wastage. As a result, this three-step process for designing and implementing rainwater harvesting systems is discussed in detail under the heading of rainfall components, system design components and approaches for operational efficiency.

3.1 Rainfall Components

Generally, RWH system design focuses on the effective flow mechanism governed by R (rainfall). Conceptual portioning of rainfall (R) and its flow on site or surface is divided into components as suggested by Helmreich (2009) where R is rainfall, Ec is plant transpiration, Es is evaporation from soil and loss by interception, Roff is surface runoff and D is deep percolation (p. 118). These components are graphically depicted in *Figure 2*. Rainwater harvesting systems are highly dependent on the local climate because of these components. These components are not only crucial in determining the operational efficiency of the designed system but are also the guiding factors for system size and system cost.

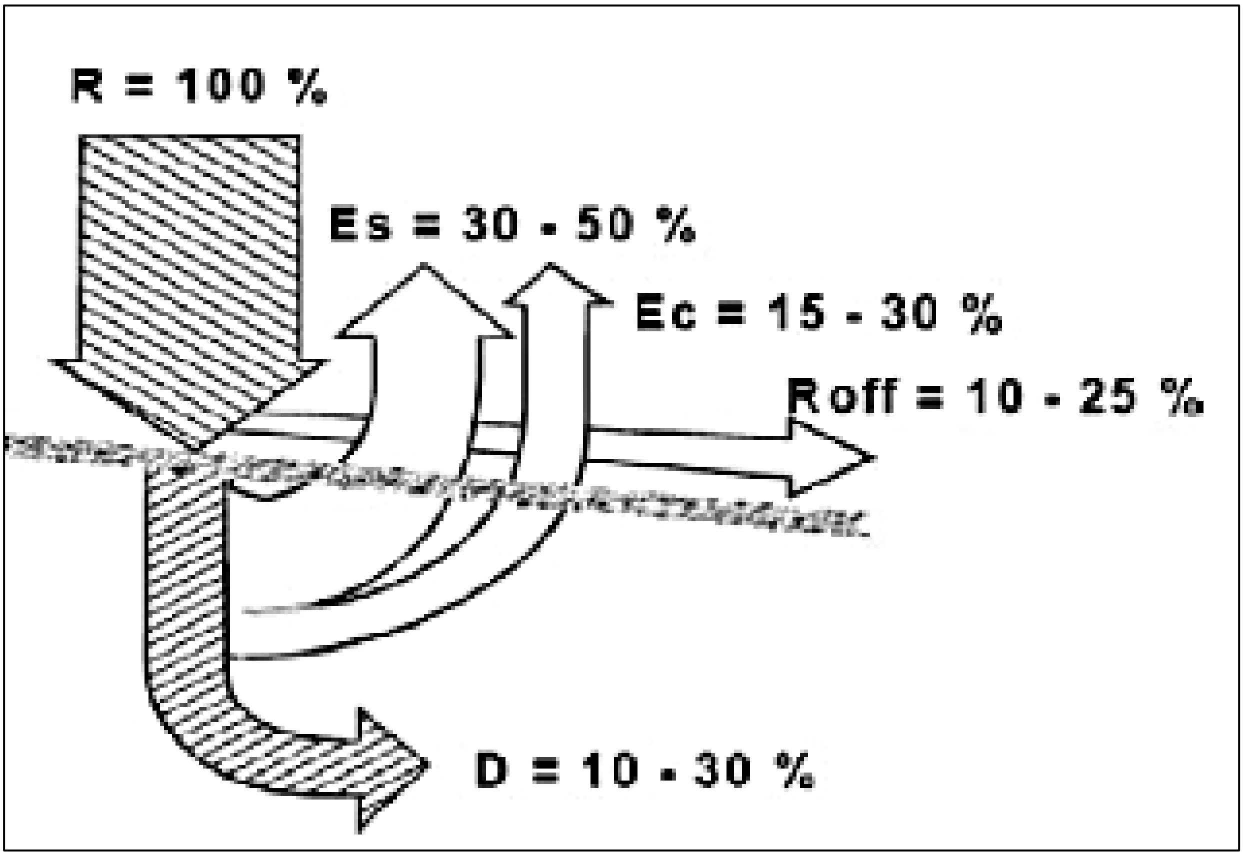


Figure 2 Rainfall flow components (Helmreich & Horn, 2009, p. 119)

3.2 System Design Components

Among the rainfall components of falling rainwater, only surface runoff (Roff) offers the possibilities of control and design intervention that contributes towards rainwater harvesting system design. RWH system design is largely determined by its capture mechanism, making the catchment surface crucial to its implementation. As the first step, collection systems including catchment areas and connected conveyance pipes systems are used for water collection and conveyance. The second step is to install a storage system for harvested water for later consumption. Followed by treatment systems to improve harvested water quality, if needed depending on site conditions, and to ensure its safety prior to distribution. Last but not least, distribution systems consist of pipes, connections, pumps, and header tanks to distribute water from storage tanks to end uses. These are the basics involved in designing an RWH system. However, as part of current practice influenced by **green building certification**

systems, these RWH system design also includes a backup water supply mechanism. This kind of design arrangement might utilize municipal city water supply or any additional water source to act as back-up supply, in case of rainwater shortage or absence due to dry periods or system failure conditions. This back-up mechanism enables switching between rainwater & back-up supply sources as needed depending upon the strategy implemented on the selected site. Such arrangements are implemented to ensure continuous supply and minimize maintenance issues due to the absence of water. These issues include pipeline scaling, metal corrosion, and water stagnation in pipelines. It reduces the operational costs and effort associated with repairing and maintaining water supply systems. Additionally, such arrangements ensure that no water is wasted, as the back-up supply source is only used when the rainwater supply is not enough and therefore improves the operational efficiency of rainwater systems and reduce the overall costs involved in its sustainable operation.

3.3 Approaches for Operational Efficiency

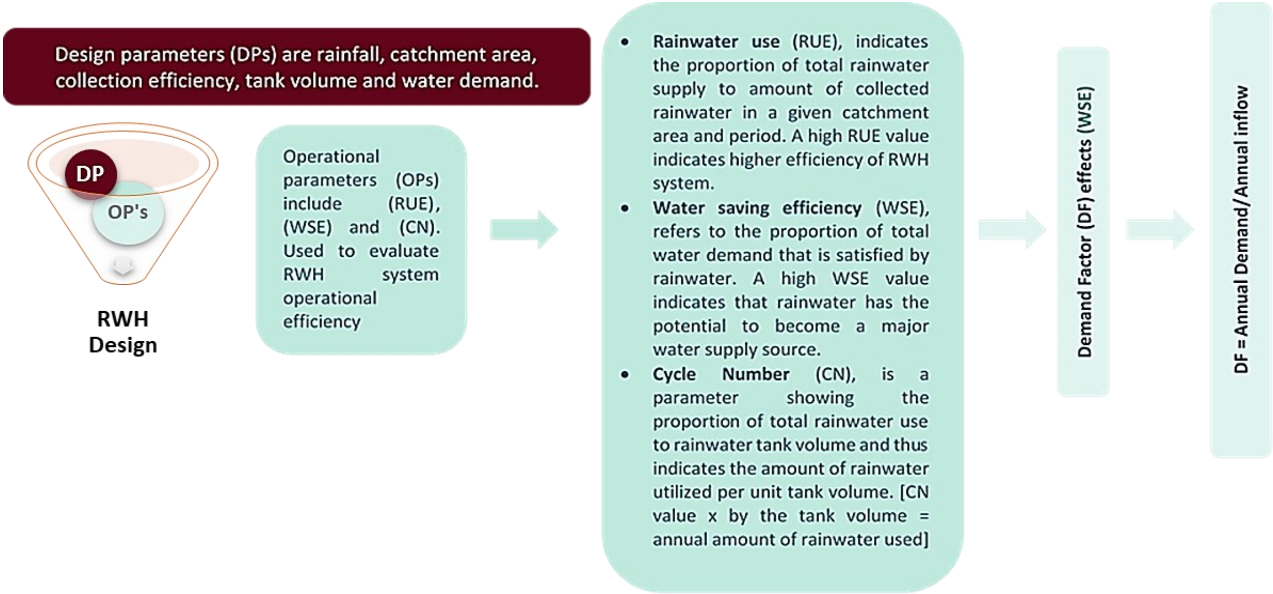
RWH system performance efficiency has been the subject of numerous research and subsequent theories. As an alternative water supply system for green certified buildings and projects, it has been extensively studied for its efficacy. It has received much debate and attention in recent years to provide local support for water sustainability on sites. Its design efficacy is determined by its functional components, which include environmental components (introduced under the heading of rainfall components in this chapter) and design components (introduced under the heading of system design components in this chapter). Natural components like local precipitation, climatic conditions and existing site conditions are called environmental conditions which are beyond design controls but every other RWH system component that becomes operational after receiving runoff (Roff), offers opportunities for intervention and enhancement, which affects the design and performance efficiency of RWH systems. There are multiple approaches to understanding the performance efficiency of design components. This chapter discusses the most relevant approaches to the design of rainwater systems in green certified building contexts. These include collection-based, supply-oriented, consumption-oriented, and demand-based approaches to assess and understand RWH systems' performance efficiency. These approaches can be used to optimize the design of rainwater systems to ensure sustainable water supply and support water sustainability. These approaches are discussed as follows:

Collection based: Project variables, including site specific physical elements as catchment areas offers the first possibility for design intervention. These catchment areas include roof surface, courtyard surface, road surface or any other surface area acting as collectors of falling rainwater. Rainwater collection estimates and system design evaluations are based on these areas. In addition to offering means and methods of collection, the efficiency of collection depends on the material used on these surfaces. Material could enhance or reduce surface efficiency towards rainwater collection. For example, paved surfaces will provide significant quantities of runoff (Roff). In contrast, loose vegetation ground will allow for more deep percolation, resulting in reduced runoff (Roff). This combination of surface areas with surface materials contributes to a "building package and plays a significant role towards the RWH catchment, which is defined as the quantity of rain harvested water" (Şahin & Manioğlu, 2019, p. 368).

Supply oriented: Another approach to rainwater systems operational efficiency is identified by Chiu (2018). This approach looks at operational efficiency in terms of rainwater collection quantities and quality. This is where, "rainfall depth, tank volume, rooftop area, and water demand" (Chiu, 2018, p. 214), govern the basic performance of most RWH systems. Installation systems are categorized as catchment & conveyance systems, which govern collection quantities. Alternatively, the receiving ends are divided into storage and water treatment systems that support the quality of collected water (Gikas & Vassilios, 2012, p. 01). The quantity and quality of collected rainwater vary significantly depending on the environmental components of the collecting area. It is therefore understood that in order to ensure efficient water collection and storage, these components need to be carefully considered.

Consumption-oriented: Besides, collection efficiency is another aspect of RWH system efficiency attributed to the user end, with respect to the use of collected water. As discussed by Sousa (2018) regarding demand patterns governing water storage systems in relation to “stored water influenced by water demand patterns” (p. 19290) In this approach, the focus is placed on these demand patterns determined by a variety of factors. These factors include user activity, physical characteristics, and supply system features such as water fixtures and sanitary installations efficiency. This focus on demand reduction makes it more suitable for green building certification, where water fixture efficiency qualifies for points. These points are essential for a building to achieve the best possible level of certification. This approach promotes demand management and offers insights into how water demand can be managed and reduced through smart technologies like sensors, metering systems, and water-efficient fixtures. This approach is also relevant in the sense that user demand in a desert climate will be different from cold climates. Similarly, the difference in water consumption in a school building versus a residential building. Other researchers, such as Mayer et al. 1999; Höglund 1999; Dalhuisen et al. 2003; Flörke and Alcamo 2004; Inman and Jeffrey 2006; Williset et al. 2011, have also stressed the importance of demand patterns in estimating RWH systems design efficiency.

Demand-based: A popular approach to defining RWH system performance is governed by a set of components defined under "operational parameters and design parameters” (p. 01), respectively. This approach is represented in *Figure 3* below. In this figure, the design parameters are like the ones explained by the supply-oriented approach in addition to the operational parameters focused on real-time actual water quantities and their assessment compared to actual water demands. This actual demand is crucial in impacting the water saving efficiency of an RWH system. This water saving efficiency falls under the operational efficiency of rainwater systems and determines how well the system can satisfy water demands with rainwater. This approach is particularly useful for green building certifications such as LEED, BREEAM and the Living Building Challenge, since these certifications evaluate sustainable performance based on water savings achieved. As a result, an extensive study was conducted on demand fractions by Palla et al. (2011). This study examines "RWH system characteristics [storage capacity], as a function of two non-dimensional parameters, namely the demand fraction and the storage fraction". The "storage fraction is defined as the ratio (S/Q) between the storage capacity of the system S(L3) and the annual inflow Q (L3) whereas the demand fraction is defined as the ratio D/Q between the annual water demand D(L3) and the annual inflow Q(L3)" (p. 67). Based on this study it is understood that the storage capacity of the system increases, as the demand fraction and the storage fraction increase. It is also noted that the storage fraction has a more significant impact on storage capacity than the demand fraction. A higher storage fraction yields higher storage capacity, which dictates the operational efficiency of the designed water system.



Design parameters (DPs) are rainfall, catchment area, collection efficiency, tank volume and water demand.

Operational parameters (OPs) include (RUE), (WSE) and (CN). Used to evaluate RWH system operational efficiency

- **Rainwater use** (RUE), indicates the proportion of total rainwater supply to amount of collected rainwater in a given catchment area and period. A high RUE value indicates higher efficiency of RWH system.
- **Water saving efficiency** (WSE), refers to the proportion of total water demand that is satisfied by rainwater. A high WSE value indicates that rainwater has the potential to become a major water supply source.
- **Cycle Number** (CN), is a parameter showing the proportion of total rainwater use to rainwater tank volume and thus indicates the amount of rainwater utilized per unit tank volume. [CN value x by the tank volume = annual amount of rainwater used]

Figure 3 Parameters effecting rainwater harvesting systems design and performance assessments

As a result of the understanding developed around operational efficiencies for RWH system design. The next chapter delves into rainwater harvesting (RWH) system design challenges. It discusses quantitative and qualitative assessments, providing readers with methods and models to assess rainwater harvesting systems feasibility and effectiveness.

4

RAINWATER HARVESTING SYSTEM DESIGN CHALLENGES

This Chapter delves into rainwater harvesting system design challenges. It discusses quantitative and qualitative assessments, providing readers with methods and models to assess rainwater harvesting systems' feasibility and effectiveness. This chapter outlines the barriers, challenges opportunities and prospects involved in the development of rainwater systems, thus representing its design landscape.

Quantitative and qualitative assessments play a crucial role in rainwater harvesting systems. The quantitative methods and model help determine the appropriate storage capacity required to efficiently collect and store rainwater. By considering factors such as catchment area, annual rainfall patterns, and water demand, sizing methods enable the system to meet water needs while avoiding oversizing or under sizing issues. On the other hand, qualitative assessment focuses on ensuring harvested rainwater quality is suitable for various purposes, such as irrigation. These treatment techniques like filtration, disinfection, and sedimentation help remove impurities, contaminants, and pathogens, making the water safe for its intended use. Both these assessments are critical for the operational efficiency of RWH systems and ensure their effectiveness and reliability. Consequently, they promote sustainable water management and reduce the environmental impact of water treatment and transportation. Both of these assessments are discussed in this chapter along with their role in improving the operational efficiency of RWH systems. As a result, this chapter represents the potential design landscape of RWH systems and examines the barriers, challenges, opportunities and prospects involved in its development.

4.1 Quantitative Assessment Using Methods and Models

RWH systems efficiency is the ratio between stored and collected water. This is similar to the explanation of storage fractions presented in chapter 3 of this book under Demand-based approach. Considering stored water as a function of environmental conditions, installation systems and collected water are mainly influenced by RWH tank size. This was identified in an experimental study citing "main challenge in designing RWH systems is sizing water tanks to provide adequate storage capacity" (Sousa, Silva, & Meireles, 2018, p. 19284). As the main element in RWH systems design, many researches have been dedicated to this area. A variety of methodological approaches are available and classified under simplified methods and simulation methods used for tank sizing.

Simplified methods are approximate methods, useful for the pre-design stage with methods combining both demand & supply side approaches to complement user-defined rules. As mentioned by Sousa et.al. (2018), the demand side approach is best suited for areas with year-round rainfall, achieved by multiplying the "daily water demand by the average long dry period" whereas the supply side approach is more appropriate for areas with low or uneven rainfall and is more like the design of public water supply reservoirs" (p. 19285). On the other hand, the simulation methods are based on the performance of real systems modelled numerically. These are similar to the energy simulation method required by green building certification systems to predict energy consumptions and apply reduction measures. For rainwater these simulations methods explore interactions between system and consumption patterns.

It uses a balance equation that simulates the balance between water collected, stored, and used. This balance equation is used to estimate RWH systems' water efficiency based on precipitation and water consumption patterns. However, the rainwater simulation methods are not required by green building certification systems similar to energy simulation methods and models.

Quantitative assessments of storage sizes are provided by both of these methods, utilizing different intervals. In general, large storage performance is predicted by using monthly time intervals, whereas small storage performance is predicted by hourly time intervals. As a means of predicting the efficiency of rainwater collection, it is suggested by Fewkes (2000) that “hourly models exhibit the highest accuracy followed by daily and then monthly models” (p. 106) and Young (2012) suggests acquiring “specific daily water-demand data” (p. 01). Both these suggestions intend to achieve realistic storage capacities for rainwater harvesting systems instead of approximated values. As identified by Fewkes (2000) there are two types of storage systems, large volume storage, conserving large volumes > 95% and small volume storage, conserving <50%. Both reduce flows into municipal or surface water sewer networks (p. 100). Based on the performance of these storages, the effectiveness of rainwater collection systems is assessed under WSE and DRE, as illustrated in *Figure 3* in chapter 3. WSE is water saving efficiency (WSE) as noted by Palla et al. in 2011, which measures the quantity of conserved mains water in comparison to the overall demand and discharge reduction efficiency (DRE) added by Fewkes et al. in 2000 as a “measure of flow reduction into the municipal or surface water sewer” (p. 101).

As part of current practice many systems are still designed and assessed using simplified approaches. For example, sizing the rainwater tank based on a given number of days' supply, or a specified percentage of annual demand. As an alternative to simplified methods, Roebuck (2011) recommends models that simulate physical behaviour to determine RWH tank size and financial performance (p. 359). These models aim to identify the most efficient operation scenario to meet water demands by evaluating RWH system components There are several methods for evaluating

RWH systems, including the one proposed by Fewkes and Warm (2000), which focus on mathematical relationships to establish a suitable tank size. The input ratio for the desired RWH system is calculated using: Tank size calculation: S=XD (X=no. of days storage, D=Average Daily demand {D/365}). Another evaluation approach is recommended by Environment Agency (EA) (2008), as a rule of thumb which sizes the tank based on user-defined percentage of average annual rainfall or demand using: S=PACFR (P=user defined 5, C=Runoff coefficient, F=System filter efficiency). This rule is recommended for smaller RWH systems only such as domestic systems, whereas the previous calculation is more used for sizing large systems.

Despite its proven benefits, rainwater harvesting's low operational efficiency has greatly impeded its adoption. According to Imteaz (2012), this is due to "a lack of information about the effectiveness of harvesting systems, and the optimum size of storage required to meet performance requirements" (p. 52). As a result, many rainwater harvesting systems are underutilized or over-utilized, leading to problems with water quality, over-extraction, and under-utilization of stored water. Rainwater harvesting is therefore a successful practice only when proper storage tanks are sized. In order to minimize the gaps existing due to this lack of information, a number of water balance models have been proposed to improve operational efficiency, including the following: a simple model based on historical rainfall data by Vaes and Berlamont in 2001. PURRS water balance model (Probabilistic Urban Rainwater and Wastewater Reuse Simulator) analysis of the possibilities for effective retention and storage by Coombes in 2007. An estimation model called SARET (Storage and Reliability Estimation Tool) is a stochastic precipitation generator. Plugrisost is a rainwater harvesting system simulator used to analyze environmental impacts including cost analysis and life-cycle analysis. Aquacycle is a daily water balance model capable of modelling a single land block to an entire urban catchment using the yield-before-spillage (YBS) algorithm.

Another significant model is RainCycle, which is an Excel-based model. It uses the yield-after-spillage (YAS) algorithm to factor in a whole life costing approach. This can also work with the YBS approach. Numerous research studies including Fewkes, 2000; Liaw and Tsai, 2004 and Mitchell, 2007, have investigated the accuracy of behavioural models established on two commonly exploited supply spillage approaches, Yield after Spillage (YAS) and Yield before Spillage (YBS). The choice of the YAS operational rule is based on results from previous research studies including Campisano (2012), stating that "YAS operating rule assumes the current yield as the minimum value between the volume of stored rainwater at the previous time interval and the demand in the current time interval" (p. 10). Fewkes (2000) demonstrated that the "YAS reservoir operating algorithm gives a conservative estimate of system performance irrespective of the model time scale" (p. 104). Additionally, Mitchell (2007) recommended using the YAS algorithm based on its "lower sensitivity to variations in storage capacity and water demand" (p. 66).

In addition, the RainTANK model, shown in *Figure 4*, simulates the water savings potential of a rainwater harvesting system, whereas the EEAST model, shown in *Figure 5*, is a life cycle-based model called Economic and Environmental Analysis of Sanitation Technologies (EEAST). This model is used to "evaluate the economic and environmental impacts of RWH and composting toilet-based technologies" (p. 397). It is a spreadsheet model that compares water savings, cost, energy and GHG emission criteria of a portable water system with alternative water system or decentralized technology options. This is done substituting potable water used in flushing and irrigation models, early in the design stage. EEAST compares five modeling scenarios with a typical case to identify the most sustainable method of harvesting rainwater for irrigation and toilet flushing. As a result, it provides informed decisions to predict operational efficiencies accurately based on economic and environmental impacts.

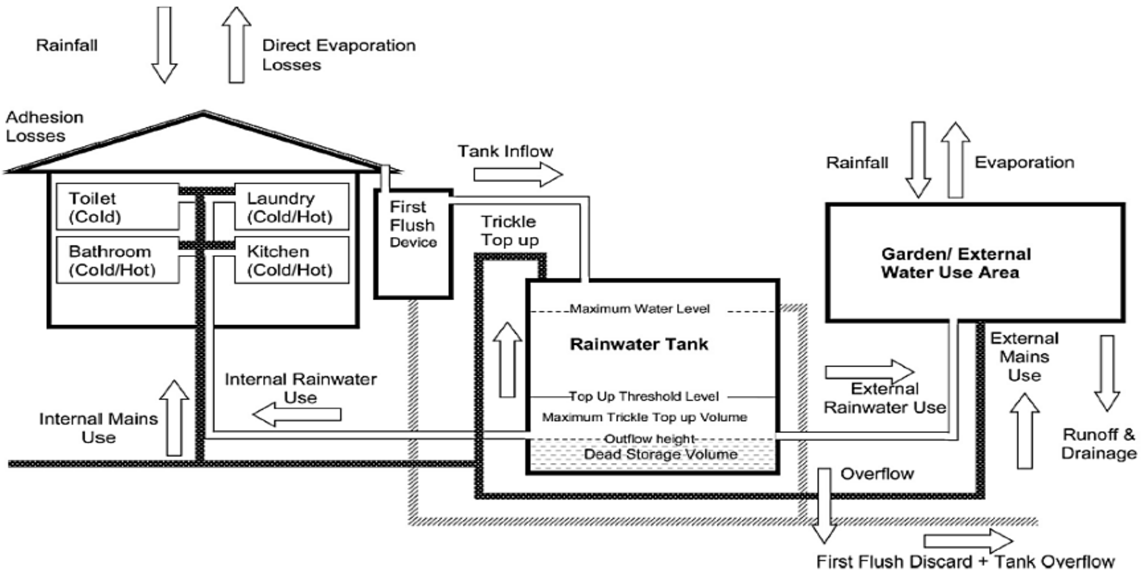


Figure 4 Rain tank model (Leong, et al., 2018, p. 948)

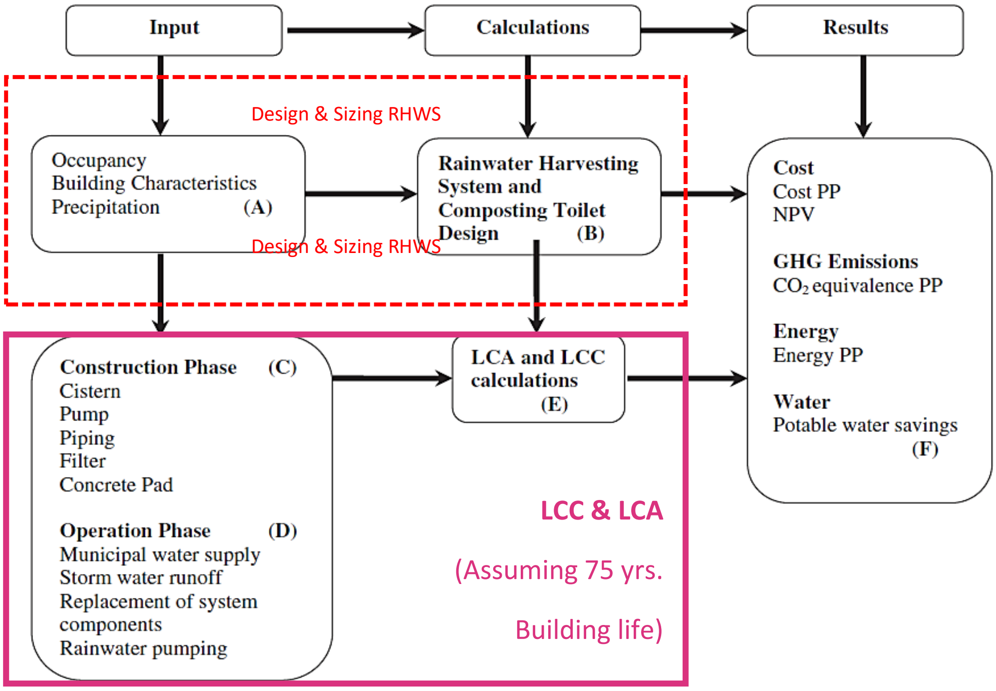


Fig. 2. Conceptual model structure of EEAST.

Figure 5 EEAST Model (Devkota, Schlachter, Anand, Phillips, & Apul, 2013, p. 397)

4.2 Qualitative Assessment

Similar to the design challenges involved in rainwater harvesting systems based on quantitative assessments of their collection, conveyance and storage systems, there is a need to address design challenges arising from qualitative assessments. Qualitative assessments involve soft factors such as system aesthetics, user acceptance, regulatory permits and guiding policies. These soft factors can have a large impact on the success and social acceptance of RWH systems. Stratigea (2014) mentions the factors affecting qualitative assessment, which are dependent on air-quality, collection surface area like land-based or roof-based and the “residence time of water within the rainwater tank” (p. 249). Rainwater collection surfaces have been investigated in several research studies, due to their importance for RHW system performance. As evident from Helmreich (2009) findings "atmospheric pollutants” and catchment surface “material concentrations” are the two major factors affecting RWH Quality (p. 121). Atmospheric pollutants affecting rainwater quality include accumulated solids or dust particles, fecal deposits from rodents and birds, over catchment surfaces during dry conditions. Pollutants can be increased by materials such as asphalt and gravel, while pollutants can be reduced or eliminated by concrete and plastic. In addition, there is the possibility of leaching through the metal parts installed in the harvesting system. As a result of these pollutants, harvested water quality is affected, resulting in adverse health effects while limiting its social acceptance.

Gikas (2012) proposed using principal component analysis (PCA) for detecting factors affecting rainwater characteristics while considering WHO regulations (2006). This refers to safe reuse of water and drinking water standards set by European Union in case it needs to be consumed for drinking purposes” (p. 123). To ensure safe water quality, water disinfection measures are suggested in addition to the pollutant risk associated with roofing materials. Campisano et al. (2017) identifies gutters used in drainage systems, as a major contributor to heavy metal pollutant contamination found in roof runoff water samples, especially metals like zinc and aluminum (p. 200). The distribution piping within RWH systems has also been identified as another significant source of contaminants, including those studied by Morrow et al., 2010 and Martin et al., 2010. Further, Ward et al. (2010) suggest that the selection of plumbing materials should be determined according to the “hardness of rainwater in the selected area to minimize the potential leaching of metals and the consequent deterioration of harvested rainwater” (p. 1708). As a result, it is understood that the potential treatment options for such source pollutants in RWH systems include both pre-storage (debris screens and filters and first-flush diversion) and post-storage measures.

In pre-storage treatment options, the first flush reduces incoming pollutants entering the storage tank, ensuring the quality of the water before storage. This reduces the burden of treatment processes scheduled for post-storage conditions. Post-storage treatment methods are costly and involve more intensive infrastructure including in-line sediment filters on pumps, slow sand filtration, clari-flocculation and disinfection (Campisano, et al., 2017, p. 202). As a result, pre-storage treatment options have become popular as they improve RWH systems' life span, reduce maintenance costs and reduce environmental impact. Disinfection through chlorination is the most commonly used method for treating post-storage harvested water. Slow sand filtration is a cheap method to improve bacteriological quality, whereas a rapid sand filter using activated charcoal for removal of hazardous substances is the least commonly employed. To reduce membrane fouling and inactivate microorganisms, additional technologies, like solar pasteurization using UV-A radiation combined with heat and ozone bubbles, are considered. New techniques in this category include rotating disc filters with ceramic membranes developed at the Fraunhofer Institute. These filters are specifically designed to remove bacteria and viruses from rainwater (Helmreich & Horn, 2009).

According to the discussion around quantitative and qualitative assessments above, it is evident that data-driven decision making for RWH design and deployment as well as an integrated approach addressing the environmental, public health, water governance, economic and social implications are essential to ensure its long-term sustainability. These assessments directly influence the design, operational efficiency and social acceptance of RWH systems. The next chapter explores existing literature and real-world examples to identify these quantitative and qualitative assessments.

5

RAINWATER HARVESTING APPLICATIONS

This Chapter provides a comprehensive understanding of rainwater harvesting's potential as an effective strategy for green building design. It helps identify the gaps between its literature and application landscape. The literature landscape is a valuable resource for rainwater harvesting researchers. While the applications landscape takes a practical approach by analyzing 14 case study sites. This chapter provides real-world examples that can guide researchers and technology developers, as well as inform designers, green building practitioners and policy makers, and expand the discourse on how rainwater harvesting can be utilized to create sustainable green environments.

This chapter aims to delve into the existing research literature and case studies that showcase design applications for rainwater harvesting. It intends to explore and examine how quantitative and qualitative assessments are applied to research and real-world case studies. This exploration focuses on RWH applications in green building design on higher education campuses. Through an analysis of the research literature landscape, this chapter aims to identify trends, challenges, and breakthroughs in rainwater harvesting design. Additionally, by examining various case studies that constitute its application landscape, this chapter will offer practical insights into the successful implementation of rainwater harvesting strategies in real-life scenarios. Comparing both landscapes sheds light on its applicability to green building design and the gaps between its literature and its application landscape.

The literature landscape is presented in section 5.1 and the application landscape is discussed in section 5.2 of this chapter. This information can be used to guide future rainwater harvesting research, inform decision-makers, and expand the discourse on how rainwater harvesting can be utilized to create sustainable green practices. Using a theoretical and practical basis, this chapter offers insights into the importance of rainwater harvesting in the context of climate change as well as future directions to make rainwater harvesting more effective.

5.1 Significant Researches in RWH (Literature Landscape)

For a better understanding of the future direction and its potential application to green building certification, it is imperative to examine the research literature available in the field of RWH. This literature landscape on rainwater harvesting is critical for understanding its potential, as well as its limitations, challenges and possibilities for future application as a design strategy. A literature landscape like this further enables future innovation and market development for RWH integration into green building technologies. It also contributes to make harvested water more acceptable to the public by understanding the various technical, social and environmental factors involved. As a result, this literature landscape helps to identify gaps and needs for further research, insight into the economic analysis of RWH technology, and create an evidence-based understanding of RWH benefits and potential that can be used to inform policy and design decisions. This knowledge is essential for everyone concerned with RWH including infrastructure planners, researchers and practitioners to develop and promote rainwater harvesting technologies.

During the assessment of this literature landscape, various researches in addition to the ones mentioned in the previous chapters of this book were identified. The majority of these researches concern monitoring and assessing RWH systems' performance. In order to capture a more detailed understanding for the purpose of this book these researches are summarized in *Table 2* under the categories of models, investigations and methods. These researches address different components involved in RWH design and performance evaluations. As a result, *Table 2* identifies the research findings under each category and outlines the objectives behind the RWH research. These objectives are primarily related to the quantitative and qualitative assessments of RWH, the design of RWH systems, financial assessment, general assessment of efficiency and the use of GIS based approaches to improve efficiency.

Most of these research findings address a general overarching design scenario while some are location specific. Besides numerous research models, methods and investigations there is a separate set of studies dedicated to RWH design implementation based on GIS knowledge. Through spatial information modelling, these studies analyze and define potential rainwater harvesting locations. *Table 2* underlines the inclination of this literature landscape that dominates the field of RWH applications. This table is indicative of the fact that this landscape is directed at ensuring collection efficiency and subsequent measures to boost harvested water productivity and requires further investigation into how to optimize RWH systems design for specific geographies, climates, and other environmental and socio-economic conditions.

Table 2 List of Models, Methods and Investigations

	Year	Researcher	Findings	Addressing
Models				
1	1978	McMahon and Mein	Identify three general types of reservoir sizing models, namely; critical period, Moran and behavioral models	Water Quantity
2	1999	Dixon	DRHM – Maas balance with stochastic elements for demand profiling, simulates quantity, quality and costs	

3	1999	Fewkes	Produced a series of design curves used in estimation of tank sizes based on roof area and water demand patterns	Water Quantity
4	2001	Vaes and Berlamount	Developed a model to identify effectiveness of tanks using long term historical rainfall data + Reservoir model called Rewaput, rainfall intensity-duration-frequency relationship and triangular distribution	Water Quantity
5	2003	Coombes and kuczera	Identified RWH tank sizing resulting in mains water savings, Sydney, Australia. (used for toilet and washing machine only) + Probabilistic behavioral, continuous simulation, evaluating source control strategies, PURRS Model	Water Quantity
6	2004	Fewkes	Produced a model called RCSM	
7	2005	Mitchell	Model named Aquacycle, water balance simulation using the Yield before spill algorithm	
8	2006	McMahon et al.	Suggested Volumetric reliability approach (The volumetric reliability, also known as water-saving efficiency, is defined as the total volume of rainwater supplied divided by the total demand during the entire simulation period)	
9	2006	Kim and Han	Model named RSR, RWH tank sizing for stormwater retention and reducing flooding, used Seoul as a case study	
10	2006	Roebuck and Ashley	Rain cycle, excel-based mass balance model using YAS algorithm and whole life cycle costing approach	
11	2006	Liu et al.	Behavior-based continuous simulation using Simulink	
12	2007	Coombes	Conducted studies on the modelling of rain water tanks and opportunities for effective retention and storage using the PURRS	
13	2008	Cowden et al.	Implemented a stochastic rainfall model to design rainwater harvesting systems in the West African region	Design System

14	2010	Khastagir & Jayasuriya	Demonstrating the impact of precipitation spatial and temporal fluctuations on the design of rainwater harvesting systems	Water Quantity
15	2010	Tam et al.	Investigating the cost effectiveness of rainwater tank applications for residential buildings in Australia	Financial Assessment
16	2011	Palla	Proposed behavioral model to help estimate water saving efficiency and detention time affecting water quality	Water Quality
17	2016	Melville-Shreeve et al.	Multiple Criteria Analysis demonstrated additional benefits of RWH such as energy savings and environmental benefits due to reduced raw water abstraction, pumping, and water treatment	Water Quantity
18	2013	Montalto et al	Explore the impact of economic incentives on the adoption of green roofs and raingardens for decentralized water technologies	Water Quantity
19	2017	Rahman, A.	Integrated RWH system with stormwater runoff management model (SWMM) in Zhong-He District, Taiwan, developing a simulation model to substitute for SWMM	GIS based Approach
Investigations				
20	2002	Albrechtsen	Investigated the microbial quality of rainwater collected on seven roofs supplying toilet flushing in Denmark	Water Quality
21	2005	Villarreal and Dixon	Investigated the water savings potential of stormwater harvesting systems from roof areas and discovered mains water savings of 30% using a RHW tank sized 40m3 in Sweden	Water Quantity
22	2007	Ghisi et al.	Identified potential water savings from rainwater harvesting systems in Brazil (South America). For the cities studied, average potable water savings per year ranged from 12–79%	Water Quantity
23	2007	Sazakli et al.,	Investigated treatment processes are most likely the cause of better-quality stored water than roof runoff. In many cases,	Water Quality

			lead to compliance with potable water guidelines and standards	
24	2009	Hanson et al.	Proposed a simple equation for calculating the required storage capacity for a rainwater harvesting system installed in a generic location within the United States	Water Quantity
25	2009	Cheng and Liao	Developed a rainfall zoning system for Taiwan and a database for DRWH system design throughout the region	Water Quantity
26	2012	Campisano et al.	Investigated a typical single-family home scenario to support benefit-cost analysis for RWH implementation in Sicily, Italy	GIS based Approach
27	2015	Chiu et al.	RWH contribution to water-energy nexus – Integrating rainfall database, water balance model, spatial technologies, energy-saving investigation, and economic feasibility analysis for eight communities in Taipei, Taiwan	GIS based Approach
Methods				
28	2000	Fewkes,	Mass balance simulations	Water Quantity
29	2007	Guo and Baetz	Developed statistical methods	Water Quantity
30	2010	Basinger et al.	Probability matrix methods	Water Quantity
31	2010	Ward et al.	User-defined relationships	Water Quantity
32	2016	Adham et al.	Analytical hierarchy process (AHP) aided with GIS application were used to evaluate the performance of existing RWH techniques in (semi-) arid areas at the Oum Zessar watershed, Tunisia	GIS based Approach
33	2017	Rahman	Mexico municipalities identified domestic RWH installation sites using a regional approximation. Considering monthly rainfall data, number of occupants per household, water demand and run-off coefficient to calculate catchment area and tank size needed for a single dwelling	GIS based Approach

34	2016	Shreeve et al.	Quantitative multi criteria analysis used to assess RWH system in UK, using whole life cost assessments that aim for financial savings to out-perform the traditional RWH system	GIS based approach
35	2017	Rahman	Evaluated the role of 10 non-technical and technical impact factors in RWH for agriculture irrigation in Beijing. Highlighting that non-technological factors such as public perception and motivation are also significant along with technological factors such as reliability and financial benefits of the RWH system	GIS based Approach
36	2017	Campisano et al.	Use of Supervisory Control and Data Acquisition System (SCADA)-based devices to improve automation and control of RWH systems for optimal management of stored rainwater resources	

5.2 Rainwater Harvesting Design Applications Analysis (Application Landscape)

Based on the available literature assessed in previous section dedicated to literature landscape, it has been observed that 90% of the researches in the field of RWH are dedicated to non-standard volumetric analysis, serving a highly specialised objective. These researches are exclusive to a given condition and therefore no normative approach is discovered for implementing a rainwater harvesting strategy. It is also evident that this particular strategy is mostly used and carries future research potential towards green certified buildings and sustainable water design. The importance of rainwater design systems in addressing environmental issues on university campuses is cited by various researchers. As a result, this chapter provides a comprehensive understanding of RWH as a design strategy in the context of higher education institution. It intends to identify rain water harvesting practical and actual applications to investigate, inquire and evaluate the extent of the relationship between actual practices and the elements, components, parameters, methods and models reviewed through literature review. This set of investigations focuses on case studies claiming water sustainability at buildings and sites particularly operating in an institutional setup claiming innovative implementations.

These investigations are listed in *Table 3*, which includes fourteen case study sites. These case study sites include: Innovation Centre Phase 2 Building Streatham Campus at the University of Exeter in UK, Mahasarakham University, Khamriang Campus in Thailand, Tianjin University Peiyang Campus in China, University of North Carolina at Chapel Hill in USA, Emory University in suburban Georgia in USA, CIRS Building at University of British Columbia in Canada, University of Kebangsaan in Malaysia, Bullitt Centre University of Seattle in USA, Democritus University of Thrace in Greece, Barone Campus Fair Field University in USA, Horticulture Services Building at Macdonald Campus Sainte-Anne-de-Bellevue in Canada, Adama Science and Technology University (ASTU) in Ethiopia, Dormitory complex at Seoul National University (SNU) in Korea, and the Figtree Place experimental site operated by the University of Newcastle in Australia. This *Table 3* highlight the extent of RWH application as well as the experiential learning aspect offered by these case study sites. For the selection of these case studies, higher education institution campuses were evaluated using their websites and secondary data sources. The purpose of this evaluation is to explore information that asserts and demonstrates rainwater harvesting strategies as a major sustainability design intervention.

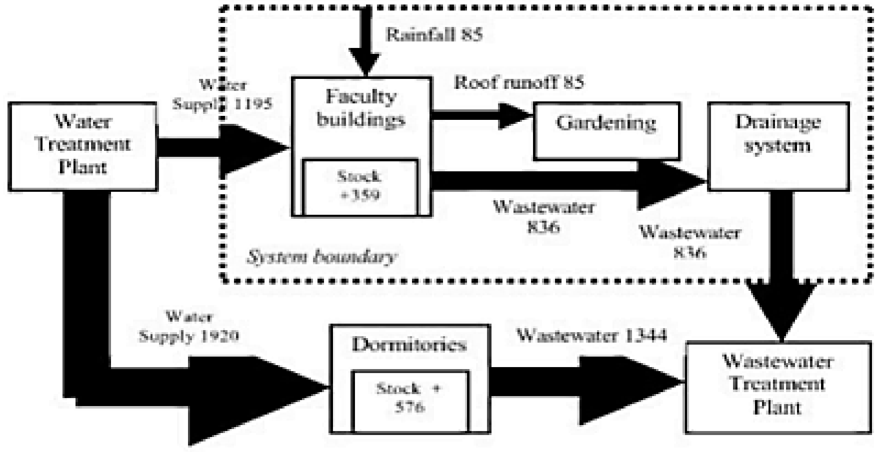
Based on the explanation provided in chapter 4, natural components are beyond the system design control and therefore this analysis will only focus on design components at the listed case studies in *Table 3*. These design components get operational only after receiving onsite runoff (Roff), as identified by Helmreich in 2009. A performance efficiency analysis of the selected RWH systems is conducted at the selected sites using this component. This will include a careful review of collection, conveyance, storage, treatment, distribution and back-up systems, to capture effectiveness in terms of operational efficiencies, highlighting the designated collecting and receiving ends of RWH systems suggested by Gikas et al. (2012). Additionally, it will also try to identify the use of methods and models in actual design (if any) discovered through literature review in chapter 3, 4 and chapter 5 of this book. This analysis will identify the gaps between research literature and actual design implementations.

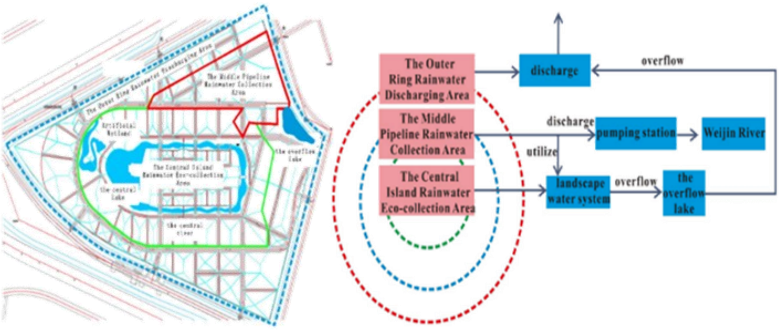
Case study details included in *Table 3* provides physical statistics information including land area used for rainwater capturing, total water usage on site, total demand offset with rainwater, total water savings achieved using rainwater, etc under the heading of project specification. Under this heading quantitative data is presented to authenticate claims of water sustainable operation on the selected sites. On the other hand, this *Table 3* presents rainwater systems details under the heading of operating performance assessment column. This column provides details on RWH system description and additional information (if available) regarding tank sizing, overflow arrangements, filtration mechanism, treatment systems, scale of application, innovative methods and applicable concepts, etc. The data presented in this column is used to generate a water flow and circulation pattern for each selected case study. This pattern informs rainwater handling mechanisms onsite from their point of capture to their receiving ends. It helps identify the systems involved, best practices, and innovation in the field of (actually implemented and practiced) rainwater harvesting strategies. It also provides contextual information and notes on each step of the cycle and associated risks, costs, and opportunities. It serves as a reference tool and starting point for deeper research and analysis.

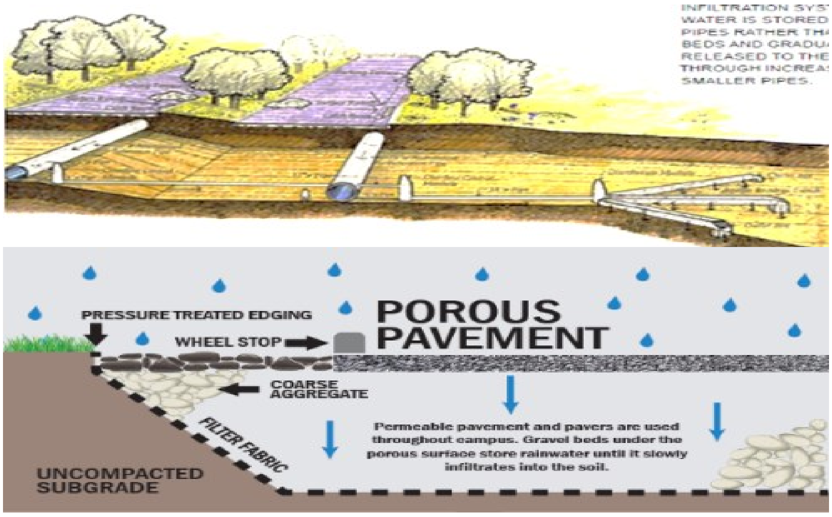
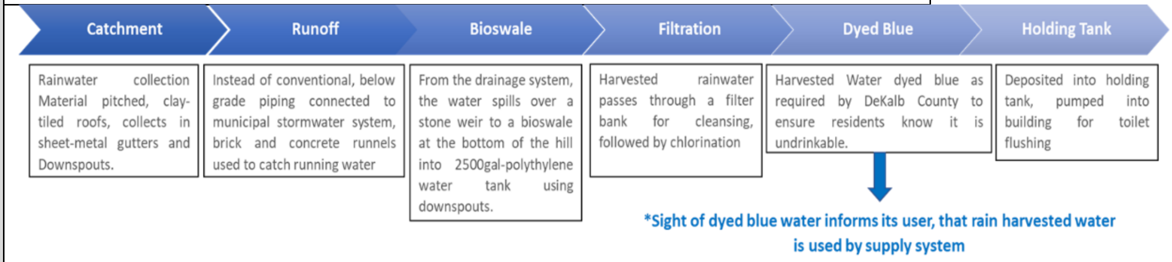
The rainwater handling mechanism supplying water to offset irrigation demands like gardening is displayed in green colour and recharging ground water aquifer in purple colour. In contrast, the mechanism supplying rainwater for other purposes, including flushing, storage tanks, etc is depicted in dark blue colour. In this analysis, there were examples of using harvested rainwater to achieve net-zero water operations. These net-zero operations have multicoloured representations to highlight receiving ends. These patterns are generated based on the rainwater handling mechanisms identified at the selected case study sites. These provide the basis for a tailored approach to onsite rainwater harvesting system design and illustrate the entire design lifecycle of onsite rainwater graphically. As a result, these serve as the framework for this book's summary and recommendations chapters.

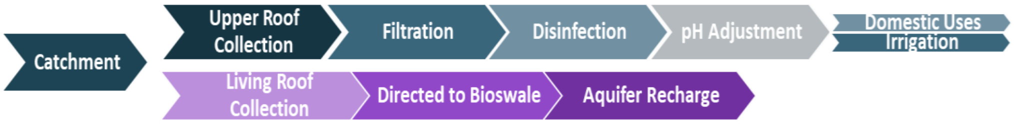
Table 3 Case Studies:

		Operating Performance Assessment	**Project Specifications**
1	Innovation Centre Phase 2 Building, Streatham campus, University of Exeter, UK	**System Description:** This case study uses a modelling tool to design parameters as explained by Chiu (2008) in chapter 3, section 3.2 of this book, under supply-oriented approaches. These parameters include local annual rainfall, roof area, estimated annual demand, in addition to parameters like "number of days required for storage, filter and runoff coefficients and system efficiency" (Ward, Memon, & Butler, 2010, p. 06). The harvested rainwater supplied by the system is used for flushing toilets and complemented by a mains water top-up. This is similar to the explanation provided in section 4.2 System design components of chapter 4 under components for design considerations. Rain water stored after collection is pumped to a header tank, located on the roof. Under gravity, this acts as an interim storage tank (Ward, Memon, & Butler, 2012, p. 5128) **Sizing Methods for Tanks:** Rainwater metering and mains water data were used to calculate the water saving efficiency (Et) which is the percentage of mains water conserved in relation to total demand. Using the simple and detailed approaches for tank sizing (as per Sousa, 2017), they are calculated to be 60% and 46% respectively for an 8-month monitoring period. A detailed approach was implemented where the metered data was compared to estimated data obtained from the Rain Cycle modelling tool. This approach resulted in an annual cost savings of 1459 euro (Ward, Memon, & Butler, 2012, p. 5133) • Simple/Intermediate approach: annual water savings 816m3, 25m3 Tank size, 300 occupants, 1469-euro cost saving • Detailed approach: annual water savings 619m3, 9m3 tank size, 111 occupants, 1459euros cost saving	Rating system: BREEAM 'Excellent' rating • Model used: Rain Cycle modelling tool for RWH system design • Methods used: Proxy method used for estimating cost of energy associated with pumping harvested rainwater. Total roof (Catchment area): 1500m2 Total volumes of harvested rainwater: 193.07 m3 Intended use: Non-portable **No information regarding RW treatment systems*

2	Mahasarakham University, Khamriang Campus, Thailand	 *Figure 6 Campus Application (Chaimoon, 2009, p. 782)* **System Description:** An onsite water treatment plant supplies water to all buildings, and waste water from all buildings is treated on-site. • **System Boundary Application Method:** Water use in dormitories is excluded from system boundaries due to domestic activity consuming 60% of total supply and the rest 40% forms the system boundary. Rainwater is only used within the system boundary to offset 7% of total water consumption within the system boundary. Figure 6 shows this system boundary. The existing water supply storage distribution system is downward in each building connected with a roof storage tank. This is done to collect roof top water to a pond or storage tank on the ground for gardening. (Chaimoon, 2009, p. 782). • **Building Application:**  	Rating system: UI Greenmetric Total Roof area: 3,024m2 Total Rain runoff: 30,860m3/yr (85m3/day) Existing Water supply: 3,200m3/day distributed to buildings in campus. **No information regarding Models for sizing or methods for evaluation, neither for RW treatment and filtration systems*
3	Tianjin University, Peiyang Campus, China	**System Description:** Campus wide application of a multilevel rainwater collection, use and discharge system, where stormwater utilization for flood discharge is prioritized and backed up by rainwater. This unique approach is intended for underground rainwater infiltration and storage for use in artificial water bodies on campus. It demonstrates LID practices like vegetative swales, sunken green space, and permeable pavement. **Campus application of multi-level discharging system method:** • Outer Ring (discharging area 923,900m2) ensures safe flood discharge and stormwater management on campus. It stores rainwater underground or by letting it flows into the Weijin River (surface water resource) and campus moat by the surface facility. • Middle Ring (discharging area 292,800m2) adopts permeable pavements for water collection, infiltrating into soil for ground	Rating system: NA Total campus area: 2.5 million m2 (Total water area: 154,000m2 Total rainfall volume: 621,500m3 Runoff reduction achieved:

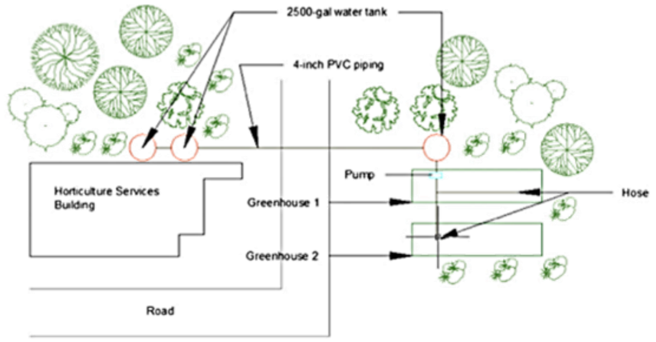
		water recharging and reducing road runoff. Water collected by the pipeline is used to create an artificial water body on the campus. Surplus rainwater from this system is injected into the Weijin River through a pumping station • Central Ring (discharging area 856,700 m2) act as an integrated ecosystem offering collection, infiltration & storage to minimize flood peaks & mitigate surface runoff pollution (Peng, Cui, & Ji, 2018, p. 01).  *Figure 7 Multi-level rainwater circulation system at Peiyang Campus (Peng, Cui, & Ji, 2018, p. 02)*	328,152m3 from initial 430,000m3 after application of control measures (central & middle island) **No information regarding Models for sizing or methods for evaluation, neither for RW collection, treatment and filtration systems*
4	University of North Carolina, Chapel Hill	**System Description:** The UNC campus has an integrated reclaimed water and rainwater system, utilizing roof top potential along with intervention from other available surfaces for collecting additional rainwater using infiltration beds. **Capturing mechanism:** • **Storage/infiltration beds under other surfaces:** A number of areas on campus, besides parking lots, are potentially suitable for the construction of storage/infiltration beds, to hold and infiltrate stormwater, in addition to surfaces provided by Athletic Fields, Intermural Play Fields and Recreation Areas. *Figure 8* shows how multiple impermeable surfaces, such as permeable pavements, artificial turf, and parking lots, drain to a subsurface stone infiltration/storage bed. This infiltration mechanism avoids sending nutrients downstream to protect Jordan Lake. • **Runoff capture and re-use systems:** Rainwater that falls on campus is stored in lined, stone-filled cisterns underground (capable of storing up to 350,000 gallons of water). These underground cisterns hold rainwater to irrigate campus green roofs and athletic turf. Some quantity of rain water is also used to flush toilets in certain buildings (Hill, 2019).	Rating system: STAR Total catchment area: 18.9 million square foot Total water uses on campus: 675 million gallons/year (potable 75% + non-potable 25%) **No information regarding Models for sizing or methods for evaluation*

		 *Figure 8 Infiltration bed under surfaces at UNC (Associates, Associates, & Group, 2004, pp. 4-7)*  	
5	Emory University in suburban, Georgia	**System Description:** A campus wide rainwater strategy is implemented to capture roof runoff, using a special design element called Runnels, instead of the conventional below-grade piping mechanism. Making rainwater movement visible from its capture all the way through runnels to Bioswales for collection and treatment. • **Bioswale System description:** The top layer of the swale is designed as a wetland of plants growing in 4 feet of specially blended topsoil. Under this garden is a layer of filter fabric placed over a minimum of six inches of gravel. This allows water to drain from the surface while keeping the topsoil in place. Below the gravel, a row of half-cylindrical plastic chambers (162 Stormtech SC-740 chambers) supply a storage capacity of 89,000 gallons, enough to provide 2,168 gallons of water per day, needed to flush all toilets in the buildings. 39% reduction in storm water runoff achieved compared to pre-development site conditions. • **Capturing mechanism:**  Rainwater collection Material pitched, clay-tiled roofs, collects in sheet-metal gutters and Downspouts. Instead of conventional, below grade piping connected to municipal stormwater system, brick and concrete runnels used to catch running water From the drainage system, the water spills over a stone weir to a bioswale at the bottom of the hill into 2500gal-polythylene water tank using downspouts. Harvested rainwater passes through a filter bank for cleansing, followed by chlorination Harvested Water dyed blue as required by DeKalb County to ensure residents know it is undrinkable. Deposited into holding tank, pumped into building for toilet flushing *Sight of dyed blue water informs its user, that rain harvested water is used by supply system	Rating system: LEED Total Campus Area: 600 Acre RWH Water Savings: 704,194 gallons/year(potable) & 791,320 gal/year (toilet flushing) **No information regarding Models for sizing or methods for evaluation*

6	CIRS Building, University of British Columbia	**System Description:** Rainwater harvesting is one of the 5 priorities in UBC's Water Action Plan. It is implemented to reduce cliff erosion at UBC's stormwater outfalls. The campus operates on a closed loop collection system (for storm water) which eliminates run-off from the building, thus reducing flooding and erosion risks on campus. Water collected from the living roof, which is used for non-potable purposes, is discharged into a natural water feature, which eventually infiltrates into the groundwater supply. 100% potable water requirements are met by on-site collected rainwater + 100% stormwater is treated & used or infiltrated on-site. - **Building Application:** CIRS building is designed to be entirely water-self-sufficient. All potable water in the building is supplied by rain falling on roofs. Using a simple system, rainwater is harvested from the building roofs and stored in a cistern below the building. Rainwater is filtered and disinfected onsite and distributed throughout the building for potable water applications. - **Campus Application:** Besides stormwater management is a significant concern on campus, due to the cliff location and hydrogeology of the area. The University is shifting towards a natural systems approach to water management that values rainwater as a resource and identifies a number of applications for it on campus, including use in "facilities, water features and irrigation" (Columbia, 2019). - **Capturing mechanism:** Roof - Collection – Storage - Filtration - Disinfection – pH Adjustment – Treated water tank (Harvested rainwater is stored in a 100m3 cistern underneath the building). 	Rating system: Living Building + LEED Water Availability: Total Collection Area (Roof): 1000 square meters Total Rain harvested water: 3,358.9ltr/day Water Demand: Estimated average demand (potable): 2,000 liters/day **No information regarding Models for sizing or methods for evaluation*
7	University of Kebangsaan Malaysia	**System Description:** As part of its sustainable development initiative, the university has installed a pilot rainwater harvesting building project. Rainwater is conveyed from the rooftop via a series of gutters and down pipe through a manhole to the filtration tank. It passes through the filter before being stored in a storage tank. Volume of rainwater harvested: 91,997.17litres (lowest rainfall case) / 3,68,752.15liters (highest rainfall case) - **Capturing mechanism:** Catchment system – conveyance system – Filtration tank – Filtration chamber – storage tank – submersible pump – Delivery tank – Plumbing System	Rating system: NA Total catchments area: 1090.66sq meters **No information regarding Models for sizing or methods for evaluation*

			
8	Bullitt Centre, University of Seattle	**System description**: According to the Bullitt Centre website, the design achieves 61% restoration of water into the ecosystem using its slow release catch, using "either ground infiltration or evaporation to mitigate stormwater during and after rain events" (Foundation, 2019). • **Capturing mechanism:** Rainwater first hits the solar panels before dripping onto the roofing membrane and funneling into the downspout that leads to the cistern for collection. The collected rainwater is piped into a common line and directed to a vortex filter system. The vortex filter contains a 280-micron filter screen that removes debris from the water stream. The collected rainwater is stored in a basement concrete cistern with a total storage volume of 46,200 gallons. It is equipped with a level sensor and a temperature sensor. The stored water is pumped into building's distribution system using a skid mounted booster pump assembly, dividing water supply into portable & non-portable. The potable system at Bullitt centre provides flow for drinking fountains, showers, and sinks. The non-potable system provides water to foam flush toilets and a small irrigation area outside. 	Rating system: Living Building + LEED Total catchment area:6,880ft2 Total rainwater harvesting: 126,290 gallons/year **No information regarding Models for sizing or methods for evaluation*
9	Democritus University of Thrace, Greece	**System Description:** RWH system implemented at Duth Campus, Democritus University of Thrace, Greece • **Capturing mechanism:** A rainwater harvesting system consisting of a roof, horizontal gutters and down drains that flow into a polyethylene storage tank was installed. Gutters made of zinc and down drains of zinc or PVC with special plumbing arrangements for toilet flushing. The harvested water is used for indoor and outdoor uses including toilet flushing, washing machine, for car washing and for garden watering. This system is also installed with a first-flush system to improve rainwater physicochemical quality. 	Rating system: NA **No information regarding Models for sizing or methods for evaluation, and RW treatment systems*

10	Barone Campus, Fair Field University, USA	**System Description:** The team designed a system based on variable concepts, intended for reducing water consumption, storm water runoff, and most importantly for implementing green infrastructure on campus sites for student learning (Reckinger, Bocchino, Jackowitz, & Perry, 2014, p. 133). • **Tank System Design:** A 1,100-gallon polyethylene tank, using Polyvinyl Chloride (PVC) piping connected to a rain leader, redirect rainwater to the inlet of the tank. The system's current and functioning design fills the tank with the town's water supply to keep the tank filled at 200 gallons at all times. Once the tank has accumulated water, the current irrigation pump will pump the water out of the tank. This is done by using a single direction flow controller installed inside the PVC piping that runs from the tank exit to the pump inlet. Utilizing gravity, the pipe provides an exit for any sediment that may collect at the bottom of the tank by opening the discharge valve. The discharge valve and hose attachment prevent sediment and other contaminants from building up. Once the float valve falls below the 200-gallon mark, it triggers the town water to fill the tank to 200 gallons. The ball valves open and close the various pipes to divert or stop the water. The solenoid valve is triggered by the float valve to ensure that the tank is filled with a minimum of 200 gallons of water. The overflow pipe is connected to the top of the tank if the solenoid valve fails and the tank overflow (Reckinger, Bocchino, Jackowitz, & Perry, 2014, p. 131). 	Rating system: NA Total Catchment Area: 200 acres of land (suburban setting) Total Rain Harvested water: 449,000 gallons/yr (since installation in 2010) Total water use: approximately 2,853,000 gallons yearly Total yearly Savings: $10,014
11	Horticulture Services Building (Macdonald Campus, Sainte-Anne-de-Bellevue, QC, Canada	**System Description:** The design includes steps for collection, filtering, storage, and delivery for irrigation without chemical treatments. Collected rainwater is naturally soft water without minerals, chlorine, fluoride, and other chemicals, good for watering greenhouses and nearby garden areas on campus. • **Tank Design**: Each tank is connected in series to other identical tanks placed at decreasing elevations. Gravitational pull and the accumulated head pressure in each tank govern the flow of water between the tanks. Tanks are connected via 4inch PVC pipes, with 4inch valves and overflows to control the inflow and outflow of water. These overflows help discharge water into the surroundings.	Rating System: NA Total Roof area: 610m2 (Catchment area) System Design: weather data used for tank sizing, System designed to withstand a 1 in 10-year storm event

		- **Overflow Control:** The overflows in the first two tanks are combined with a "T-junction" and the water is discharged into the nearby vegetation, whereas the 3rd Tank is connected to a 1horsepower centrifugal water pump that supplies irrigation water to both greenhouses (@flowrate of 22gal/min and 40psi of pressure). This pump is automatic and helps meet peak irrigation needs (Islam et al. 2013, p. 222).  *Figure 9 Site Layout Diagram showing RW collection points (Islam, Lefsrud, Adamowski, Bissonnette, & Busgang, 2013, p. 222)* RW Collection Filtering Storage Tanks Used for Gardening	**No information regarding Models for sizing or methods for evaluation, neither for treatment and filtration systems*
12	Adama Science and Technology University (ASTU) Ethiopia	**System Description:** Demonstration project used as training site for one-day seminar gathering information about social perception of RWH systems. - **Capturing mechanism:** The system includes a collection roof, downpipes, a first flush tank, a storage tank, a calm inlet, and drainage pipes designed to satisfy the quantity and quality of water that the building needs. Applying particle separation theory, a first flush tank, a calm inlet, and horizontal storage tanks are used in the design to improve water quality. The first flush tank collected the first runoff, which is used to wash dirt from the roof after the long dry season. In order to divert water from the first flush tank to the storage tank once the first flush tank is full, the first flush tank was constructed from polyvinyl chloride (PVC) with a floating ball that closes the top tip of the tank. Besides these components, the system has two 4 m3 horizontal storage tanks. These tanks were selected to give enough settling time and area for suspended particles not collected by the first flush tank. Finally, a drainage pipe was installed to wash out settled particles when cleaning the tank (Temesgen, Han, Park, & Kim, p. 5207). Catchment Gutter & Downspouts First Flush Storage Tank Calm Inlet Storage Tank	Rating System: NA Total catchment area (roof): 1130 m2 **No information regarding methods & Models for sizing*

13	Dormitory complex at Seoul National University (SNU) in Korea	**System Description:** In addition to coordinating water balance-based design method for RWH systems with operational data from the RWH system (Mun & Han, 2012, p. 148). the system suggests a range of Design Parameters that can be used to improve RWH system design and operation. - **Capturing mechanism:** The harvested rainwater is passed through a filter before collection in a 200-ton storage tank, from which it is supplied to dormitories for toilet flushing. This supply was monitored and measured from 2004 to 2007, during this period a combination of 8 m3 (tap water) + 120 m3 (rainwater) = 208 m was implemented with recorded supply for toilet flushing as 9364, 3961 and 5403 m3, respectively. The harvesting efficiency replaced 50% of the 6.6 tons of water required daily for the dormitory's toilet flushing and gardening needs.	Rating System: NA Total Catchment Area (Roof): 2098 m^2 **No information regarding Models for sizing or methods for evaluation*
			
14	Figtree Place, University of Newcastle, Australia	**System Description:** RWH implemented at a Bus Station to decontaminate onsite pollutants, reduce downstream floods and meet 50% in-house needs for hot water & toilet flushing, 100% domestic irrigation needs, and 100% bus-washing water demands on site. - **Capturing mechanism:** Roof top collected rainwater flows through a ``first-flush'' pit before reaching a storage tank. Pumps supply this water for hot water systems and toilet flushing. These pumps are designed as fail-safe systems with a second pump to operate in case of failure and a solenoid to switch between tank supply and mains supply if electricity supply is interrupted or if a low water level is detected in the rain tank (Coombes et al. 2000, p. 336). - **Tank Design:** Reinforced concrete underground rainwater tanks are used fitted with first flush diversion devices. Each tank contains an inlet from a first-flush pit, a clean-out chamber for sludge removal, a low water level monitor, an outlet for domestic supply and a pipe conveying overflow to a recharge trench. - **Overflow Control:** An overflow condition is directed to a gravel trench which recharges ground aquifer. These trenches are located on both the front and the back sides of 19 homes on site. Additionally, all runoff from the paved area (carriageway and driveways) is diverted to a central Detention Basin Recharge Area, which is a grass depression with gravel enclosed in geofabric.	Rating System: NA Total Catchment area: 3 hectares Total water savings of Figtree Place: 60% (in comparison to its conventional equivalent) Total water saving (residences) 1190 kl/annum Irrigation saving: 830 kl/annum Bus-washing saving: 1700 kl/annum overall savings: $3422 per annum

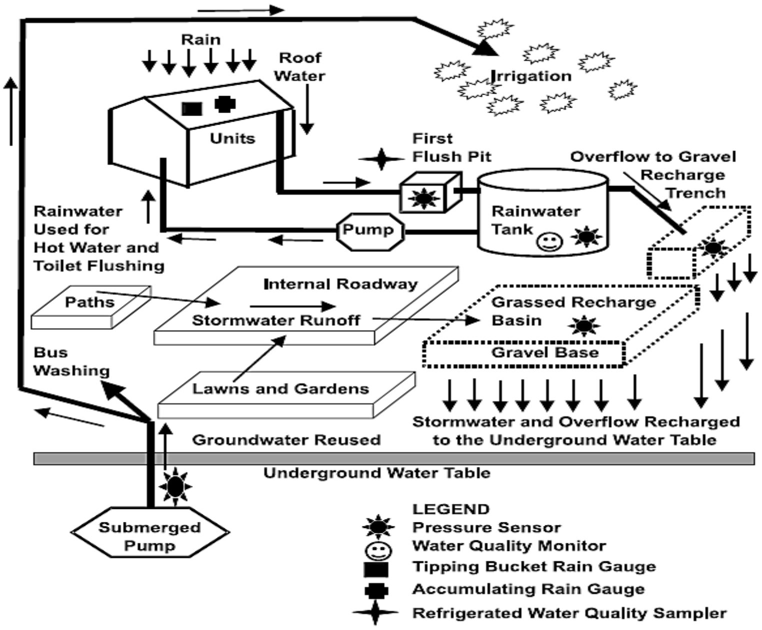


Figure 10 Water Sensitive Design Concept (Coombes, Argue, & Kuczera, 2000, p. 339)

- **Water treatment** includes flocculation, settlement and bio-reaction in rainwater tanks

**No information regarding Models for sizing or methods for evaluation*

6

SUMMARY AND RECOMMENDATIONS

This Chapter brings together the summary and recommendations based on the understanding developed from all previous chapters. It highlights the key aspects of rainwater harvesting system design and applications, such as collection points and receiving ends. Additionally, it discusses future research opportunities and emphasizes the importance of experiential learning. In addition to discussing RWH system compliance with different green building certification systems, the chapter provides recommendations for exploring the impact of these certification systems on the adoption of RWH technology.

RWH is emphasized in this book as a key to sustainable development and a means of addressing climate change and water scarcity. The book offers a thorough understanding of how RWH is promoted at the regional level using various incentives, law enforcement, and government campaigns. These aspects are examined in chapter 2 which highlights the social components and legal governance aspects that promote RWH applications at a regional scale. This chapter serves as an effective guide for transforming these regional scale applications tailored to the local context and governing their wider social acceptability for green building applications. On the other hand, the technical landscape concerned with RWH system design offers insights into the environmental and design components that guide the operational efficiency of RWH systems. It is these components that guide technological innovation, future development, and justify RWH for green building applications. These components described in chapter 3 captures the technical landscape involved in RWH system implementation. Chapter 4 discusses quantitative and qualitative assessments, providing readers with methods and models to assess rainwater harvesting systems' feasibility and effectiveness. This chapter outlines the barriers, challenges opportunities and prospects involved in the development of rainwater systems, thus representing its design landscape. The comparative analysis presented in chapter 5 compares and analyzes the relevant literature and application landscapes related to RWH. This chapter provides real-world examples using fourteen case studies that guide researchers and technology developers, as well as inform designers, green building practitioners and policy makers, and expand the discourse on how rainwater harvesting can be utilized to create sustainable environments and green practices.

A detailed analysis of chapters 2, 3, 4 and 5 assists in understanding the dynamics involved in RWH strategies. Components involved, approaches to operational efficiencies, assessment methods and models for quantitative assessments and the soft factors influencing qualitative assessment, constitute requirements for RWH system design. Based on the real-world examples presented in chapter 5 using fourteen case studies, it is identified that the majority of these implemented actual design cases have made no claims and provided no evidence of following any models or methods for sizing and evaluation as identified through the design challenges in chapter 4 and literature landscape in chapter 5 outlining significant researches in RWH. Except for the case study of Innovation Centre Phase 2 Building Streatham campus at the University of Exeter in UK, using a Rain cycle modelling tool and a method for tank sizing. This model and method are discussed in chapter 5 under the design landscape of RWH. These observations reaffirm the gap between RWH research literature and actual design implementations.

Based on the understanding developed from each of these chapters, the application landscape capturing best practices from 14 Case Studies is further analyzed to summarize the findings. As a result, the final summary is categorized under collection points, receiving ends, experiential learning aspects, and scale of intervention addressing RWH applications. This summary is supported by the rainwater handling mechanism patterns generated in Table3 of chapter 5 and highlight the physical factors supporting quantitative assessments discussed in chapter4. Each of these headings highlight offers insights into best practices, innovative applications and future directions. These are discussed as follows:

- Collecting point: The design applications analysis represents the whole designed life cycle of onsite rainwater from its point of capture to its receiving ends. All of the selected case studies have a common and consistent practice at point of capture through collection or catchment systems. This is explained with a detailed explanation attributed to this stage but beyond this all the sites have different systems and the stages involved in rainwater handling mechanism varies. For example, some have implemented conveyance systems after catchment, some use filtration systems, some use storage systems, and some have implemented solar panels before conveyance systems. Additionally, there are examples where filtration systems are positioned before conveyance systems, indicating an erratic practice. These observations project a huge variation in the hierarchy of implementations among systems between the point of capture and receiving ends as suggested by Gikas et al. (2012).

- Receiving ends: The analysis identifies a lot of diversity at the receiving end of rainwater harvesting systems. The processes and systems implemented on site vary in accordance with the end use designated for rainwater. Four case studies utilize harvested rainwater for flushing & other non-potable uses onsite including the example from the University of Exeter in UK, University of Kebangsaan in Malaysia, Democritus University of Thrace in Greece, and the dormitory complex at Seoul National University (SNU) in Korea. Three case studies offer systems for collecting rainwater in storage and holding tanks for later distribution on site including Emory

University and Fair Field University in USA, and the Adama Science and Technology University (ASTU) in Ethiopia. There are two examples utilizing rainwater only for irrigation purposes, namely Horticulture Services Building (Macdonald Campus, Sainte-Anne-de-Bellevue, QC, Canada and Mahasarakham University, Khamriang Campus, Thailand. Additionally, two examples that qualify as net-zero water facilities, are University of North Carolina at Chapel Hill and Bullitt Centre at University of Washington in USA. These facilities present an innovative scenario of campus sites becoming net-zero and water positive after fulfilling their water demands, which offers a promising area for further research. Additionally, case studies like CIRS Building at University of British Columbia in Canada fulfill domestic and irrigation demands as well as ground aquifer recharge, and the Figtree Place experimental site with Newcastle university in Australia, meets flushing demands besides ground recharging. Both of these examples display complex parallel systems recharging the aquifer and fulfilling other water demands on site. These are represented as parallel systems using purple color in table 3 under chapter 5. Using parallel systems such as recharging trenches, living roofs, green walls, bioswales, etc. is another promising area for future research.

- Experiential learning aspect: During the case study analysis in chapter 5, several components of the rainwater handling mechanism were identified. As a result of this identification, Emory University in suburban Georgia was identified with an innovative strategy. In its water supply system, the university uses dyed blue water to indicate that nonpotable rainwater is used. This design intervention is in addition to the use of runnels as demonstration elements in their landscape design. Both these interventions provide visual cues that remind students and faculty members of the university's commitment to sustainable practices. It also helps to educate the community on water conservation initiatives and highlight the importance of rainwater management. Additionally, examples like Adama Science and Technology University (ASTU) in Ethiopia, Figtree Place in Australia, and Peiyang Campus in China demonstrate low-impact development (LID) practices. These LID practices include a vegetative swale, sunken green space, and permeable pavement. These practices are used for public learning, social engagement and encouragement towards the rainwater harvesting strategy. Such examples on higher education campuses strengthen water sustainability concepts. Future applications should consider combining demonstration elements with parallel systems and net-zero applications to achieve a net-positive water management scenario. This will drive community and academic engagement, while also creating a symbol of climate action on campus. This recommendation underscores the need for educational awareness and creates an interactive and tangible way to demonstrate water sustainability. The interactive demonstration can be used as an educational tool for other organizations, allowing them to gain a deeper understanding of water sustainability and open up opportunities for future research.

- Scale of intervention: Different scales of intervention were observed in selected case studies. This variation explains the extent and details involved in rainwater harvesting systems' actual implementation on site. The application of the system boundary concept can be seen at Mahasarakham University's Khamriang Campus in Thailand. This eliminates rainwater systems from dormitory areas because of domestic activity, despite accounting for 60% of its total supply. Tianjin University, Peiyang Campus, China uses a multilevel ring system carrying multiple rainwater mechanisms within one site. This presents an innovative case of multilevel ring application. However, there is no substantial evidence regarding its capturing mechanisms and the systems involved in its rainwater design life cycle. On the other hand, the CIRS Building at the University of British Columbia, for example, offers a compelling case for consideration, as it operates at both the building and campus scale.

It is also observed that the selected case studies offer broader insights into building scale interventions than campus scale interventions. These interventions represent conventional as well as innovative design applications. Additionally, these case studies reflect compliance with Building Research Establishment Environmental Assessment Methodology (BREEAM), UI Greenmetric World University Ranking system, Sustainability Tracking, Assessment & Rating System (STAR), Living Building Challenge (LBC) and Leadership in Energy and Environmental Design

(LEED) certification systems. It is also noteworthy that net-zero water applications are only identified in case studies certified with both LEED and LBC systems. Therefore, it would be interesting to see how this combination of certification systems affects the application and design landscape of RWH systems in the future. Given the fact that this field is evolving, further research is strongly recommended to analyze the impact of these certification systems on RWH technology adoption. This will explore how different incentives can be used to encourage the use of RWH technologies for green building applications and their social acceptability. As a result, designers, researchers, green building practitioners and policy makers should consider how to create an environment enabling RWH technologies to be adopted on a larger scale. Moreover, research should also focus on developing effective strategies for the implementation of RWH systems in different contexts and identify the possibilities for incentives that will motivate people to adopt RWH technologies. It would also be helpful to use experiential learning aspects similar to those found at Bullitt center and Emory university in the USA to raise awareness and educate people about RWH systems. Through these learning aspects, the social value and technological aspects of RWH systems are underlined, and the significance of RWH systems can be effortlessly and naturally articulated.

7

APPENDIX

LIST OF TABLES

LIST OF FIGURES

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