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Resilient Water Management Strategies in Urban Settings

Innovations in Decentralized Water Infrastructure Systems

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ISSN 2364-6934 ISSN 2364-8198 (electronic)
Springer Water
ISBN 978-3-030-95843-5 ISBN 978-3-030-95844-2 (eBook)
https://doi.org/10.1007/978-3-030-95844-2

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For

Satoru, Camina, Taesha

Ana Soeun, Siwoo

Hana, Max, Malcolm, Liam

The 21st Century Generation Who Are
Shaping the Future of the Planet Earth!

Preface

Worldwide, over 56% of the population lives in urban areas; in the USA, Europe, and many Central and South American countries, the percentage is over 80%. It is also important to note nearly 40% of the world population and 30% of the US population live in coastal regions, which are highly urbanized. Urbanized areas around the world are characterized by the existence of significant paved areas/buildings, high population growth and, consequently, high water demand. It is noted that by the year 2025, about 70% of the world's population will likely suffer from problems associated with water scarcity mostly caused by anthropogenic factors. Furthermore, high water demand in urban areas has required considerable use of surface and groundwater resources, which are mostly imported from outside of the urban boundaries. Consequences of high water demand associated with urbanization include significant impact on surface water ecosystems due to combined effects of high water withdrawal, urban stormwater runoff discharge, groundwater depletion in general, saltwater intrusion in coastal aquifers due to increased groundwater withdrawal, and reduced natural infiltration to aquifer system. The changing climate has caused significant uncertainty in urban water management and sustainability.

The sustainability and resilience of urban water infrastructure—potable water supplies, wastewater treatment and discharge, and urban stormwater runoff control—have become a major concern in the twenty-first century. There is a significant need for a paradigm shift toward resilient water management strategies to cope effectively with the existing and emerging problems, such as climate change. The new paradigm will consist of holistic, resilient, and cross-disciplinary approaches that integrate the interconnectedness of natural and engineered systems and smart technologies into urban water infrastructure system planning, design, operations, and management. The major component of the envisioned holistic and resilient strategy is by employing Decentralized Green Water-Infrastructure Systems (DGWIS) in urban settings. The holistic system will be based on utilizing/reusing locally available alternative water sources—captured rainwater, graywater, stormwater runoff, wastewater, saltwater/brackish water—and locally available renewable energy sources—solar, wind, micro-hydro power, geothermal, biomass, and other new emerging techniques. Furthermore, the system planning and design will consider Food-Energy-Water (FEW) nexus in order to enhance food security and community development in urban settings.

This volume contains ten chapters. The central theme of this volume is innovations in DGWIS. This volume documents innovative approaches and case studies of decentralized green water infrastructure around the world. Specific topics include: (1) uses of locally available alternative water sources in urban settings; (2) smart technologies applied to urban water management system; (3); integrating locally available renewable energy use in urban water management system; (4) food-water-energy nexus in urban environments; and (5) disaster mitigation strategies in urban environments. The book chapter sequence documents global case studies and prospects (Chaps. 1–7) followed by challenges facing decentralized water infrastructure (Chaps. 8–10).

In chapter "Decentralized Green Water-Infrastructure Systems: Resilient and Sustainable Management Strategies for Building Water Systems", Lee, Younos, and Parece (editors of this volume) discuss the challenges facing urban water infrastructure and propose a conceptual framework for a DGWIS for large buildings (industrial, commercial, government, and office) that integrates locally available water sources (rainwater and graywater) with renewable local energy sources (solar and wind) for building water treatment and distribution. Authors conclude that the DGWIS can function as a standalone infrastructure element, but also could be an attractive option for high-density population urban areas where water scarcity is a serious issue, particularly for large buildings such as shopping centers, high-rise buildings, hotels, and dormitories.

In chapter "Advances in Wastewater Reclamation and Reuse Technologies: Selected Case Study Projects in Japan", Takeuchi and Tanaka discuss the concept of reclaimed water potential as a water resource, as well as a heat and energy source. They introduce two commercial buildings in Osaka where advanced environmental technologies such as an onsite water reclamation system, a biogas power generation system, and a heat recovering system from reclaimed water have been installed. Authors conclude that by using reclaimed water as a water resource, as well as heat and energy source, these buildings can successfully save the amount of tap water and energy consumption required for hot water supply and heating and cooling systems in the facilities.

In chapter "Smart Decentralized Water Systems in South Korea", Chae and Lee discuss integrated water resource management practices focusing on smart decentralized water systems in South Korea. Smart Decentralized Water Management (SDWM) connects multiple alternative water resources within individual buildings and continuously balances their utilization to enhance self-efficiency and build resilience. It also supports more efficient water supply portfolio/transfer/trade within district water networks. Authors conclude that SDWM will play an important role in augmenting the efficiency of integrated water management planning and operation through closer interactions among stakeholders and informed decision-making at all levels.

In chapter "Open Datasets and IoT Sensors for Residential Water Demand Monitoring at the End-Use Level: A Pilot Study Site in Naples (Italy)" Di Mauro et al. discuss the results of their study on water end use demand using Internet of Things (IoT) technology for the fixtures of a specific single-family apartment. They discuss insights for new perspectives and further research related to the importance of high-resolution data to improve water demand-side management. This case study represents a first step toward a decentralized monitoring water system aimed to increase the user awareness and to promote water conservation.

In chapter "Maximizing the Benefits of Rainwater Harvesting Systems: Review and Analysis of Selected Case Study Examples", Gee and Sojka present an analysis of the available literature on case studies of several rainwater harvesting systems—a commercial system where rainwater is used for potable purposes, a residential community that incorporates rainwater harvesting and on-site wastewater treatment, and rainwater use on a university campus—to identify key features such as frequency and consistency of water use, appropriate tank sizing that maximizes potable water use reduction, financial savings, and environmental benefits of rainwater harvesting systems.

In chapter "Pathway to Scaling up Onsite Non-potable Water Systems", Kehoe and Nokhoudian," focus on localized solutions to treating water onsite for reuse on a small scale using numerous examples from around the world. They argue that utilities can enable and allow decentralized, neighborhood-scale water treatment systems by creating shared responsibility and ownership of managing water resources within the community. They conclude that opportunities exist for localized systems to not only produce non-potable water but also become effective vehicles for resource recovery, tapping into the potential for thermal heat, nutrient and biosolids recovery, as well as a potential source of drinking water.

In chapter "Integrated Water Management for a Sustainable Office Building", Thompson, Porter, and Stenkamp introduce the Bullitt Center in Seattle (US). The Bullitt Center was designed to meet the "Living Building Challenge," which includes beauty, energy, health and happiness, materials, place, and water. In the chapter, authors focus on the potable water, graywater, and blackwater treatments systems, discuss regulatory issues, and present performance data for the integrated water management system in this building. The chapter authors conclude that the decentralized water and wastewater treatment systems could meet or exceed regulatory standards. They also discuss the strong potential of solar power use in rainy Seattle and the successful story of operating the "Living Building."

In chapter "Examining Drivers and Barriers of Urban Water Reuse Through Case Studies in Oklahoma, USA", Wade examines water reuse issues in the state of Oklahoma, a drought-prone region with no precedent of potable reuse. Author discusses how water reuse projects occur and what determines their success. The author argues that the success of municipal wastewater reuse is often dependent on public perception and willingness to use recycled water. Psychological reactions of disgust create the primary barrier to this success. The author concludes that community education initiatives can decrease disgust and increase willingness to support water reuse projects.

In chapter "The Impact of Location on Decentralized Water Use in Urban Agriculture", Parece presents the results of four case studies (two in wet regions and two in semi-arid regions, USA) that analyze rainwater harvesting's ability to irrigate urban agriculture, save energy, and reduce greenhouse gas emissions. Study results show that location does matter because rainfall directly affects the ability for cities in semi-arid regions to harvest rainfall for irrigation. A significant difference is apparent in rainwater availability between arid and wet regions of the USA because of the significantly lower amount of precipitation in arid regions, as well as the number of days in arid regions where there is insufficient rainfall to produce runoff. Author stressed that even in arid regions, rainwater harvesting has the potential to lower potable water use, save energy, and reduce greenhouse gas emissions.

In chapter "Water Sector Reconstruction for Post-disaster Housing Settlements: A Tale of Two Governance Models", Juran, Oliver and Read examine outcomes of the two governance models in the adjacent territories of Nagapattinam District (Tamil Nadu) and Karaikal District (Puducherry), India through the lens of water by linking primary data to the theoretical literature. The study outcome, which is incongruent with many theories on governance, development, and project management, is problematized and discussed in depth to better integrate the water sector into disaster and urban planning.

Chapters presented in this volume provide a cross-disciplinary knowledge-base for smart and futuristic water management in urban settings, and a significant opportunity for sharing smart and decentralized water management strategies at the local, regional and global level. We hope this volume serves as a reference source for water resources and environmental science graduate students and researchers, as well as classroom instruction for those interested in holistic and resilient water management practices. Equally, we hope this volume serves as a valuable guide for practice engineers and landscape planners who consider integrating decentralized water infrastructure in planning and design of sustainable and resilient urban water management systems.

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Contents

Decentralized Green Water-Infrastructure Systems: Resilient and Sustainable Management Strategies for Building Water Systems

Juneseok Lee, Tamim Younos, and Tammy E. Parece

Abstract In this chapter, we draw attention to urban cities' building water systems management strategies, focusing on both sustainability and resilience of water and energy resources. Rainwater harvesting and graywater recycling have long been identified as alternative water sources for the sustainable management of water resources. We present a conceptual framework for a Decentralized Green Water-Infrastructure System (DGWIS) for large buildings (industrial, commercial, government, and office) that integrates locally available water sources (rainwater and graywater) with renewable local energy sources (solar and wind) to support water treatment and distribution. The optimization framework for DGWIS introduced in this chapter will quantify the energy and water potentially saved. DGWIS can function as a standalone infrastructure element and could also be an attractive option for high density population urban areas where water scarcity is a serious issue, particularly for large buildings such as shopping centers, high-rise buildings, hotels and dormitories.

Keywords Decentralized water infrastructure · Graywater · Sustainability · Resilience · Rainwater harvesting

1 Introduction

Increasing urbanization and high density populations, aging built infrastructure, measures needed to mitigate the effects of climate change, resource shortages

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T. Younos et al. (eds.), *Resilient Water Management Strategies in Urban Settings*,
Springer Water, https://doi.org/10.1007/978-3-030-95844-2_1

affecting both water and energy supplies and their competitive uses, and environmental concerns with emerging contaminants are all issues we encounter in our daily lives, and are a vital part of planning for future generations. Solutions to these challenges require thoughtful sustainability- and resilience-oriented strategies that include a careful consideration of socioeconomic and quality of life issues and cultural and social norms, in addition to scientific and technological considerations. The National Academy of Engineering announced 14 major challenges that will need to be addressed in the twenty-first century, many of which are closely linked to water and energy resources [1]. The National Academies of Sciences, Engineering, and Medicine recently addressed energy-water nexus issues intensively. While other priority issues can, and should, be addressed, water and energy are paramount, particularly as countries around the world continue to develop and use ever more water and energy [2].

At present, 80.7% of the U.S. population live in urban areas [3]. The strong correlation between urban development and population growth is driving the continuing deterioration of natural resources, largely due to the associated need to expand/replace/repair urban infrastructure. According to the United Nations, the urban population in 2018 accounted for 55% of total world population, up from just 34% in 1960. Global urban population is growing rapidly, especially in developing countries [4].

The twenty-first century has brought significant issues for urban water management. For example, in the aftermath of the September 11 terrorist attack in New York City in 2001, water security and cybersecurity became a major consideration. The impact of climate change on water and energy resources and their infrastructure management and policy has also become a prominent issue, and this will continue to attract attention. The ongoing Flint Michigan Water Crisis in the U.S., wildfire issues, and the unexpected global COVID-19 pandemic have exposed a diverse range of preexisting water and energy vulnerabilities, management issues, and infrastructure problems not only in the U.S. but across the world [5–8]. This is likely to be a particularly serious issue for low-income households and communities from an environmental justice perspective [9].

The concept of *sustainability*, which used to be closely associated with the design of products and systems, has now become a mainstream term applied to any domain [10]. *Resiliency*, namely the ability to return to business as usual after a disaster has occurred, has also become a critical core design objective for water systems. Consider the problems experienced due to wildfires in California, and elsewhere. The 2018 Camp Fire created a significant drinking water quality problem in the local water mains in the town of Paradise, California, USA due to benzene contamination when the plastic pipelines in their water distribution systems melted [7, 8]. This highlights the importance of the way municipal infrastructure elements are interconnected and how they function after a disaster. It is critical that today's engineers are well versed in this multi-dimensional system-wide view with *resilience and sustainability as a central objective*. In this chapter, we draw attention to urban cities' building water systems management strategies, focusing on both *sustainability* and *resilience*.

2 Emerging Issues in Water Resources and Infrastructure

The demand for water continues to rise due to the combined effects of urban development and population growth, leading to the need to significantly expand and enhance the water infrastructure in urban areas around the world [11, 12]. The U.S. is no exception, with municipalities around the country addressing critical and urgent issues related to water scarcity, promoting water efficiency, improving water quality, reducing water related energy use, and renovating our deteriorating water infrastructure. Significant impacts that threaten our *water resources* include, but are not limited to: (1) declining groundwater tables due to the combined effects of excessive groundwater withdrawal and reduced groundwater recharge (i.e., reduced infiltration due to urbanization); (2) saltwater intrusion into coastal aquifers caused by pressure imbalances affecting the interfaces between freshwater aquifers and saltwater due to declining groundwater tables; (3) widespread pollution of surface water—rivers/tributaries and lakes—and ecosystem degradation caused by both point and non-point sources of pollution, particularly that caused by urban stormwater runoff [13]. It's estimated that about 10 trillion gallons of untreated urban stormwater runoff enters U.S. rivers and waterways every year [14].

There are also a number of other emerging problems associated with our aging urban water infrastructure [13]: (1) significant water loss (i.e. non-revenue water) from pipeline breaks/leakages [15–20]; (2) contaminant intrusion into drinking water systems via old and deteriorating water distribution systems [21]; (3) significant energy loss at the distribution systems level [22–24]; (4) the unintended consequences of water conservation on water quality [25, 26]; (5) emerging contaminants—pharmaceuticals/hormones and chemical byproducts [27]; and (6) cyber security threats to our large drinking water systems [28]. These issues have led to the American Society of Civil Engineers (ASCE)'s recent C+ rating for the U.S. drinking water/infrastructure [29], a borderline failing grade.

2.1 Twentieth Century Water Infrastructure

Today's water-infrastructure planning and design are largely based on historical twentieth century goals, and are thus limited by the level of technical knowledge at the time [13]. These infrastructure elements include the *potable water infrastructure*, which includes water source development, water treatment and delivery, and premise plumbing systems; the *wastewater management infrastructure*, namely wastewater (domestic/industrial) drainage, treatment, and discharge network; and the *urban stormwater drainage infrastructure*, consisting of the pipe network that removes surface runoff from paved surfaces and building rooftops. The primary characteristics of modern water-infrastructure systems can be summarized as follows: (1) centralized and large-scale systems that serve large areas and populations; (2) high volumes of wastewater are generated; (3) a strong dependence on a myriad of pipeline systems that deliver potable water to consumers and drainage pipe networks that transport wastewater and stormwater runoff away from urban population centers; and (4) significant amounts of fossil-fuel based energy are needed for water distribution, discharge, and treatment [13].

2.2 New Paradigm for the Twenty First Century

Based on our observations from both the research community and water industry trends, Table 1 compares the major characteristics, design philosophy, and goals for urban water infrastructure systems in the twentieth and twenty-first centuries [13]. These twenty-first century infrastructure and quality of life goals and challenges demand a major paradigm shift, emphasizing sustainability and resilience as core objectives, if we are to cope effectively with critical emerging problems.

Table 1 Infrastructure and quality of life in urban environments (Adopted from [13])

Infrastructure	Twentieth century goals	Twenty-first century goals
Drinking water distribution network	Water treatment plants, available tap water in homes and buildings	Sustainable (i.e., water-energy nexus), resilient, and safe tap water in homes and buildings for public safety
Wastewater systems and treatment network	Sewer disposal pipes for homes/buildings, wastewater treatment	Zero pollutant discharge to natural waters and ecosystem preservation
Stormwater management network	Municipal separate storm sewer system (MS4)	Low impact development, best management practices, green technologies, urban aesthetics
Water source development	Build dams and reservoirs Excessive groundwater withdrawal	Use alternatives: sustainable and resilient water sources: rainwater harvesting, stormwater runoff, wastewater reuse; diverse portfolio including desalination and water reuse
Housing/buildings	Affordability	Energy/water use efficiency
Energy	Fossil-fuel imported from outside city boundaries	Shift toward using renewable energy resources
Food	Food imported from outside city boundaries	organic food products, urban agriculture
Emerging problems in urban water management	–	Emerging contaminants (e.g., PFAS, OPPPs, etc.) anthropogenic drought/flood, wildfire, adopting to climate change, cyber security

In this chapter, we argue that a holistic approach can best be realized by incorporating small-scale decentralized water and energy production systems into buildings in urban settings. Lee et al. [30] introduced a framework for *Decentralized Green Water-Infrastructure Systems* (*DGWIS*) that would do just that. Their framework provides a solid foundation for a paradigm shift towards water and energy sustainability, and resilience in urban environments. Decentralization maximizes the development and use of both locally available water resources—captured rainwater, stormwater runoff, and graywater—and locally available renewable energy resources—solar, wind, micro-hydro power, geothermal, and biomass—for local consumption. Food security, as well as equity and environmental justice in urban areas, is another emerging issue. Integrating decentralized urban food production systems into the water and energy nexus can be an innovative solution that supports sustainable living initiatives and resilient community development in urban areas. More information about food security in urban environments can be found in Chap. 9.

We expect that the DGWIS will help chart a new paradigm shift in urban water and energy management by optimizing the potential for capturing and reusing rainwater and graywater to augment domestic water supplies, while reducing water related fossil-fuel energy usage by adopting renewable energy technologies in urban buildings. Critical components of the DGWIS are discussed in the following sections.

3 Rainwater Harvesting

The U.S. Green Building Council (USGBC) has developed a Green Building Rating System known as the Leadership in Energy and Environmental Design (LEED) to encourage the global adoption of sustainable green building development practices [31]. The way we provide, distribute, and use energy and water in buildings are key elements of green building design. Commercial and government buildings consume significant amounts of potable water, which is supplied through municipal water systems. It is important to bear in mind that water supply and distribution are very energy intensive processes due to water's high specific weight and density. To make matters worse, more than 65% of the high-quality potable water produced is consumed for *non-potable uses such as flushing toilets*, *washing cars and landscape irrigation.* Adopting and promoting water efficient strategies could therefore have a significant impact. One option could be to incorporate Rainwater Harvesting (RWH) into such systems to deliver a major portion of the water sources that buildings use for non-potable purposes in a rational manner. In this section, we specifically discuss futuristic applications and the potential challenges of RWH, as a critical DGWIS component that could make a significant contribution toward an integrated and resilient water management approach in urban settings [32].

In urban areas, 30–40% of the impervious area consists of building rooftops. As an example, a 100 m^2 rooftop area can collect one cubic meter of water per 1.0 cm of rainfall. In the absence of a rainwater harvesting system, the rainwater from urban rooftops is usually discharged straight to stormwater drainage network systems and is thus a major source of surface water pollution [23, 24, 32]. Diverting this rooftop rainwater for non-potable uses reduces stormwater runoff to the drainage networks and can thus represent a best management practice (BMP) for stormwater runoff control.

It is possible for up to 80% of the rainwater falling on urban rooftops (after initial abstractions such as depression storage, evaporation and splashing) to be captured and made available for various indoor and outdoor uses [32]. Recent technological advances in pre-filtration, first-flush design, and the availability of small-scale water treatment units suggest that captured rainwater could also be more widely used as a potable water source [32]. Advances in small-scale and packaged water treatment technologies such as reverse osmosis, carbon filtration, and UV disinfection devices allow small-scale decentralized water production systems to be installed as satellite systems within buildings to treat and use locally available water sources, including captured rainwater and reclaimed graywater. A typical small-scale packaged water treatment system with a capacity of up to 50,000 L per day can easily be configured as a water treatment unit at the individual building level in urban areas [33].

There is a significant potential for self-sufficiency in water use, with a good example being the ReNEWW house in West Lafayette, Indiana, USA, which has the capacity to switch the drinking water source from municipal to rainwater harvesting systems that include filtration/UV treatment. The Los Angeles Waterboard's stormwater management rules now require all new and redevelopment construction projects to capture a portion of storm runoff on-site; the City of Long Beach, California, USA has a similar requirement for home remodels. Figure 1 shows the rain barrel installed to satisfy this requirement for a project in Long Beach. The rain barrel installed has a capacity of 1000 L, but is only about 0.9 m tall and would fits nicely in the average U.S. backyard. Another example, described in more detail in Chap. 7, utilized RWH for potable water use for an office building in Seattle, WA, USA (Thompson and Porter 2020). Chapter 6 also discusses the use of RWH in San Francisco, CA, USA.

3.1 RWH for Potable Use

Single-home or small-scale RWH for potable use is common in small rural communities, often being used in conjunction with private water wells, where a conventional water supply infrastructure would be cost-prohibitive or where sufficient water resources are simply not available. Potable use of rainwater in urban buildings is now a rapidly emerging concept. As mentioned earlier, there is a significant potential for rainwater to play a useful role for potable use in urban settings due to recent advances in small-scale water treatment technologies. However, it is important to note that RWH for potable use in high population buildings is considered a public water system and is, thus, required to comply with all the existing public water regulatory requirements [32]. See also Chaps. 2 and 3.

Fig. 1 Rain barrel in the city of Long Beach, CA (1,000 L; Courtesy of Dr. Suzanne Dallman, California State University Long Beach)

3.1.1 RWH for Energy Saving

Given that our existing urban water infrastructure depends on significant amounts of energy for water supply, distribution, and treatment, the use of locally available rainwater for non-potable uses can contribute to significant potable (utility) water and energy saving, thus reducing the carbon footprint of our water consumption. For example, Younos et al. reported a case study of a single school building in Washington DC; based on an average annual rainfall of 100 cm and assuming a 30% water loss from the system, the building's rooftop area (over 7700 m^2) has the potential to generate as much as 5.0×10^3 m^3/year of water that can be used for non-potable uses such as flushing toilets, urinals, and landscape irrigation in place of an equivalent volume of potable water from the public water supply system [34]. Based on estimates from standard electricity use data, 5.0×10^3 m^3/year water delivered by a municipal utility would require 3,145 kWh of electricity per year. The equivalent rainwater harvesting system requires just 776 kWh/year to provide the same volume of water for non-potable uses, resulting in a potential energy savings of 2,370 kWh/year and significantly reducing the school's carbon footprint. Obviously, the impact of RWH on energy and water saving would be significant if implemented on multiple buildings in urban settings.

3.1.2 RWH for Food Security

Mougeot defined urban agriculture as growing, processing, and distributing food and non-food products through plant cultivation and animal husbandry in and around cities [35]. Urban food production, which includes elements such as small backyard gardens, community gardens, greenhouses, orchards, food production on vacant inner-city lots, schoolyard gardens, restaurant-supported gardens, and rooftop gardens, is considered a major component of sustainable and green urban environments, as well as beneficial for food security and community development. The benefits of urban agriculture include: (1) conservation of water and energy resources; (2) environmental stewardship; (3) lower food cost; (4) job creation and economic development in low-income areas; (5) community revitalization; and (6) promoting public health through the fresh produce, improved nutrition, and opportunities for exercise urban agriculture provides [31]. A more comprehensive review of urban agriculture and its benefits can be found in Chap. 9.

3.1.3 RWH Challenges

There is potential for rainwater use at multiple scales, ranging from a single building through neighborhood communities to a regional level, which supports sustainable and resilient water management. However, there are barriers to the widespread adoption of RWH systems including, but not limited to [13]: (1) the design/maintenance guidelines/regulations are not consistent across state and local governments and are often ambiguous, to say the least, which is a significant impediment to those seeking to implement local, regional and nationwide RWH systems; (2) in some U.S. states, RWH is encouraged, but in others it is simply designated as legal with restrictions; (3) public perceptions of RWH operations and maintenance in urban settings are that it is quite cost-prohibitive. The results of recent Cost–Benefit Analysis exercises to quantify the true benefits of RWH in terms of environmental and financial impacts have shown that the results depend on climate factors and urban/local characteristics, with a number of articles showing the significant benefits gained by installing RWH [23, 24]. It has been also pointed out that that capturing the social benefits of RWH in a tangible manner remains challenging. See Chap. 5 for more details.

4 Graywater

Graywater is untreated domestic wastewater that has not been polluted by either toilet or kitchen (dishwasher) discharges [36]. Graywater includes wastewater from showers, bathtubs, bathroom sinks, washing machines and laundry sinks in buildings. Although some treatment may be needed, both RWH and graywater can be used for a range of non-potable uses including, but not limited to, irrigation, and toilet flushing, thus potentially providing crucial alternative water sources. Although both options may be applied at larger scales (i.e., regional/neighborhoods, multi-residential developments), in this chapter we focus on graywater use at the building level.

According to National Academy Press, the use of graywater for toilet flushing/laundry can reduce domestic potable water use by up to 36%. This number can increase for multi-residential buildings through economies of scale [37]. This not only enhances the diversity of a local water supply portfolio, but could also possibly help by relieving the load on wastewater treatment plants, especially in rapidly growing urban settings. Graywater could be more effective than RWH in arid regions due to the relatively steady sources involved, especially during dry seasons—for example, the state of California has very little rain during April to October. The benefits of graywater are more pronounced for residential, multi-residential, and some commercial buildings such as hotels, dormitories, laundromats, and fitness facilities [37].

4.1 Graywater Risk

As yet, there have been no reported ill effects on human health due to the use of graywater, but more research is needed to ensure public safety and health, and build citizen confidence in implementing graywater systems for onsite non-potable water uses (see Chap. 8 for more details on building citizen confidence). Human pathogens may occur in graywater, although the specific sources, types, concentrations, occurrence and timing can vary significantly. The organic matter present in graywater could also help accelerate microbiological growth under certain conditions, and sodium and other chemicals can impact the quality of graywater intended for irrigation and landscaping as not all plant types cope equally well [37]. Plants such as fruit trees, berries, and riparian plants do well with graywater irrigation, while root crops, drought-tolerant plants, and turf grass fail to thrive and the use of graywater for irrigation is not recommended [36].

If a house/building is using water softener, then a potassium-based treatment would be better than its sodium-based equivalent due to sodium's possible adverse environmental impact on plants. The long term buildup of some graywater impurities may pose risks to plant, and soil health, which needs more research. In general, the risks associated with graywater use are determined by the chemical/microbiological concentrations and human exposure levels. Just as when performing risk assessments for drinking water consumption (i.e., assuming 2-L of water consumption), a full chemical and microbiological risk assessment for graywater containing a variety of chemical/microbiological constituents should be clearly defined and developed, although as yet only very limited data are available on the pathogen contents typically found in graywater [37].

4.2 Graywater Practical Considerations

The state of California has strong initiatives encouraging graywater use (see Chap. 6 for more details). For example, San Francisco Public Utilities Commission (SFPUC) has a so-called laundry to landscape (L2L) program that offers residents a $125 discount towards the purchase of a L2L graywater kit, which typically retails at $175. L2L is known to save about 64.4 L per person per year or about 56,781 L per household per year [38]. Given that more than 60% of indoor water use may end up as graywater and around 50% of all water demand is used in landscaping, the potential for graywater is promising. Installing an L2L system costs between $1,500–$3,000 USD, with the rebate effectively covering the cost of the materials cost. Depending on the system size and complexity, a whole house graywater system could cost up to $15,000 USD, not including the permitting cost and any modifications needed to satisfy the backflow prevention requirements [38].

Note that graywater systems for toilet flushing require dual plumbing systems, with a connection to potable water systems, as well as a backflow preventer. Also, these toilet flushing systems should incorporate disinfection for risk reduction (e.g., the prevention of microbiological activities), as well as regular maintenance and inspections. For broader applications, reliable systems that require less maintenance and incur lower costs for the home and building owners are urgently needed. However, there are several studies reporting reasonable financial pay-back periods for certain climate conditions. For example, a simple L2L graywater system can achieve a payback period as short as 2 years, with the shortest payback periods being found in southwestern U.S. states where the precipitation rate is very low. Although there is as yet only very limited data on this, additional incentives could help delay the need for what would otherwise be urgent large infrastructure investments/expansion in urban settings [37]. See Chap. 2 for examples in Japan.

4.3 Graywater System Regulations

To protect local watersheds, graywater systems must comply with a number of regulations. For example, one utility specifies that graywater systems should be at least 30 m away from natural water bodies, such as streams and lakes, and the depth to groundwater elevation must be at least 1.5 m [36]. If these requirements are not met, then the rebate will not be reimbursed to the building/homeowners. The graywater system should also be strictly within the property boundaries, with no runoff allowed. Since July 2015, all new construction with a gross floor area of 23,226 m^2 or more in the State of California must satisfy Article 12C, which regulates the installation and operation of onsite non-potable water systems to treat and reuse available graywater and rainwater for toilet and original flushing and irrigation. New development projects with a floor area of 3,716 m^2 or more are required to submit water budget calculations that include the amount of rainwater and graywater, as well as the anticipated demand for toilet/urinal flushing, and irrigation [36]. There is clearly growing interest in gray water systems, and many states are now revising their regulations/code/laws related to the use of graywater. As of 2014, 26 states in the U.S. allowed the use of graywater [39].

5 Renewable Energy Use

Centralized water infrastructure is highly energy dependent and may account for anywhere from 4 to 10% of the U.S. total energy use, most of which is generated from fossil fuel-based sources with their associated significant economic, social and environmental impacts [40, 41]. According to the EIA (2016), fossil-fuels generate more than 80% of the energy used in the U.S. each year. To effectively address the immediate and long-term energy requirements of water infrastructure in urban environments, we need a paradigm shift towards the more efficient use of water and energy [42]. To meet these goals, we contend that the water industry *should consider integrating renewable energy into urban water infrastructure to reduce the sector's dependency on fossil-fuel based electricity use.* Practical applications and novel research in the domain of renewable energy applications for water infrastructure are rapidly evolving [43, 44]. In this section, we introduce examples where the water infrastructure is powered by renewable energy sources, focusing on solar and wind energy.

At present, about 52,000 conventional or centralized potable water treatment and distribution systems and 35,000 wastewater treatment systems operating in the U.S., with most being powered by fossil-fuel based energy distribution systems [45]. In 2009, the electricity consumed by the nation's public drinking water and wastewater utilities for pumping, conveyance, treatment, distribution, and discharge was estimated to be 56.6 billion kWh or approximately 4–10% of the total national energy consumption [40]. The energy used for water treatment and delivery in the U.S. is reported to be in the range of 0.07–0.92 kWh/m^3 with an estimated average of 0.38 kWh/m^3 [46], with the energy requirements for a specific water system depending on the system layout, local topography, and source water quality, among other factors. The energy demand for water infrastructure is projected to increase by approximately 30% over the coming decades due to increased urban water demand and a greater reliance on energy intensive treatment processes for non-fresh water sources, such as desalination and reclaimed wastewater [47]. Since the existing centralized water infrastructure depends primarily on fossil-fuel based electricity, any increase in the amount of water being treated and delivered will inevitably be accompanied by an increase in the carbon footprint.

As mentioned earlier, green building designs can ameliorate much of this adverse impact by incorporating practices that improve the efficient use of water and energy through better design, operation, and maintenance across a building's entire lifecycle, although there is an emerging concern related to a degradation in water quality due to the longer dwell times in domestic plumbing systems, which can result in stagnant water [26]. From an energy conservation perspective, however, the advantages of conservation strategies may ultimately be offset by increasing demand. We, therefore, believe that reducing the overall energy use in conjunction with implementing renewable energy sources in place of fossil-fuel based energy sources should be a critical objective for water infrastructure planning and design. The discussions below follow Lee and Younos [42].

5.1 Solar Energy

Solar energy is a proven way to integrate renewable energy into large-scale applications such as water and wastewater treatment. Currently, the most promising solar energy technology consists of photovoltaic (PV) arrays made of silicon chips. In the U.S., several water utilities are already at least partially powered by solar energy. For example, the New Jersey American Water Canal Road Water Treatment Plant has raised the overall capacity of the site to 698 kW DC by installing a solar array consisted of more than 2,871 solar PV modules at the treatment plant. It is reported that the solar array currently satisfies approximately 20% of the Canal Road WTP's peak usage [48]. USEPA provides several examples that show the estimated annual energy savings and CO_2 emission reductions attributed to solar energy, respectively, for selected water and wastewater treatment plants [49, 50]. Water scarcity in many parts of the world has increased demand for the desalination of seawater and brackish waters, particularly in high population coastal cities and island countries. Although the technologies are developing rapidly, desalination technologies are still relatively energy intensive, so for areas of the world that receive plenty of sunshine solar energy can prove a significant energy source to support the production of freshwater [51].

5.2 Wind Energy

Wind turbines are driven by the wind, creating mechanical energy that is converted to electrical energy. In the U.S., several water utilities are now powered by wind energy. For example, the Washington Suburban Sanitary Commission (WSSC) uses wind energy to power one-third of their water and wastewater operations [48]. The wind power used by WSSC is provided by 14 wind turbines installed on a farm in southwestern Pennsylvania, generating 70,000-megawatt hours of power a year. Lee and Younos [42] presented the estimated annual energy savings and reduction in CO_2 emissions attributed to wind energy for selected wastewater treatment plants.

6 Sustainable and Resilient Water Management Strategy

In this section, we present a conceptual framework for a *Decentralized Green Water-Infrastructure System (DGWIS)* for large buildings (industrial, commercial, government, and office) that integrates locally available water sources (rainwater and graywater) with renewable local energy sources (solar and wind) to support water treatment and distribution [30]. Rainwater harvesting and graywater recycling have long been identified as alternative water sources for the sustainable management of water resources [23, 24, 43, 44]. DGWIS will incorporate advanced small-scale water treatment technologies based on patterns of anticipated water use. The production and consumption of energy at the individual building level for harvesting and treating water on site are expected to increase service reliability and technical efficiency, and reduce environmental impacts by decreasing the energy required. An added benefit would be that decentralized systems should also improve the resilience, sustainability, and Levels-of-Service (LOS) by reducing service interruptions in the distribution networks.

The optimization framework for DGWIS introduced in this chapter will quantify the energy and water potentially saved based on the assumption that the supplemental water supplies provided by DGWIS will replace conventional tap water supplies. *Our hypothesis is that DGWIS can provide a partial solution to the water/energy supply and water quality challenges facing communities in the US and around the world*. As mentioned earlier, the potential contributions of self-sufficiency and a greater wastewater recovery rate for sustainable water resource management have been highlighted in several recent studies [52, 53]. We, therefore, sought to chart a new paradigm shift in urban water/energy management by evaluating and optimizing the capture and reuse of rainwater/graywater to augment domestic water supplies, while at the same time reducing water-related energy usage by adopting renewable energy technologies in the buildings. At present, solar and wind energy have considerable potential for providing renewable energy for water and graywater treatment in domestic water systems. In the future, potential applications of renewable energy use could include water source treatment of captured rainwater and graywater and distribution within buildings. The proposed DGWIS would thus be a significant step toward sustainable and resilient water/energy use in urban environments.

6.1 Optimization Framework

This section presents the optimization framework for the proposed DGWIS. The discussion follows Lee et al. [30], with updated formulations. Graywater recycling and rainwater harvesting are considered alternative sources that can be used for toilet flushing and other non-potable purposes (e.g., landscape irrigation) and renewable energy sources are used to operate pump and water treatment facilities within the building.

It is critical to understand the details of the process dynamics of the building water systems for optimal management of both the water (graywater, RWH, and municipal tap water) and renewable energy resources. Several critical constraints are considered: (1) the renewable energy available—in particular, solar and wind energy being generated at time t; (2) the graywater production rate and amount available at time t; (3) the harvested rainfall at time t; (4) variations in water demand over time; (5) the availability of sufficient water storage volumes to accommodate both graywater and harvested rainwater; (6) the water supplied from city mains; and (7) treatment capacities. Clearly, the available renewable energy, graywater production rate, available rainfall, and water demand are stochastic by nature and thus require uncertainty analyses.

The boundary of a DGWIS (i.e., its control volume) considers inflows (the water supplied from city systems and electricity from the grid), outflows (to sewer systems) and water recycling, subject to the unique constraints of each system (Fig. 2). Wastewater from showering/washing, cooking, and laundry represents a potential source for water recycling (R_t). The rainwater capture potential (P_t) is evaluated by considering the various storage tank sizes and treatment capacities as a function of time; two separate and variable tank sizes (S_p, S_r) are used for rainwater harvesting and graywater, respectively. Depending on the desired treatment capacity, the volume of a treatment unit can be defined in terms of its hydraulic residence time. The objective of the DGWIS model is to minimize consumption of the water supplied by the city (I_t) and electricity from the grid ($E_{c,t}$). This performance goal can be accomplished by implementing water efficient technologies and maximizing water recycling rates and/or rainwater harvesting use rates, while satisfying the tank limits at all times.

The optimization framework aims to minimize the net consumption of both the water supplied from the water mains and the energy from the grid in terms of cost (Eq. 1). Constraint 2 requires that the electricity (demand) used for the water treatment and pump operation ($E_{1,t}$, $E_{2,t}$, $E_{3,t}$) cannot exceed the electricity harvested from the solar panels and/or wind turbines ($E_{r,t}$) plus that supplied by the city ($E_{c,t}$). Constraints 3 and 4 are, respectively, the water supply restrictions for the two types of water demand depicted in Fig. 2. For instance, Constraint 3 ensures that the water consumption amounts for toilet use and landscape irrigation cannot be greater than the total available from the total water delivered from rainwater harvesting (P_t), recycled water (R_t) and the water mains (I_t). Constraints 5 to 7 show the functional relationships (g) for the energy requirements for treatment and pumping as a function of P_t and R_t. Water quantities, in conjunction with pump/systems characteristics, are converted into water pressure variations in Constraint 8, and Constraints 9, 10, and 11 ensure that the critical parameters for water pressure, velocity, and water quality, respectively, inside the plumbing system remain within specified ranges. Water quality parameters such as disinfectant concentrations (e.g., Free Chlorine, Chloramine), disinfectant by product, water age, temperature, pH, TOC, heavy metal concentration, microbiological quality, and turbidity also need to stay within the allowable range [54]. The parameters used in this model require detailed information on solar panel efficiency, the hours of available sunlight, energy transmission rates from solar panel/wind turbine to pump, the capacity of the treatment facilities, and

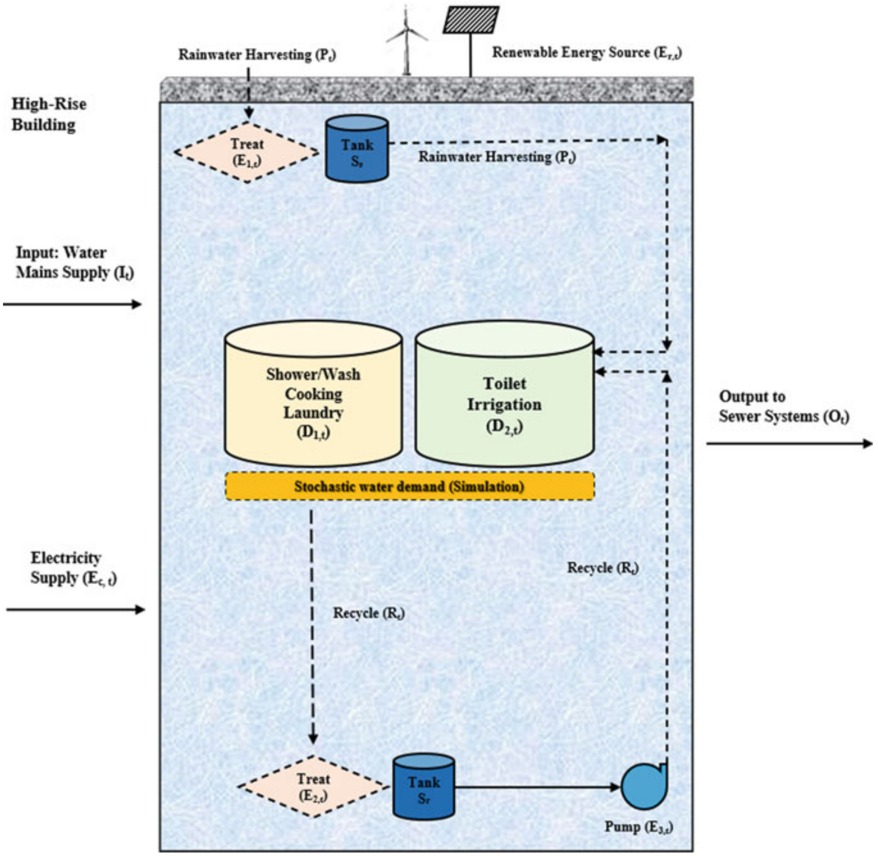

Fig. 2 Configuration of the decentralized green water-infrastructure system (*Adopted and modified from* [30])

the operational characteristics of the pump/systems. All variables with a 't' subscript have a time varying stochastic nature. The current model considers the situation at the individual building level, and a long term (e.g., 10 years) basis Cost Benefit Analysis can also be performed.

Objective Function:

$$\text{Minimize}\alpha(I_{1,t} + I_{2,t}) + \beta E_{c,t} \tag{1}$$

Subject to the following constraints:

$$E_{c,t} + E_{r,t} \geq E_{1,t} + E_{2,t} + E_{3,t} \tag{2}$$

$$P_t + R_t + I_{2,t} \geq D_{2,t} \tag{3}$$

$$I_{1,t} \geq D_{1,t} \tag{4}$$

$$E_{1,t} = g_1(P_t) \tag{5}$$

$$E_{2,t} = g_2(R_t) \tag{6}$$

$$E_{3,t} = g_3(R_t) \tag{7}$$

$$PR_t = f_1(I_t,\ P_t,\ R_t,\ \text{pump characteristics}) \tag{8}$$

$$PR_{\min} \leq PR_t \leq PR_{\max} \tag{9}$$

$$V_{\min} \leq V_t \leq V_{\max} \tag{10}$$

$$C_{\min} \leq C_t \leq C_{\max} \tag{11}$$

Decision Variables:
$I_{1,t}$: water main supply to $D_{1,t}$.
$I_{2,t}$: water main supply to $D_{2,t}$.
$E_{c,t}$: electricity supply from the power grid.

Parameters:
α: penalty coefficient for the use of mains water.
β: penalty coefficient for the use of electricity supplied by the grid.
$D_{1,t}$: water demand for showering/washing, cooking, and laundry.
$D_{2,t}$: water demand for toilet and irrigation.
$E_{1,t}$: energy required to treat harvested rainwater; a function of P_t.
$E_{2,t}$: energy required to treat graywater (from showering, washing, cooking and laundry); a function of R_t.
$E_{3,t}$: energy required to operate the pump; a function of $\mathrm{R_t}$.
$E_{r,t}$: harvested renewable energy.
P_t: potential harvested rainwater.
R_t: potential water recycling.
$PR_{\min}$: minimum required pressure inside the plumbing system.
PR_t: actual pressure inside the plumbing system.
$PR_{\max}$: maximum required pressure inside the plumbing system.
$C_{\min}$: minimum concentration for water quality parameters.
C_t: concentration of water quality parameters.
$C_{\max}$: maximum concentration for water quality parameters.

6.2 Solution Procedure

To implement the optimization framework for a real case, it is useful to consider a simulation model that incorporates both discrete event simulation (DES) and system dynamics (SD; e.g., EPANET). DES generates discretized stochastic demand per unit time t, sampling from a distribution of the best fit (e.g., normal distribution) and is thus a computational and analytical tool that allows the stochastic characteristics within a complex system to be modeled, subject to variability. It is also possible to test several different ‘what if’ scenarios, for example by changing the weather over time, to identify the best case scenario among the various alternatives.

As two separate tanks (S_p and S_r) control the rates of the water inflows and outflows, the use of an SD technique facilitates modeling a system that continuously changes from one state to another by applying differential equations to measure changes in the rates of the state variables over time. To solve this optimization problem, we can consider an evolutionary algorithm (e.g., a genetic algorithm) that conducts a random search while exploring a feasible region and exploiting solutions [55]. Given an initial set of solutions, the algorithm evaluates these solutions via a simulation model and then applies genetic operations such as crossover and mutation to produce a new solution, which it then includes in the set of updated solutions. The string of values for the decision variables represents each point in the solution space, which integrates simulation and metaheuristic search procedures and enhances each solution quality during the search process. The outcomes of this research can be used to develop short-term optimal operational guidelines for the DGWIS as well as a prescriptive decision support tool for addressing strategic long-term planning and management problems.

7 Conclusions

In this chapter, we discussed the need for a paradigm shift in urban water management and introduced a conceptual model, *DGWIS*, supplemented with RWH, graywater, and renewable energy. This model is based on a mathematical framework designed to optimize the use of captured rainwater, recycled graywater, and renewable energy resources. DGWIS is defined as a building-scale localized water supply system that utilizes rainwater and graywater and integrates advanced small-scale water treatment systems and renewable local solar and wind energy sources for water treatment and distribution in buildings. The dynamics and complex interactions among the elements of the defined systems are described in detail. Based on this new framework, the optimized theoretical input and output and the maximum recycling rate can be calculated for the selected sites at each time step. Furthermore, the resulting model could be integrated into a smart water grid (SWG), a high-efficiency water management system that integrates information and communication technologies (ICT) [56]. DGWIS can function as a standalone infrastructure element and could also be an attractive option for high density population urban areas where water scarcity is a serious issue, particularly for large buildings such as shopping centers, high-rise buildings, hotels and dormitories. The proposed DGWIS optimization framework is expected to provide a firm foundation for future research to develop more sustainable and resilient water management strategies for use in urban settings.

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Advances in Wastewater Reclamation and Reuse Technologies: Selected Case Study Projects in Japan

Haruka Takeuchi and Hiroaki Tanaka

Abstract Japan has been developing non-potable water reuse systems mainly for urban applications such as toilet flushing, urban stream water augmentation, and landscape irrigation. Recently in Japan, reclaimed water has attracted attention not only as water resource but also a heat and energy source. Because sewage temperature is more stable than atmospheric temperature, the efficiency of heat pump systems improves when reclaimed water is used for the heat source/sink than when air is used for. In addition, a cogeneration system applying a biogas power generator is considered as an effective option that can produce electricity and heat energy from food waste and excessive sludge of biological treatment processes. Two commercial buildings in Osaka have installed advanced environmental technologies such as an onsite water reclamation system, a biogas power generation system, and a heat recovering system from reclaimed water. By using reclaimed water as water resource, as well as heat and energy source, these buildings can successfully save the amount of tap water and energy consumption required for hot water supply and heating and cooling systems in the facilities. This chapter describes the two case study projects in Osaka.

Keywords Water reuse in Japan · Onsite water reclamation system · Membrane bioreactor · Biogas power generation · Heat recovery

1 Introduction

Japan has a wet and mild climate and its average annual precipitation is about twice the world average [1]. However, the amount of water resources per capita in Japan (about 3,300 m^3/year) is less than half the world average (about 7,800 m^3/year) because of seasonal variations in rainfall and the small land area. This low availability of fresh water is a difficult challenge in terms of water resource management, especially in large urban areas.

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T. Younos et al. (eds.), *Resilient Water Management Strategies in Urban Settings*,
Springer Water, https://doi.org/10.1007/978-3-030-95844-2_2

To overcome the situation, non-potable water reuse has been implemented in several cities in Japan since the 1980s, mainly for urban applications such as toilet flushing, urban stream water augmentation, and landscape irrigation [2, 3]. In addition to water scarcity, environment conservation is a major driver for water reuse in Japan. Currently, stream flow augmentation is the most common application of reclaimed water in Japan. Another possible driver for water reuse in Japan is as a measure against natural disasters. When a severe earthquake occurs, water and wastewater treatment plants can be severely damaged, leading to water supply restriction. Water reuse systems, in particular onsite systems, can be attractive solutions for such emergency situations. In order to emphasize the importance of water reuse and to promote its implementation, the Japanese government established "The Basic Act on the Water Cycle" and "New Sewage Vision" in 2014, and "Water Resources Policy" in 2015. The history and situation of water reuse in Japan is provided elsewhere [4].

Recently in Japan, reclaimed water has attracted attention for, not only water resource, but also heat and energy source. Because sewage temperature is more stable than atmospheric temperature, the efficiency of heat pump systems improves when reclaimed water is used for the heat source/sink than when air is used for. In addition, biogas power generation systems are considered as an effective option that can produce electricity from food waste and excessive sludge of biological treatment processes. Two commercial buildings in Osaka have installed advanced environmental technologies such as an onsite water reclamation system, a biogas power generation system, and a heat recovering system from reclaimed water. By using reclaimed water as water resource, as well as heat and energy source, these buildings can successfully save the amount of tap water and energy consumption required for hot water supply and heating and cooling systems in the facilities. The case study projects in Osaka are described in the following sections.

2 Water Reuse in Osaka

Osaka is located in the Yodo River system. Most of its water source depends on Lake Biwa, the largest lake in Japan. Thus, it can be argued that Osaka is a low water stress city and that water scarcity is not a strong driver for water reuse. However, Osaka experienced a serious drought in 1994 and water supply was restricted for 44 days. In addition, Osaka was struck by the Great Hanshin-Awaji Earthquake in 1995, in which the damage from the fire was enormous, especially in areas where wooden houses were densely populated. In order to realize a stable water supply even at the time of drought and disaster, the Osaka city government started to promote the installation of water recycling facilities to treat wastewater for landscape irrigation, fire protection and miscellaneous uses at the time of disaster. Since the 2000s, reclaimed water has attracted attention as not only an alternative water resource but also a heat source that can potentially contribute to a low-carbon society. Because sewage temperature is lower in summer and higher in winter than atmospheric temperature, using reclaimed water as a heat source improve the efficiency of heat pumps and water-cooled chillers of air conditioning systems and hot water supply systems.

Two commercial buildings in Osaka have installed advanced environmental technologies such as an onsite water reclamation system, a biogas power generation system, and a heat recovering system from reclaimed water. Abeno Harukas is a commercial complex in Osaka City which installed and onsite water reclamation system and a biogas power generation system. The water reclamation system (i.e. aerobic membrane reactor (MBR)) can produce reclaimed water using greywater from the hotels, offices and department stores in the building. Aeon Mall Sakai Teppocho is a shopping center located in Sakai City in Osaka Prefecture. This facility uses reclaimed water as the source of toilet flushing water as well as the heat source in the large commercial facility. The detailed explanations for the facilities are provided in the following sections.

2.1 Abeno Harukas

Standing 300 m tall, Abeno Harukas in Osaka is the tallest skyscraper in Japan. The building stands on the top of the Kintetsu Osaka Abeno-bashi Station. It houses a department store, an art museum, a hotel, an observation deck and offices (Fig. 1). Abeno Harukas was built in 2014 as a part of renovation of Abeno-bashi station and the adjacent department store. In order to develop a sustainable society, the project focused on designing a system from a comprehensive perspective: economic, social and environmental aspects. In particular, the environmental aspect was emphasized in the project. It promoted the area use of energy and advanced environmental technologies such as biogas power generation system and onsite water reclamation system for reducing the impact on urban infrastructure (Fig. 2). The biogas generation system and the water reclamation system are located on the 5th basement floor.

Environmental innovations featured in Abeno Harukas include:

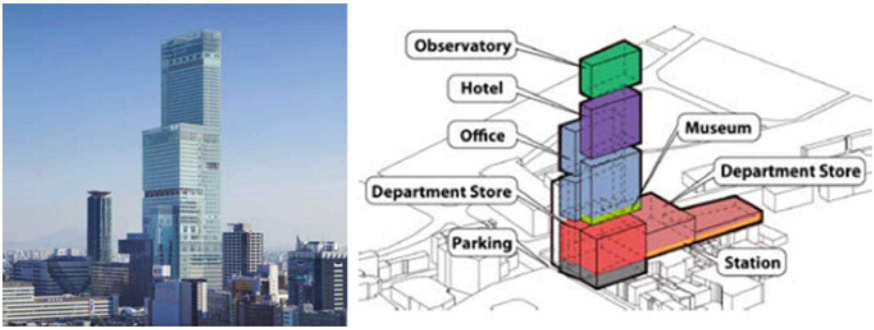

Fig. 1 Abeno Harukas and the facilities located in the building [5]

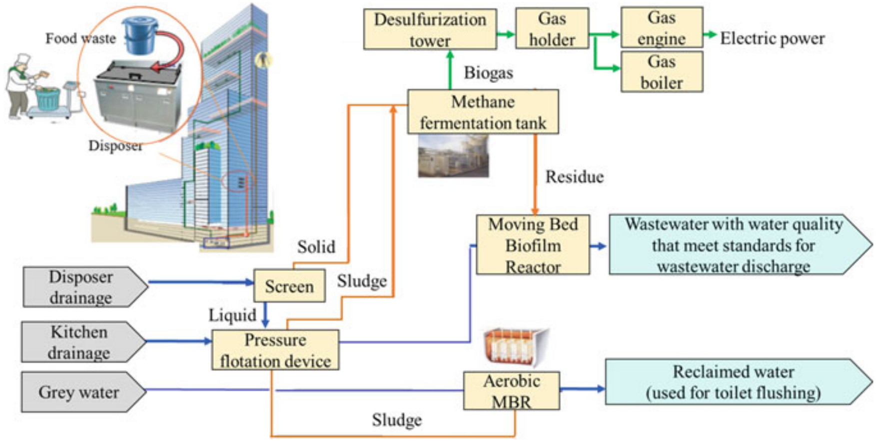

Fig. 2 Water reclamation and biogas generation systems in Abeno Harukas [5]

- reduced energy consumption (resulting in reduced CO_2 emissions) for lighting and air conditioning through effective use of open spaces that let in natural light and air;
- recycling of wastewater (rain water from the roof using sand filtration and greywater from the hotels, offices and a department store in the building using an aerobic membrane bioreactor (MBR));
- biogas power generation from food waste, solids from kitchen drainage and excessive sludge of the MBR system; and
- rooftop green space.

Abeno Harukas has been awarded "S-rank", the highest rating in CASBEE (Comprehensive Assessment System for Built Environment Efficiency) Osaka promoted by the Osaka City with the support of the Ministry of Land, Infrastructure, Transport and Tourism.

2.1.1 Onsite Water Reclamation System

In Abeno Harukas, a water supply system was constructed to use reclaimed water for toilet flushing (planned value (PV): 450 m^3/day) and purified tap water for drinking water (PV: 1,355 m^3/day) with a dual plumbing system. In this building, reclaimed water is produced using rainwater from the roof (PV: 122 m^3/day) and greywater from the hotels, offices and department stores in the building (PV: 328 m^3/day). Greywater from the facilities is reclaimed with an aerobic MBR system installed in the basement of the building and reclaimed water is stored in the reclaimed water tank (PV: 600 m^3/day). Rainwater from the roof is also collected and stored in the reclaimed water tank after sand filtration. The reclaimed water is then chlorinated and supplied to the hotels, offices and department stores and used for toilet flushing.

It should be noted that blackwater (i.e. toilet drainage) is not included in the onsite water reclamation system because using reclaimed water processed by onsite systems from toilet drainage is prohibited by Building Standards Law in Japan.

Excessive sludge generated from the MBR system is used for biogas generation in the building. After removing the sludge with the pressure flotation device, the excessive sludge is digested in the methane fermentation tank. The onsite water reclamation and biogas generation systems contribute to reduce not only the amount of drainage, but also reduce the amount of water used.

2.1.2 Biogas Power Generation System

In general, food waste generated from restaurants in commercial facilities requires a large collection point and a large amount of energy for transportation and processing. Food waste disposers can be a viable option to reduce waste disposal costs. However, in order to introduce disposers and to prevent damage on public sewerage systems due to disposer debris, it is obligatory to apply a wastewater treatment system before discharging to public sewers according to the regulations of the local government based on Sewage Law, resulting in increased energy consumption and costs.

Biogas power generation systems are considered an effective option for recovering energy from food waste. In the system, electricity can be generated from methane obtained from methane fermentation treatment of food waste. Abeno Harukas installs an onsite biogas power generation system that generates biogas from food waste, solids from kitchen drainage and excessive sludge of the MBR system (Fig. 2). In this building, food waste is crushed with a disposer. The collected disposer drainage is transported to an underground plant via pipes and then separated into a solid content and liquid component using a screen. The collected solids are guided to the methane fermenter, while liquids are treated with a pressure flotation device for further solid–liquid separation. In addition to the liquids component of the disposer drainage, kitchen drainage and excessive sludge from the reclaimed water system (i.e. MBR process) are also treated with the pressure flotation device. The obtained flotation scums are guided to the methane fermenter. The recovered methane gas is selected and burned by a digestion gas boiler and mixed combustion gas engine generator according to the load requirement. The heat generated with the biogas power generation system is used for thermophilic digestion and heat source of the building. The residue after methane fermentation and the effluent from the pressure flotation device are guided to a moving bed biofilm reactor (MBBR), and treated to the level that can be discharged into the public sewer.

Although the profitability of a biogas power generation system is relatively low on a small scale, in Abeno Harukas, disposer drainage with high organic contents generated from the kitchen waste is used for methane fermentation as well as sludge generated from the water reclamation system (i.e., MBR process). Because the sludge is methane-fermented, no cost for sludge disposal is necessary and further energy recovery is possible. In addition to sludge, solids recovered from kitchen garbage after grinding by disposers can highly contribute biogas production by fermentation. In this way, profitability of the onsite biogas power generation system can be improved by complementing solid content treatment and wastewater treatment (Fig. 2). By installing this system, this building can reduce the disposal cost for sludge and food waste and is estimated to reduce CO_2 emissions by 250 tons per year [5].

2.1.3 Evaluation of Energy Saving

The energy balance in Abeno Harukas has been estimated with two scenarios as shown in Table 1. In the first scenario, methane fermentation is performed using food waste, excessive sludge of MBR and solids recovered from kitchen drainage. In the second scenario, methane fermentation is performed with food waste only. In the estimation, equipment which requires energy for methane fermentation included a solid–liquid separation screen, pumps for stirring and feeding the methane fermentation tank, and a heating device. Energy is converted into primary energy with a power generation efficiency of 37% and a boiler efficiency of 98%.

In the first scenario, the methane fermentation system can generate 540 Nm^3/day of biogas with methane concentration of 60% which can produce energy of 11,598 MJ/day. On the other hand, the methane fermentation system consumes 6,078 MJ/day (electric power 180 kWh, heating utilization 4,240 MJ/day). As a result, the biogas power generation system can generate 5,520 MJ/day of surplus energy, which can be used for other facilities. The water reclamation system (i.e. MBR) and the treatment system of kitchen drainage (i.e. the pressure flotation device and aerobic treatment system) require 7,104 MJ/day and 7,591 MJ/day, respectively. It is estimated that the energy produced by the biogas power generation system can cover 77% of the energy required for operating the water reclamation system.

On the other hand, when the methane fermentation system is performed only with food waste, the amount of generated biogas is 290 Nm^3/day, which can produce energy of 6,229 MJ/day. Since the energy required for methane fermentation is 2,332 MJ/day (electric power 116kWh, heating utilization 2,232 MJ/day), the surplus energy is calculated to be 2,720 MJ/day. It is about half of the value estimated in the first scenario. Based on this estimation, it can be concluded that the integrated methane fermentation system can make a biogas generation system more profitable on onsite systems.

2.2 Aeon Mall Sakai Teppocho

Aeon Mall Sakai Teppocho is a shopping center located in Sakai City in Osaka Prefecture. This facility receives reclaimed water from a nearby municipal wastewater treatment plant and uses the reclaimed water as the source of water supply and the heat source for the large commercial facility (Fig. 3) [6]. Since the efficiency of heat pumps that use air as a heat source decreases as the atmospheric temperature decreases, the efficiency can be improved in winter by using reclaimed water as a heat

Table 1 Estimation of energy balance in Abeno Harukas [5]

<table>
<tr><th colspan="6">Calculation conditions</th></tr>
<tr><td colspan="6">Inflow conditions</td></tr>
<tr><td colspan="2">Food waste and disposer drainage</td><td colspan="2">Kitchen drainage</td><td colspan="2">Gray water</td></tr>
<tr><td>Food waste [t/day]</td><td>3</td><td>Flow rate [m^3/day]</td><td>700</td><td>Flow rate [m^3/day]</td><td>550</td></tr>
<tr><td>Total solids [%]</td><td>20</td><td>BOD [mg/L]</td><td>800</td><td>BOD [mg/L]</td><td>200</td></tr>
<tr><td>Flow rate [m^3/day]</td><td>24</td><td>SS [mg/L]</td><td>400</td><td>SS [mg/L]</td><td>200</td></tr>
<tr><td colspan="6">Outflow conditions</td></tr>
<tr><td colspan="3">Wastewater with water quality that meet standards for wastewater discharge</td><td colspan="3">Reclaimed water</td></tr>
<tr><td colspan="2">Flow rate [m^3/day]</td><td>730</td><td colspan="2">Flow rate [m^3/day]</td><td>550</td></tr>
<tr><td colspan="2">BOD [mg/L]</td><td><600</td><td colspan="2">BOD [mg/L]</td><td><20</td></tr>
<tr><td colspan="2">SS [mg/L]</td><td><600</td><td colspan="2">SS [mg/L]</td><td><30</td></tr>
<tr><th colspan="6">Estimated results</th></tr>
<tr><td colspan="2"></td><td>Electric power [kWh]</td><td>Heat [MJ]</td><td>Biogas [Nm^3]</td><td>Primary energy equivalent [MJ]</td></tr>
<tr><td colspan="6">Scenario 1. Methane fermentation with disposer drainage kitchen drainage and excessive sludge.</td></tr>
<tr><td colspan="2">Input energy</td><td>180</td><td>4,240</td><td>–</td><td>6,078</td></tr>
<tr><td colspan="2">Generated energy</td><td>–</td><td>–</td><td>540</td><td>11,598</td></tr>
<tr><td colspan="2">Surplus energy</td><td>–</td><td>–</td><td>–</td><td>5,520</td></tr>
<tr><td colspan="6">Scenario 2. Methane fermentation with disposer drainage.</td></tr>
<tr><td colspan="2">Input energy</td><td>116</td><td>2,332</td><td>–</td><td>3,508</td></tr>
<tr><td colspan="2">Generated energy</td><td>–</td><td>–</td><td>290</td><td>6,229</td></tr>
<tr><td colspan="2">Surplus energy</td><td>–</td><td>–</td><td>–</td><td>2,720</td></tr>
<tr><td colspan="6">Energy required for operating the pressure flotation device, MBBR and aerobic MBR processes.</td></tr>
<tr><td colspan="2">Pressure flotation device and MBBR</td><td>780</td><td>0</td><td>–</td><td>7,591</td></tr>
<tr><td colspan="2">Aerobic MBR</td><td>730</td><td>0</td><td>–</td><td>7,104</td></tr>
</table>

Fig. 3 Schematic diagram of the supply of reclaimed water to Aeon Mall Sakai Teppocho [6, 7]

source, which has a higher temperature than the atmosphere. In addition, in summer, the efficiency of the water-cooled chiller can be improved and power consumption can be suppressed by using reclaimed water, which has lower temperature than atmosphere.

The reclaimed water is supplied from the Sambo Water Reclamation Center which is located 1.8 km away from the shopping center. This municipal wastewater treatment plant produces reclaimed water with a fiber filtration process following a step-feed biological nitrogen removal process. The reclaimed water can be used for application in which people are not directly exposed to the reclaimed water. This plant supplies reclaimed water to Aeon Mall Sakai Teppocho, the Japanese largest soccer national training center (J-GREEN Sakai) and a large-scale enterprises including liquid crystal display panel factories in a coastal area. The reclaimed water is used for sprinkling, toilet flushing and industrial water. When reclaimed water is used for sprinkling in the soccer national training center, it is further ozonated with an onsite ozonation system.

After reclaimed water is supplied to Aeon Mall Sakai Teppocho, heat in the reclaimed water is recovered with a heat recovering system and used in multiple stages for hot water supply, and heating and cooling systems of the large commercial facility (Fig. 4) [8]. In summer, reclaimed water is used as a heat source for hot water supply. On the downstream side where the temperature drops after using it as heat source for hot water supply, it is used as a heat source for air conditioning. On the other hand, in winter, it is used as a heat source for preheating an external conditioner

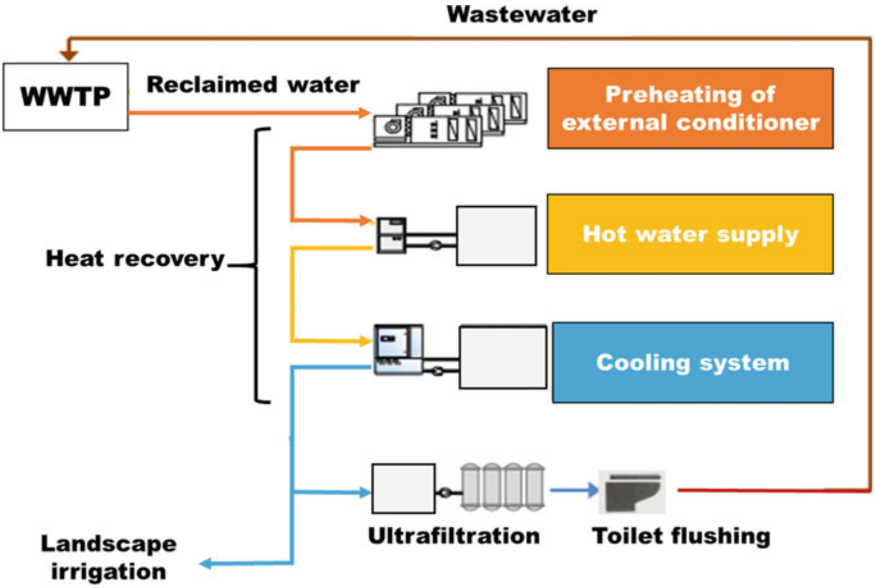

Fig. 4 Schematic diagram of heat recovery and water reuse system of Aeon Mall Sakai Teppocho [8]

(an air conditioner that adjusts the temperature using a refrigerant or cold and hot water when taking in outside air) in the daytime, and then used as a heat source for hot water supply. By using reclaimed water as a heat source, this facility achieved 4.3% energy saving and reduced CO_2 emissions by 8 tons in 2017 [8].

After the heat recovery, the reclaimed water is further used for toilet flushing in the facility and landscape irrigation on the facility as well as for stream flow augmentation in an adjacent green park (Fig. 2). Before using the reclaimed water to toilet flushing and landscape irrigation, the reclaimed water is further treated with an onsite ultrafiltration system followed by chlorination. By using the reclaimed water as a resource of water supply, this facility can successfully save 40% (30,000 m^3 per year) of water supply [8].

3 Conclusions

Japan has been developing non-potable water reuse systems in several cities mainly for urban applications such as toilet flushing, urban stream water augmentation, and landscape irrigation. Recently, reclaimed water has attracted attention not only as a water resource but also heat and energy source. Two commercial buildings in Osaka have installed an onsite water reclamation system, a biomass power generation system and a heat recovering system.

Abeno Harukas is the most famous commercial complex for its onsite water reclamation and biogas power generation system. This facility applies an aerobic MBR system to produce reclaimed water using grey water from the facility. By applying reclaimed water for toilet flushing, this facility can successfully save the amount of water supply. Besides, Abeno Harukas applies a biogas power generation system for recovering energy from food waste, excessive sludge of the MBR system and solids from kitchen drainage. By integrating the water reclamation system and biogas power generation system, the biogas power generation system can cover up to 77% of the energy required to operate the water reclamation system.

Aeon Mall Sakai Teppocho receives reclaimed water from a nearby municipal wastewater treatment plant and uses the reclaimed water as the source of water supply and the heat source in the large commercial facility. After reclaimed water is supplied to the facility, heat in the reclaimed water is recovered with a heat recovering system and used as the heat source of hot water supply, and heating and cooling systems of the large commercial facility. After the heat recovery, the reclaimed water is treated with an onsite ultrafiltration system and applied to toilet flushing, landscape irrigation in the premises, and stream flow augmentation in an adjacent green park. By using reclaimed water as a heat source, this facility achieved 4.3% energy saving and reduced CO_2 emissions by 8 tons in 2017. Besides, this facility is capable of saving up to 40% (30,000 m^3 per year) of water supply by using reclaimed water.

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Smart Decentralized Water Systems in South Korea

Sookwon Chae and Juneseok Lee

Abstract This chapter introduces selected cases of integrated water resource management practices focusing on smart decentralized water systems in South Korea, where industry/government bodies have made significant progress in smart water use. SDWM (Smart Decentralized Water Management) connects multiple alternative water resources within individual buildings and continuously balances their utilization to enhance self-efficiency and build resilience. It also supports more efficient water supply portfolio/transfer/trade within district water networks. We expect that SDWM will play an important role in augmenting the efficiency of integrated water management planning and operation through closer interactions among stakeholders and informed decision-making at all levels.

Keywords Decentralized water systems · Smart water management · South Korea

1 Introduction

In this chapter, we introduce examples of integrated water resource management practices in South Korea, focusing on smart decentralized water systems. Water resource planning and management is critical for the economic competitiveness of a country and the well-being of its inhabitants. The water industry and government agencies in South Korea have thus been devoting considerable effort to develop and implement smart water technologies, building on their strong research and development capabilities in Information and Communication Technology (ICT). We begin by describing South Korea's major waterwork infrastructure and general water management characteristics, and then move on to discuss several case studies of projects that utilize

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T. Younos et al. (eds.), *Resilient Water Management Strategies in Urban Settings*,
Springer Water, https://doi.org/10.1007/978-3-030-95844-2_3

smart decentralized water systems before closing the chapter with some concluding remarks.

2 Historical Development of Major Waterworks in South Korea

The period from 1900 to 1945 represents the “initial stage” of waterworks facilities in Korea. The first water treatment plant was built in Tukdo in 1908 and had a treatment capacity of 12,500 m^3/day. Korea was annexed by Japan in 1910, and its status as a vassal state of Japan continued until the end of the Second World War. As of 1945, only 2 million South Koreans were living in areas where water was supplied and the country’s water treatment capacity was only 27,200 m^3/day (total population was about 17 million in 1945). The period between 1950 and 1990 is often referred to as the “growth stage”. The Korean War between North Korea and South Korea (1950–53), among the most devastating wars of the modern era, left the entire country in ruins and made Korea one of the poorest countries in the world. After the war ended, however, the immense redevelopment and reconstruction effort undertaken enabled South Korea to achieve rapid economic growth based on a series of successful five-year economic development plans that included the construction of a national water infrastructure system [1].

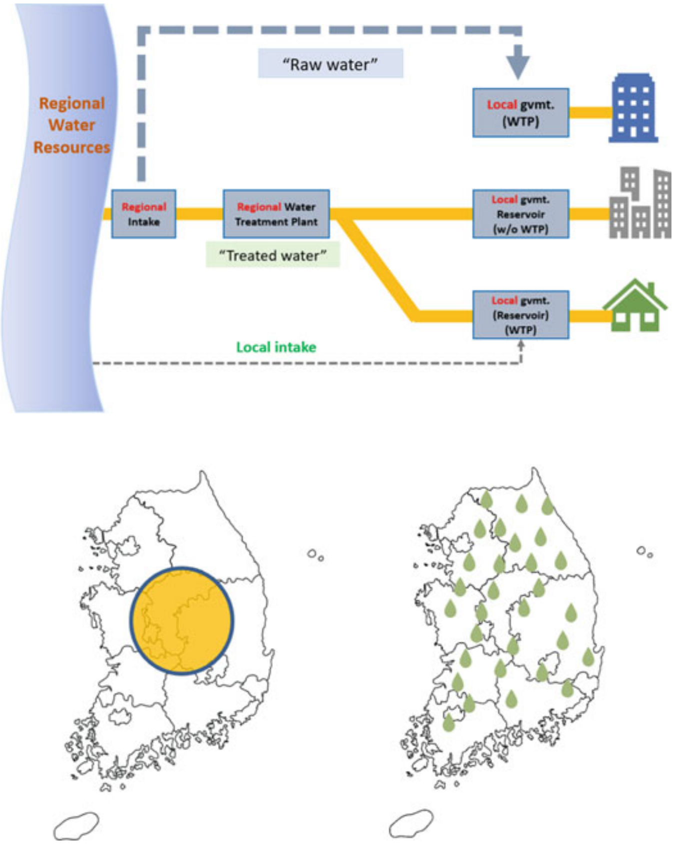
Unfortunately, this rapid economic growth also brought some negative effects, one of which was environmental pollution. Amidst the economic development, the amount of both sewage and untreated wastewater increased, causing serious environmental pollution in the country’s rivers and basins. South Korea built its first wastewater treatment plant in Cheongye in 1976, treating 150,000 m^3/day. The 24th Summer Olympic Games, which were held in Seoul in 1988, led to rapid economic growth. As many foreigners were expected to visit South Korea to watch or compete in the Games, the Korean government invested heavily in creating a clean and healthy environment to create a good impression [1].

Today, South Korea has a population of ~51 million people; the national water supply rate increased from 97.4% in 2009 to 99.2% in 2018. The number of water purification plants actually decreased over the same period, dropping from 546 in 2009 to 484 in 2018. This reduction is primarily due to the closure of old water purification plants, the integration and abolition of water purification plants between regions, and the expansion of metropolitan waterworks [1].

3 Water Supply and Demand in South Korea

South Korea’s precipitation is about 1.3 times the global average, at about 1000 to 1800 mm. However, the available water per capita is just 12% of the worldwide average. This discrepancy means Korea has abundant rainwater but lacks available water. Two-thirds of the country's rainfall is concentrated in July and August, and South Korea's terrain, which is hilly and mountainous, means that this excess precipitation tends to flow quickly downhill to the sea, leaving the country with insufficient water resources.

South Korea has two types of water supply systems: regional (large-area) waterworks and local waterworks. Regional waterworks, which provide raw or purified water to two or more local governments (Fig. 1), are managed by K-water, South Korea's public water company, and are responsible for nearly 50% of the total water supply. The remaining 50% is supplied by local waterworks. Regional water resources are sent to regional water treatment plants through regional intake facilities, while raw water is sent to local government water treatment plants. Where



Service Provider – K-Water

Service Provider: 161 Municipalities

Fig. 1 **a** South Korea's water supply model: regional and local government; **b** service providers in South Korea. *Source* Author there is no local water treatment plant, regional waterworks supply treated water directly to individual households. Where there is a local water treatment plant, the local waterworks treat water and send it to a local reservoir for water supply. Where there is a local intake facility, water from local water resources is sent directly to local water treatment plants that treat and supply water to local households. The underlying concepts that guide the design of multi-regional water supply systems in South Korea can thus be summarized as follows: first, solve regional imbalances in water resources to balance the water supply across the region; second, redistribute water from intake sources with plentiful water resources to provinces where the water resources are scarce; and third, utilize multi-purpose dams as intake sources [2].

The amount of water use has risen steadily since 2016 to a level of about 348 L per person per day in 2018. This increase is largely due to an increase in the number of single-person households. The revenue water ratio increased from 82.6% in 2009 to 84.9% in 2018, and the leak rate dropped from 11.4% in 2009 to 10.8% in 2018 as a result of a new policy that was implemented to conserve water and improve the water use rate.

4 Integrated Water Resource Management (IWRM)

Integrated Water Resource Management (IWRM) is based on a holistic approach that takes into account the quality and quantity of sustainable water, healthy ecosystems, culture, and disaster mitigation and avoidance. The principles of IWRM in the context of South Korea can be described as follows [2]:

(1) *Equity*: Stakeholders are encouraged to participate actively in the decision-making process in order to achieve societal consensus.
(2) *Environment*: Achieving ecologically sustainable water cycles is a major objective.
(3) *Economy*: Economic profitability is taken into account and IWRM implemented at the river-basin level.

South Korea has been utilizing IWRM to predict and address water shortages by promoting the coordinated development and management of water, land, and related resources to maximize economic and social welfare equitably, without compromising the sustainability of vital ecosystems. IWRM can help alleviate the peak loads in water distribution, reduce greenhouse gas emissions, prevent unnecessary leaks, and protect valuable water resources. These features combine to achieve substantial reductions in water consumption, increase public awareness, and reinforce behavioral/perception changes related to water use reduction and recycling.

5 Smart Decentralized Water Management (SDWM)

SDWM is a system that connects alternative water resources within the same building to form a network that balances the combined flow of water within that building. A bidirectional real-time network is created that receives data from sensors, measuring devices, and controllers installed throughout the building. These sensors monitor the pressure, energy consumption, temperature, and water quality at various locations. Additionally, the system controls functions such as local pressure regulation, pumps, distribution valves, and graywater/rainwater utilization. Software and specialized apps that remotely monitor important parameters and diagnose problems can also be included. The fundamental concepts of SDWM lie in intelligently planning and operating the water system within each building, focusing on providing a self-sufficient and reliable water supply for the occupants.

There are essentially four phases involved for IWRM-SDWM: (1) mapping the water resources and weather forecasting, which requires on-site terrestrial sensing, geological information systems, Internet access, and appropriate sensor networks; (2) asset management for the water system network, which includes buried asset identification and electronic tagging, smart pipes, and real-time risk assessment and repairs; (3) setting up an early warning system, meeting the various stakeholders, and establishing procedures for rainwater harvesting, flood management, the management of aquifer recharge, smart metering, and process knowledge systems; and finally; (4) SDWM manages water intelligently by making necessary decisions in real time based on the data provided by the geographic information systems, sensor networks, and the Internet. When sensor information, control information, and asset management information are monitored and disclosed to the consumer portal through SCADA, SDWM can become the core of IWRM. The fundamental principles governing the effective implementation of SDWM-IWRM in the South Korean context are as follows [2]:

Principle 1. The timely provision of data and information is at the heart of all smart technologies.
Principle 2. System analysis provides an effective means of communication and highly reliable decision-making tools.
Principle 3. Innovation and new ideas are integrated into the smart water grid operations to enable it to adapt to changes and meet future needs.
Principle 4. Two-way management provides more effective and timely decision-making.

Over the last three decades, South Korea has devoted considerable effort to promoting IWRM by further developing SDWM. However, these efforts have been hampered by issues, such as the ministry's siloed approaches to water management, failures in coordination between sectors that has resulted in overlapping investment in water-related projects, and the formation of an unnecessarily bloated organizational tree due to work duplication. To address these problems, the government enacted two new pieces of legislation, the Framework Act on Water Management and the Act on Water Technology Industry, and revised the existing Government Organization Act in 2018 to provide the necessary legal framework for integrated water management. There are significant benefits to be gained through implementing SDWM-IWRM in intelligent, ecologically sound green building projects, which will eventually help promote the smart management of information that supports conflict prevention and resolution, improves disaster risk management, and boosts the eco-efficiency of basin operations. The next section presents several case studies that demonstrate how these principles can be applied in real world projects [2].

6 Decentralized System Cases in South Korea

6.1 *Case 1. The 2nd Lotte World Tower*

The 2nd Lotte World Tower is the tallest building in South Korea, at 555 m, with 123 above-ground stories (Fig. 2). The building consists of the Podium (floors 1–8), offices (floors 14–38), officetel (multi-purpose residential/commercial units, floors 42–71), a hotel (floors 76–101), premium offices (floors 108–114), and an observatory (floors 117–123). There are six intermediate machine rooms and shelters on every 20th floor. The building utilizes five alternative water resources: rainwater (1900 m^3/day, greywater (1200 m^3/day), groundwater(3,000 RT of underground heat), lake water (for emergencies such as water shortage), and river water(5⁻8

Fig. 2 The 2nd Lotte World Tower [3]. *Source* Wikipedia

m^3/month). Green power sources include a geothermal system installed under the building, a solar module installed on the glass of the high-rise exterior wall, and a small wind turbine installed on the roof. A ‘wide-area water supply method’ using the temperature difference between the ambient temperature within the building and that of the raw water coming into the building via the wide-area water supply pipe passing under the Songpa-main street is also utilized. Taken together, these sources provide 30% of the energy needed to cool and heat the building.

6.1.1 Rainwater Treatment Facilities

The 2nd Lotte World Tower has two rainwater treatment facilities, one with a design capacity of 500 m^3/day on the west side and another larger one than can treat 1400 m^3/day on the east side. The rainwater is passed through a sieve screen to remove larger particles and other debris and then through a fiber pore filter, after which it is stored in a rainwater treatment tank before being passed through a filtration system and sent to a rainwater storage tank for reuse. Once the storage tank is full, the filtration process stops automatically and an emergency pump discharges the excess rainwater out to the municipal storm drain system [4].

6.1.2 Graywater Treatment Facility

The drainage coming off the 2nd Lotte World Tower is recycled as graywater with the water quality complying with the legal graywater quality standards. The building has a dedicated graywater treatment facility to ensure effective water reuse. The design criteria include an inflow of 1200 m^3/day, BOD 250 mg/l, COD 200 mg/l, and SS 250 mg/l for the incoming water, and better than BOD 5 mg/l, COD 15 mg/l, SS 5 mg/l or higher than residual chlorine 2 mg/l, a chromaticity of 5 NTU, and a turbidity of 2 NTU for the treated water. The treatment process involves a combination of MBR, ozone, and activated carbon in the following order: raw water inflow, flow control tank (capacity: 586 m^3, residence time: 11.7 h), aeration tank (capacity: 236.9 m^3, residence time: 4.7 h), membrane tank (capacity: 493.02 m^3, residence time: 9.9 h), ozone contact tank (capacity: 140.76 m^3, residence time: 2.8 h), filtration tank (capacity: 162 m^3, residence time: 162 h), and discharge tank (capacity: 244.88 m^3, residence time: 24.9 h). The membrane tank maintains a dissolved oxygen concentration of 2.0 to 3.0 mg/l, and microorganisms adsorb and oxidize organic matter in the inflowing sewage, after which an immersion-type membrane with a pore size of 0.1 μm is immersed in the tank, and suction filtration is performed at low pressure using a pump. Finally, the microbes and the treated water are separated into solids and liquids to produce clean treated water [4] (Fig. 3)

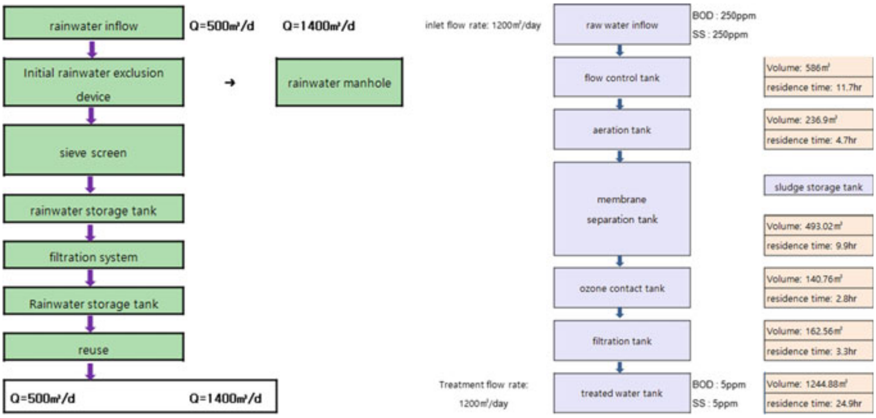


Fig. 3 **a** Rainwater treatment facilities; **b** Graywater treatment facilities. *Source* Author

6.1.3 Other Alternative Sources and Uses

Seokchon Lake, which is close to Songpa Naruto and the 2nd Lotte World Tower is an artificial lake formed as part of the Han River reclamation project. Because it is an artificial lake, the lake's water level is maintained at 5 m by injecting from 5 to 8 m^3 of Han River water every month. Currently, there are concerns about the deteriorating water quality in Seokchon Lake caused by the discharge of various pollutants, which has increased due to the rapid rise in the number of visitors to the site. There are also concerns about the deteriorating air quality, including the high levels of fine dust created by traffic congestion in the Jamsil area.

Securing and retaining multiple water resources is one of top priorities. Multiple urban water resources such as city water, stormwater, graywater, and groundwater are now being utilized to supply newly constructed skyscrapers to supplement local conventional water resources such as river and lake water as part of the city's strategy to support the goal of integrated management of the various water resources. Seoul's metropolitan water supply of 50,000 m^3/day is being boosted by the 2nd Lotte World Tower's water recycling and water-saving facilities, which include a 1200-m^3 graywater treatment facility and an 1900-m^3 rainwater storage tank. The new building's facilities can also convert about 40,000 m^3/day of domestic sewage into recycled and reused water resources, with the excess being sold/transferred to nearby buildings, thus representing a water resource that creates additional economic value as a third alternative water source.

In the area around the 2nd Lotte World Tower complex, various Low Impact Development (LID) techniques have also been implemented. These include permeable sidewalk blocks, penetration flower beds, and penetration landscaping. Various environmental sensors have already been installed in and around the new building complex. These include the area around Seokchon Lake, where the integrated water management is made intelligent by installing additional smart sensors. Water quantity and quality sensors, various building operation management sensors, and unit platforms have been installed and 23 underground water level gauges and eight ground subsidence gauges are in operation to support the safe management of the area around Seokchon Lake (esp. related to sink hole issues nearby the lake).

Multiple water sources are in continuous use, linked to the large-scale stormwater storage tank (31,000 m^3) at the nearby Jamsil Stadium. This supplies and distributes water intelligently for purposes such as road cleaning, fine dust reduction, heat island effect reduction, and environmental water uses such as stream maintenance water, in conjunction with water from two lakes, Seongnaecheon and Mongchon. For example, fine dust, which is a serious issue in South Korea that often causes problems in Songpa-gu, can be reduced by spraying water cannons in an appropriate direction from the 2nd Lotte World Tower. A surge in water consumption can often be predicted in advance when a major cultural event is held in the park that will be attended by a large crowd. This can be planned for and water consumption cut by producing and supplying water from alternative resources such as rainwater, graywater, and groundwater. Water for various purposes, such as hotel swimming pools, hand-washing water for restaurants, and water purifier purified water can also be provided from these sources.

Several outstanding issues have yet to be addressed, however, including (1) reducing the cost of using raw Han River water to maintain the water level in Seokchon Lake, which cost 200 million won (about US$ 170,000) for 1.23 million m^3 of water in 2014, by replacing it with rainwater, groundwater, and graywater; (2) enabling the multi-water resources produced and treated in the 2nd Lotte World Tower to be supplied and traded to other nearby buildings; and (3) reducing the consumption of water supplied to the entrance of the complex in one direction, which would generate further economic benefits by reducing water consumption as a result of using the multiple water sources secured within the 2nd Lotte World Tower Complex. It is important to note that the 2nd Lotte World Tower project is specifically designed to support direct citizen participation in decision-making for water demand issues and the supply methods to be used for various distributed water resources. Furthermore, a future hyper-connection based on digital water informatization, digital twin, cyber-physical system, and Living lab operation could become possible by building a platform where all things (i.e., multi-purpose water sources), all services (i.e., multi-purpose water supplies), and all humans (i.e., multi-purpose water consumers) can converge and communicate [5].

6.1.4 Use of Renewable Energy Sources

The 2nd Lotte World Tower is an energy-efficient building that is designed to satisfy 15% of its total energy use with renewable energy sources, including geothermal, hydrothermal, sunlight, and solar heating. The building's overall cold (air conditioning) load is 29,100 RT (Refrigeration Tons), and its heating system total design load is 90.7 m^3/h. The heat source system uses ice storage, geothermal, and shrinkable heat as its main sources, divided into low-rise and high-rise plants. The heat source supply to the lower floors utilizes a header method, while the heat source supply to the upper floors is supplied by pumping up steam or cold water and exchanging heat with air or water in each zone [5].

Ice heat storage operates the refrigerator with electricity at night and stores cold heat in the heat storage tank in the form of ice, using this as a cooling source during the day. The geothermal cooling/heating system installed in the energy center has a capacity of 3,000 RT. To construct the system, 720 150 mm diameter holes were drilled to a depth of 200 m below ground level on the site using a vertically sealed method; 696 of the holes were drilled under the building itself. The underground heat is used to heat and cool the lower floors of the building. An important feature of this wide-area water temperature differential heat-storage system is that it combines a heat pump and a heat-shrinkage system using a wide-area water supply as a heat source. At night, the heat pump is operated to store hot and cold water in a heat shrink tank that can then be used for heating/cooling during the day. Water flows within the pipeline 24 h a day, with the raw water moving back to the purification plant at night. Since this thermal energy would otherwise be unused, the system's energy efficiency is high. The circulation pump controls the heating and cooling temperature by circulating cold or hot water through the building, while the geothermal condensate circulation pump controls the heating temperature through heat exchange, circulating water that has been heated deep underground through the building's heating/cooling system before sending it back into the ground [5].

Lotte World Tower's Building Energy Management System (BEMS) consists of a single-platform distributed server. The BEMS and the automatic machine equipment control system are composed of a single platform with the same logic, but data are stored in separate servers so the BEMS monitors the building's energy use, analyzes it, and then transmits data to the automatic control system for the mechanical equipment. The DDC (Direct Digital Control) energy-saving algorithm then calculates the optimization point and controls the machinery. This system saves energy by preventing losses due to operation errors, administrator and user mistakes, and low-efficiency operation by taking into account vacancy time and optimizing power-saving operations, enthalpy control, and device start-up times. The building's water supply system is divided into multiple zones and an elevated water tank used to reduce the load on the pump. The objective here has been to integrate a long-life design into the structure from the outset by installed water recycling and water-saving equipment. As a result, the company earned a LEED Gold rating as it completed its construction [5].

6.2 Case 2. Star City

Completed in March 2007, Star City in Seoul contains 1310 households spread across four buildings with different heights (58 floors, 50 floors, 45 floors, and 35 floors). The complex was built on a site that habitually flooded, hence water management was a priority from the outset. The Star City complex covers an area of 62,500 m^2,

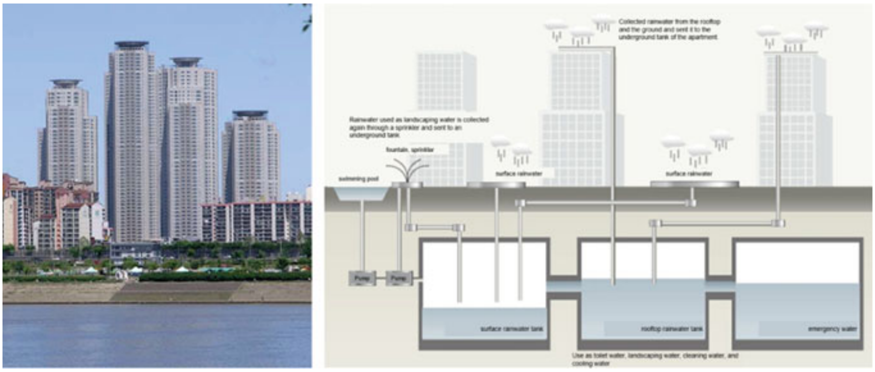


Fig. 4 Rainwater use in Star City Building [7, 8]. *Source* Building Korea and Joins.com

with rainwater being collected at ground level (45,000 m^2) and the building rooftops (6200 m^2) for a total of 51,200 m^2. Three concrete tanks holding 1,000 m^3 each were installed on the fourth basement level to store rooftop rainwater, surface rainwater, and emergency water, respectively (Fig. 4). Rainwater stored in the tanks is used for landscaping, fountains, and streams in the complex's Central Park and the public toilets on the 1st basement level and the 1st floor. The water in the second tank is used for landscaping, and the cost of water for one month is 200 won (US$ 0.2) per household, although the water is free to customers. In the event of a sudden interruption in the water supply, the emergency water collected in the third tank is sufficient to supply the entire complex for more than a week, demonstrating the benefits of a decentralized system. Under normal conditions, Star City's underground rainwater reservoir is only filled to two-thirds of its total capacity, leaving one third, i.e. 1,000 m^3, available to prevent flooding due to torrential rains in the summer months. Of the 2,000 m^3 of water regularly stored here, 1,000 m^3 are used for the public restrooms, landscaping, and cleaning, while the other half is reserved as firefighting water. Large fire trucks usually transport 10 m^3 of water, hence this water is equivalent to that carried by 100 large fire trucks is stored on site [6].

6.3 Case 3. Local Government Initiatives

6.3.1 Rainwater Policies

In Korea, more than 50 local governments, including Suwon City and Namhae County, have enacted an "Ordinance on Rain Water Management" that recognizes their status as a *Rain City*. *Rain Cities* recognize the importance and utility of rainwater, establishing and implementing systems and regulations for collecting and using rainwater. *Rain Cities* restore natural water through active water circulation improvements based on their local rainwater conditions. They aim to be sustainable and eco-friendly cities whose citizens actively participate in water conservation efforts, becoming low-carbon, green-growth cities that have reduced the energy required for their water supply by utilizing the rainwater that falls to supply their own needs [9].

6.3.2 Recycling and Reusing Water in Paju Unjeong, New Town

In order to build an ecological city with water recycling, the Paju Unjeong new cities created a stream and an artificial lake using graywater from chemically treated sewage and rainwater in the city. Before planning and implementing an environmentally friendly city, three preconditions must be observed. First, in addition to the traditional civil engineering aspects of developing a new town, expert ecological environmental engineers must be involved from the outset. Second, if a problem is encountered when creating a new city, it must be solved using an "improvement design" approach. Third, once the eco-friendly new town has been successfully built, experts and citizens should remain involved, actively monitoring progress and protecting the city's eco-credentials. To develop Paju Unjeong New Town in an environmentally friendly way, the following four models were implemented [9]:

1. Of the 62,000 m^3/day of sewage effluent generated, 28,000 m^3/day are tertiarily treated and the water used to feed four 8.5 km long brooklets, one small river and a lake.
2. Recycled water must be treated to a level where it is safe enough for swimming and scientifically proven to be safe for inhabitants.
3. The stream that circulates through the new city will improve the health of the residents and foster an attitude of respect for the environment.
4. Above all, it is vital to ensure that sufficient water resources are available to achieve these objectives prior to construction commencing.

6.3.3 Utilization of Distributed Water Resources in Suwon City

In August 2019, Samsung Electronics expanded its graywater facilities to supply environmental (and sprinkler) water to Suwon City. In addition, environmental water was provided free of charge to Suwon City. Samsung Electronics expanded the graywater supply facility at their business site, which was initially 400 m^3/day, to 1680 m^3/day, and Yeongtong-gu, Suwon-si gave the company access to city-owned land where Samsung Electronics' graywater facility and supply piping could be connected to the city's environmental water distribution network. As a result, Yeongtong-gu is now able to secure sufficient environmental water (e.g., restoration of natural water bodies or open channels) to meet their needs from Samsung Electronics' graywater supply. In the future, when fine dust, yellow dust, heat waves, droughts and other similar events occur, the environmental water supplied by Samsung Electronics will be sprayed onto road surfaces to reduce dust and lower the road temperature. It will

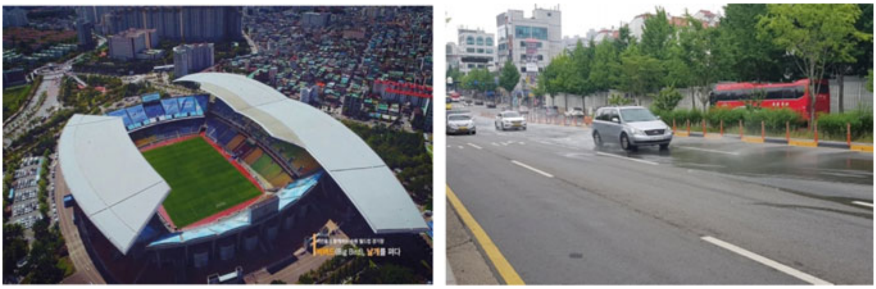


Fig. 5 **a** Installation of rainwater reuse facility underground—Suwon World Cup Stadium. **b** To reduce the heat island phenomenon, rainwater from the rainwater storage tank is sprayed onto the road [10, 11]. *Source* South Korean Newspaper

also be used for landscape water. Using this extra 10,000 m^3 of graywater each year will reduce the greenhouse gases the city generates by 3,000 kg per year [9].

Suwon City is working towards becoming a "water cycle city" by steadily building its own rainwater recycling system. By August 2020, 317 public and private rainwater storage facilities had been installed in the city, with a total storage capacity of 103,983.48 m^3 of rainwater. These rainwater storage tanks are spread across eight locations, including the Suwon World Cup Stadium, Suwon Sports Complex, and Gwanggyo Middle School, which has 47,090 m^3 capacity (Fig. 4). For the 'Rain City Suwon Season 2 Project', the city of Suwon conducted a pilot project for the 'Green Rainwater Infrastructure Creation Project' with the Ministry of Environment in 2014, building the first 'Green Rainwater Infrastructure' in the country on the grounds of their Jangan-gu Office [9] (Fig. 5)

For this project, porous block pavers, a rainwater infiltration gutter, a rainwater storage tank capable of storing 300 m^3, and an underground infiltration channel were installed in the land surrounding the office building. On the sidewalk around the city hall intersection, rainwater utilization facilities such as bicycle paths with permeable pavements, rainwater blocking fences that prevented the generation of nonpoint pollution sources, and porous blocks were installed using a 'low impact development (LID) technique.‘ The water collected and stored in the rainwater storage tank is available for use in the 'automatic surface road sprinkling system.‘ When a fine dust and/or heatwave warning is issued, the collected rainwater is sprayed on the road to mitigate the hazards [9].

6.3.4 Water Recycling in Guri City

In April 2021, Guri City installed a new graywater facility (65 m^3/day) that purifies and reuses sewage such as the pool water used in the multi-sports center and rainwater, allowing it to be reused for flushing toilets, cleaning and landscaping, among others. This water will be treated at a level that satisfies a water quality standard that is stricter than that normally required for sewage discharge water. Reusing 65 m^3 of water that would otherwise be wasted every day will save more than 100 million won (about US$ 85, 241) a year, while at the same time creating a heated shelter through a vertical garden installation using recycled water in the multi-sports center, and installing a reusable water supply so that the sprinklers can use the water recycled on the premises [9].

6.3.5 Using Distributed Water Resources in Pangyo New Town

For the creation of natural rivers in the Unjung and Geumto streams in Seongnam Pangyo New Town, a plan for securing distributed water resources for effective water environment management was reviewed and established as follows: (1) setting target flow to maintain the function of the river, (2) researching and distributing the natural water resources that can be secured, (3) examining various ways to secure the shortage, and (4) minimizing the impact on the river ecosystem. The optimal supply method according to the water securing strategy/scope is shown in Fig. 6 [11]. All flow units are in m^3/day. The overall treated water ratio is about 45% and the BOD ranges from 0.3–1.7 mg/L [12].

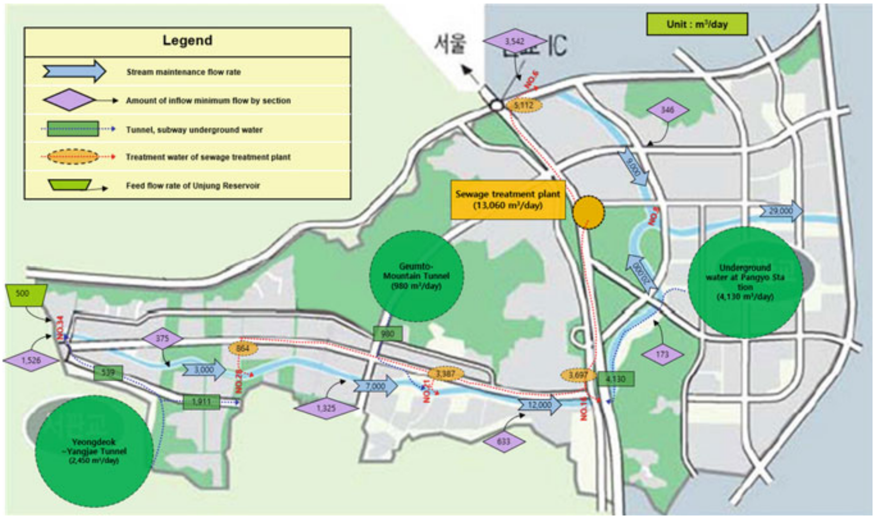


Fig. 6 River maintenance water using distributed water resources in Pangyo New Town [11]

7 Concluding Remarks

In this chapter, we presented some interesting examples of the use of SDWM practices in South Korea in the context of IWRM. South Korea is actively developing/embracing SDWM with a wide range of new ICT technologies. Alternative decentralized water resources such as groundwater, surface water, rainwater, and graywater can be utilized to elevate the self-sufficiency level of each building, flowing into the network to supplement the demand from other locations. SDWM can thus be used to address the ever-increasing demand for water while at the same time preserving our existing energy and water resources, preventing missing and illegal connections, preserving the environment and monitoring and improving water quality in real-time.

Adopting SDWM-IWRM can make multi-water source management more effective, enabling facility managers to respond to the increasing complexity of building water use and district unit management, including at the boundaries between district units. District-level smart information systems such as the ones described here are based on a type of governance that supports conflict prevention and resolution, and provides better decision-making tools. A smart information management system for water-related efforts can provide prediction capacities and rational decision support at various levels to produce three types of benefits: societal, economic, and environmental. We confidently expect that SDWM-IWRM will play an important role in augmenting the efficiency of integrated water management planning and operation through more effective interactions between stakeholders and informed decision-making at all levels.

Acknowledgements This work was supported by Korea Environment Industry & Technology Institute (KEITI) through Smart Water City Research Program funded by Korea Ministry of Environment (MOE) (2019002950004).

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Open Datasets and IoT Sensors for Residential Water Demand Monitoring at the End-Use Level: A Pilot Study Site in Naples (Italy)

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Abstract Water infrastructure systems management is one of the most urgent global issues, as urbanization and population continue to rise. Monitoring and analysis of water demand is one of many challenges faced by researchers in the past decades. The spread of smart technology improves the way in which data can be collected. Water utilities are starting to try out innovative smart meters instead of traditional water meters to read water consumption with a high-resolution rate. This new trend made available a great amount of data opened new opportunities to improve water services and fostered the interest in understanding the use of water in domestic environments along with direct implications on identifying demand patterns, forecasting future demands, detecting leakage, improving users' awareness, and customizing users' profiles. This chapter presents a pilot study site of water end-use demand monitoring in a residential apartment located in Naples (Italy). A monitoring system based on Internet of Things (IoT) technology was implemented and installed on the fixtures of a single-family apartment. Data gathered have been used to realize an open dataset available in the research community to train data-driven algorithms. Overall, the chapter provides insights for new perspectives and further research related to the importance of high-resolution data to improve water demand-side management. This case study represents a first step towards a decentralized monitoring water system aimed to increase user awareness to promote water conservation.

Keywords Water demand data · Smart meter · Residential demand monitoring · Water end-use disaggregation · Open dataset

1 Introduction

The water crisis of recent years has reminded us that only 3% of the Earth's water is potable and that the careful management of water as a resource is one of the greatest challenges facing the community worldwide today. Indeed, from a technical,

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T. Younos et al. (eds.), *Resilient Water Management Strategies in Urban Settings*,
Springer Water, https://doi.org/10.1007/978-3-030-95844-2_4

economic and social point of view, it is unacceptable that more than 40% in Italy, and 30% of drinking water worldwide, is wasted mainly due to problems of malfunction and poor management of infrastructures [1–3]. Proper management of urban water systems is essential for sustaining cities and providing safe, reliable and cost-effective water services. Estimating urban water demand has always been a challenge for water utility managers and policymakers [4]. Optimizing operations, maintenance and monitoring is a key challenge for any water utility, from both a technical and economic point of view. Currently, these tasks are complicated by urban population growth, which is expected to increase further, especially in developing countries [5]. The ever-increasing demand for water and the need for efficient services, combined with ongoing climate change, urbanization, droughts and supply shortages, make water systems critical infrastructures to manage and increase the attention to water scarcity [6, 7].

To meet urban water demand requires technical actions such as leakage control, pipe breaks and pressure monitoring, use of water-saving devices, water monitoring, alternative water resources, etc., which are an essential component for sustainable development [8]. In such a context, large-scale centralized water infrastructures struggle to meet the needs of rapidly growing populations, and decentralized water system infrastructure has piqued the interest of infrastructure professionals, researchers, and international stakeholders [9].

Decentralized water management approaches that reduce freshwater use, and wastewater and stormwater generation at the individual building level are increasing. Water utilities have started to encourage customers to adopt water reuse, water conservation, and stormwater treatment technologies as a result of water shortages and limited budgets, resulting in a decentralized water service system. Within urban water infrastructure systems, transitioning from a centralized to a decentralized approach will change demands and have an impact on the performance of existing infrastructure, as well as the use of energy and water resources [10].

One of the factors that drive the decentralization of urban water infrastructure is the interaction between water systems and users. In the case of a water crisis, consumers may voluntarily adopt conservation techniques or technologies, or in response to ordinances and policies enacted by utility managers. Here, water demand-side management and residential water demand (RWD) monitoring assume a significant role as an alternative strategy to ensure reliable water supply, reduce water utility costs, improve infrastructure planning and network efficiency [11]. Moreover, in the era of Smart Cities, where the smart water and smart grid paradigms are key concepts of technological progress, innovative and intelligent management of water services at the household level is a key element for water-saving and improving water efficiency [12].

Over the past several years, the adoption and integration of innovative metering technologies in the water sector is a viable solution for better decision support and increased efficiency. The spread of Internet of Things (IoT) and Information and Communication Technologies (ICT) allow data collection at different spatial and temporal resolutions. The availability of water demand data enables the development and application of data analytics tools and machine learning models to extract valuable information from water datasets. Nevertheless, existing data are frequently difficult to access or use, so the need for open datasets to investigate water issue emerges [13]. To address these issues, this chapter presents an IoT solution for monitoring in real-time residential water end-use consumption used to realize an open dataset available in the research community to train data-driven algorithms.

This chapter discusses the main outcomes in the framework of an Innovative PhD project Industry 4.0 PON 2014–2020 titled "Innovative models, technologies and methodologies for the analysis and management of hydraulic big data to be integrated into water utilities as decision support system" of the University of Campania Luigi Vanvitelli (Italy). The chapter is organized as follows: Sect. 1 presents the opportunities and challenges associated with residential water demand modelling that motivate the development of the experimental case study described in this chapter. Section 2 provides an overview of the water demand datasets available in the urban context with reference to earlier work by some of the chapter authors. Section 3 illustrates the monitoring and management of water demand in residential areas. Section 4 describes the experimental case study of the development and installation of an IoT monitoring system to detect water consumption at the end-use level. Section 5 presents the main application areas for residential water demand modelling linking some applications developed or in progress related to the case study. Section 6 describes our contribution to residential modelling through the software WEUSEDTO. Finally, Sect. 7 provides a summary of the results presented in this chapter and a discussion of the challenges associated with the pilot site and RWD modelling.

2 General Trend of Decentralized Water Infrastructure Systems: Opportunities and Challenges of Modelling Residential Water Demand

Traditional urban water management relies on a centrally organised infrastructure, the main elements of which are the drainage network and the water distribution network. In order to meet new challenges such as climate change, growth in population, increasing droughts and water scarcity, it is generally accepted that water infrastructure needs to become more flexible, adaptable and sustainable.

Large-scale rehabilitation of the water infrastructure system will be costly or perhaps not even economically infeasible. Decentralization of the urban water supply system represents a more feasible approach [9]. A decentralized water supply system brings appropriate services closer to customers and promotes interaction between the water supply system and users. In this regard, the proposed pilot study in Naples, IT, represents an innovative example of interaction between users and the water system.

The possibility to record water consumption at different spatial and temporal scales using smart water meters plays a key role in smart water system management [14]. High-resolution water data can support water utilities in decision making by incorporating innovative aspects such as demand forecasting, leakage detection, water network modelling, user awareness, efficient water use, and more [13]. In addition, the availability of high-resolution household data provides an opportunity to adopt user profiling techniques that have been widely applied in other fields such as artificial intelligence, data science, and information science [15]. Through user profiling, customers are characterized by a set of rules, attitudes, needs, interests, behaviours, and preferences [16], and the collected data can then be used to derive information and improve the customization of services.

Although the water community would benefit from increased accessibility to open data, high-resolution water demand data comes with a number of potential drawbacks and significant challenges, including data ownership, sharing restrictions, privacy concerns, technical data management, and security risks [17]. On this front, utilities and policymakers are paying attention to data privacy legislation such as the EU's General Data Protection Regulation (GDPR) that went into effect in 2018 and other policies that followed in other countries across the world [18]. This will support the increasing trend of open datasets at household and end-use levels to profile users' behaviours [13].

Several studies in the field of urban water supply [19–21], have highlighted the importance of end-use and profile data for various purposes. These include: (1) understanding the average and maximum end-user volume of different fixtures (shower, toilet, etc.) at hourly, daily, and monthly levels to improve the planning process; (2) evaluating daily water end-use patterns to identify trends and spikes in water use over time, providing up-to-date information on per capita demand that is no longer evaluable using traditional methods that do not account for social changes over time; (3) examining peak demand in a day to understand the types of household practices that drive peak use; and (4) evaluating seasonal impacts of water use. Furthermore, as there is a strong link between highly personalized services and water-saving impacts, user profiling is a fundamental strategy to promote water-saving [22].

Another benefit of smart water management based on innovative household demand modelling is the reduction of energy consumption in water supply systems. Since water supply systems include numerous pumping stations, a significant amount of the energy required for pumping is wasted in compensating for flow and pressure deficits caused by outdated piping, tanks, valves, control devices, etc. Advanced user profiling can help water utilities improve pump scheduling according to customers' actual needs and reduce energy consumption and water waste.

3 Urban Water Demand Data: An Overview of Open Datasets

The management of water systems has evolved in recent decades, with water consumption data recognised as an input to decision-making processes in water distribution system policy and infrastructure planning. Improvements in smart water meter technology mean that high-resolution data are now available, offering significant benefits for water demand modelling and management.

In the urban context, comprehensive and reliable water use data enable policy-makers and water utilities to evaluate water efficiency programmes. However, rational and equitable water management decisions require systematic scientific studies based on data-driven models. Scientific studies are known to rely on the collection and analysis of measured data and seek training data sets to utilize machine learning techniques, calibrate models, and test, analyse, and identify innovative solutions. Water demand studies require data that are available in formats that meet the needs of researchers, at a relevant spatial and temporal resolution that is useful for studying water use patterns and issues. In the urban context, as Di Mauro et al. [13] reported, water demand data (WDD) are available at different scales, e.g., urban, district, household and end-user, which adds value to water management.

Di Mauro et al. [13] presented an overview of datasets available at suburban scale through a review of 92 water demand datasets. The authors examined existing datasets on urban water use at different spatial and temporal scales, evaluated their data access policies, and identified freely available data for future research and applications. Figure 1 provides a distribution on the spatial scale of analyses, and 120 related peer-review publications compiled in the last 45 years, Fig. 2 shows the chronological break down of spatial scale studies (every 5 years). The review not only helped to sift through available datasets, but also to create a public repository from which available datasets can be downloaded by various users for research purposes.

In the following sections, we highlight the main characteristics of datasets at district, household and end-use level, an overview of the main use of this dataset in water demand studies and links to download datasets available in the literature.

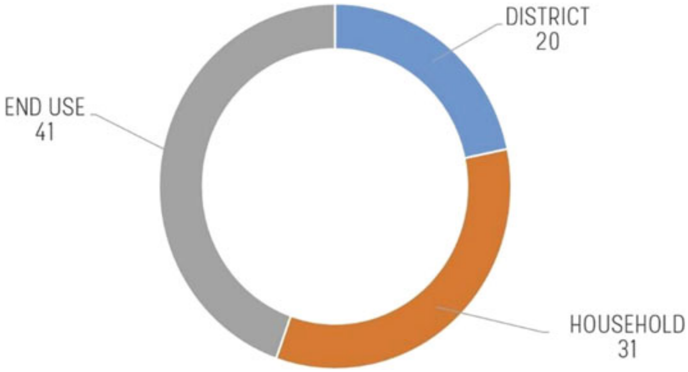

Fig. 1 Distribution of the 92 reviewed datasets across 3 spatial scales, i.e., district, household, and end-use. *Source* Authors

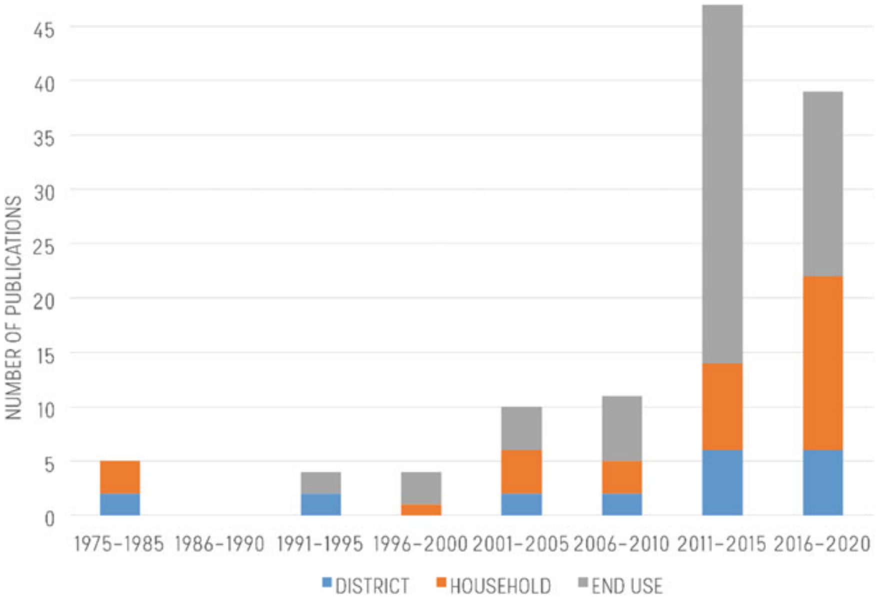

Fig. 2 Five-year count of the 120 scientific publications reviewed in the study Di Mauro et al. (2021)

3.1 District Level

A district is a part of an urban centre. The spatial scale of a district refers to a group of residential buildings in one or more municipalities. In many cases, districts coincide with water district meter areas (DMAs), which are sub-areas of a water network delineated by the closure of boundary valves. In the case of small towns or villages, the district and town scales may coincide.

District-level WDD are mainly used to study water network partitioning, estimate water balances [23], evaluate the hydraulic performance of the network system [24], improve the benefit of pressure regulation, and identify and locate leakages [25]. The aggregation level of these WDDs depends on the network configuration and/or DMA design and often refers to the water demand at the network nodes.

WDD collected at district level relate to specific areas of a water distribution network. They are primarily used to monitor aggregate water demand patterns in the network (for example to better understand the effects on peak water demand due to users' mobility), to provide input information for water distribution system simulation models or identify the best sensor placement in a partitioned water distribution network [26]. District-level WDDs are typically collected by water utilities for ad hoc analyses of specific case studies within their controlled water system facilities and are generally not released to the public, but only to researchers under confidentiality agreements.

Table 1 List of fixtures and methods of measurement

End points	Measured Yes/No	Methods
Washbasin	✓	IoT system
Bidet	✓	IoT system
Shower	✓	IoT system
Kitchen Faucet	✓	IoT system
Flush toilet	✗	App HTTP request shortcuts
Dishwasher	✗	App HTTP request shortcuts
Washing machine	✓	IoT system

A list of open datasets available at District scale can be found in Table 1 of Di Mauro et al. [13].

3.2 Household Level

The household level includes a single apartment or single-family home connected to an individual water meter. We also include multi-family dwellings in this category if they are connected to one water meter. Depending on the type of household, water consumption may be allocated to indoor use only or both indoor and outdoor use.

Household-level WDDs represent household consumptions and are primarily used to build descriptive and predictive models of water demand, estimate the timing and magnitude of peak demand events to manage the operation of the water network, and inform water conservation campaigns and demand management measures [27]. Water demand data collected at the household level deal with the spread of sensor technologies which allows data collection with a sub-daily temporal sampling resolution, down to a few seconds [28]. Household-level WDDs include at least some open and many accessible but restricted datasets. To protect the privacy of water consumers, data anonymization, access restriction, or access control filters are commonly used.

A list of open datasets available at Household scale can be found in Table 2 of Di Mauro et al. [13].

3.3 End-Use Level

The end-use scale refers to an individual water fixture within a single apartment/household. End-uses can refer to indoor (e.g., shower, dishwasher, toilet, etc.) or outdoor uses (e.g., garden, swimming pool, etc.). End-use level WDDs are used to improve our understanding of household water use patterns, develop disaggregation models to estimate the share of individual fixtures in household water use, develop tailored water demand management strategies and billing reports, and overall increase customer engagement and assist water suppliers and customers in promoting efficient water use [29, 30]. Water data at the end-use level are of great interest for behavioural studies and provide important information for promoting water conservation, designing water tariffs, promoting more sustainable resource use, characterizing peak water demand, and improving demand forecasting and management capabilities [20, 31].

End use-level WDDs are sparse and mainly restricted. Synthetic end-use data generation methods have been developed because of limited data availability. A list of open datasets available at End-use scale can be found in Table 3 of Di Mauro et al. (2021) [13].

4 Residential Water Demand Monitoring and Management

The general increase in total municipal water demand and interest in water scarcity in many developed and developing countries is prompting cities to search for new appropriate management strategies [32].

In the urban context, water consumption is distributed between domestic, agricultural, industrial and recreational uses. Although most water generally goes to the agricultural sector, household water demand already plays an important role.

As noted in Sect. 1 *General trend of decentralized water infrastructure systems: opportunities and challenges of modelling residential water demand*, population growth, combined with diminishing freshwater supplies and rising infrastructure costs, has led utilities to refocus on water demand management (RWDM) to control consumption.

Residential water demand management has been extensively studied over more than four decades, taking into account various aspects such as population demographics, water prices, regulations, household characteristics, weather, and social factors that influence consumers' habits and attitudes [33, 34].

RWDM provides detailed knowledge of household consumption patterns and thus enables predictive management of water supply, leading to significant savings in distribution and storage of water in the networks [35, 36]. It also provides the basis for new water demand management strategies aimed at reducing water consumption, reducing or shifting consumption peaks [11, 37, 38], and it can even help to better detect costly leaks in the water distribution network [25, 39, 40]. Identifying water leakage and waste at the household level is also a cost-effective tool for utilities to avoid the costs of leak detection campaigns, resulting in significant savings, e.g., in water waste, itself, and the associated energy required to treat and pump water in the distribution system [41]. Finally, RWDM can promote water distribution and consumption efficiency by analysing and predicting urban water demand [42–45].

These multiple opportunities offered by RWDM, combined with digital disruption and societal change in recent decades, have changed the way water is used and monitored in the residential environment, making RWDM a major challenge to support water efficiency and utility. One way to address this challenge is through advances in sensor and communication technologies that provide high-frequency data and improve many systems, including water system data analytics [14]. The integration of innovative smart technologies into the water sector has provided a large amount of data on water use that can be used to improve utility practices and make consumers aware of their water use [46].

Water consumption data collected in residential areas represent a significant value to both water utilities and water customers. From the water utility's perspective, residential water consumption data helps to assess detailed consumption patterns, improve leak detection, avoid significant network water storage and pumping energy costs, increase water conservation, define itemized bills, and improve demand forecasting. From a customer perspective, information on water use patterns associated with household appliances can help identify household leaks, increase user awareness of sustainable behaviours, prevent water waste, and generate cost savings on water bills.

5 Residential Water Consumption Monitoring at the End-Use Level: A Pilot Study Site in Naples (Italy)

Conservation and sustainability programs, with innovative smart sensors and new incentives for metering consumption, have increased the need for an easy-to-use predictive model for water resource management based on a better understanding of the factors that determine household water demand. Residential water demand management has taken on new importance with the need to better understand user behaviour, demand patterns, peak periods, the impact of seasonal and climatic conditions on water use, etc. [19, 47].

Motivated by the increasing attention to water use in the domestic environment from water utilities and policymakers to increase their governance but also to reduce supply-cost and establish customized billing, end-use studies are assuming a key role for water management. To reach a detailed understanding of how water is used in the residential environment, information on water fixtures' use is needed (i.e., water use for shower, toilet, tap, etc.). Due to the lack of inexpensive and non-invasive metering infrastructure, smart water meters are installed on water mains and provide aggregate water consumption data that must be disaggregated to obtain individual end-use categories [48, 49].

Disaggregation requires pointwise and high-resolution data to apply machine learning techniques [50]. Water use at the end-user level is one way to understand how and where water is used in households, and to explore and validate innovative solutions for disaggregation. Defining user behaviour can provide an opportunity for water utilities to improve water service and customer awareness [51].

Traditional water meters record water consumption at the household level and do not provide real-time end-user data that could understand user behaviour and help water utilities intelligently manage distribution systems. Despite innovative automatic meter reading, smart water meters (SWM) are unable to read consumption at the tap level due to high costs and time-consuming installations. Moreover, due to the complexity of assessing case studies [52], i.e., smart meters can be intrusive, create privacy issues and positional constraints, etc. In such a context, a case study of water consumption monitoring at the end-use level in a residential apartment sited in Naples (Italy) was developed with the aim of detecting and characterizing individual water usage at the fixture level.

5.1 Residential House Characteristics

This case study deals with the data collection of water end-use consumption in a residential apartment located in the historical centre of Naples (Italy). The flat is inhabited by one person and is equipped with seven fixtures: washbasin, bidet, shower, kitchen faucet, dishwasher, washing machine, and flush toilet. In order to monitor all water end-use consumptions, different solutions have been selected. In fact, due to positional constraints, the IoT water end-use monitoring system able to collect water consumption data is installed on all the fixtures at the pilot site except on flush toilet and dishwasher. These two fixtures have been monitored using an HTTP request shortcuts app.

The monitoring systems used for the case study are summarized in Table 1 and described in more detail in the following section.

5.2 An IoT System for Monitoring Residential Water End-Use Consumption

In this section, the flexible IoT based sensing and monitoring systems to detect water end-use consumption in the residential apartment are presented. The main characteristic of system architecture, installation and data collection are described. Moreover, in the supplementary materials, we report the links to the datasheets on the equipment used to assess the case study reported in this chapter.

5.2.1 Monitoring System Architecture Design and Implementation

As reported in Di Mauro et al. [53], the conceptual architecture of the IoT water end-use monitoring system is shown in Fig. 3. It is composed of three main elements: a flow sensor, a micro-controller and a Content Management System (CMS), which

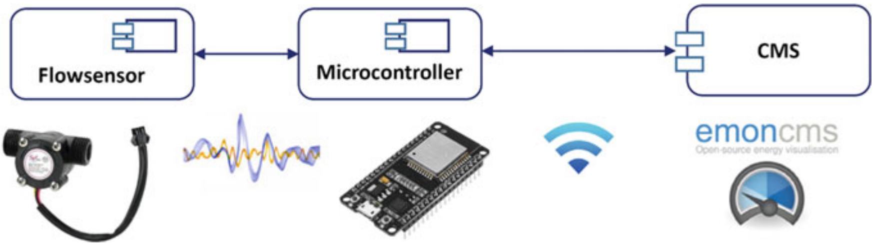

Fig. 3 Conceptual architecture of the IoT system. *Source* Authors

implements a data collection platform and integrates simple processing and visualization capabilities. The CMS can be deployed at the edge, in the user's household or in the Cloud, where it can handle data of different users.

The water flow sensor (WFS) used for the IoT node is the YF-S201. Flow sensor YF-S201 sits in line with the waterline and contains a pin-wheel sensor to measure the quantity of water passing through it. There is an integrated magnetic Hall-Effect sensor that outputs an electrical pulse with every revolution. By counting the pulses from the output of the sensor, it is possible to calculate water flow (each pulse is approximately 2.25 millilitres). The WFS comes with three wires: Red/VCC (5–24 V DC Input), Black/GND (0 V) and Yellow/OUT (Pulse Output) used to interface the sensor to any micro-controller.

The microcontroller used for the IoT solution is the ESP 32 a low-power system on a chip (SoC) series with both Wi-Fi and Bluetooth communication interfaces. The ESP32 has been programmed to read the output pulses coming from the WFS and to upload the water flow to the CMS. An interrupt service routine is used to count the WMS pulses in a time slot of 1 s. When the water flow is 0 for more than 5 s, the micro-controller switches to the stand-by mode and wakes up at the next pulse.

For flush toilet and dishwasher, due to positional constraints, it was impossible to install the SWM. So, to register water consumption of the flush toilet the user is asked to push a button on their smartphone. An open-source app has been configured to send to EmonCMS flush toilet cistern capacity value and dishwasher water use per cycle. The app allows for defining buttons shortcuts to invoke HTTP hyperlinks. The app screens are shown in Fig. 4.

SWMs have been installed and programmed to collect high-resolution data for all the fixtures present at the pilot site, see examples in Fig. 5.

5.2.2 *Water End-User Data Collection*

Data collection refers to water consumption data spanning from 1st March 2019 to 15th May 2021. The CMS used for the IoT solution is EmonCMS,[1] a flexible, open-source and user-friendly platform for collecting, visualizing monitored data and

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[1] http://www.emoncms.org.

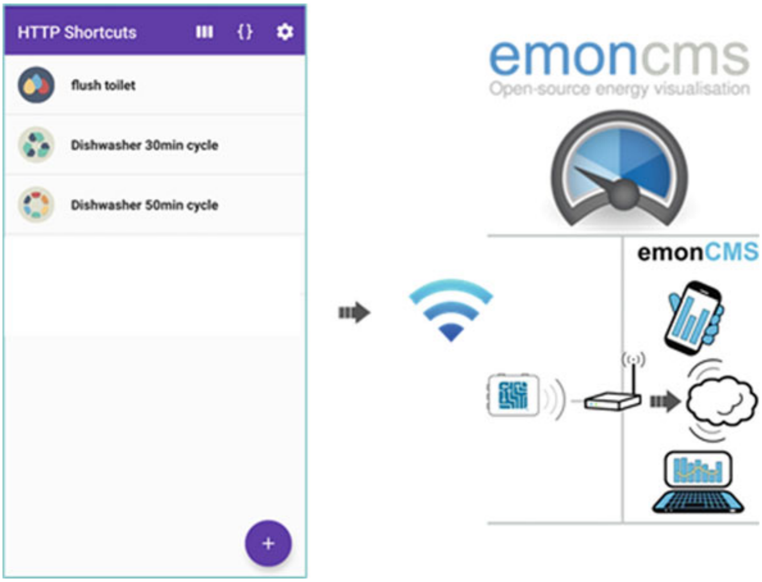
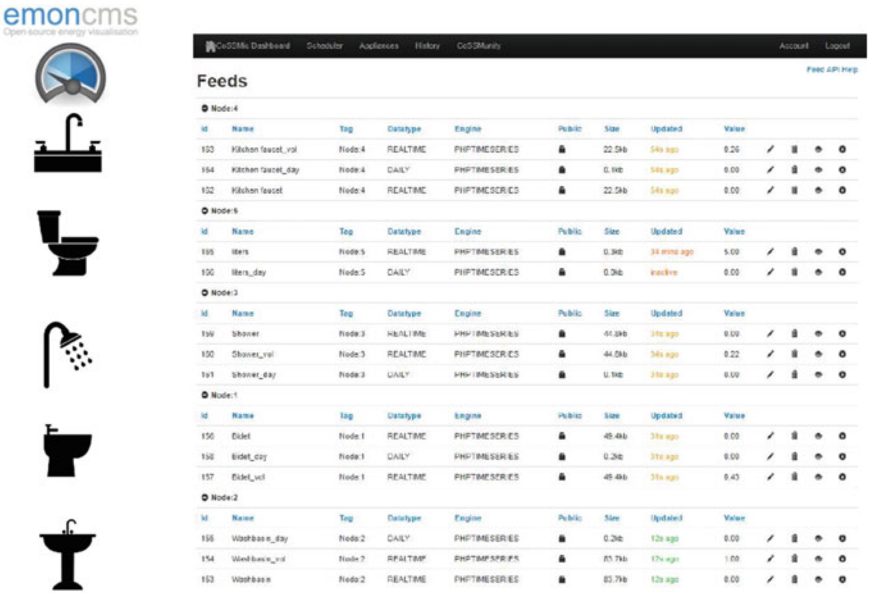


Fig. 4 HTTP request shortcuts architecture. *Source* Authors

Fig. 5 Shows an example of IoT system installation on water fixtures. *Source* Authors

remote controlling of devices. In the current deployment, water end-use consumption measures are detected real-time, processed and uploaded to a remote server via HTTP. Each metering node is directly connected to the Internet through the Wi-Fi home gateway. All data collected at the pilot site are stored and visualized through the EmonCMS platform. Figure 6 shows a screenshot of the EmonCMS page in which it can be possible to visualize that each node (Feed) is associated with a specific fixture.



Feeds

Node:4

Id	Name	Tag	Datatype	Engine	Public	Size	Updated	Value
163	Kitchen faucet_vol	Node:4	REALTIME	PHPTIMESERIES	🔒	22.5kb	54s ago	0.26
164	Kitchen faucet_day	Node:4	DAILY	PHPTIMESERIES	🔒	0.1kb	54s ago	0.00
162	Kitchen faucet	Node:4	REALTIME	PHPTIMESERIES	🔒	22.5kb	54s ago	0.00

Node:5

Id	Name	Tag	Datatype	Engine	Public	Size	Updated	Value
165	liters	Node:5	REALTIME	PHPTIMESERIES	🔒	0.3kb	34 mins ago	5.00
166	liters_day	Node:5	DAILY	PHPTIMESERIES	🔒	0.0kb	inactive	0.00

Node:3

Id	Name	Tag	Datatype	Engine	Public	Size	Updated	Value
159	Shower	Node:3	REALTIME	PHPTIMESERIES	🔒	44.8kb	31s ago	0.00
160	Shower_vol	Node:3	REALTIME	PHPTIMESERIES	🔒	44.0kb	34s ago	0.22
161	Shower_day	Node:3	DAILY	PHPTIMESERIES	🔒	0.1kb	34s ago	0.00

Node:1

Id	Name	Tag	Datatype	Engine	Public	Size	Updated	Value
156	Bidet	Node:1	REALTIME	PHPTIMESERIES	🔒	49.4kb	31s ago	0.00
158	Bidet_day	Node:1	DAILY	PHPTIMESERIES	🔒	0.2kb	31s ago	0.00
157	Bidet_vol	Node:1	REALTIME	PHPTIMESERIES	🔒	49.4kb	31s ago	0.43

Node:2

Id	Name	Tag	Datatype	Engine	Public	Size	Updated	Value
155	Washbasin_day	Node:2	DAILY	PHPTIMESERIES	🔒	0.2kb	12s ago	0.00
154	Washbasin_vol	Node:2	REALTIME	PHPTIMESERIES	🔒	83.7kb	17s ago	1.00
153	Washbasin	Node:2	REALTIME	PHPTIMESERIES	🔒	83.7kb	12s ago	0.00

Fig. 6 EmonCMS platform. *Source* Authors

The platform allows for evaluating and visualizing the daily use, the instantaneous flow and the total volume.

5.3 *Smart Monitoring System for Residential Water Household Consumption*

Disaggregation techniques useful to model water users' consumption behaviours and to forecast water demand also need high-resolution measures of aggregate consumptions. Such datasets are necessary to train disaggregation algorithms based on machine learning techniques, which can identify a correlation between aggregate and disaggregate data to avoid the placement of sensors at the end-use level in users' households.

Traditional household water consumption is typically recorded manually on a quarterly or half-yearly basis from water utility operators and does not allow for the identification of household events crucial to understand users' behaviours. Considering that, and the goal of creating a high-resolution end-use water consumption dataset, in our pilot site, a high-resolution water meter has been installed at the water mains to detect aggregate water consumption.

The Water Flow Sensor AXIOMA Ultrasonic Water Meter QALCOSONIC W1/F1 was installed in parallel with the traditional water metering at the pilot site, (Fig. 7). The ultrasonic water meter QALCOSONIC W1 is designed for accurate measurement of water consumption in households, apartment buildings, and small commercial premises. In Europe, it integrated the LORA technology. The flow meter was installed together with a LORA gateway for data transmission the MikroTik Routerboard wAP LoRa8 kit (Fig. 8). Axioma ultrasonic water meter QALCOSONIC W1 transmits with its LoraWAN radio 868 MHz a payload of 48 bytes with a frequency of 10 s. Data transmission was based on the LORA protocol. Figure 9 reports the architecture of the installed household sensor. Data are collected and stored by the same platform EmonCMS used for the end-use data collection.

The high-resolution flow sensor installed at the service line allowed for a comparison between the value measured at a single fixture level and the aggregate household consumption. The total water consumption, obtained by adding the consumptions of the fixtures, leads to an error of 5% in determining the total consumption value. It mainly depends on the water consumption estimated by the shortcuts of the HTTP requests. The app registers the value for the capacity of the toilet cistern and the water consumption of the dishwasher per cycle, which is given in the manuals datasheets. However, water consumption often depends on the operating conditions of the appliances at the time of measurement. For example, the water consumption of a dishwasher depends on many factors, such as water hardness, building pressure in the pipes, etc.

Fig. 7 High-resolution measurement and traditional water metering at the pilot site. *Source* Authors

Fig. 8 MikroTik Routerboard gateway. *Source* Authors

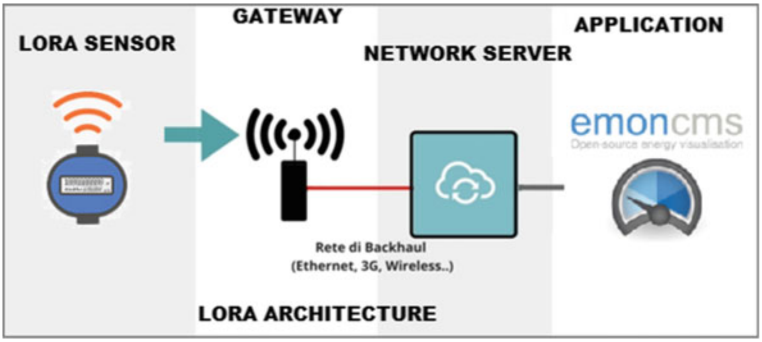


Fig. 9 LORA data transmission architecture. *Source* Authors

6 Residential Water Demand Modelling

As a result of the interest in the impact of human behaviour on water use, data generated by economic and social changes in recent decades, there has been an increasing interest in modelling end-user data to investigate how users manage water use. Extracting information about water use behaviour from smart meter data allows an understanding of how water is used in the domestic environment. Water demand studies require data that are readily available in formats that meet the needs of researchers, at relevant spatial and temporal resolutions that are useful for studying water issues. In addition, the available data need software and/or statistical tools to extract meaningful information that can be used for more effective decision making

[54]. The experimental case study described in the previous section contributes to these challenges providing an open water end-use dataset and software to model high-resolution data.

Moreover, several studies have been conducted in the water research literature that focuses on the application of end-use measurements to model RWD to assist water utilities with their management systems.

Currently, studies on residential water demand modelling address the following emerging issues: profiling users' behaviour, water end-use disaggregation and water demand forecasting. In the following, we introduce the main issue related to residential demand modelling, linking it to some applications developed or in progress based on the experimental case study.

6.1 Profiling Users' Behaviour

Modelling the consumption behaviour of water users is achieved by descriptive models, which aim to segment users by analysing observed water use patterns and historical trends [19, 55]. Profiling users' behaviour can lead to the identification of water use patterns and peaks discovering wasteful water use habits or water leaks, providing the basis for sustainable behaviour change and cost savings on water bills [22, 56]. The identification of customers' habits allows a more efficient water management based on resource-efficient initiatives.

The experimental case study in this chapter provides an example of how high-resolution data at the end-use level can be useful to understand user behaviour in the residential environment. Di Mauro et al. [57] describes the statistical analysis and summary measures used to analyse the data collected for the various fixtures at the pilot site over 8 months of observation. Each time series was processed to identify individual consumptions for each fixture, filtering out anomalies and outliers. Consumption as an individual event has been characterized by the amount of water consumed, the duration of the consumption, and the hour and day of the week on which the event occurred. The distribution of water consumption over months, weeks and days has been evaluated. Then, the distribution of probability expressing how often the event occurs on a particular day (that is the ratio between the numbers of event occurred on that day and the total number of events) is estimated with reference to a single fixture.

Here, we report some results of the statistical analysis which show the heterogeneity of fixtures' use during daily and monthly use. Figure 10 shows the distribution of probability related to the use of specific fixtures (kitchen) during weekdays for different months, and Fig. 11, shows number of uses during day hours for different fixtures evaluated over 8 months of measurements.

It is worth noting that the results presented in Fig. 10 represent the average distribution of probability for the observation period. The figure highlights a significant change in this distribution related to the habits of the users in each month that are influenced by climatic and seasonal variations, different timing of usage due to changes

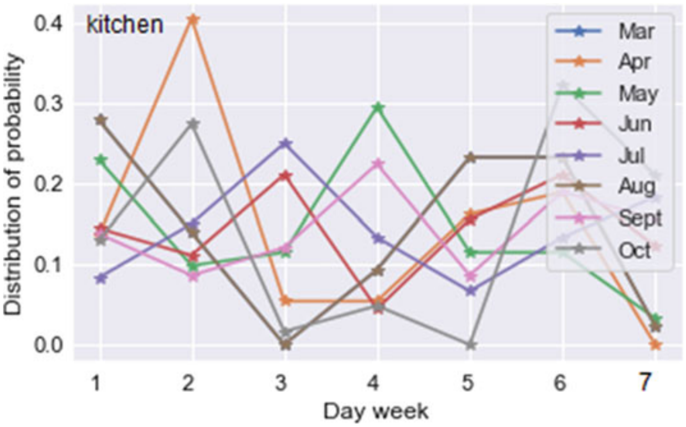


Fig. 10 Distribution of probability related to a specific fixture (kitchen) during weekdays, for each month of detection. *Source* Authors

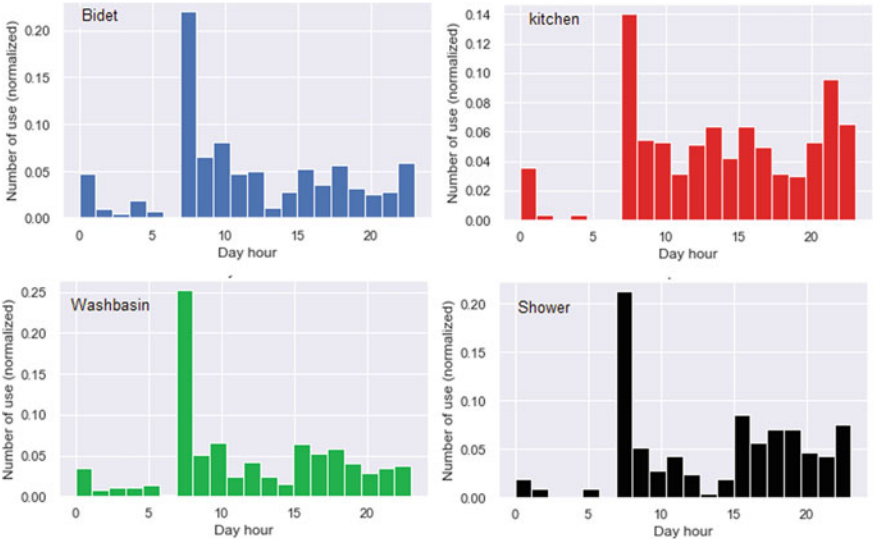


Fig. 11 Number of uses during day hours for different fixtures evaluated on 8 months of measurements. *Source* Authors

in personal habits, etc. Figure 11 shows that usage is concentrated between 7 and 10 a.m. and after 8 p.m., reflecting the profile of the user who is an employee and generally works throughout the day.

During the last two years, the importance of user profiling is underlined by the emergence of the COVID-19 pandemic, which has changed the lifestyle of an entire population and consequently the typical water consumption and behaviour. Recent studies of the impact of COVID-19 based on aggregate demand data have revealed a significant shift in peak demand as well as an increase in peak daily consumption [58, 59]. Although the difference in water use is due to the pandemic as people are forced to stay at home, it highlights how users' profiling represents a challenge for a water utility to understand the characteristics of increased water demand, implement a new demand forecasting model, and improve the service offered in the event of a change in socioeconomic parameters [60].

6.2 *Water End-Use Disaggregation*

Disaggregation is one of the most used non-intrusive metering techniques which allow us to understand how much of the household water use belongs to a single fixture in the home (Fig. 12). Disaggregation algorithms, also known as Non-Intrusive Load Monitoring (NILM) algorithms, aims to divide water consumption data metered at the household level into single end-use categories (i.e. shower, toilet, etc.).

One of the main interesting ways to model RWD is the use of disaggregation algorithms to break down overall household consumption data into different end-use categories [48, 61, 62]. Disaggregation plays a key role in end-use detection, as fixture-level sub-meters are too invasive, encouraging the use of non-invasive techniques and approaches. Disaggregation provides the opportunity to develop innovative demand forecasting models, generate detailed bills, and provide personalized savings recommendations that help utility segment customers [50, 63–65].

Our experimental case study contributes real water consumption data, both to the household (meter at water mains) and end-use (meter at fixtures) level, useful to test disaggregation algorithm to identify a correlation between aggregate (household) and disaggregate (end-use) data.

A disaggregation algorithm Factorial Hidden Markov model (FHMM) [66], already used in the energy sector, has been tested using 1 month of data collected at the pilot site to verify the application in the water sector.

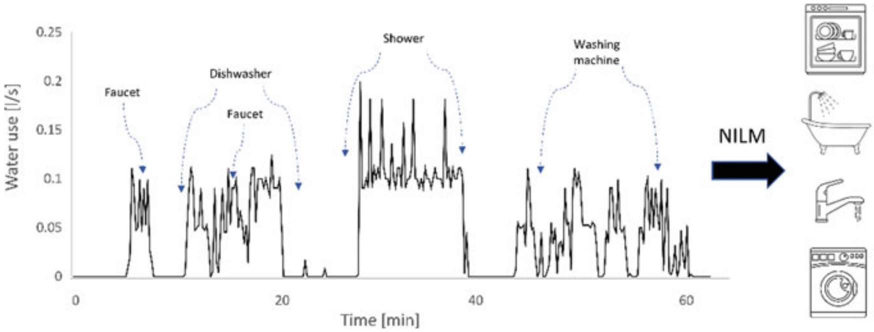


Fig. 12 Water end-use disaggregation scheme. *Source* Authors

FHMM allows to identify the most probable sequence of states (i.e., the consumption of each fixture) of a Markovian process when the examined system is formed of several sub-components (i.e. single fixtures as shower, dishwasher, etc.) and the state of the whole system is a combination of the hidden states of each sub-component. In FHMMs, each of the several fixtures of the system is characterized by a finite number of hidden states, described by a prior probability distribution and a matrix of transition probabilities between couples of states. Each fixture can thus be modelled with a Hidden Markov Model (HMM) [67]. Then, the HMMs of each fixture are combined in an FHMM, taking into account that there is a specific probabilistic relationship between the observation and the combinations of hidden states (i.e. emission probability). More details about the HMM and FHMM formulation can be found in Zoha et al. [67], Ghahramani and Jordan [66] and Mor et al. [68].

In order to explore to portability of the model from the energy to water sector, we performed an initial analysis considering that the number of states for each fixture is equal to two.

Figure 13 shows an example of fixtures disaggregation for one of the fixtures of the case study (shower). It reports an example of disaggregation for the fixtures shower on the entire period of analysis, the figure shows in blue the total aggregate consumption (water main reading), in orange the real consumption traces (GT ground truth) and in green, the FHMM predicted value (Predict).

In order to better understand, Fig. 14 reports a finer time scale for disaggregation of some fixture shower events in which a comparison can be made between the real traces of shower events with a predicted one. The figure shows in blue the real

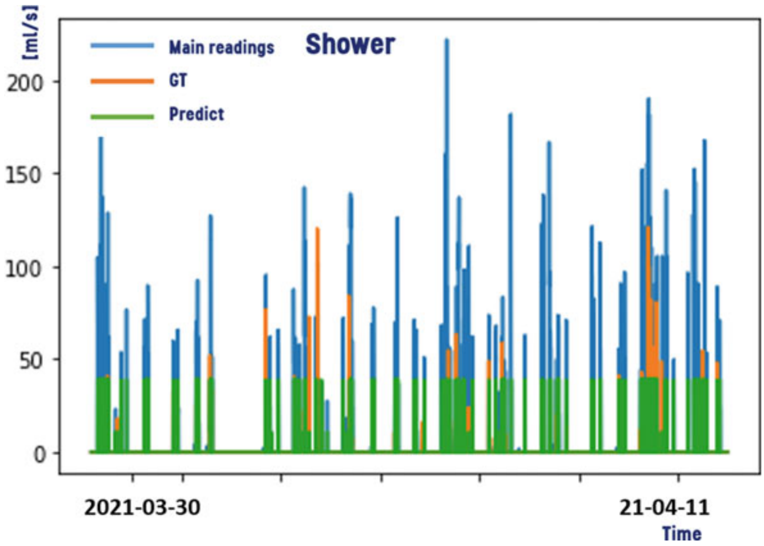


Fig. 13 Example of disaggregate water consumption profiles obtained through the FHMM algorithm for one of the fixtures: Shower. *Source* Authors

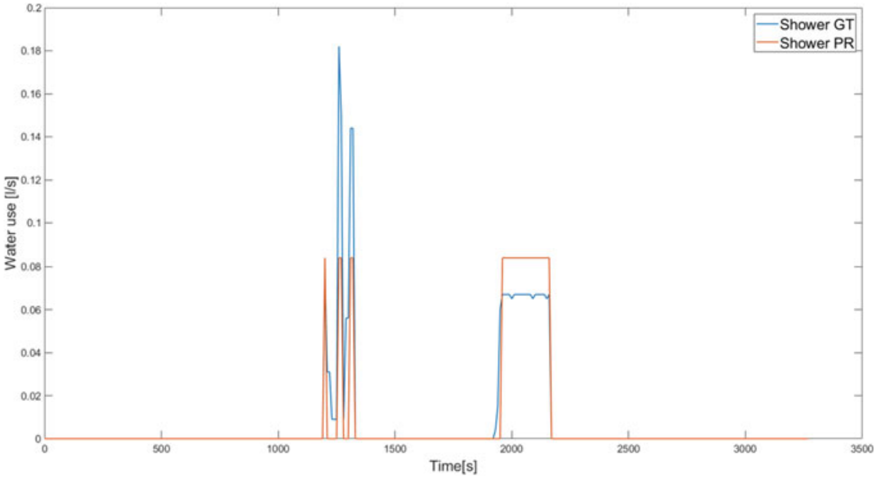


Fig. 14 Disaggregate water consumption events at a finer scale, obtained through the FHMM algorithm for one of the fixtures: Shower. *Source* Authors

consumption traces (GT ground truth), and in orange, the disaggregated FHMM predicted value (Predict). Here, we report only shower disaggregation as an example of the application of the disaggregation algorithm to real end-use water consumption. The preliminary results obtained show that the FHMM algorithm can estimate the use of the fixtures of the residential apartment. Nevertheless, looking at Fig. 14, showing the consumption trajectories estimated for shower fixtures by the FHMM algorithm, it is worth noticing that the predicted traces do not capture the peak.

This is related to two main aspects. First, for computational reasons, we have assumed for the application that the number of states for each fixture is equal to two (i.e. on/off category representing two states that refer to no use, and an on state that corresponds to a certain amount of water).

It is not easy to decide, from the start, which number of states is appropriate to accurately describe the consumption pattern of the different fixtures, since each fixture has its own consumption pattern and multiple states (i.e. washing machine and dishwasher) require a higher number of states to be properly modelled. As a result, the consumption trajectories estimated by FHMM for each fixture take the form of piecewise constant lines, i.e., only the on/off operating states are detected, while an accurate representation of the water consumption patterns is missing at this stage. However, this two-state result is not suitable to accurately reflect the consumption patterns that cannot be captured by a two-state sequence but allows to identify the specific fixture used [67].

Second, it is straightforward to observe that water data collected for each specific consumption point, differently from energy consumption, are conditioned by human activity and infrastructural condition (i.e. piping infrastructure pressure, degree of sink opening, etc.) and that the consumption will change over time. Further analysis on a real water consumption dataset will allow to test different disaggregation algorithms, already used in the energy sector, to understand how to better model water and energy traces.

The application of disaggregation algorithms to real water end-user data is an ongoing challenge. The initial results presented above with reference to the case study data are reported to illustrate the potential of high sampling frequency data, while further analysis on disaggregation (new algorithms, longer time series, etc.) are under development.

6.3 Water Demand Forecasting

The water demand forecasting approach deals with predictive models. Estimates of expected water demand at the household level may depend on socioeconomic, such as income, education, number of kids, etc., or on alternative plans to manage water demand. In the literature, various machine learning models for water demand analysis and forecasting have been proposed showing how they can be applied to better understand the spatial and temporal patterns of future water usage in order to improve system operations, plan future investment for system development, or forecast future revenue and expenditures [45, 69–71].

Our experimental case study was used to develop software made up by data analytics tools that can extract a water consumption profile and predict fixture usages. More details are presented in the following section.

7 A Water End-Use Consumption Dataset and Data Analytics Tools

The experimental case study presented in the previous section allowed the collection of real water consumption data with high temporal frequency. In the scientific community is emerging the need to find new approaches to data modelling to manage this type of data and enable smart water management. To this aim, our research developed a set of data analytics tools capable of managing raw data, splitting consumptions, calculating statistical analysis and modelling a water consumption profile for each device named Water End-use Dataset and Tools (WEUSEDTO) software. Both the dataset and the Python notebook are publicly available to support machine learning research for water data. WEUSEDTO is available in a public GitHub repository (https://github.com/Water-End-Use-Dataset-Tools/WEUSEDTO).

Data gathered at the pilot site refers to nine time series of raw data. They correspond to the fixtures that were monitored in the home used as a case study, and the total water consumption at home. The collected data have a resolution of 1 s for the disaggregated time series, and 10 s for the aggregated measurements. Water end-use data spanned 2 years from March 2019 to May 2021.

7.1 Software Description

WEUSEDTO represents a model for obtaining a parametric water consumption profile able to characterize a household in terms of fixtures usages. Moreover, it shows how the availability of water data at high-resolution can be applied to profile users and demand data forecasting (Fig. 15).

The model combines:

- a statistical approach to extract significant features to instantiate a consumption model,
- a clustering approach to classify water usages, and
- a regression approach to describe water end-use consumption usages representative of clusters.

Figure 15 reports, with more detail, an overview of the methods used to develop the software.

The upper box reports the methods used to synthetize a user profile consisting of:

- a statistical analysis of time series collected in order to obtain significant information on users' consumption behaviours (i.e. frequency of use of a fixture, fixture usages distribution, etc.),
- a time series clustering to classify similar usages in terms of water consumption.

The bottom box reports the methods used to large scale (several users, buildings, etc.) simulation consisting of:

- random generation of fixture usages occurrences,
- learning and prediction of cluster to predict fixture usages.

More details about WEUSEDTO are reported in Di Mauro et al. [72].

7.2 Software Modules

The software is organized by four Python packages: time series, model, learning and simulation, Fig. 16.

The time series modules detect when each fixture is used (start and end). A simple splitting function compares the samples to a threshold value. In addition, a more complex algorithm was developed to account for sensor transmission delays and to cut out uses with a volume below a specified defined value. Moreover, the module includes a function to perform statistical analysis and calculate significant parameters of each usage.

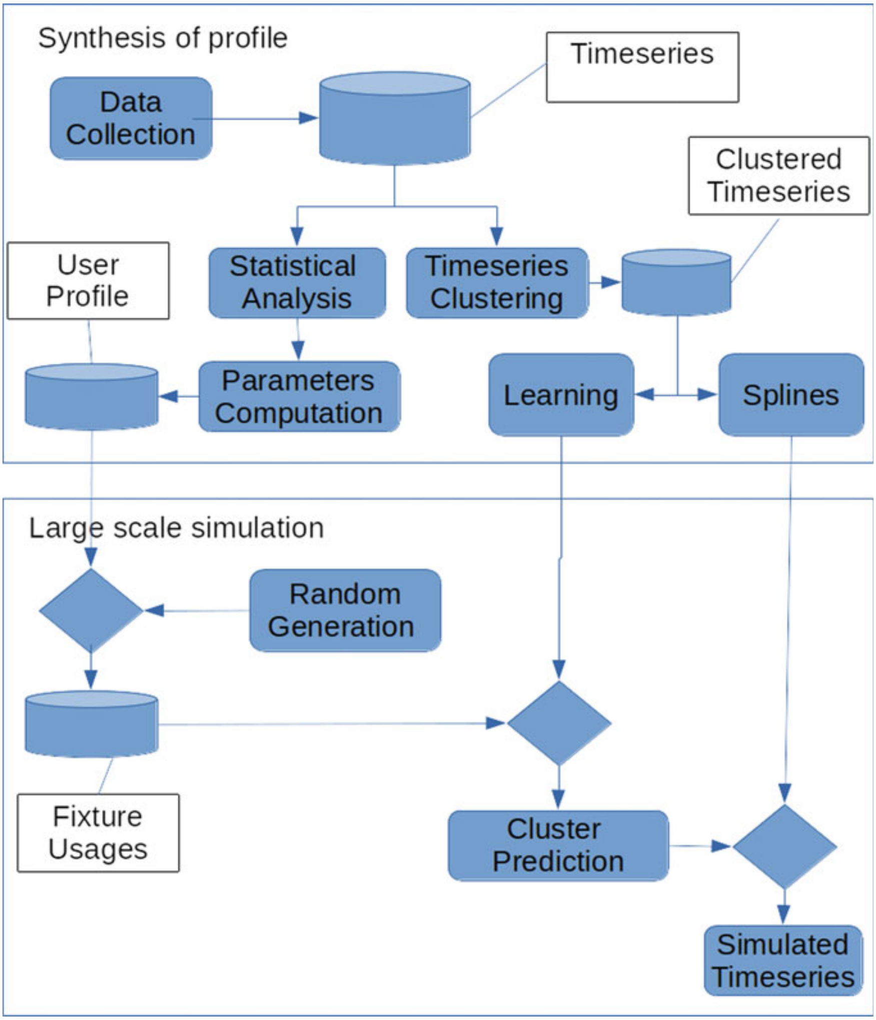


Fig. 15 Flowchart of the software methods from data collection to large scale time series simulation. *Source* Authors

The model module allows the extraction of statistical parameters from the set of detected uses to model user behaviour related to the use of single fixtures. Three types of user logs can be generated by the software: global, monthly and weekly usage.

The learning module uses machine learning techniques for time-series clustering and for the prediction of fixture usages.

The simulation module uses the models created in the model module and machine learning techniques (clustering and random forest) to simulate the water use of

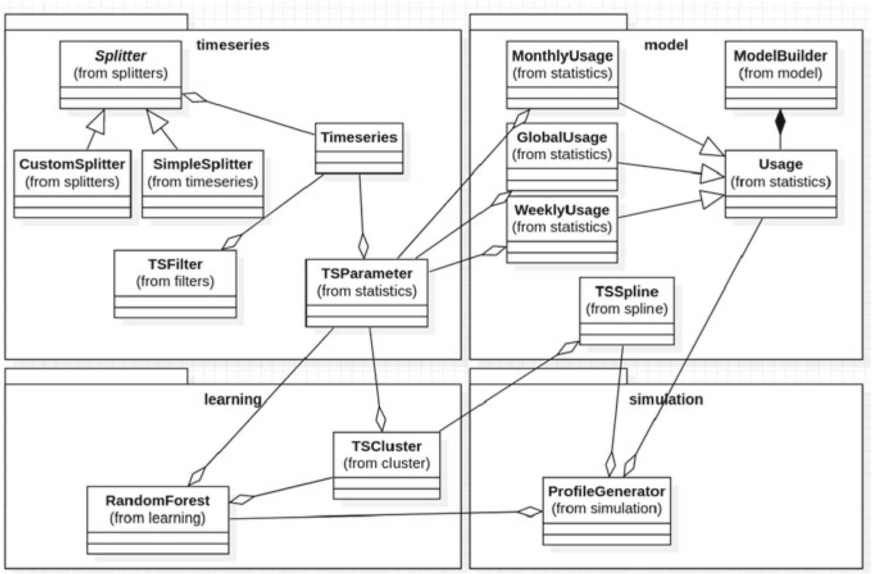


Fig. 16 Software architecture. *Source* Venticinque S. (The image is realized for this chapter by the authors)

multiple users whose behaviour can be equated with the behaviour obtained from the measurements.

More details about WEUSEDTO modules and functionalities are reported in Di Mauro et al. [72].

8 Conclusion

Urban water infrastructures consist of drinking water, wastewater, stormwater and remote monitoring system which are generally treated as centralized facilities. Recent water strategies include several initiatives to reduce water consumption and face water scarcity based on decentralised systems that encourage users to adopt water reuse, conservation and stormwater treatment technologies [73].

The interaction between water systems and customers is one of the reasons that drive the decentralization of urban water infrastructure. Water demand-side management and home water demand monitoring play an important role in ensuring reliable water supply, lowering water utility costs, and improving infrastructure development and network efficiency.

In this chapter, we presented a pilot site of a decentralized water monitoring system that allows individual households to check the water consumption of each fixture in real-time. Several studies on the topic reported how improving consumer behaviour at home, by informing users of their end-use consumption and saving measures, can save a significant percentage of household electricity and water use on the average helping decentralized water infrastructure development.

Furthermore, we have discussed how the technological innovation in the construction of water management systems is accelerating.

Consequently, the research efforts are spent to develop methodologies and techniques, which can exploit the large amount of available information. However, the availability of pilot cases and public datasets offering high-resolution measurements is still limited. In this chapter, we demonstrated how the application of the IoT solution to a residential apartment, even with one inhabitant, enabled understanding the limitation of the method that can be improved for the application in different and more complex pilot sites such as different residential apartments (i.e., flats, terrace house, etc.), with a different number of inhabitants (i.e. a couple, a family, group of friends, etc.), or non-residential building. This novel possible application will allow to test the IoT solution in a more complex configuration and customer's behaviour to identify consumer's profiles.

A second challenge for the case study could be related to the battery life of the smart meters. The new smart meters being deployed by water utilities at the household and district level are battery-powered. Due to difficulties in accessing the water assets, many water utility companies employ battery-powered nodes, which restrict the use of high sampling rates as reported in this reference paper [74]. Data resolution has a major impact on battery life. Here, battery life analysis for the monitoring system developed in the case study could be of interest to both utilities and sensor manufacturers.

Finally, the case study could be used to explore water users' feedback on the system and consumption. User comments about the intrusiveness of the system and awareness of water consumption can assist utilities in water conservation campaigns to avoid water waste and promote sustainable behaviours. Moreover, applications developed and in progress related to residential water demand modelling are introduced highlighting how data sampled with high temporal frequency can offer new possibilities on disaggregation techniques, demand-side management and forecasting.

Supplementary materials: Here we reported the links to the datasheets on the equipment used to assess the case study reported in this chapter:

- Flow sensor YS-201: https://components101.com/sensors/yf-s201-water-flow-measurement-sensor
- Microcontroller ESP32: https://www.espressif.com/sites/default/files/documentation/esp32_datasheet_en.pdf
- Water Flow Sensor AXIOMA Ultrasonic Water Meter QALCOSONIC W1/F1: https://www.axiomametering.com/en/products/water-metering-devices/ultrasonic/qalcosonic-w1
- MikroTik Routerboard gateway wAP LoRa8 kit: https://mikrotik.com/product/wap_lr8_kit

Disclaimer: Mention of the product, vendors and trade names in this chapter are only for research and education purposes, and does not constitute an endorsement by the authors of this chapter and/or editors of this volume.

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

Kathy DeBusk Gee and Sarah Sojka

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

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

1 Introduction

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

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T. Younos et al. (eds.), *Resilient Water Management Strategies in Urban Settings*,
Springer Water, https://doi.org/10.1007/978-3-030-95844-2_5

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

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

2 Water Supply Benefits

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

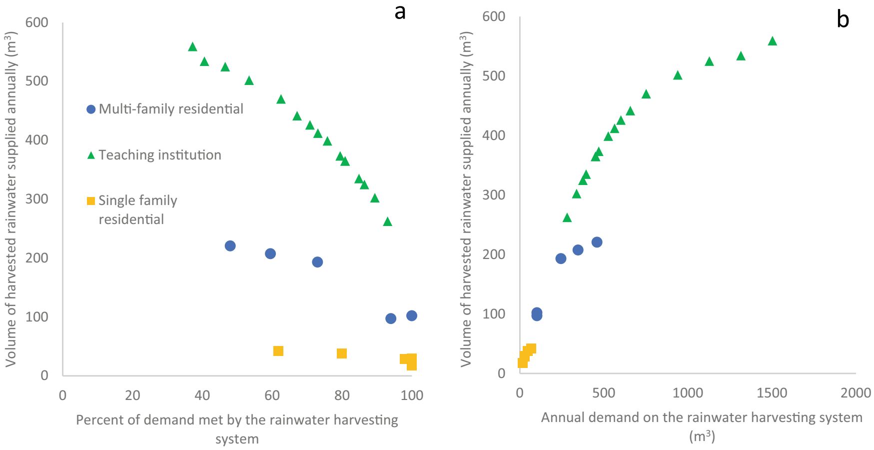

Fig. 1 The relationship between volume of water supplied by rainwater harvesting systems **a** the percent of demand met by the system (water saving efficiency) and **b** the annual volumetric demand on the system. *Source* created by the authors using data from [7, 11]

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

2.2 Optimize the Tank Size

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

2.3 Use the Harvested Rainwater for Multiple Uses

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

2.4 Consider the Impacts of Climate Change

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

2.5 Consider the Interaction of Factors

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

3 Stormwater Management Benefits

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

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

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

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

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

3.1 Account for Location

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

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

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

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

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

3.2 Maximize and Optimize Water Demand

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

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

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

3.3 Consider Active or Passive Release

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

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

3.4 *Combine RWH with Other Stormwater Management Practices*

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

4 Financial Benefits

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

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

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

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

4.1 Maximize Water Supply Benefits

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

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

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

4.2 Prioritize Replacing High-Cost Water

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

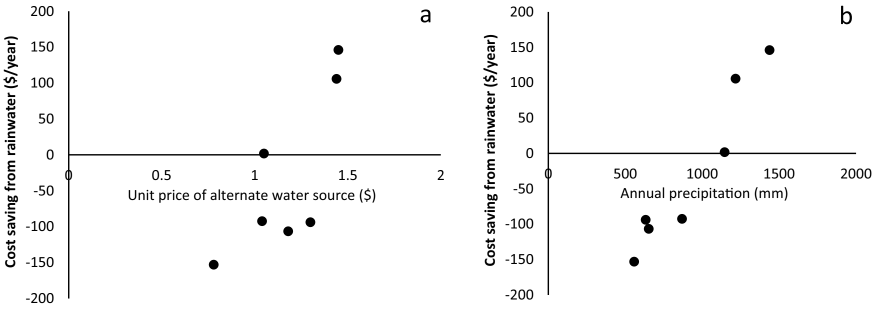

Fig. 2 Lifecycle costs of rainwater harvesting systems in seven cities in Australia with varying **a** water costs and **b** precipitation. *Source* created by the authors with data from [49]

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

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

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

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

4.4 Incorporate RWH into the Stormwater Management Plan

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

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

4.5 Consider Ancillary Benefits

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

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

5 Additional Benefits of RWH Systems

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

5.1 Reduction of Combined Sewer Overflows

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

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

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

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

5.2 Energy Consumption

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

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

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

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

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

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

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

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

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

5.3 Climate Change Adaptation

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

6 Case Studies

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

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

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

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

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

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

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

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

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

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

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

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

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

Components of this system are shown in Fig. 3.

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

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

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

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

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

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

6.2 Case Study: Warrenton-Fauquier Airport, USA

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

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

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

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

6.3 Case Study: Market at Colonnade

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

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

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

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

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

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

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

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

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

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

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

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

6.4 Case Study: Ecovillage at Currumbin

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

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

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

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

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

7 Conclusion

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

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

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

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Pathway to Scaling up Onsite Non-potable Water Systems

Paula Kehoe and Taylor Nokhoudian

Abstract Water is a defining issue of our time. Water and sanitation systems are stressed as infrastructure systems are aging, climate and weather patterns are changing, and populations are moving and rapidly growing. The ability to provide reliable, safe water and sanitation services is becoming increasingly difficult for communities across the world. This chapter focuses on localized solutions to treating water onsite for reuse on a small scale. Utilities can enable and allow decentralized, neighborhood-scale water treatment systems by creating shared responsibility and ownership of managing water resources within the community. This chapter highlights numerous examples from around the world, projects and lessons learned so that they may share proof of concepts to encourage transformation. Looking to the future, opportunities exist for localized systems to not only produce non-potable water, but become vehicles for resource recovery, tapping into the potential for thermal heat, nutrient and biosolids recovery, as well as a potential source of drinking water.

Keywords Resource recovery · Onsite non-potable water system · Water reuse · One water · Circular economy

1 Introduction

Water is a defining issue of the 21st Century. Water and sanitation systems are increasingly stressed as infrastructure systems are aging, climate and weather patterns are changing, and communities are rapidly growing. As a result, the ability to provide safe and reliable water and sanitation services is becoming increasingly difficult for urban and rural communities across the world.

This chapter highlights global challenges for water and sanitation services, as well as localized solutions to treating wastewater for reuse on a smaller, decentralized scale. Key examples from the U.S. highlight onsite water reuse as a strategy to assist with solving water and sanitation challenges. Utilities and governments can

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T. Younos et al. (eds.), *Resilient Water Management Strategies in Urban Settings*,
Springer Water, https://doi.org/10.1007/978-3-030-95844-2_6

expand traditional water portfolios by enabling decentralized, neighborhood-scale water treatment systems. These onsite water treatment systems can create a shared responsibility of managing water resources within a community.

Numerous people around the world were contacted to share their stories, projects, and lessons learned so that they may share proof of concepts to encourage transformation in the water sector. Additionally, opportunities exist for localized systems to not only produce non-potable water, but become vehicles for resource recovery, tapping into the potential for thermal heat, nutrient and biosolids recovery as well as a potential source of drinking water.

Section 2 of this chapter starts with an examination of global water and sanitation challenges and the limitations of a twentieth century model of managing water and sanitation systems. Section 3 discusses the need for rethinking traditional approaches and to imagine new partnerships and business models to help solve our water challenges. The concept of onsite non-potable water reuse is introduced and the benefits and a few case studies are explored. Section 4 focuses on San Francisco, California, USA as a prime example of transforming water management through onsite water reuse. This section also discusses San Francisco's efforts to lead a national collaborative of municipalities, water utilities, and public health agencies that is advancing onsite water reuse in North America. Section 5 highlights key U.S. policies and regulations for onsite non-potable water systems. Section 6 reviews important considerations for implementing onsite non-potable water systems. Section 7 covers a variety of innovative examples from around the world of onsite water reuse. Section 8 concludes the chapter by expanding on additional resource recovery opportunities.

2 Water and Sanitation Challenges

In many parts of the world, the approach to water and sanitation services incorporates large-scale centralized systems with extensive piping networks. Water networks are designed to transport water from great distances, often requiring significant energy to pump the water to urban centers. In many cases, another network of piping is built to discharge the wastewater away from urban centers. This linear approach of "water in and water out" became the norm during the late nineteenth century, and continued throughout the twentieth century. This historical approach became common practice for many good reasons: providing clean sources of fresh water to consumers and discharging polluted waters far away from humans to protect public health.

Today, the centralized design of urban water management systems in the United States (U.S.) poses significant and increasing economic, social and environmental costs to the communities they serve [1]. Within the U.S., drinking water systems comprised of over 3.5 million kilometers of underground pipes are aging and underfunded; and there is a water main break every two minutes and an estimated 22.7 million m^3 of treated water are lost each day [2]. Furthermore, according to the American Society of Civil Engineer's 2020 economic study, the annual drinking water and wastewater investment gap will grow to $434 billion USD by 2029. Given the costs associated with aging infrastructure, many cities struggle to provide safe water at an affordable rate [1]. Additionally, while substantial progress has been made in the U.S. to ensure access to clean drinking water and sanitation, billions of people around the world—mostly in rural areas—still lack these basic services.

Safe drinking water and sanitation are recognized as basic human rights. However, according to the United Nations, 3 in 10 people lack access to safely managed drinking water services and 6 in 10 people lack access to safely managed sanitation facilities. Moreover throughout the world, more than 80% of wastewater resulting from human activities is discharged into rivers or seas without any pollution removal. To meet the future needs for water supply and sanitation worldwide, it has been estimated that $6.6 trillion USD will be needed by 2030, and another $22.6 trillion USD by 2050 [3].

In addition to the challenges stemming from neglected capital investments, insufficient infrastructure refurbishments, affordability concerns, and resource inefficiencies and vulnerabilities, conventional water systems are also inherently limited by their centralized design [1]. These large-scale systems were built for conditions very different than the conditions we face in the twenty-first century. Extreme weather events have brought dramatic flooding and drought conditions degrading water quality and threatening public health throughout the world. To deal with the impact and drivers of climate change, communities need to make substantial changes in the way the Earth's limited resources are used and reused [4].

The United Nations estimates that the world's population is expected to increase to over 9 billion people by 2050, with the number of people living in urban areas expected to double to over 6 billion [5]. Managing the supply and availability of water is one of the most critical natural resource issues facing the world, and with the rapid pace of urbanization, new approaches to urban water supplies are urgently needed. Centralized systems are not flexible and are difficult to scale up with rapid population growth, and solutions that focus solely on centralized water and sanitation systems may have limited success as large systems take a long time to plan and installing large-diameter pipes beneath city streets is a massive undertaking, both financially and logistically [5].

3 New Approaches to Old Problems Are Needed

Centralized water and wastewater systems are one of the most significant public health advancements of our time. However, to meet our water and sanitation challenges in the future, it will require us to transform not just our water infrastructure, but how we think about water in creating opportunities to engage and mobilize local communities. These changes ultimately will require that we manage water in different ways and adapt our traditional governance and utility business practices with water utility leaders proactively seeking new management approaches, partnerships, and business models. By reimagining their traditional role, utilities can become more active partners to ensure that water management practices advance economic growth, environmental sustainability, and equity in their communities.

3.1 Adjust Our Thinking

Existing water systems are often inefficient, from catchment to consumer and back to catchment, water is lost, polluted, wasted, and misused [6]. Transitioning to a new approach requires us to adjust our old ways of thinking to develop a new vision for delivering water and sanitation services. This new path forward includes integrated water management approaches such as *One Water* or *Circular Economy*. *One Water* is based on the concept that all forms of water in an urban area (e.g. rainwater, groundwater, surface water, drinking water, or used water) are linked and form a system that is best managed in an integrated fashion to provide effective urban water services [7].

The good news is that water managers across the world are incorporating *One Water* approaches. Many water utilities are incorporating innovative strategies to conserve, reuse, and diversify their water supplies to address the needs associated with rapid urbanization. For example, water utilities are actively working with customers to install low flow fixtures in their homes and businesses to reduce their water consumption. Many are treating wastewater to irrigate golf courses, parks, and agriculture. Some are incorporating desalination facilities, and a growing number of utilities are turning to treating wastewater to supplement traditional drinking water supplies. Concepts such as local water, onsite water reuse, nutrient recovery, and biogas generation are being integrated into the utility's water supply and wastewater planning. Cities such as San Francisco USA have embraced *One Water* by adopting a more holistic and integrated approach to water and wastewater management. Other cities such as Los Angeles and New York have also incorporated *One Water* approaches that emphasize integrated resource management.

Circular Economy refers to shifting from a conventional mode that has been designed for linear production and consumption patterns to a model that supports the transition to renewable resources and less dependence on finite resources [6]. Systems thinking and environmental stewardship are core concepts to *Circular Economy* and for the management and supply of water [8]. Similar to the *One Water* approach, the *Circular Economy* approach to water includes integrated resource management, connecting to stakeholders, innovation, new business models, and utility leadership.

3.2 Localized Solutions

Now more than ever, we have an opportunity to build and manage our cities to be more resilient and sustainable with localized (i.e., decentralized) solutions. Localized solutions can include capturing and treating water onsite, or on a smaller scale than what traditionally occurs with complex centralized water and wastewater systems. For example, we can re-think building designs, re-imagine how water can be used more efficiently, and create new, local water supplies by utilizing decentralized, onsite water treatment systems. These localized solutions create opportunities for shared responsibility over water systems between the government and communities.

Buildings are sources of water and produce a variety of alternate sources of water including rainwater, stormwater, foundation drainage, graywater, and blackwater (see Fig. 1 for definitions of these alternate water sources). When collected and treated properly, these water sources can be used for non-potable applications such as toilet flushing, irrigation, and cooling towers. Onsite water treatment systems embody the *One Water* principle of matching the right resource to the right use because it promotes treating water to the appropriate level that is needed for its end use. Moreover, these systems can transform the way water is managed in buildings. For example, onsite water systems can reduce potable water use up to 45% in residential buildings, and up to 75% in commercial buildings [9].

3.2.1 Building and Neighborhood Examples

One of the early adopters of onsite water reuse systems in San Francisco, California, USA was the San Francisco Public Utilities Commission (SFPUC). In 2012, to demonstrate a commitment to water efficiency and innovation in its new headquarters building, the SFPUC incorporated two separate non-potable water systems. Combined, the two non-potable water systems reduce the SFPUC building's potable water usage by approximately 50%. The first system is a rainwater harvesting system that captures rainwater in a 94,635 L cistern, treats, and uses it for landscape irrigation. The second system is a constructed wetland system that treats all of the building's wastewater using a series of tidal and vertical flow wetlands. Known as the *Living Machine* (Fig. 2), the SFPUC's wetland system treats about 18,927 L per day of wastewater, which is then pumped for reuse for toilet and urinal flushing throughout the building [10].

In addition to SFPUC's *Living Machine*, there are other innovative onsite reuse systems being implemented elsewhere. The Hassalo on Eighth development in Portland, Oregon, USA is a four-block sustainable urban district treating and reusing wastewater using a constructed wetlands system (Fig. 3). The system produces treated, disinfected wastewater that is reused for toilet flushing, cooling tower make-up water, and landscape irrigation [11].

Beijing, China and Japan are also challenged with water scarcity. Faced with rapid urban growth and intense stress on its water supply, Beijing is turning to onsite water recycling. In Beijing, it is required that new residential developments over 30,000 m^2 incorporate onsite water recycling. Whereas in Japan, as of 2003, more than 1,000 commercial buildings and apartment complexes have installed onsite water recycling systems to reuse wastewater for non-potable applications [12].

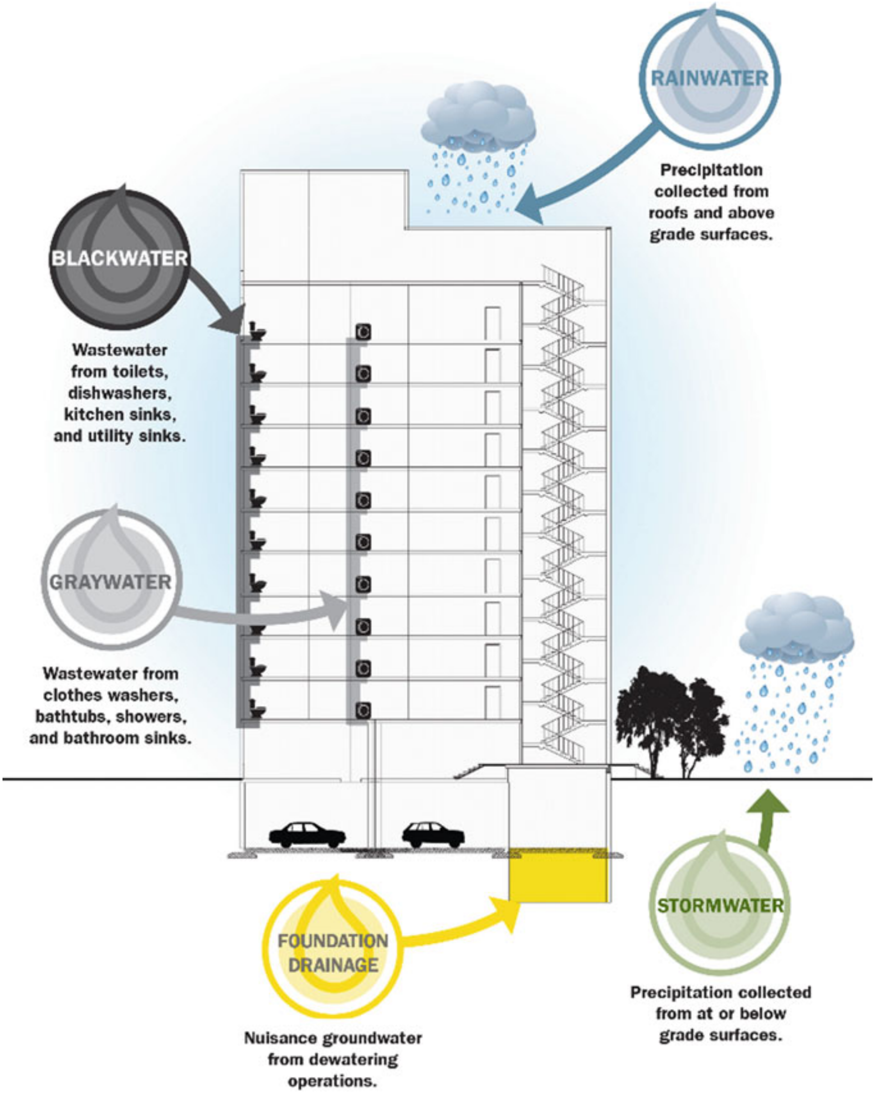

Fig. 1 Types of alternate water sources produced by buildings. *Source* Author

3.2.2 Commercial Brewery Example

Water collection and treatment is not limited to the building sector. It most certainly can apply to commercial and industrial applications. Water plays an important role in breweries, as it makes up more than 90% of the product and is used for numerous applications. Brewers know the value of water, as a typical brewery can use up to 26 L of water to produce about 4 L of beer. Much of this water is used for rinsing bottles

Fig. 2 *Living machine* at SFPUC headquarters in San Francisco, CA. *Source* Author

Fig. 3 Hassalo on Eighth in Portland, OR. *Source* Public Domain

and cleaning equipment. This type of water, also known as 'process water', can be collected and reused onsite at the brewery. Treating and reusing process water onsite can help breweries reduce their water footprint by as much as 50%.

However, breweries receive limited guidance in how to safely reuse process water onsite. In San Francisco USA, breweries interested in process water reuse looked to the SFPUC for help. To address this gap, the SFPUC developed guidance materials, including pathogen and chemical control strategies for process water to be reused for tank and bottle rinses, floor wash down, boiler feed water, and as a source water for the beer. The guidance includes requirements for source water characterization, source control, treatment, and ongoing monitoring to ensure the water is safe for these uses. The guidance also ensures the same level of public health protection as the California drinking water standards for chemicals, and is consistent with the risk-reduction goals of the California drinking water standards for microbial pathogens.

In California, several innovative breweries have implemented process water reuse onsite in order to use water more efficiently. In addition to saving water, brewery process water treatment systems can also reduce the volume and strength of discharges to the sewer system, which can help breweries reduce their sewer bills and comply with local regulations. Some examples include Seismic Brewing Company in Santa Rosa, California, USA (Fig. 4) that is recycling 95% of process water generated onsite for applications such as cleaning and boiler feed water, Anchor Brewing Company in San Francisco, California, USA, Stone Brewing Company in Escondido, California, USA and Lagunitas Brewing Company in Petaluma, California, USA.

Fig. 4 Seismic Brewing Company in Santa Rosa, CA. *Source* Public Domain

3.3 *Realizing Benefits*

By integrating smaller, decentralized, onsite water systems with broader centralized systems, utilities can improve their ability to respond to disruptions in water service delivery that may come as a result of drought, increased storm events, or other impacts of changing climates. For example, Superstorm Sandy in 2012 proved the resilience of distributed systems. The New York/New Jersey region of the U.S. was hit hard by flooding, knocking out many of the low-lying centralized sewage treatment facilities, but dozens of onsite, distributed wastewater recycling systems in the region (i.e., decentralized systems) were all back up and running on generators 24 hours after the storm [5]. With this added redundancy and flexibility, our water and wastewater systems can be more resilient and better equipped to reliably serve our communities in the future.

Additional opportunities of localized water reuse systems include:

- Matching the right resource to the right use, significantly reducing the use of drinking water for non-potable demands;
- Capturing rainwater and stormwater to help reduce runoff from entering drainage systems during storm events;
- Reducing energy needs as less pumping of water is needed;
- Responding to rapidly growing communities as compared to public investments in centralized infrastructure;
- Providing additional benefits through resource recovery opportunities, such as producing thermal energy;
- Mobilizing and engaging the community, civil society, and corporations in the management of water;
- Reducing capital expenditures for utilities, and mobilizing private investment for public benefit; and
- Enhancing resiliency by creating hybrid systems with decentralized water systems connecting to centralized infrastructure.

Communities throughout the world are already embracing decentralized water systems and the technology to recycle water onsite is available in the marketplace. As these systems scale up, it is critical to ensure public health protection. As these systems are generally operated by the private sector, oversight and management are critical to ensuring public health protection. The role of governance in protecting public health and additional examples of onsite water reuse projects will be explored in later sections.

4 San Francisco, California, USA, Leads the Way

Understanding the importance of water supply diversification, the SFPUC is actively embracing integrated water resources management by developing local water supplies, including water conservation, groundwater, recycled water, and onsite water reuse.

4.1 Transforming Water Management with Onsite Water Reuse

Led by the efforts of the SFPUC, San Francisco became the first municipality in the USA to adopt a groundbreaking program that encourages buildings to collect, treat, and reuse water onsite to meet non-potable demands such as toilet flushing and irrigation. San Francisco's Onsite Water Reuse Program established a streamlined process for allowing alternate water sources, such as rainwater, stormwater, foundation drainage, graywater, and blackwater, to be reused in commercial, mixed-use, and residential buildings. The SFPUC piloted the city's first onsite blackwater treatment system at their own headquarters in 2012 for toilet and urinal flushing (see Sect. 3.2.1 above).

Following this success, the SFPUC supported the implementation of onsite non-potable water systems in other buildings by establishing local oversight and management for public health protection. Implemented by four city departments, the Onsite Water Reuse Program is a successful example of investing in collaboration and eliminating barriers to using water more efficiently. It's important to note that the first step was to establish a city ordinance that clarified the roles and responsibilities of each city department—SFPUC, San Francisco Department of Public Health-Environmental Health (SFDPH-EH), San Francisco Department of Building Inspection (SFDBI), and San Francisco Public Works (SFPW). The Non-potable Water Ordinance helped to smooth conflicts about jurisdiction and authority and promoted inter-agency cooperation. SFDPH-EH is the key enforcement agency and is responsible for issuing water quality requirements, reviewing engineering reports, and issuing permits-to-operate for the onsite non-potable water system, among other important responsibilities. SFDBI oversees construction and reviews plumbing plans. When a district-scale or neighborhood-scale system is proposed, SFPW reviews utility conflicts in the street and issues an encroachment permit for infrastructure located in the public right-of-way. SFPUC is the program administrator and is responsible for approving water budget applications, potable water offset tracking, and managing a robust cross-connection control program. The four city agencies collaborate on an ongoing basis to review projects, discuss ways to improve communication, and further streamline the permitting process. SFPUC developed the *Onsite Water Reuse Program Guidebook* to assist projects with the permitting process (available at https://sfpuc.org/construction-contracts/design-guidelines-standards/onsite-water-reuse) [9].

While the program began on a voluntary basis, the installation and operation of onsite water systems was made mandatory in 2015 for new development projects with a footprint of 23,225 m^2 or greater.

Table 1 Evolution of San Francisco's Non-potable water ordinance (*Source* Author)

September 2012	The City and County of San Francisco adopts Article 12C in the San Francisco Health Code. Also known as the Non-potable Water Ordinance, it established an oversight program to allow the onsite collection, treatment, and use of alternate water sources for non-potable applications at the building scale
October 2013	The Non-potable Water Ordinance is amended to allow district-scale non-potable water systems consisting of two or more buildings sharing non-potable water
July 2015	The Non-potable Water Ordinance is further amended to mandate the installation of onsite non-potable water systems in new developments 23,225 m^2 or greater
December 2016	The Non-potable Water Ordinance is amended to clarify the requirements for implementation of district-scale non-potable water systems

4.2 Timeline of San Francisco's Non-potable Water Ordinance

To streamline the permitting of onsite non-potable water systems in San Francisco, the City and County of San Francisco adopted Article 12C of the San Francisco Health Code. This ordinance has evolved over time to further streamline requirements and increase opportunities for potable water savings in buildings (Table 1).

4.3 Scaling up Onsite Non-potable Water Systems

Onsite non-potable water systems can serve as a management tool to assist communities that have different water and sanitation challenges such as water scarcity and urban flooding. While the technology is available to reuse water onsite, and the benefits are verified, there continues to be institutional and policy barriers to widespread national implementation. First, communities lack guidance on how to develop oversight and permitting programs for onsite non-potable water systems. Second, there is a need for consistent water quality standards that are protective of public health.

The SFPUC has undertaken several actions to address these challenges. In 2014, the SFPUC, with support from the Water Research Foundation (WRF) and the Water Environment and Research Foundation (WERF), convened a meeting of nationwide public health agencies, water agencies, and research institutions for an Innovation in Urban Water Systems conference. The conference's goal was to identify common challenges and discuss achievable solutions for a path toward widespread application of onsite non-potable water systems. One result of the meeting was the development of a guidebook for establishing oversight and management programs called *Blueprint for Onsite Water Systems: A Step-by-Step Guide for Developing a Local Program to Manage Onsite Water Systems*. The Blueprint instructs communities interested in developing a local oversight program to begin by convening a working group, and then establishing monitoring and reporting requirements while providing clear direction for project sponsors and developers. The Blueprint can be accessed online at www.watereuse.org/nbrc.

The Innovation in Urban Water Systems conference also confirmed that the critical issue communities face in implementing onsite reuse is the development of water quality standards and monitoring strategies to ensure protection of public health. To address this challenge, the SFPUC convened a public health coalition to evaluate existing water quality standards for alternate water sources, develop recommendations to help public health agencies regulate onsite non-potable water systems, and establish uniform practice among states. The coalition included public health agencies from several U.S. states including California, New York, Hawaii, Oregon, Minnesota, and Washington, and was supported with funding by WRF and WERF. This work resulted in the publication of the report, *Risk-Based Framework for the Development of Public Health Guidance for Decentralized Non-potable Water Systems* (available at www.watereuse.org/nbrc) in March 2017.

The report was prepared by a 6-member Independent Advisory Panel, appointed by the National Water Research Institute (NWRI), with input provided by the public health coalition and a stakeholder advisory committee consisting of additional public health agencies and water utilities. Using Quantitative Microbial Risk Assessment (QMRA) modeling, the NWRI Panel established a water quality approach centered on risk-based log reduction targets (LRTs) for the treatment of pathogens including viruses, protozoa, and bacteria. The research did not include chemical exposures because it was concluded that the removal of pathogens are considered the greatest concern to human health in onsite systems for non-potable applications. The risk-based approach for pathogen reduction uses a methodology widely accepted for potable reuse and drinking water practices and is in alignment with the Water Safety Plan approach promoted by the World Health Organization.

In addition to establishing the LRTs, the Independent Advisory Panel emphasized continuous online monitoring as critical to the success of this approach. Continuous monitoring involves the ongoing verification of system performance using sensors that allow operators to monitor each treatment process in real time. Coupled with the ability to perform automatic diversions of off-spec water, this framework is increasing the reliability and effectiveness of onsite water reuse systems during operation. Continuous online monitoring is also broadly accepted in drinking water and potable reuse regulations, and this research extends the approach to onsite non-potable water systems. This framework differs from current practices, which rely on periodic end point sampling of coliform and other water quality parameters. According to the report, *Risk-Based Framework for the Development of Public Health Guidance for Decentralized Non-potable Water Systems*, monitoring and control systems assess the operation, performance, and status of a given component or process of a treatment system. Because pathogens and fecal indicator organisms (FIOs) cannot be measured continuously, process monitoring should involve the use of surrogate parameters that correlate with the integrity of the treatment process. Preferably, surrogate parameters should be monitored continuously using appropriate sensors and instrumentation;

therefore, the purpose of performance target monitoring is to ensure that the treatment barriers—designed to meet the requirements of microbial risk assessment (i.e., LRTs)—are operating as intended. It is analogous to the best management practices used in operating drinking water systems [13].

Continuing to lead the way, in 2016, San Francisco partnered with the U.S. Water Alliance to formally convene National Blue Ribbon Commission for Onsite Non-potable Water Systems. With financial support provided by WRF and WERF, the National Blue Ribbon Commission includes representatives from public health agencies (many of whom participated in the aforementioned public health coalition), water and wastewater utilities, and municipalities from 14 U.S. states, the District of Columbia, U.S. EPA, U.S. Army, and two Canadian cities—Toronto, and Vancouver. Today, the group is supported by the WateReuse Association, and its mission is '*to promote public health protection, science-based policy, a consensus-based approach, and honoring local issues and applications.*' As well as serving as a forum for collaboration and knowledge, the National Blue Ribbon Commission conducts research to advance the implementation of onsite water systems.

The National Blue Ribbon Commission advocates for consistent policy frameworks across cities and states to help increase the adoption of onsite non-potable water systems. Identifying the need for guidance on developing and adopting regulations to oversee these systems, the National Blue Ribbon Commission received funding from WRF to develop the *Guidebook for Developing and Implementing Regulations for Onsite Non-potable Water Systems* (available at www.watereuse.org/nbrc). It is intended to help communities adopt regulations and oversight programs for onsite systems by including model templates for state regulations, local ordinances, and program rules. As a result of the development of these resources and the risk-based public health guidance, states and cities have begun grappling with the question of how to implement the risk-based water quality standards into practice.

SFPUC recognized early on the need for more guidance for practitioners seeking to implement the risk-based LRTs. The SFPUC took the lead in developing a pathogen crediting approach and guidance on designing treatment systems that was incorporated into the city's Onsite Water Reuse Program. What resulted were new rules and regulations and guidance that bridged the gap between the established LRTs and how an onsite water reuse system in San Francisco can meet the standards. The bridging guidance focused on available treatment technologies that could be used to achieve the LRTs and the existing regulatory frameworks for crediting these technologies with pathogen removal or inactivation. This guidance was combined with example treatment train diagrams to show potential approaches for the design of an onsite reuse system using existing pathogen crediting frameworks, an example of which can be found in the SFPUC's *Onsite Water Reuse Program Guidebook* (available online at https://sfpuc.org/construction-contracts/design-guidelines-standards/onsite-water-reuse)). This guidance ultimately led to the National Blue Ribbon Commission developing the *Onsite Non-potable Water System Guidance Manual* (available at www.watereuse.org/nbrc), which includes detailed information about designing and regulating onsite water reuse systems using the risk-based public health framework.

In addition to pushing forward on developing guidance, the National Blue Ribbon Commission continues to advance the risk-based science. Since the LRTs were developed in 2017, research continues to improve pathogen characterization in rainwater, validate and assess assumptions in the underlying Quantitative Microbial Risk Assessment (QMRA models), identify additional surrogates for online monitoring, and develop systems analysis to inform planning. For example, the National Blue Ribbon Commission's key research partner, the U.S. EPA, recently developed a web-based calculator that provides an initial life cycle assessment for any large building in the U.S. implementing an onsite non-potable water system. The Non-potable Environmental and Economic Water Reuse (NEWR) calculator (available online at https://www.epa.gov/water-research/non-potable-environmental-and-economic-water-reuse-newr-calculator) is intended to help practitioners understand what are the most environmentally and cost-effective alternate water sources to meet large building non-potable water needs [14]. Additional research efforts have focused on examining the risk of using treated non-potable water for end uses such as bathing and showering to support water reuse in rural Alaskan communities.

Beyond San Francisco, communities across California and the United States are also recognizing onsite water systems as a promising approach to meeting our current water challenges. Armed with technical and policy resources, there has been a significant shift in the perspective of several public health regulators who participate in the National Blue Ribbon Commission. Not only are public health regulators embracing the risk-based water quality framework, several U.S. states, including California, Colorado, Minnesota, Washington, Hawaii, Austin, Texas, and Washington D.C., are using the tools and risk-based science to advance legislation or policies supporting onsite reuse, while others including Alaska and Oregon are considering similar steps forward. These initiatives are outlined in the next section.

5 Key U.S. Legislation and Policies for Onsite Non-potable Water Systems

Jurisdictions across the U.S. are implementing legislation and policies to advance onsite water reuse. These initiatives are increasing national momentum for adopting a one water approach (Table 2).

6 Considerations for the Integration of Onsite Water Systems

When considering how and where it makes sense to integrate onsite water systems in a community, it's important to first honor local context and acknowledge that each community has different drivers that influence decisions around water management.

Table 2 Key U.S. Legislation and policies advancing onsite water reuse (*Source* Author)

San Francisco, California	San Francisco's Onsite Water Reuse Program established local oversight and a streamlined permitting process for treating and reusing alternate water sources onsite for non-potable applications. San Francisco was the first city in 2015 to require new commercial, mixed-use, and multi-family development projects 23,225 m^2 or greater to install and operate an onsite water reuse system. In 2017, San Francisco updated its Onsite Water Reuse Program Rules and Regulations to align with the risk-based water quality standards [15]
Minnesota	Increasing interest in water reuse prompted the Minnesota Department of Public Health to develop recommendations for a statewide water reuse policy. In March 2018, the Minnesota Department of Public Health published the report *Advancing Safe and Sustainable Water Reuse in Minnesota*, which included recommendations to adopt the risk-based approach [16]
Colorado	As a result of Colorado's history of water supply challenges, increased political support for water reuse, and the publication of the risk-based public health guidance, Colorado Department of Public Health and Environment updated Regulation #84 to allow localized non-potable water systems to treat onsite wastewater for toilet flushing and irrigation using the risk-based approach [17]
California	The push for uniform standards for onsite water reuse garnered support from practitioners, the public, and the legislature, and in September 2018, California passed Senate Bill 966. SB 966 directs the State Water Resources Control Board to establish risk-based water quality standards for onsite non-potable water systems by December 2022 [18]. The legislation directs local jurisdictions to permit and oversee onsite water systems. Amendments to San Francisco's program may occur to comply with the state's new standards
Hawaii	Hawaii is experiencing new found momentum for scaling water reuse as stakeholders from across the state engaged in a Water Reuse Task Force in 2018. As a result, Hawaii passed House Bill 444 in 2019 directing the Hawaii Department of Health to adopt rules for onsite non-potable water systems with guidance from the National Blue Ribbon Commission [19]
Washington	Recognizing the need for a regulatory structure for the safe and efficient use of onsite non-potable water systems, the Washington Legislature passed House Bill 1184 in 2021, which directs the Washington Department of Health to develop risk-based water quality standards for onsite non-potable water reuse systems in commercial and multi-family buildings [20]

While water scarcity may drive water reuse in some locales and regions, other areas are turning to onsite water reuse to help alleviate combined sewer overflow issues.

In San Francisco, the city has embraced a *One Water* approach, seeing value in both centralized recycled water and decentralized non-potable water systems. As a seasoned practitioner in this space, the SFPUC has learned how to streamline the integration of onsite water systems within a dense urban community. San Francisco's onsite water reuse regulation targets new construction and areas of the city where major redevelopment is occurring. By first targeting new construction, onsite water reuse projects can reduce capital costs when compared to retrofitting an existing building to incorporate an onsite water system. Furthermore, requiring new construction to install and operate onsite water systems can result in more immediate water savings rather than relying on the municipality to build a centralized recycled water source.

With this requirement in place for new large developments, the SFPUC had to overcome challenges within the utility regarding the potential impacts of these systems on the city's municipal wastewater system. Perceptions that onsite systems lead to declining flows and odor problems in the wastewater system, were creating institutional barriers that needed to be addressed.

To overcome this challenge, the SFPUC's water and wastewater divisions collaborated internally to develop a process for assessing impacts on flow and odor. The process involves conducting a hydraulic analysis each time a large development proposes to include an onsite water system. Hydraulic modeling can be a useful tool to help communities plan for where onsite reuse systems make the most sense. The SFPUC uses San Francisco specific data in its models to evaluate impacts in terms of odor and flow. The SFPUC also uses the models to assess various hypothetical scales of implementation of onsite water systems. Even in a scenario where there is high proliferation of onsite systems throughout the city, the hydraulic analysis shows minimal impacts in terms of odor and flow issues on the wastewater system. However, because the analysis results are site specific, the SFPUC continues to run the analysis on each project, and also offers guidance to projects on alternatives to discharging solids from the onsite reuse system directly to the sewer. Example alternative strategies include occasional flushing of the impacted sewer line or trucking the solids offsite.

In addition, buildings within flood vulnerable zones may wish to consider infrastructure solutions. In San Francisco, flooding issues are addressed in the design and construction of a project. For example, buildings located in areas of San Francisco that have a high groundwater table are designed and constructed to prevent water from entering the building or the buildings rely on continuous de-watering operations.

7 Examples of Onsite Water Reuse Projects

The following case studies are intended to show proof of concepts and encourage transformation in the water sector. These projects range from individual buildings recycling wastewater to entire neighborhoods actively engaged in the management of their water. While water reuse remains a central theme within the case studies, each project showcases a unique, innovative approach to using more water efficiently.

7.1 City of Austin Permitting and Development Center—Austin, Texas, USA

Completed in the summer of 2020, Austin's Permitting and Development Center, highlighted in Fig. 5, demonstrates and promotes sustainable water management practices. The building incorporates an onsite blackwater system that treats 100% of the building's wastewater through a 18,927 L per day membrane aerated bioreactor (MABR) and recycles the water for toilet and urinal flushing. Rainwater from the building's roof and air conditioning condensate are also collected in two 75,700 L storage tanks and reused for landscape irrigation and a circulating water feature [21]. The building was designed to locate the blackwater treatment system and equipment room under an outdoor pedestrian walkway, with aesthetically pleasing plants growing out of one of the treatment reactors blending with the walkway's landscaping.

The City of Austin was driven towards this project by the adoption of its Water Forward Plan in 2018, a 100 year integrated water resources plan. Water Forward Plan recommends that the city adopt an ordinance to require new commercial and multifamily buildings over a specified threshold size to install dual plumbing and to reuse water generated onsite for indoor and outdoor non-potable purposes. The installation and operation of the reuse systems at the Permitting and Development Center provide valuable experience that is informing the City's development of an onsite reuse ordinance [22].

Fig. 5 City of Austin permitting and development center in Austin, TX. *Source* Public Domain

7.2 Denver Water Administration Building—Denver, Colorado, USA

Located in a high plains desert, where its water supply is frequently threatened by drought and climate change, Denver is actively taking measures to secure future water supply resiliency. With construction recently completed, Denver Water's Administration Building will be capturing rainwater from the roof and from the solar panels that cover a portion of the new parking garage. This water will be filtered and stored for landscape irrigation. In addition, the building will also be treating and reusing 100% of its blackwater. Blackwater collected from sinks, toilets, drinking fountains, and cafeteria operations in the building will undergo large-object screening, aerobic and anaerobic biological treatment, three stages of wetland treatment (tidal and plug flow), cartridge filtration, ultraviolet light disinfection, and chlorination (Fig. 6) [23].

The treatment process is designed to meet Colorado regulations for onsite non-potable reuse, with 8.5-log virus, 7.0-log protozoa, and 6.0-log bacteria removal. Treated water from this process will be used to flush toilets in the Administration Building and any excess will supplement captured rainwater for irrigation. After basic equipment testing and commissioning by the contractor, Denver Water staff will start, optimize, and run the system.

Fig.6 Denver water's wetland system treating the building's blackwater in Denver, CO. *Source* Public Domain

7.3 Mission Rock—San Francisco, California, USA

Mission Rock will be a new mixed-used neighborhood spread over 28 acres, including parks, open space, residential, commercial, and retail (Fig. 7). The 11 buildings within the district will be connected to a district-scale blackwater system that will meet demands for toilet flushing and irrigation, which are the primary non-potable water needs of the site. The blackwater system is being built to comply with San Francisco's Non-potable Water Ordinance and will be located on the ground floor of one of the future office buildings. The blackwater treatment plant will be an advanced water recycling facility treating up to 162,770 L per day of blackwater collected from the development's toilets, showers, and sinks [24]. The project's business model involves partnering with third-party utility operator to form a non-profit entity that will manage the day-to-day operation and maintenance of the district-scale blackwater system.

Fig. 7 Rendering of a new neighborhood, Mission Rock, in San Francisco, CA. *Source* Public Domain

7.4 Alliance Field at Midway Development District—Saint Paul, Minnesota, USA

In collaboration with the Capitol Region Watershed District, the City of Saint Paul developed a district-scale rainwater harvesting system capable of saving over 7,570,820 L of water annually. Completed in 2019, the project is located at Allianz Field, the new stadium for the soccer team, the Minnesota United FC.

The rainwater harvesting system utilizes a 675,000-gallon underground storage tank (Fig. 8) to collect roof runoff from the stadium and in the future from neighboring buildings once they are built. Water is pumped from the storage tank through a treatment system called a "smart hub", which can read weather forecasts to predict rainfall and adjust water levels accordingly. The treated water is used to irrigate the entire stadium site, which includes 13,935 square meters of green public space and 200 mature trees. New development in the area will be able to connect to the system for supply of recycled water for non-potable uses such as laundry, irrigation, or restroom flushing [25].

Fig. 8 Installation of underground rainwater storage tank at Allianz Field in St. Paul, MN. *Source* Public Domain

Fig. 9 Water Hub at Philip Morris USA in Richmond, VA. *Source* Public Domain

7.5 The WaterHub at Philip Morris USA—Richmond, Virginia, USA

Located on the site of a former coal-fired power plant, the WaterHub at Philip Morris USA is a symbol of an industrial park's turn to green infrastructure (Fig. 9). The WaterHub, which began operation in 2019, treats up to 2,460,500 L per day of blackwater, which serves as the primary water supply for the industrial campus' energy system. The WaterHub is expected to decrease total potable water use for the industrial park by approximately 40% and decrease total wastewater discharge by up to 70% [26].

7.6 Nye Sustainable Suburb—Aarhus, Denmark

Nye, a new suburb of Aarhus, Denmark, is a city-driven initiative to meet Aarhus's increasing housing demand with a water-wise urban district that will make sustainable living more effortless for its citizens (Fig. 10). Nye is designed to be resilient to climate change by incorporating blue/green structures that will also serve as natural amenities for residents and increase biodiversity. The private developer, local water utility Aarhus Vand, and Aarhus municipality collaborated to build a district-scale rainwater harvesting system, which is the first of its kind in Denmark. Rainwater from roofs, roads, and open areas will to be conveyed through a network of trenches and

Fig. 10 Nye suburb in Aarhus, Denmark. *Source* Public Domain

ponds to a central lake, which will serve as a storage reservoir. A central treatment plant will treat and distribute recycled water to meet the non-potable water demands of the community's households, such as toilet flushing and laundry.

The Nye suburb is still under construction, but its first inhabitants moved in during 2018. It is anticipated that the district-scale rainwater system will reduce total household water use by approximately 40% [27].

7.7 *Mazda Stadium—Hiroshima, Japan*

The Mazda Zoom-Zoom Stadium, home to the baseball team the Toyo Carp in Hiroshima, Japan, underwent a massive renovation to incorporate an onsite regional stormwater project, which includes a rainwater reuse system (Fig. 11). Completed in 2019, the renovation installed a reservoir below the baseball field to collect stormwater runoff from the stadium and surrounding area, managing a total drainage area of 51.2 hectares (128 acres). About 7% of the reservoir (999,340 L) is segmented for the rainwater reuse system, while the other 13,248,940 L of storage capacity prevent stormwater from inundating the sewer system, most critically preventing flooding of the nearby Hiroshima Station, which has an underground plaza and passageways. The rainwater treatment system disinfects the runoff with chlorine and passes it through a filtration system before it is re-used for the baseball field's sprinkler irrigation, for the stadium's toilet flushing, and for a publicly accessible and interactive circulating water feature outside the stadium called the "Amaoto no Komichi" [28].

Fig. 11 Rainwater used to irrigate Mazda Stadium in Hiroshima, Japan. *Source* Public Domain

8 Where Do We Go from Here?

Treating water onsite provides the opportunity to save drinking water from non-potable uses. With this opportunity, transformative water management can occur in communities around the world. This transformation need not be limited to producing non-potable water. Additional resource recovery opportunities exist as onsite water treatment systems can produce thermal heat, nutrients, and drinking water. These additional opportunities can lead to delivering a circular water economy.

8.1 Producing Thermal Energy

Buildings incorporating onsite water systems can benefit from thinking beyond water savings by also considering wastewater heat recovery. Wastewater heat recovery refers to the extraction of thermal energy from warm wastewater, or treated non-potable water, and subsequent beneficial use of this energy to offset existing energy requirements. The benefits of wastewater heat recovery include offsetting some or all of the energy needed for onsite water treatment, decreasing energy costs, reducing greenhouse gas emissions and reliance of fossil fuels, and achieving potential green building certification credits. Recognizing this benefit, the SFPUC provides financial assistance for buildings with onsite water reuse systems to install wastewater heat recovery [9].

In the early 2000s, the Solaire building in New York City, USA incorporated an onsite blackwater treatment system to produce non-potable water for toilet flushing in the residential units, cooling tower make-up water, and irrigation of the green roof. Over the years, the onsite water system was upgraded to reduce its energy consumption by installing a thermal energy recovery process which has allowed the system to achieve net zero energy use. The heat recovery system (Fig. 12) is designed to extract sensible heat from treated effluent and pre-heat the domestic hot water. This has resulted in a net energy neutral operation reducing the buildings overall carbon footprint. It also increases cooling tower efficiency by reducing the temperature of the make-up water [29].

Fig. 12 Wastewater heat recovery system at the Solaire in New York City. *Source* Public Domain

Fig. 13 NEMA in San Francisco, CA. *Source* Public Domain

8.2 Nutrient Recovery

In addition to saving water, onsite water reuse systems can produce positive environmental benefits from nutrient recovery. A San Francisco based company, Epic CleanTec, is promoting a modern, circular approach for more sustainable cities by enabling buildings to recover value from solid waste. Epic CleanTec piloted a solids recovery system at NEMA, a residential tower in San Francisco (Fig. 13). Solid waste from the building is filtered from the wastewater, dewatered, and captured. The solids are collected and transported off-site where it is converted into a high-quality sterile soil amendment. This soil product can be used as a bulk amendment for public parks to a bagged product for distribution and sale in gardening stores [30].

8.3 Producing Drinking Water from Rainwater

Georgia Tech, located in Atlanta, Georgia, USA, is leading the U.S. in demonstrating innovative green building design. Georgia Tech's Kendeda Building for Innovative Sustainable Design (Fig. 14) has a unique rainwater harvesting system for potable

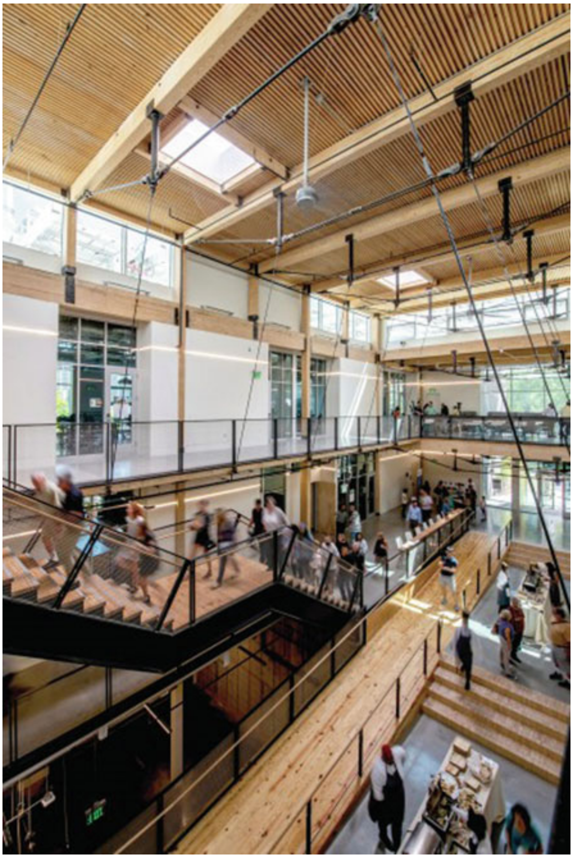

Fig. 14 Kendeda Building for innovative sustainable design in Atlanta, GA. *Source* Public Domain

use. Rainwater is harvested from the roof, collected in 189,270 L cistern, treated, and then piped throughout the building for potable water needs [31]. The State of Georgia's Environmental Protection Division approved the rainwater-to-drinking system in 2020, and issued a permit that validates the system is producing safe drinking water. The treatment includes filtration, ultraviolet disinfection, and continuous chlorination disinfection. In addition to rainwater, the building also recycles graywater and stormwater to recharge the surrounding aquifer [32].

8.4 Rainwater for Beer Making

Manchester City, an English football club based in Manchester, England teamed up with brewers Heineken and water treatment technology company Xylem to brew a limited edition beer from rainwater collected from the Etihad Stadium roof. The rainwater is purified from the stadium roof before providing it to Heineken's

Manchester brewery to produce the beer. The beer, called Raining Champions, was produced to raise awareness about the rising difficulties faced by many countries from environmental changes [33].

8.5 Producing Drinking Water from Blackwater

The future of water reuse includes opportunities to produce drinking water from blackwater. With an eye to the future, the SFPUC piloted one of the nation's first building-scale direct potable reuse demonstration project. Dubbed PureWaterSF, the project was aimed at better understanding the opportunities and challenges of decentralized potable reuse along with collecting data relevant for both small- and large-scale potable reuse.

The PureWaterSF treatment system train was temporarily added to a pre-existing constructed wetland system that treats blackwater for toilet flushing at the SFPUC headquarters in San Francisco. The system included ultrafiltration, reverse osmosis, and an ultraviolet advanced oxidation process to purify the effluent from the existing wetland system. The system, which was designed to have a small footprint while producing high-quality water able to meet drinking water standards, was able to treat approximately 85% of the water from the wetland system.

The PureWaterSF system was installed as a pilot project for a limited duration. The treatment and monitoring systems were designed and installed in June 2018 and the system was tested and monitored for eight months. Analytical samples were collected at every stage of the treatment train to verify the system's ability to meet drinking water standards and to document treatment performance. After analysis, all the water produced by the system was returned to the building's toilet flushing system [34]. While the pilot project has concluded, the SFPUC currently is exploring the potential of including a permanent PureWaterSF system in its headquarters building.

8.6 Forward-Looking Vision for Plug and Play Systems

Reimagining our urban water systems demands collaboration and cross-cutting ideas. Looking to the future, plug and play water reuse systems are ideal, where the complexities of operating and installing these systems can be minimized. More plug and play systems can lead to increased uptake of onsite water reuse by taking advantage of modular approaches to allow for scaling up and simplifying the design of treatment systems. Consistency in policies and approaches can also pave the way to more plug and play systems and reduced burden on technology vendors and designers through more uniform standards. Having uniformity in plumbing codes and standards is an important consideration moving forward as states and municipalities adopt legislation promoting onsite water reuse. Furthermore, utilities have an important leadership role in actively promoting integrated water resources management and building an enabling environment for water supply diversification.

Small-scale water reuse is an innovative solution with demonstrated success in addressing today's pressing water challenges. Interest is growing in funding such advancements. For example, the U.S. Department of Energy (DOE) is investing $20 million USD to improve water and wastewater treatment system infrastructure. DOE's investment seeks to advance transformational technology and innovation to meet the global need for safe, secure, and affordable water. This funding opportunity is part of DOE's Water Security Grand Challenge, which has the goal of doubling resource recovery facilities by 2030 [35].

Other prominent efforts such as the National Alliance for Water Innovation (NAWI) Energy-Water Desalination Hub are also supporting the development of water treatment technologies. The Hub is leveraging $100 million USD in investment over five years to conduct early-stage applied research involving U.S. universities, industry, and national labs. One of the primary research topics will be process innovation and intensification to facilitate distributed reuse [36].

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Integrated Water Management for a Sustainable Office Building

Phillip L. Thompson, Russell L. Porter, and Justin K. Stenkamp

Abstract The Bullitt Center (Seattle, Washington) was the first office building in the world to fully meet the rigorous requirements of the Living Building Challenge. This chapter discusses the design of the building's potable water, graywater and blackwater treatment systems. It also reviews the treatment performance of these systems for the first eight years of operation. The chapter discusses capital, operation and maintenance costs and offers lessons-learned that may assist owners and designers of future sustainable building projects.

Keywords Potable water · Graywater · Blackwater · Living building challenge

1 Introduction

Located in Seattle, Washington, the Bullitt Center is a general-purpose office building that opened on Earth Day in 2013, and at the time it was regarded as the "World's Greenest Commercial Building" [1]. Much like the Douglas fir trees that had occupied the property for centuries before, the Bullitt Center was designed to thrive within its footprint. It was built to use only as much energy as was available through annual solar radiation, and the building's water needs would be met by the precipitation that could be captured from its roof.

The broader design goal for the Bullitt Center (Fig. 1) was to meet the "Living Building Challenge Version 2.0" which was developed by the International Living Future Institute. The petals of a flower are used to symbolize each of the seven areas of the challenge which include beauty, energy, equity, health, materials, place and

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T. Younos et al. (eds.), *Resilient Water Management Strategies in Urban Settings*,
Springer Water, https://doi.org/10.1007/978-3-030-95844-2_7

Fig. 1 The Bullitt Center (Seattle, WA) is a 6-story office building that houses approximately 170 tenants from a variety of businesses (*Source* Phillip Thompson)

water [2]. The building's stunning architecture has been recognized by a host of architects and engineers [3] and its 1300 m^2 (14,000 ft^2) array of 575 solar voltaic panels produces up to 230,000 kWh and an average of 30% more power than the building uses per year. This incredible efficiency is due in part to the use of a well-designed building envelope, passive ventilation, natural daylighting and a ground-source heat pump that provides radiant floor heating and cooling to maintain the building's temperature throughout the year. To avoid the use of battery storage, the solar array sends electricity to Seattle Public Utility's grid throughout the day while the building draws power from a separate line to support its operations. The City of Seattle provided a variance to allow the solar array to extend into the right-of-way, because planners saw no future conflicts at over 18-m (60-ft) above street level.

The health of the ~170 tenants is enhanced through the promotion of beautiful, irresistible stairs and naturally-lit, open office spaces. Building and tenant health was also addressed by ensuring that no hazardous materials were used to construct any part of the building and by constructing the building in an urban area that is easily accessible by foot, bicycle, and public transportation. To further discourage the use of motorized vehicles, the City of Seattle provided an additional variance by eliminating the parking requirement for new buildings.

Perhaps the most unique features of the Bullitt Center are its water and wastewater systems. This chapter will describe the potable water, graywater and blackwater treatments systems and present performance data from startup through June 2021. We hope that the lessons from the Bullitt Center will inform the design and contribute to the resilience of future buildings as humanity faces the need to adapt to climate change.

2 Potable Water System

2.1 Regulatory Requirements

Over five and a half years after opening its doors to the public, the Bullitt Center's potable water treatment system went online in November 2018. The delay was partially a result of navigating the regulatory process that governs water systems in the State of Washington which is overseen by the Washington State Department of Health (WSDOH). Because the drinking water treatment system would provide water to the public, WSDOH classified it as a separate Group A private water system which is specifically defined as a non-transient, non-community water system. Regulations further required a pathway analysis to ensure that no water molecules would encounter hazardous materials prior to the point of treatment. For the 650-m^2 (7,000-ft^2) contributing roof area of the Bullitt Center, it became clear that the solar panels would meet the "substantial contact" regulatory threshold. The panels would need to be tested, and this further delayed the implementation of the potable water treatment system. Fortunately, the solar panel manufacturer, SunPower (San Jose, CA), agreed to pay for the testing, and in 2018, the panels were found to be compliant with National Sanitation Foundation (NSF) International safety standards. In addition to the solar array, the roof membrane material was brought into compliance by sealing it with a white elastomeric roof coating that had an NSF P151 certification and was specifically formulated for rainwater-catchment roofing applications.

In addition, regulations require water treatment systems to maintain a detectable residual disinfectant at the farthest point in the distribution system. Consequently, chlorine or chloramines must be used even if *Giardia* and virus inactivation have been met with another form of disinfection such as ultraviolet (UV) light. This disinfectant residual mandate led to a change in the Living Building Challenge which requires that no hazardous materials be used to construct or operate the building with the recent exception of chlorine. The system was also mandated to have daily water quality testing for chlorine residual and turbidity as well as semi-annual or quarterly testing for regulated parameters such as lead, copper and disinfection byproducts.

The water treatment system designers had to ensure compliance with the Safe Drinking Water Act (SDWA) and the Surface Water Treatment Rule. Administered by WSDOH through the Washington Administrative Code [4], these regulations require 99.99% (4-log) removal of viruses, 99.9% (3-log) removal of *Giardia,* and 99% (2-log) removal of *Cryptosporidium* [4]. All treatment system components must also be NSF certified according to WSDOH regulations, and a combination of disinfection and filtration may be used to achieve pathogen removal. To assess the treatment system's pathogen removal performance, regulators apply filtration removal credits for methods such as diatomaceous earth, slow sand or rapid sand filtration. If third-party performance testing data is available, WSDOH may also allow removal credits for membrane filtration. Even if a selected filtration technology can meet pathogen removal requirements, treatment systems must still meet regulatory requirements for disinfection.

2.2 Rainwater Storage and Treatment

2.2.1 Water Storage

Rainwater for the building's tenants and visitors is routed from the roof to a 236,400-L (~52,000-gal), concrete, basement-level cistern that was sized to ensure enough water during the dry summer months. While the cistern would provide potable water, the building was also connected to the Seattle Public Utilities water supply network to provide an emergency backup source of water and to ensure adequate pressure and flow for its fire suppression system. The cistern was designed based on average historical precipitation data, for the 650-m^2 (7,000-ft^2) of contributing roof area, and a collection efficiency ranging from 85 to 95% (Table 1). Contrary to Seattle's rainy reputation, the July, August, and September months have a combined average of only 9.4-cm (3.7-in.) of precipitation [5]. Because these are also the peak months for water demand, the cistern was sized for an average of approximately three months of storage and a minimum of 34-days of stored water at any time throughout the year.

Designers originally estimated that the potable water demand for tenants and visitors would be 40,694-L (10,750-gal) per month, or approximately 7.9-Lpcd (2.1-gpcd) for each of the 170 full-time tenants. Water use was expected to be reduced by approximately 56% compared with a traditional building due to the implementation of low-flow fixtures for showers (for bicycle commuters), sinks, and dishwashers. The use of composting toilets, which require approximately 89-mL (3-oz) of water to produce a foaming, biodegradable surfactant, compared with 6.1-L (1.6-gal) of water per flush for a conventional fixture also contributed to a significant portion of water savings.

Table 1 Average annual precipitation [5], roof collection efficiency, and available stored water for the Bullitt Center (Seattle, WA)

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Average
Precipitation, cm	13.0	10.3	9.8	7.0	5.0	4.0	2.3	3.0	4.0	8.0	14.3	15.3	8.0
Collection Eff., %	95	95	95	95	90	85	85	85	85	90	95	95	91
Days of storage	147	147	147	126	115	93	67	47	34	39	79	119	95

2.2.2 Water Treatment

A cyclone filter removes leaves and other large debris from rainwater prior to entering the cistern. The building's 15.1-Lpm (4-gpm) drinking water treatment system (Fig. 2) uses a 5-μm carbon-briquette pre-filter which is followed by a 0.5-μm carbon-block filter for removing pathogens and dissolved organic carbon (DOC). While the 0.5-μm carbon filter can achieve 99.95% cyst removal (3.3-log removal), the WSDOH only granted 2-log cyst removal by filtration and required that the remainder be removed through disinfection. After carbon filtration, initial disinfection is provided by a UV light sterilizer unit at a dosimetry rating of 40-mJ/cm^2. Because of the difficulty of reliably verifying UV performance in small systems, no inactivation credit was granted by WSDOH. To provide a relatively inexpensive level of redundancy an additional 0.5-μm carbon filter was installed after the UV unit in case the initial filter ever failed. Filtered water then flows through a calcium carbonate contactor, which adjusts the pH to 7.5 and adds alkalinity of 10 mg/L as $CaCO_3$ for corrosion control.

For the last stage of treatment, a sodium hypochlorite solution (5.25% diluted 50:1) doses the finished water with a target concentration entering the distribution system of 0.8 mg/L as chlorine to achieve a 1-log disinfection credit for cysts. The finished water is then piped through 12.8-m (42-ft) of 7.6-cm (3-in.) copper pipe and 11.6-m (38-ft) of 30.5-cm (12-in.) high-density polyethylene pipe. This piping provides a total volume of 863-L (228-gal) and approximately 56-min of contact time at the design flow rate which exceeds the required $C \times T$ value of 44 min-mg/L for pH 7.5, at 10 °C, and at the target concentration. The finished water is then distributed to all six floors of the building at a minimum target pressure of 206 kPa (30 psi) on the sixth floor.

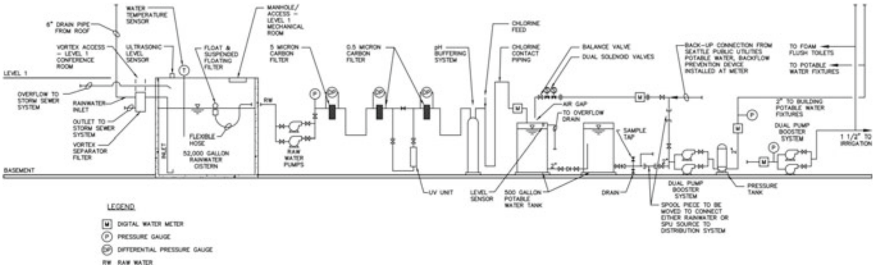

Fig. 2 The potable water treatment system for the Bullitt Center uses microfiltration, ultraviolet light disinfection, calcium carbonate for pH control and chlorine for residual disinfection

2.3 Potable Treatment System Performance

The water treatment system began providing the Bullitt Center's potable water on Nov. 1, 2018. During the 32-month study period described here, there was an average demand of 15,900-L (4,200-gal) per month while the monthly water demand ranged from 11,400 to 30,000-L (2,500 to 6,600-gal). The actual available water storage for the cistern generally agreed with the predicted values (Fig. 3), and there was never less than five months of available stored water. The actual storage volume fell significantly short of the predicted volume during February 2020 because operators frequently replaced the cyclone filter with a diverter. Ample water was available during the summer of 2020 due to the reduced demand that resulted from the COVID-19 pandemic. In general, during normal operations, the greater availability of stored water was primarily because the average daily water demand of 3.7-Lpcd (0.7-gpcd) was one-third of the anticipated demand of 7.9-Lpcd (2.1-gpcd) which resulted in an average peak hourly rate for water demand of 19.7-Lpm (5.2-gpm) (Fig. 4).

The average daily water demand was comparable to the 5-Lpcd (1.3-gpcd) of graywater production by office buildings reported by Zadeh et al. [6]. The average daily demand was 94% less than the median water consumption of 49-Lpcd (13-gpcd) for typical office buildings in the United States [7]. The Bullitt Center's low water demand can be attributed to the conservation ethos held by many tenants and visitors as well as the low flow fixtures and composting toilets.

The raw water quality had an average monthly turbidity of 0.16-NTU (Fig. 5), which was well below the 1.0-NTU finished water standard. As would be expected for rainwater, the raw water was corrosive with an average pH of 5.9, had a negligible amount of alkalinity, and had a Langlier saturation index (LSI) score of –5.6. Small amounts (<30 CFU/100 mL) of coliform bacteria were also present. Effluent turbidity

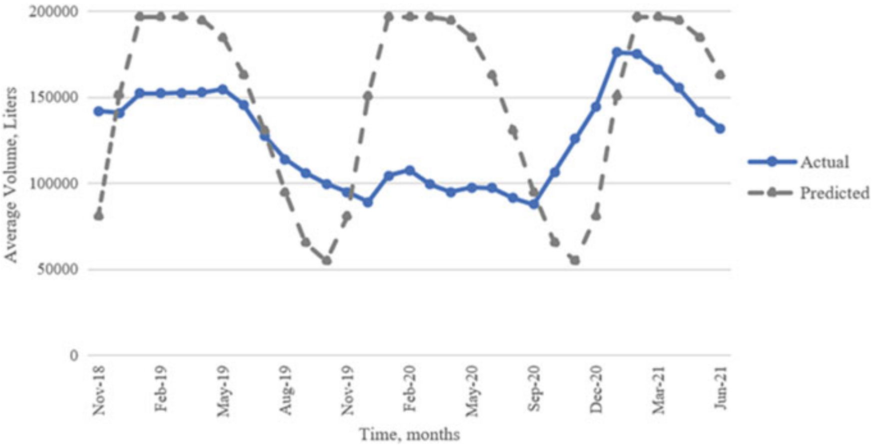

Fig. 3 Actual and predicted water storage for the 46,000-gal cistern

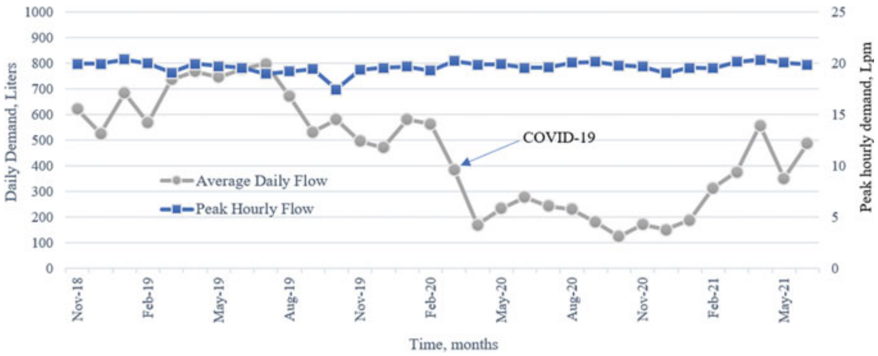

Fig. 4 Average daily and peak hourly demand versus time

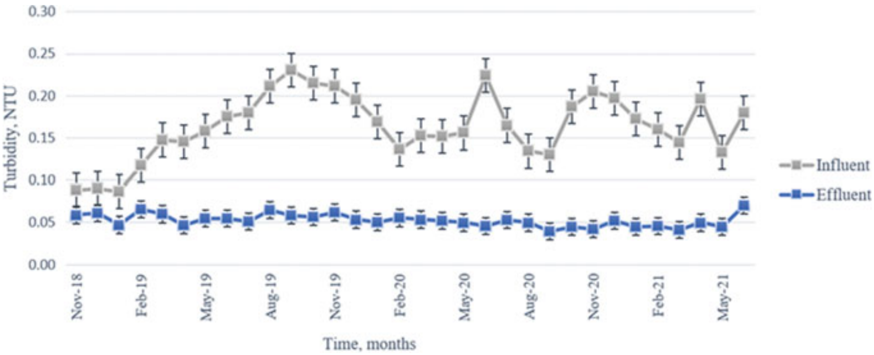

Fig. 5 Average monthly influent and effluent turbidity over time. Error bars are standard deviations. N = 15 for monthly samples

values (Fig. 5) averaged 0.06 NTU resulting in a 62.5% removal efficiency for the filtration system.

The treated water had a consistent pH of 7.6 and an average temperature of 18.3 °C which had a subtle seasonal variability (Fig. 6) due to Seattle's temperate climate and the concrete cistern's underground location. Quarterly grab sampling indicated consistent compliance with the SDWA's Lead and Copper Rule action levels of 15 μg/L and 1.3 mg/L, respectively. The point-of-use copper concentrations averaged 0.14 ± 0.06 mg/L despite a slightly corrosive LSI of –0.8. Lead was not detected despite the use of some brass fixtures.

The chlorine concentration at the point of entry to the distribution system averaged 1.3 mg/L, which was higher than the 0.8 mg/L target concentration for $C \times T$ calculations. This resulted in an actual average system $C \times T$ of 72 min-mg/L. Chlorine residual was always detected at the farthest point in the distribution system, located on the sixth floor of the building where it averaged 0.6 mg/L (Fig. 7).

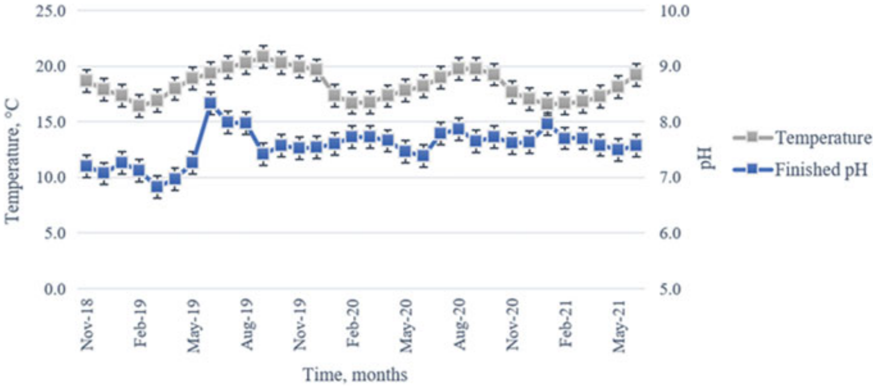

Fig. 6 Average monthly water temperature and pH. Error bars are standard deviations. N = 15 for monthly samples

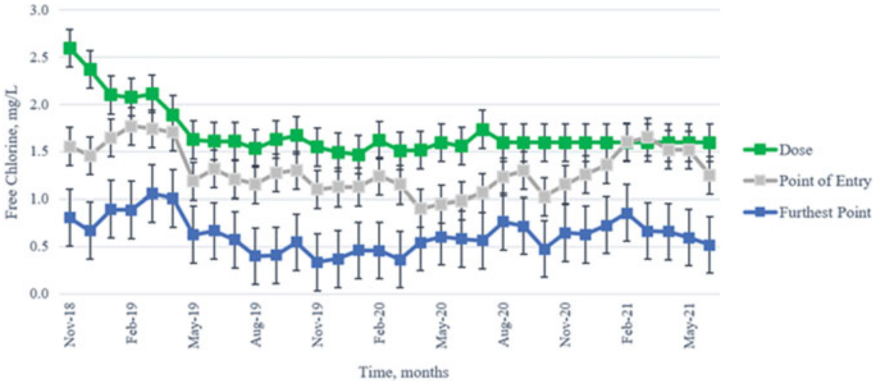

Fig. 7 Average chlorine concentrations by location versus time. Error bars are standard deviations. N = 15 for monthly samples

Disinfection byproducts (DBPs) were sampled quarterly. Total trihalomethane (TTHM) concentrations averaged 15 μg/L and were primarily associated with chloroform. Haloacetic acids averaged 9 μg/L with mono- and dichloroacetic acids as the predominant species present. The concentration of disinfection byproducts were significantly lower than those found in tap water provided by Seattle Public Utilities (Table 2), and their presence confirmed that carbon treatment was not capable of completely removing DOC precursors. For an extra level of safety at the point-of-use, all taps in the building have carbon filters for the removal of DBPs, chlorine, copper residuals and other taste and odor constituents.

Table 2 Average copper, lead, total trihalomethanes, and haloacetic acid concentrations for potable water from the Bullitt Center and Seattle Public Utilities [8]

Analyte	Bullitt center	Seattle public utilities
Cu (ppm)	0.1	0.1
Pb (ppb)	Not detected	2
TTHM (ppb)	15	46
HAA5 (ppb)	9	45

2.4 Triple-Bottom-Line

The Bullitt Center has successfully demonstrated that it can meet its potable water needs by treating rainwater to a very high level of water quality. To evaluate the building's overall sustainability, we performed a triple-bottom-line analysis which considers environmental, social and economic outcomes. With regard to environmental sustainability, the building sets a high bar for future developers who seek to minimize the use of hazardous or carbon-intensive construction materials and maximize energy and water performance. In terms of social sustainability, the building promotes healthy spaces for its tenants, and it provides meaningful work to community members via the operation, testing and maintenance of the drinking water treatment system.

An economic analysis revealed an annualized expense of $160,000 USD for capital costs related to collection, storage, and treatment assuming a 3% discount rate over 30 years. Combining this with the $60,000 USD annual expenses for operation, testing, and maintenance, the cost of water (assuming maximum water production) is approximately $0.14 USD per liter ($0.53 USD per gallon) [9]. Labor costs for testing and maintenance account for 90% of this cost. While this is certainly a premium cost compared to the Seattle Public Utilities rate which is approximately $0.0021 USD per liter ($0.008 USD per gallon) [10], the Bullitt Center's drinking water quality is superior with regard to DPB concentrations. It is also less than half the average cost of bottled water which is approximately $0.35 USD per liter ($1.33 USD per gallon) [11].

3 Graywater Wetland Treatment System

3.1 Wetland Design

From April 2013 through April 2021, a recirculating gravel filter system (RGFS) wetland treated graywater from the Bullitt Center's sinks, showers and floor drains. After collection in a 1514-L (400-gallon) storage tank in the basement, the graywater was pumped to the RGFS wetland which was located on a third-floor balcony on the north side of the building. The wetland is shielded from precipitation by the solar array that extends above it. The 44.5-m^2 (480-ft^2) RGFS wetland (Fig. 8) was

Fig. 8 The 44.6m^2 (480-ft^2) graywater treatment wetland is located on a third-floor balcony

designed to treat an average daily flow of 1300-L (350-gal) resulting in a loading rate of 30 L/m^2-d (0.7 gal/ft^2-d).

The filter contains 0.53-m (1.75-ft) of a ceramic filtration medium, followed by a 0.1-m (0.3-ft) gravel underdrain layer and a 0.76-mm (30-mil) high-density polyethylene (HDPE) liner. The underdrain layer has a storage volume of 4164-L (1100-gal). The system was designed to have a total hydraulic residence time (HRT) of 3.2-d. Influent graywater was applied to the RGFS every 4 h and recirculated graywater from the underdrain system was re-applied every 30-min via 2.5-cm (1-in.) diameter, perforated pipes that are located 15-cm (6-in.) below the wetland surface. The wetland was planted with approximately 100 water horsetail (*Equisetum fluviatile)* plants. Effluent from the wetland overflows from the underdrain layer to a 325-m^2 (3,500-ft^2) drain field that is located in the right-of-way between the building and McGilvra Place Park. Effluent infiltrates 15-cm (6-in.) below grade via 14.5-mm (0.6-in.) drip lines.

The WSDOH originally provided a permit for the wetland effluent with discharge limits of 30 mg/L for both 5-day biochemical oxygen demand (BOD$_5$) and total suspended solids (TSS). This was modified early on when, during the summer of 2013, effluent flows were less than 40 L/d due to high evapotranspiration rates. This resulted in excessively high BOD$_5$ and TSS concentrations even though the total mass that was being discharged was quite low during this period. As a result, the final permit allowed a mass discharge of 39 g/d for both BOD$_5$ and TSS. The final permit also allowed up to 1000-CFU of total coliforms per 100-mL.

3.2 Wetland Performance

Between June 2013 and March 2021, the influent flow rate (Fig. 9) averaged 450-Lpd (118-gpd) or approximately 2.7-Lpcd (0.7-gpcd). Because the average influent flow rate was approximately 30% of the design flow, the HRT and loading rate for the wetland averaged 10.6-d and 9 L/m^2-d (0.25 gal/ft^2 -d), respectively. Over the entire period, the average daily effluent flow was 255-Lpd (67-gpd). This was 57% lower than the average influent flow due to evapotranspiration during May through September when the daily effluent flow often approached zero discharge (Fig. 10).

Untreated graywater for the Bullitt Center had a larger range of concentrations of BOD$_5$ and TSS but comparable fecal coliform concentrations to treatment wetlands reviewed elsewhere [12]. The average influent BOD$_5$ was 970 mg/L, and this was consistently reduced to below 10 mg/L (Fig. 11).

The RGFS also consistently reduced the influent TSS concentrations of 280 mg/L to an average concentration less than 5 mg/L (Fig. 12). The wetland plants and the microbiological consortium associated with plant roots and the filter medium began to approach steady-state during years 2 and 3 of operation as reflected by the consistently low BOD$_5$ and TSS effluent concentrations. As a result, the excellent wetland performance demonstrated that it could easily achieve the 39 g/d permit requirements for both BOD$_5$ and TSS. The performance was enhanced by the low influent flows which resulted in a system HRT that was three times longer and a loading rate that was one-third lower than the designed values.

Over the study period, the wetland was not able to consistently meet the target effluent concentration for fecal coliform of 1000 CFU per 100 mL for approximately

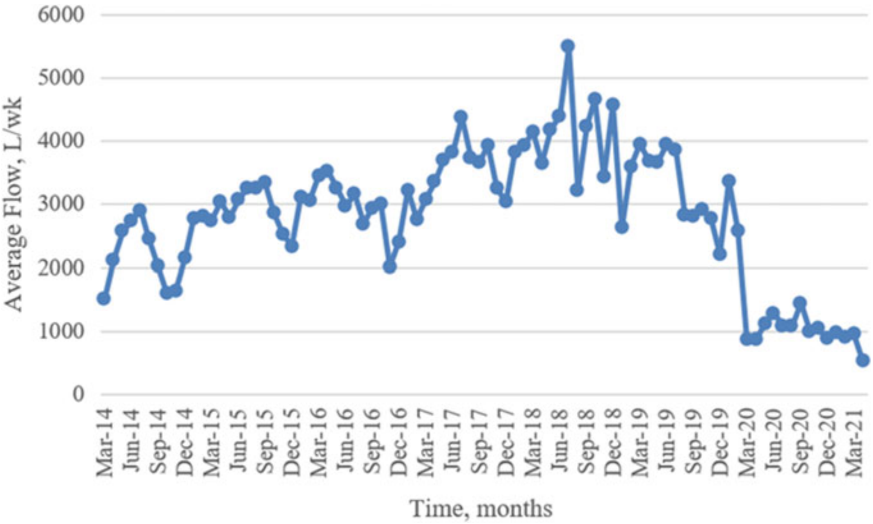

Fig. 9 Graywater production March 2014–March 2021

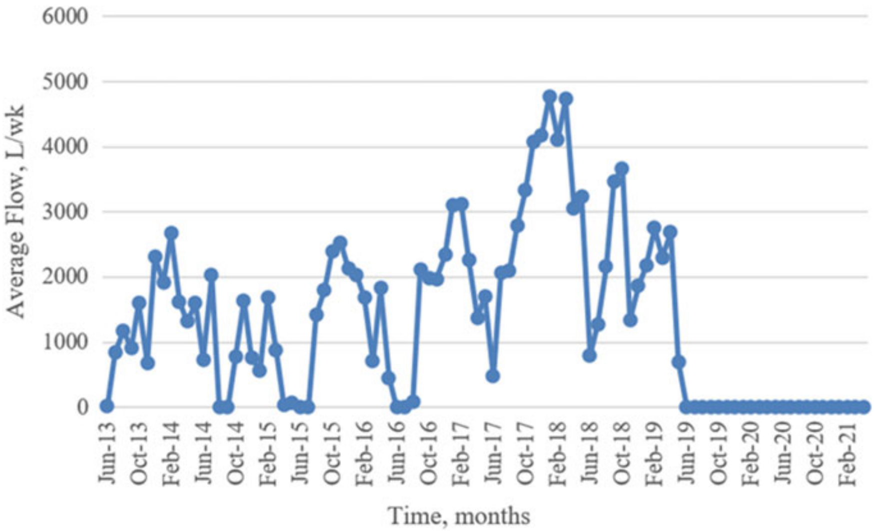

Fig. 10 Graywater effluent flow, June 2013–March 2021

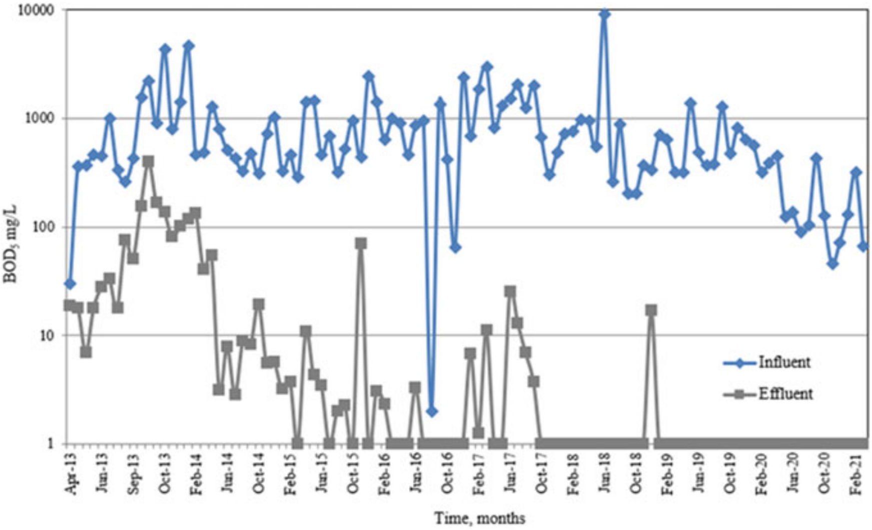

Fig. 11 The graywater wetland consistently reduced BOD_5 concentrations to meet discharge requirements

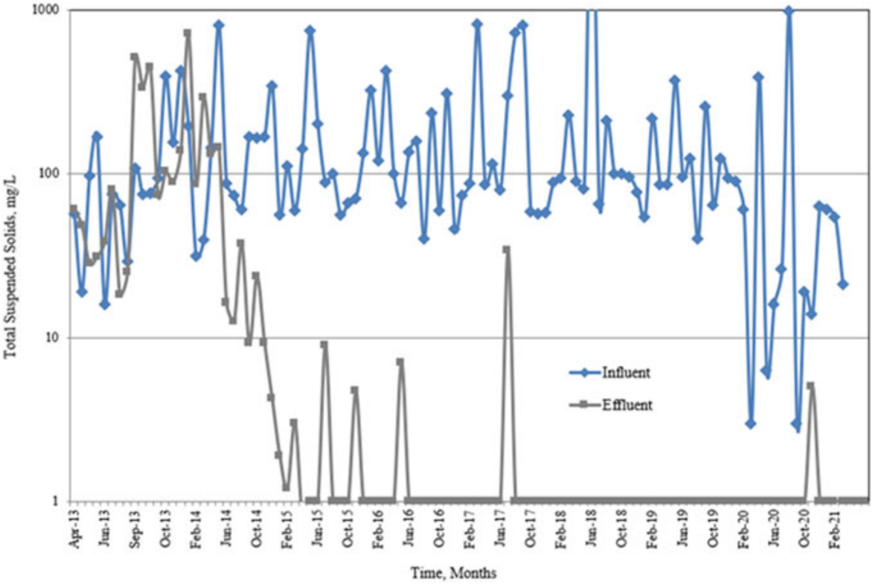

Fig. 12 The graywater wetland consistently reduced TSS concentrations to below 5 mg/L

25% of the sampling periods (Fig. 13). If a typical permit limit of 200 CFU per 100-mL permit limit for wastewater treatment facilities had been applied, the system would have exceeded the fecal coliform permit 90% of the time. Because high fecal coliform discharges for graywater treatment wetlands are common, Gross et al. [13] recommended disinfection of graywater with either ultraviolet light (UV) or chlorine. To comply with the Living Building Challenge's imperative to avoid hazardous materials such as chlorine, UV would have been a suitable alternative for the Bullitt Center's constructed wetland.

The results from this study demonstrated that it is possible to design a compact, graywater treatment wetland for a commercial building within an urban setting and achieve a very high level of treatment. After reaching a steady-state of operation, the wetland was consistently able to meet discharge limits for BOD_5 and TSS. Performance was enhanced by an average influent flow that was approximately 30% of the design flow. The RGFS wetland system met the allowable fecal coliform concentrations of 1000 CFU per 100-mL during most of the study period, but to consistently meet required fecal coliform concentration limits, an active form of disinfection such as UV sterilization is recommended for future graywater wetland designs.

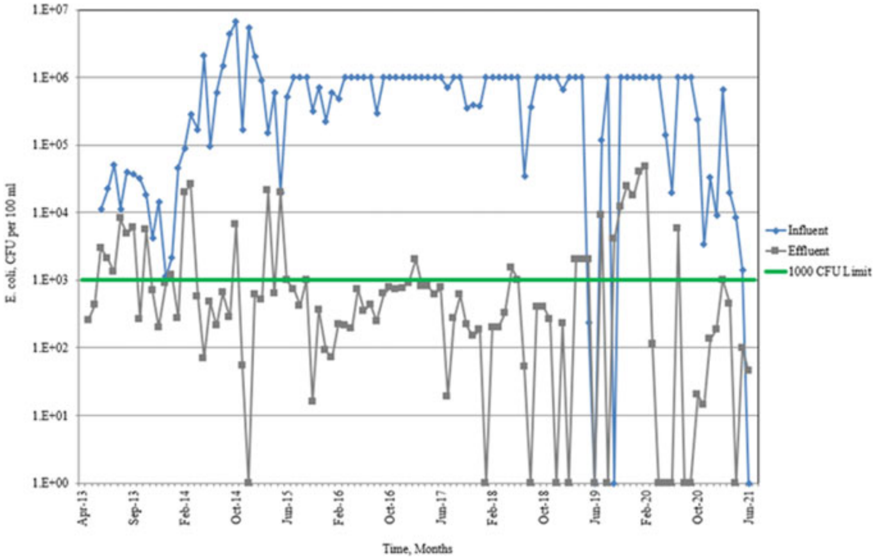

Fig. 13 The graywater wetland was unable to consistently meet the 1000 CFU per 100-ml permit requirement

4 Blackwater Treatment System

To handle the Bullitt Center's blackwater, foam-flush toilets were installed in the bathrooms for all six stories of the building. Once users would enter a bathroom stall, a sensor would activate a system that would pump approximately 89-mL (3-oz) of biodegradable surfactant into the toilet bowl. Waste would then be transported to one of the ten compost bins located in the basement. The Phoenix Composting Systems (Advanced Composting Systems, Whitefish, MT) had a total volume of approximately 2.2-m^3 (978-ft^3) and an active volume of 1.6-m^3 (57-ft^3). Wood chips were found to work better than wood shavings for mixing with the waste to provide bulking that would keep the bins aerated. After they were two-thirds full, the compost bins were emptied and the finished compost would be hauled to a King County, Washington biosolids-to-fertilizer processing facility.

Liquid waste passed through the compost bins and would be stored in one of four 1892-L (500-gal) polyethylene storage tanks. Approximately ten times per year, a vacuum truck would remove the leachate from the tanks and haul it 41.8-km (26-miles) for disposal at a King County wastewater treatment facility in Carnation, Washington. An exhaust fan continuously expelled foul air from the system out of the building except at night when it was usually in standby mode. While this system worked very well, temporary power outages would cause odors to permeate the building. This issue highlights the need for a backup power supply for future building designs.

By spring 2021, after eight years of operation, the Bullitt Foundation decided to replace the composting toilets with a vacuum toilet system due to numerous challenges [14]. Because toilet water from the building's bathrooms were piped directly to specific compost bins and because waste was produced at different rates, the bins were always at different stages of the composting process. This could have been ameliorated by piping all the waste to a single mixing tank and then distributing it evenly across the ten bins. Providing extra system capacity by increasing the number of bins by 40% or more would have also added a relatively inexpensive level of redundancy.

Maintenance and inspection of the bins was also a challenge due to the tightly designed basement space which made it difficult to access pipes and components located on the bottoms and tops of the bin. Future designs should ensure that there is abundant room around each bin and that they are adequately elevated to ensure drainage and full access to outlet piping located underneath each bin. The bins also required a unique troubleshooting skillset which was not common among the rotating staff of building engineers that were originally outsourced to a building management company. (This issue was eventually solved by hiring permanent in-house staff to manage the system.) Maintenance of the foam flush toilets was also a significant challenge as they needed frequent repair and were unable to consistently clear the toilet bowl of waste and toilet paper. As a result, up to 50% of building staff time was dedicated to maintenance of the toilets and composting system [14].

The lessons from the Bullitt Center's composting toilet system have been incorporated into PAE's headquarters in Portland, Oregon which opened in summer 2021 [15]. Their system combines a vacuum flushing system, a waste mixing tank and an adequate number of compost bins that are easily accessible from all sides. Because space limitation made an updated retrofit of the Bullitt Center's composting system impractical, The Bullitt Foundation chose to remove the composters due to their impact on operations and maintenance, and to align with a more conventional Class A Office building.

The selected option for the Bullitt Center retrofit project uses an Acorn vacuum assisted low-flow toilet system (AcornVac, Chino, CA) routed to the existing sanitary main with the use of treated graywater for flushing. The Acorn system uses 1.3–1.9-L (0.34–0.5-gal) of water per flush. A vacuum system pulls the waste from the toilets to an accumulator system located in the building basement. In addition, the waterless urinals were replaced with hybrid waterless urinals and a single urine accumulator tank located in the basement. This reduces the maintenance associated with the original, completely waterless urinals and minimizes the buildup of urea crystals in the waste piping. The vacuum system pulls from the accumulator tank and the urine is then pumped to the King County sanitary system. This approach also allows for a future urine capture and processing system that would create commercial grade agricultural fertilizer.

Because the vacuum toilets use more water than the previous foam flush toilets, the new system uses treated graywater for flushing. Using effluent from the existing graywater treatment wetland posed two significant challenges (1) the system would have to be NSF certified to meet code requirements for sanitary toilet flushing and (2)

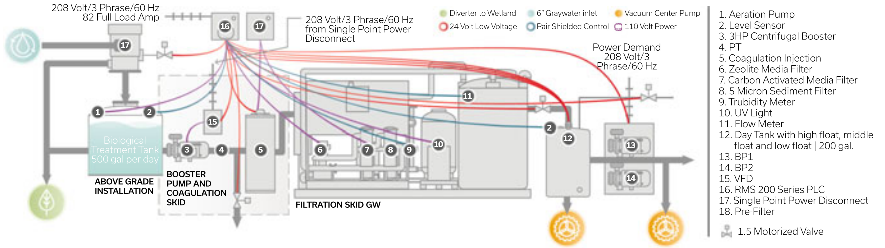

Fig. 14 The Bullitt Center's revised graywater treatment system uses biological treatment, media and cartridge filtration and UV disinfection

the system would require a significant retrofit to route piping from the wetland back into the building. Given the length of time that it took to have the solar panels NSF certified by a third party testing agency for the potable water system and the urgency to replace the composting system, an NSF-certified Grayworks W1000 packaged graywater system (Fig. 14) was installed (Rainwater Management Systems, Roanoke, VA). This system can treat up to 1892-Lpd (500-gpd). After initial filtration with a 284-μm self-cleaning vortex screen, graywater is treated in an attached growth bioreactor which is followed by a series of three filters: (1) a zeolite media filter (2) an activated carbon filter and (3) a 5-μm sediment filter. After UV disinfection, the treated graywater is stored in a 757-L (200-gal) polyethylene tank day-tank for toilet flushing. While the cost of replacing the composting toilets with a vacuum system ($630,000 USD) and a packaged graywater treatment system ($547,000 USD) was significant, these capital costs outweighed the long-term costs of maintaining the composting system.

5 Conclusion

The designers of the Bullitt Center were true pioneers in the sustainable building field. Led by Earth Day Founder and Bullitt Center President Denis Hayes, the team fulfilled the vision of creating a six-story office building that thrives within its own footprint. They demonstrated that it was possible to construct the most sustainable office building in the world within a densely populated, urban environment by using turn-key energy and water treatment systems. As a result, the Bullitt Center is a building that was built to be self-sustaining and resilient well into the future despite the challenges that climate change may bring.

The team also proved that excess solar power can be generated in rainy Seattle and that decentralized water and wastewater treatment systems could meet or exceed regulatory standards. If the expenses for operating and meeting testing requirements for these water treatment systems could be shared by multiple buildings on a campus or district level, it would increase their adoption by future design teams. Until then, using municipal water supplies (with point-of-use filters) will continue to be a significantly less expensive option for building owners. Similarly, discharging waste directly to sewer systems will continue to be less expensive and a more climate-friendly approach to managing wastewater compared to the regular hauling of liquid and solid wastes. The Bullitt Center experiment has also shown us that we can dramatically reduce our impact on municipal water and wastewater systems by adopting low-flow fixtures and toilets and by promoting a conservation ethos. These practices can be immediately implemented by current and future building owners. To further conserve our water resources and adapt to droughts caused by climate change, we can strive to promote rainwater storage and the re-use of treated graywater for irrigation and toilet flushing.

Disclaimer The mentioning of products, vendors and trade names in this chapter are only for research and educational purposes, and does not constitute an endorsement by the authors of this chapter or editors of this volume.

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Examining Drivers and Barriers of Urban Water Reuse Through Case Studies in Oklahoma, USA

Madeline Wade

Abstract Urban water reuse represents a viable and successful water management strategy to secure additional supply in places prone to drought or water scarcity. Many communities already recycle wastewater to supplement non-potable and potable water supply. This chapter outlines the drivers and barriers for water reuse as a water management strategy. It examines water reuse issues in the state of Oklahoma, USA, a drought-prone region with no precedent of potable reuse, to discuss how water reuse projects occur and what determines their success. Despite its technological and environmental advantages, the success of municipal wastewater reuse is often dependent on public perception and willingness to use recycled water. Psychological reactions of disgust create the primary barrier to this success. Some research has shown that community education initiatives can decrease disgust and increase willingness to support water reuse projects. This chapter cites a community education effort in Norman, OK that demonstrated the ability of in-person education to reduce disgust and increase support for urban water reuse projects.

Keywords Wastewater reuse · Community education · Psychology · Perception

1 Introduction

The phrase "Everyone is downstream of someone", originally coined by former US Secretary Bruce Babbitt, has become a common mantra among water planners and managers [1]. Sec. Babbitt's statement pointed out something seemingly obvious but frequently missing from the collective common sense: no water is new water. The basics of the water cycle remind us that water is constantly being recycled through processes of evapotranspiration, condensation, and precipitation. Similarly, water is recycled as it is discharged from a point, such as a municipal wastewater plant, to receiving surface waters, and withdrawn downstream by another utility or water user. Water reuse, also referred to as wastewater reuse, wastewater reclamation, or water

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T. Younos et al. (eds.), *Resilient Water Management Strategies in Urban Settings*,
Springer Water, https://doi.org/10.1007/978-3-030-95844-2_8

recycling, refers to reusing treated wastewater locally rather than discharging it to the environment. Water reuse is a broad term covering several practices under its definition. Often, the words water reclamation, water recycling, or water reuse, all refer to the treatment and reuse of wastewater. While there are many industrial and agricultural implications of water reuse, this chapter will focus on urban water reuse, with an emphasis on potable water reuse. These terms are often used interchangeably, but they may have different connotations. Throughout this chapter, the term water reuse will refer to the process of reusing treated wastewater within an urban context rather than discharging it downstream. "Reclaimed water" will refer to the water that is produced in a water reuse project.

This chapter identifies the drivers and hurdles of wastewater reuse in the United States (US), through the lens of the evolution of water reuse in Oklahoma. While reclaimed water is reused all over the world, we will focus on the context of water reuse in the United States. Oklahoma is a drought-prone arid region without extensive standards for potable reuse. While non-potable reuse projects have been implemented and more are planned, the state is behind in comparison to the extent of water reuse projects in similar states. When water reuse becomes a potential strategy for creating alternative drinking water sources, people commonly respond with a disgust reaction, also called the "yuck factor". Planning for and financing water reuse is an expensive and in-depth process, and many factors influence the viability of water reuse in a given place. This chapter will outline drivers and barriers to potable reuse projects, discuss literature related to overcoming disgust, and examine the case study of Norman, Oklahoma, and its novel indirect potable reuse project.

2 Water Reuse Categories

Water reuse can be broken down into three basic categories: Non-potable reuse (NPR), Indirect Potable Reuse (IPR), and Direct Potable Reuse (DPR). NPR refers to the treatment of wastewater to non-drinking water standards for reuses such as cooling and irrigation. NPR is by far the most common and accepted form of water reuse in the US. It often happens on-site for large industrial operations and agriculture, but many have now established NPR as a way to irrigate landscapes or crops [2]. Studies on the acceptability of NPR have taken place since the 1970s and have been met with high acceptance. A study by Bruvold in 1988 showed over 90% acceptance of reusing water to irrigate golf courses, parks, lawns, and gardens, and subsequent studies have shown comparable levels of acceptance [3, 4]. Because the water from NPR is often nutrient-rich, in some places the demand for this water has increased because of its fertilizing effects on crops [5]. Yet, the US is far from reaching the full potential for municipal water reuse. In North America, the annual reuse of treated wastewater only accounts for 3.8% of all wastewater treated [6, 7].

The second category of water reuse relates to potable reuse of wastewater. Direct Potable Reuse (DPR) is the incorporation of treated wastewater into an existing potable water treatment and distribution system, without the use of an environmental "buffer" such as a river or lake. DPR is rare in the US as compared to other forms of water reuse, primarily because of legal barriers. Only a few states have established a DPR permitting process, and most DPR projects are in their infancy or only used as an emergency drought measure.

The third and final category of water reuse is Indirect Potable Reuse (IPR) and is the primary focus of this chapter. IPR refers to the augmentation of an existing drinking water source with a portion of a utility's treated wastewater. IPR involves an environmental "buffer", such as a river, lake, or aquifer to fulfill design elements of dilution, extended retention time, and attenuation of contaminants [8]. IPR may also augment existing storage reservoirs or aquifers with wastewater treated to potable reuse standards to make existing supplies more sustainable and resilient [8]. The amount of water that can be reclaimed often depends on downstream water rights and any applicable environmental flows regulations. Any local or federal water compacts or existing uses must be considered before determining the safe amount of treated wastewater discharge that can be rerouted to a drinking water source. Guidance for technical studies and engineering reports required for IPR is described in the US EPA National Water Reuse Action Plan (WRAP) and any state or local water reuse regulations [9].

It is important to note that IPR does not necessarily equate to a lower risk of pathogen consumption or a higher water quality than water produced from DPR [8]. IPR is often perceived to be lower risk than DPR, but there is no demonstrable evidence that a natural "buffer" provides any public health protection unattainable by other methods of advanced treatment. In some contexts, DPR may be more attractive than IPR because there may not be a viable environmental buffer to divert the water, or the arid climate would result in higher evaporation and a lower yield. DPR also allows for utilities to monitor water quality throughout every step of the reuse process without relinquishing control. Localized technical studies and cost–benefit assessments should be undertaken before deciding whether IPR or DPR is most appropriate. Some argue that the terms IPR and DPR should be dropped, as they do not reflect a difference in water quality or risk [8]. However, at present, permitting programs and regulations separate potable reuse into these two categories, and this is not likely to change soon.

While it is not considered under the definition of water reuse, the presence of wastewater in drinking water sources has been a common and accepted practice for centuries [2]. The presence of upstream wastewater discharges in a municipal drinking water source is often referred to as de facto reuse because water from one utility is being reused unintentionally by another downstream. When municipalities discharge treated wastewater, it is sent downstream and diluted with a river or lake before it reaches a source that is used for drinking water. A study by Nguyen et al. found that de facto reuse accounts for about 0–13% of water samples from drinking water sources across the country, and in times of low streamflow de facto reuse can account for up to 80% of present water [10]. There is no doubt many if not most places in this country rely partially on wastewater from another place, yet for many people, water reuse elicits strong disapproval.

The illusion of the tap has convinced many that water is something constantly available and pristine, rather than something that has been treated, used, treated again, and reused for millennia. Water managers and planners planning for wastewater reuse to supplement future water supplies have the challenge of tackling the misconception that water has not been used before. The goal of wastewater reuse is to sustainably increase water supplies, especially in times of drought or scarcity by replicating the natural water cycle on a smaller scale. Rather than send water to be used downstream, a portion of wastewater is treated and reused within that community.

3 Drivers for Water Reuse

Plans for water reuse often arise out of necessity as a part of a drought contingency or resilience strategy. Three complementary goals of potable water reuse are water security, water sustainability, and water resilience, which all have to do with the longevity of supplies and the ability to plan for future demand and supply scenarios [9]. Potable water reuse projects have been successfully implemented in many arid regions which have the necessary technology, including in the western United States. Public perceptions depend on the perceived adequacy of existing supplies to meet future needs [11]. When communities have experienced the consequences of drought, they are more likely to support potable reuse [5, 12]. When water service providers plan for water reuse projects, the knowledge that existing supplies are not sufficient to meet projected demand scenarios typically drives the planning process. The need to downsize or delay the construction of new projects to obtain water supplies may be another driver of the planning process. For example, investing in potable reuse may be an alternative to the construction of new well fields or a new dam. Compared to these large infrastructure projects, water reuse may be a financially viable and sustainable option for supplementing future supply in arid regions [13]. As we discuss later, the success of water reuse often requires an engaged and involved community that supports the project [14], and in times of drought or scarcity, communities are much more likely to support and participate in water conservation efforts [15].

Beyond a water shortage triggering action to plan for water reuse, projects may be driven by policy, environmental considerations, or social factors. The evolution of water treatment technology co-evolves with regulations and policy changes. Policies can influence the adoption of new technology, and this improves overall water quality and efficiency of treatment operations. Similarly, the emergence of policy concerning water reuse may lead to more robust treatment and more direct paths to water reuse. For example, the state of Florida, USA created the Wilson-Grizzle Act in 1972 which required all wastewater discharges to meet drinking water standards. As a result, many municipalities in Florida achieved zero-waste discharge and took the opportunity to reuse the high-quality effluent locally [5]. Similarly, water reuse projects may be motivated by environmental concerns. The treatment of wastewater to reuse standards and the introduction of high-quality effluent to an existing water source may be used, in some cases, to abate pollution and reduce contamination through dilution with high-quality water [2].

Another driver of water reuse is the decentralization of water infrastructure and decreased reliance on imported water. As future water supplies fail to reach projected demand in many places, water utilities are under enormous pressure to manage demand and obtain new sources of water. Increasing populations, urbanization, and lifestyle changes have considerably increased the demand for water in many places. Aging and deteriorating water infrastructure around the country compounds this problem. As more communities face increased water demands and decreasing existing supplies, some communities, often small or rural communities, are forced to rely on imported water. Transferring water often has variable costs such as the construction of pipelines, requiring a dependency on the treatment and distribution capabilities of larger service providers. These supply and delivery challenges have led to an increased interest in sustainable, decentralized water infrastructure to facilitate individual or community-scale reuse. Investing in potable reuse allows communities to create a self-reliant source of supply rather than relying indefinitely on outside water supplies. While reuse may involve a large initial investment, it has the potential to reduce costs in the long run. Supplementing existing supplies with reclaimed wastewater allows providers to delay the construction of new infrastructure projects, reduce water withdrawn from sensitive groundwater or surface water sources, and build decentralized self-reliant sources of future water supply.

Many water service providers are motivated enough by these drivers to plan for water reuse in the future. In successful water reuse projects, all the drivers and benefits should be considered and compared to alternative water supply strategies to determine if water reuse is legally, financially, socially, and environmentally beneficial. There are barriers to the success of potable reuse projects in the US, and considerations factor into determining whether water reuse is the most appropriate strategy.

4 Barriers to Water Reuse

The inclusion of water reuse as part of a utility's water supply portfolio requires substantial financial capital. Initial investments required for water reuse, whether for installation, maintenance, operations, or distribution, are variable but may hinder the potential for water reuse [6]. While many treatment plants possess the technology necessary to treat water to US EPA standards, many of those plants are reaching the end of their life span and require expensive upgrades, especially to meet potable reuse quality guidelines. In smaller communities or areas with declining populations or low average household income, municipalities are unable to meet fiscal needs with revenue from fees paid by utility customers [9]. Inadequate technology or inadequate validation of the technology's performance can delay or prevent successful water reuse projects. For these reasons, water reuse is often only used when water conservation is not sufficient to meet future water demands.

4.1 Costs and Benefits

Costs are highly variable for water reuse projects and depend on current treatment, maintenance, operation, and distribution capabilities [6]. However, many programs are available to help municipalities meet these needs. The Water Reuse Association, a national association dedicated to advancing policy, funding, and acceptance of water reuse in the U.S., has established committees to engage stakeholders, legislators, and water service professionals to establish funding opportunities to help communities overcome the financial barriers to water reuse. Their water reuse infrastructure funding program secures funding for water reuse grant programs, desalination projects, clean water state revolving funds, and drinking water state revolving funds [16]. Title XVI of the US Reclamation Projects Authorization and Adjustment Act of 1992 (P.L. 102-575), commonly referred to as Title XVI provides federal (US) funding for needed water infrastructure. The Title XVI Water Reclamation and Reuse Program provides funding for the reuse of water for municipal, industrial, domestic, or agricultural wastewater and impaired ground or surface water [17]. Through this act, the Bureau of Reclamation identifies and investigates potential projects and provides grant funds for water reuse. Title XVI is the only US federal program that specifically allocates funds for water reuse programs [18]. In addition, many US states offer incentives or tax credits for water reuse on multiple scales and applications. As more grants and funds become available across the country, financial restrictions may become less of a significant barrier to successful water reuse programs.

Cost–benefit analyses (CBA) often overlook the social and environmental benefits of water reuse projects. Assessments of the economic viability of water reuse often only consider the *financial costs*, the monetary amount the utility will pay for construction and operation of the project, and neglect *economic costs and benefits* which account for all costs, whomever they affect [8]. An assessment of economic costs would include social and environmental costs and benefits, as well as financial costs, otherwise known as the triple- bottom- line. Analyses need to consider local context, including the size and scope of the project, water quality regulations and expectations, and any associated distribution costs. Additionally, CBA should include non-monetized benefits, such as reduced peak seasonal demands, reduced operating costs, and prolonging of existing supplies. Considering the triple bottom line requires an ongoing review of social and environmental costs [8]. Quantifying social and environmental costs and benefits is easier said than done, explaining why most analyses consider only financial components and usually end with project certification. However, there are methods to estimate the value of non-monetized benefits (see Kidson et al. [19]). A qualitative analysis should also be done to consider the social benefits of reuse and the willingness of the community to support a self-reliant water project. Failing to consider non-monetized costs and benefits of various water supply strategies may lead to a project that will be less successful or have more non-monetized costs in the future.

Economic analysis should also develop estimates for costs of other alternative water supply strategies and consider the cost of doing nothing. The cost of doing nothing often exceeds proposed costs because it involves reliance on outside, centralized water sources or the construction of expensive infrastructure. In other words, the cost of implementing water reuse should be compared to the cost of not acting or the cost of obtaining alternative water resources. Environmental benefits should be assessed either through a study of how water reuse would alter or improve ecosystem services or how it would impact water allocated for downstream environmental flows. These benefits may be quantified through studies of ecosystem services, but qualitative analyses should also be done to understand how the community values various costs or benefits of the project. Using the triple-bottom-line approach to evaluate water reuse can allow for the profitability of the project to be presented from the entire community's point of view [20]. Economic analysis paired with increased research and data availability, and stakeholder involvement, can reduce uncertainties of risk and support decision-making [4]. When considering launching a water reuse program, the agency should review investment priorities and make sure it is the top investment priority for the current situation [21].

4.2 Policy and Regulation

Policy, whether local, regional, or federal, can be inconsistent or conflicting and can pose a challenge for planning potable reuse. State environmental agencies are often the permitting institution for the construction of water reuse infrastructure and distribution. States often craft permitting policy in accordance with federal planning and operation guidelines. The latest and most comprehensive framework for developing water reuse policy, the 2019 National Water Reuse Action Plan (WRAP), discusses the potential of water reuse to meet the United States' needs and provides guidelines for water reuse project planners. The guidelines detail considerations for planning and management, potential applications, and the framework of existing state and local regulations that need to be considered. These extensive documents are key considerations of any municipality considering potable reuse as a future water management strategy [9]. Since the release of WRAP, nearly every US state has developed some guidelines, programs, or regulations for water reuse.

Historically, wastewater discharges have been subject to the guidelines of the US Clean Water Act and require a National Pollution Discharge Elimination System (NPDES) permit from the US EPA. Because rules for discharging pollutants are not focused on the potable application of effluent and are highly variable, some recommend that water reuse operations should adhere to the US Safe Drinking Water Act. Permitting potable reuse may be easier if the discharge of water for IPR was no longer classified as a "discharge of pollutants" but instead regulated as water classified for potable uses, although this change would pose some economic and policy challenges. This condensed regulatory framework would provide consistent guidance and encourage more efficient and safe water reuse operations. The streamlining of regulations would also increase the implementation of water reuse projects by making compliance with reliable and robust treatment standards easier [16].

Although water reuse operations have existed in the US since the mid-twentieth century, federal guidelines for potable reuse were not established by the EPA until 2012 with the publication of the “Guidelines for Water Reuse”. This extensive document, and subsequent guidelines published in 2017 and 2019, provide a framework for states to develop regulations and permitting processes for water reuse operations. Beyond federal guidelines, nearly every US state has developed some regulations, programs, incentives, or guidelines for water reuse. Some states have regulations for only certain types of reuse, while others, such as California and Texas, provide extensive guidelines and parameters for different kinds of reuse operations. Guidelines may be unclear or contradicting, and legal barriers are often cited as a hindrance to the success of water reuse projects [6, 9]. Because of regulatory and legal barriers, water reuse is more difficult to propose or approve in states without adequate regulations.

4.3 Public Health and Community Concerns

Other factors that should be considered when planning urban water reuse operations are public health protection and community concerns. Potable water reuse operations must make it a priority to protect the public from known and unknown contaminants. Whether risks to public health are real or perceived, they can prevent the success of water reuse operations. Utilities often use conventional treatment methods consisting of physical, chemical, and biological processes to treat municipal wastewater and drinking water. These conventional treatment practices often meet existing regulatory guidelines, but more research is necessary to understand the effectiveness of these treatment methods on trace contaminants such as PhACs and PCPs [2, 22]. Trace contaminants such as these have been labeled by the US EPA as Contaminants of Emerging Concern (CEC). These are contaminants that are unregulated but have been identified in natural systems. CEC are not included in routine monitoring programs or policies but may have depleting effects on aquatic life at certain concentrations [23]. A major concern for water planners and the public is the CEC coming from pharmaceutical and personal products. Microbial risk assessments should be undertaken to manage these contaminants, although the EPA points out that these are present in many drinking water sources. Still, these assessments are even more important for sources that will be receiving reclaimed water [9]. Another looming concern is the presence of PFAs, or “forever chemicals” in treated wastewater. These chemicals are fluorinated, meaning they are more resistant to degradation. They are also as of publication, unregulated by the US EPA, which makes it difficult to determine safe concentrations in drinking water. Various treatment methods, including oxidation, have been tested to remove these chemicals, with some success. For more information on PFAs in full-scale and concentrated wastewater treatment, see Lester [24]. Utilities planning for water reuse should determine safe concentrations of PFAs based on the health of receiving surface waters and implement studies to determine the most effective treatment method.

Perceived or actual public attitudes toward water reuse have been identified as the primary barrier to the success of water reuse projects. Research has found general support within communities for conserving water through reuse, but there is a gap between support and willingness of individuals to personally use or consume this water [25, 26]. Even if financial, legal, and technical aspects have been considered and proven to be effective, public reactions can derail water reuse projects [25, 27]. Several examples of failed projects due to perceived or actual public rejection include Toowoomba, Australia, and in the United States—San Diego, California and San Gabriel Valley in California [12, 25], although the San Diego project has since become operational and had success [16]. A review of studies published up to 2000 investigating public acceptance of water reuse by Hartley found that 10 factors contribute to a high acceptance of water reuse: minimal degree of human contact with the water, clear communication of the protection of human health, beneficial outcomes to the environment, promotion of water conservation through reuse, reasonable costs associated with treatment and distribution, a perception that wastewater represents only a small portion of water supply, high awareness of water supply problems within the community, clear communication of the role of wastewater reuse in water supply strategies, high perceptions of water quality of reclaimed water, and confidence or trust in the local officials managing the resource [4, 28].

Decision-making is a complex process, and it can be difficult to pinpoint the predictors of certain behaviors. While some argue that attitudes of water reuse tend to be consistent across contexts and cultures [29], specific concerns may need to be addressed that can only be identified through localized studies. For example, in some places, the perceived religious purity of the practice of recycling water may be important to the community [30]. Nancarrow et al. established a revised version of *Azjen's Theory of Planned Behavior* for investigating contributors to behavioral intentions regarding water reuse. They identified emotion (disgust), trust, subjective norms, and environmental obligation, perceived control, knowledge, and responsibility. Although decision-making is a complex interaction of all of the above, research can isolate and test certain variables to determine what factors may influence the extent to which a person believes in the positive outcomes of water reuse. The researchers found trust, risk, perceived control, subjective norms, emotions, and environmental obligations to be significant predictors of participant's attitudes toward water reuse [31]. Knowledge of water treatment did not have a significant relationship in this study. However, many studies have shown that knowledge of water treatment and trust in public officials have both shown to have a positive relationship with acceptance of reuse [25, 32].

4.4 The Yuck Factor

Since more municipalities have implemented or planned for wastewater reuse, many studies have been published investigating public perceptions of water reuse in various parts of the world. These studies reveal that, although contextual factors influence public opinion, disgust, or what has been coined “the yuck factor” by many, is closely tied to our acceptance of water reuse across contexts [29]. The *yuck factor* is often focused on more than other processes contributing to acceptance because of its difficulty to overcome and its relevance across contexts and cultures. Emotions have also been identified as a significant predictor of support for water reuse when controlling for other factors such as risk attitudes, trust, social pressure, and perceived control [31]. This “yuck” we feel when we think about treating our wastewater, and using it again as drinking water, is an evolutionary response that arises out of our brain’s instincts to prevent pathogen infection. Because this emotion is evolutionarily linked, it is much more automatic than other cognitive processes. This means the *yuck factor* often kicks in before our brain has had time to incorporate knowledge or seek out new information [27]. We make a snap judgment and collectively this reaction can derail or prevent the success of wastewater reuse projects. To get past disgust, we may need a certain knowledge of understanding of wastewater processes to activate the cognition that overcomes our initial emotional instinct.

Hundreds of studies have been published on overcoming disgust related to water reuse, with various and sometimes conflicting results. Some have found that objective knowledge of water treatment or existing water reuse operations can lower disgust [29], while others have found that knowledge does not accurately predict disgust [31, 33]. Some argue that the type of knowledge makes the difference, with objective knowledge while others have found that political affiliation is a significant predictor of water reuse, and can overcome knowledge of water treatment. However, some patterns can be drawn out of literature investigating the *yuck factor*, such as the fact that trust and information can mediate disgust reactions [4]. It is important to note that the *yuck factor* is not fixed, but can be changed by triggering other cognitive functions, which can be consciously activated, such as changes in attitude, a better understanding of water reuse processes and the associated risks, and a trust in public officials. The first study investigating the role of information on disgust and associated attitudes toward water reuse appeared in 1985. Lohman and Milliken (1985) conducted a study in the US that found providing tours of the potable water reuse demonstration plant was a more effective means of education than providing reading materials alone. In-person interaction with a public official, especially at the site of water treatment, has been shown to increase trust and make stakeholders feel involved in the planning process [4, 34]. It “flips a switch” in people’s minds, allowing them to see the quality of water being discharged and learn more about the de facto reuse that is common in most places. Despite Lohman’s and Milliken’s findings (1985), only a handful of studies have utilized treatment plant tours as a method of education [4, 35–37].

Psychological reactions to water reuse can be influenced by the language used in messaging. A prime example of the power of language in water reuse communication is the use of the phrase “Toilet to Tap”. You may have heard this phrase used to describe potable water reuse. It is often even used by water service providers or professors teaching water-related courses. While it is common slang, the phrase fails to acknowledge the advanced capabilities of wastewater treatment and may conjure an image of disgust that can be difficult to overcome. In 1997, San Diego, California

USA began planning a water reuse project to mix recycled municipal wastewater with imported freshwater in reservoirs. Water planners understood the importance of understanding public perceptions and listening to stakeholder concerns, and thus developed an extensive outreach and education program to gauge acceptance and increase understanding of the project. Focus groups and over 200 interviews indicated high support for the project, and an independent citizen's review found the project would be accepted and have success [25, 38]. Despite this strong support, the project became the subject of political campaigns claiming that the project was targeting the water supply of less affluent communities. These campaigns created and distributed printed materials covered with the phrase "Toilet to Tap". The response from this messaging seemed to undo the progress made through previous stakeholder engagements highlighting the benefits of the project. A hearing was called, attended by hundreds of worried citizens, and the project was eventually put on hold indefinitely [25].

Potable reuse operations, whether direct or indirect, are often only used during certain periods of drought. Planning for water reuse requires localized studies to determine safe levels of identified contaminants and establish drought triggers to begin incorporating reclaimed water. A consideration of downstream water rights and permitted environmental flows is necessary. Additional surveys of flows needed to maintain downstream ecosystems may be necessary for some places, especially those in places like Oklahoma, where there is little precedent of incorporating environmental flows into water rights [39]. A study was done at the University of Oklahoma to determine the environmental parameters of Indirect Potable Reuse in Norman [40]. The study determined the route treated water would take to be incorporated into the drinking water source and the amount of discharge that would not create substantial risk. Studies like this should be standard practice before the implementation of water reuse.

To combat resistance to potable reuse, it is essential for water service providers to engage a wide range of stakeholders in the community. Failure to engage communities before the project and at every stage of its implementation may send the message that the project is happening in secret. Community members' trust in public officials may be compromised, and trust is a significant predictor of community acceptance [31]. Community engagement should be tailored to the local community and include educational components. Knowledge of water treatment and trust of public officials, both significant predictors of public acceptance of water reuse, can be cultivated through in-person water treatment education [37, 41]. Two studies in Mawson Lakes in Australia found people who were well informed about water reuse demonstrated higher trust in public officials and a greater willingness to use reclaimed water. Researchers also found that risk perceptions of water reuse had a negative relationship with a feeling of being well-informed [41–43]. Other studies have found that objective knowledge of potable water reuse was a strong predictor of acceptance of water reuse, more so than other parameters like disgust or subjective knowledge [32].

Research on the relationship between efforts to educate the community and public attitudes toward water reuse has produced mixed results. Some education practices result in higher acceptance of water reuse, while others have shown no significant relationship. This indicates that the type of education utilized matters. Providing simple information on paper rarely results in higher acceptance [27, 37], perhaps because it does not guarantee an increase in understanding of water treatment. Other studies have found that knowledge of water treatment or awareness of water reuse projects does result in higher acceptance [29]. The method of conveying knowledge makes the difference. Community education can accomplish several goals of crafting intentional messages by increasing knowledge of water treatment and reducing exaggerated risk perceptions of water reuse. While surveys and focus groups are useful for understanding perceptions and knowledge gaps within a community, they should be supplemented with outreach and education to encourage public involvement and increased trust in public officials [44]. Properly crafted surveys can develop a baseline understanding that can guide education and outreach programs, targeting specific worries or concerns or addressing specific gaps in public knowledge [44]. Educational initiatives should be context-specific and address any concerns identified in baseline surveys.

In-depth education, including complex but digestible information, has been shown to have a more positive effect on support for water reuse than simple information [45]. One way to convey complex information in understandable terms is through in-person education, led by public officials, that allows participants to ask specific questions or raise specific concerns [14, 34, 35]. Designing community education programs that include tours of the wastewater treatment plant led by public officials, bring people face-to-face with what happens to their wastewater and where it goes after treatment. A case study of public perceptions of water reuse in Albuquerque, New Mexico USA, found facility tours increased willingness to use recycled water more than control groups or groups that received informational packets [35]. Among patrons of Valley Water in the Santa Clara Valley, California USA, researchers found tours doubled the percentage of people strongly in favor of water reuse projects [36]. Similarly, the author's presented case study of Norman, Oklahoma USA, which will be discussed later, showed facility tours to have a more powerful effect on perceptions of water reuse than information on paper [37].

Any promotional or informational materials should include comprehensive information about the proposed project. It may be beneficial to emphasize the reality of de facto reuse, as well as the wide range of social and environmental benefits water reuse can provide. Education should be focused on local issues and sources and give as specific information as possible, without including industry jargon. Messages should not be crafted on the ways water reuse is discussed by industry professionals, but rather using terms research has shown to produce favorable outcomes. For example, one study provided information about water reuse to two randomized groups, with the only difference being the use of the terms "treated wastewater" or "recycled water". While treated wastewater is a more accurate term for what is sent to augment drinking water, and is much more common in federal and state reports, researchers found those that received information with the term "recycled water" were significantly more willing to use the water and pay for a water reuse project [46]. Those crafting messages and educational materials should avoid imagery that elicits disgust, such as "treated wastewater", despite its frequency of use in official documents.

5 Case Studies in Oklahoma, USA

Now that we have examined drivers and barriers for potable water reuse projects, we will look at these factors in the context of Oklahoma USA. Oklahoma faces specific challenges when planning for or implementing water reuse projects. Oklahoma is a drought-prone state, making water reuse an attractive option, but it is also inland, meaning the complications from considerations of downstream water rights are more complex than in coastal states. Furthermore, in Oklahoma certain environmental and legal initiatives related to conservation are lacking compared to other states. For example, when allocating water rights, the state currently does not consider environmental flows and there is no legislative framework for permitting water for environmental protection [39]. Legal barriers also prevented the feasibility of potable reuse in the state since no regulations existed regarding water reuse, potable or non-potable before 2012 [39]. Potable reuse guidelines were developed by the Oklahoma Department of Environmental Quality (ODEQ) and became effective in 2018 [47]. At present, there are dozens of examples of non-potable reuse projects in Oklahoma, and both potable and non-potable reuse are major priorities of the Water for 2060 state water plan [39]. Many municipalities may also experience financial barriers to reuse. They may already rely on water imports or a shared management of water for small towns through a rural water district. Cities without substantial revenue from water service provision rely on competitive funding opportunities. For many years, Oklahoma water providers only had federal funding, such as the Title XVI program (discussed in PL 502.575), to receive funds for potable water reuse. However, more state opportunities are becoming available. The OWRB has made water reuse a priority of the drinking water state revolving fund and potable water reuse is an integral part of the state's water for 2060 plan, signaling many more local and state funding opportunities will exist in the coming decades [39].

From 2011 to 2016, Oklahoma experienced a period of drought that mimicked drought conditions of 1995–1996, one of the most severe droughts on record. Oklahoma has a history of intense droughts, especially in Western Oklahoma and the Panhandle. Historical drought measures have been crisis management and have been reactive rather than proactive [48]. The state is prioritizing a shift to proactive drought control measures to reduce strains on water service providers and the environment when drought does hit. Since 2010, representatives from several utilities in Oklahoma have expressed interest in reusing water to help efforts of water conservation in times of drought. These utilities, along with members of the ODEQ, engineering experts, and members of the community began the process of creating water reuse regulations for the state. Non-potable regulations for construction and operations became effective July 1, 2012. Those wishing to obtain a water reuse permit must submit an engineering report, a permit to construct a treatment plant, pumping, storage, or distribution infrastructure, and a permit to supply reclaimed water. Following the release of this policy, several urban non-potable reuse operations have come into existence, at multiple scales. Oklahoma uses the purple pipe system, meaning non-potable reclaimed water is distributed through pipes painted purple and with a label indicating the water is not safe for consumption. Non-potable operations are required to pass inspections and submit monthly operating reports. Oklahoma City has engaged in non-potable reuse for industrial purposes since 1996, and many non-potable reuse operations exist in the state, mostly for irrigated agriculture and industrial applications [39].

5.1 Case Study—Bartlesville, Oklahoma

Bartlesville, Oklahoma, a city of 35,000 people in Northeast Oklahoma, is planning for IPR as a part of its strategic water management plan. The city also provides water for 3 other cities in Washington County, Oklahoma. Average water use spikes to about 54,500 m^3/day in the summer and dips to around 14 to 18 m^3/day in the winter. Additional or alternative water sources will need to be developed to meet the projected 2055 demand of around 38 m^3/day. To meet these water supply challenges, the city of Bartlesville began investigating the potential for IPR in 2017. The proposed plan was compared to other alternatives and an analysis of economic and non-economic factors was undertaken. Of the six options to meet future demand, the water reuse project had the lowest initial capital costs and the lowest life cycle costs [49]. The proposed plan would divert 50% of effluent to a location 8 to 12 km above the water supply intake point. A technical study was conducted in 2018 on six different samples of effluent, water from the Caney River, and water from the point of supply intake to determine risks to public health and the environment if IPR were to be implemented (Fig. 1). The primary challenge for this study was the presence of Contaminants of Emerging Concern (CEC) which are contaminants unregulated by the US EPA due to the lack of evidence on their risks to the environment and public health [50]. The technical study revealed that 4 CEC (NP (4-nonylphenol), Amoxicillin, Iohexol, and Sucralose) were present at upper trace concentrations (>100 ng/L) after traveling 8 to 12 km from the proposed upstream discharge point, however, the plan to transfer 50% of effluent would have no adverse impact on the water quality at the current water intake point on the Caney River, based on the ability of the buffer to degrade CEC through aerobic microbial reactions [50]. This claim was supported by the results of a feasibility study undertaken by the City of Bartlesville, which states that effluent will meet all quality standards and be treated again to potable standards in compliance with the Safe Drinking Water Act before distribution. The addition of reclaimed water during summer months may provide additional benefits such as increased surface aeration and dissolved oxygen [49]. While CECs pose a challenge for water reuse feasibility, the research that goes into planning water reuse can help create a database that may help agencies understand, monitor, and set regulations for these contaminants. Since these contaminants are unregulated, there is high uncertainty of their present concentrations in water supply sources as a result of de facto reuse. More research is necessary for the US EPA to establish environmentally relevant concentrations of contaminants that could have negative effects on humans or other species [23].

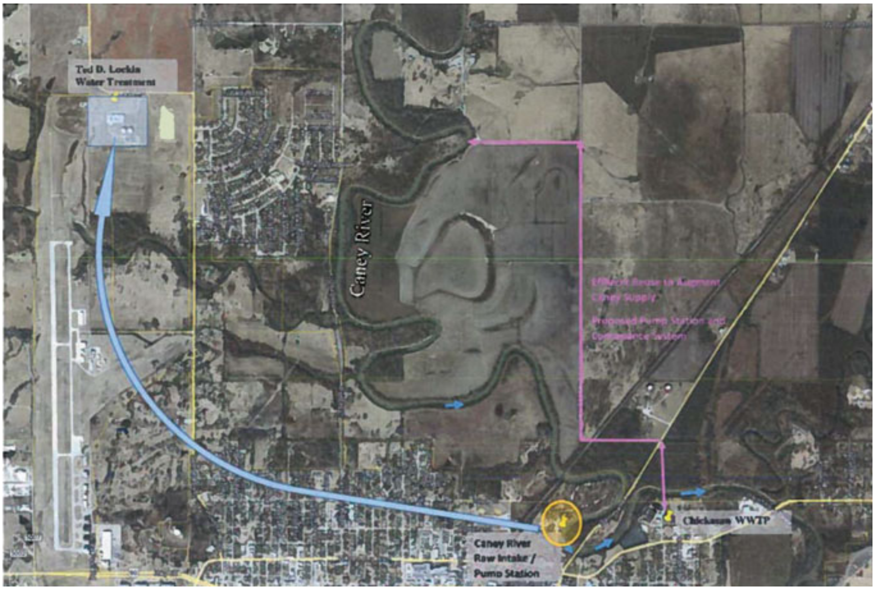

Fig. 1 Map showing proposed route of reclaimed water conveyance system to augment Caney River water supply. *Source* Public Domain [51]

To make IPR a permanent capability of the City of Bartlesville Oklahoma, the city would need to invest in a new pump station and underground pipeline, allowing them to augment the Caney River with treated wastewater during times of drought. In 2019, engineering designs were completed for the pump station for the project [49]. The project is estimated to cost around $8.2 million USD. The city is pursuing these funds through the Drinking Water and Wastewater Infrastructure Act of 2021, a federal act that provides funding for research and infrastructure improvement. The Act dedicates USD 318 million over 5 years for Oklahoma water infrastructure. The bill allocates USD 9.5 million to projects like the one in Bartlesville, although the specific amount the city will receive is undetermined [52]. If these funds are secured, the IPR project is slated for late 2022. Education and outreach plans are in development, and will likely play an important role in ensuring there is public support for the Bartlesville project.

5.2 Case Study—Norman, Oklahoma

The city of Norman, home to the University of Oklahoma, is expected to have a population growth of 85–100% by 2060 [53]. Water planners in Norman understood that secure water supplies were essential to economic growth. The city's 2014 Strategic Water Supply Plan (SWSP) aimed to predict future supply and demand conditions and propose potential solutions. Projections of future demand showed that Norman would experience a supply shortage of around 22,730 m^3/day by 2024 and a shortage of around 68,200 m^3/day by 2060 [53]. During the 2011–2016 drought, former Director of Utilities for the Norman, Ken Komiske, set his sights on potable reuse. He recognized the potential for the high-quality effluent from the Norman Reclamation Facility to supplement the city's supplies, rather than be discharged downstream to be used again from Lake Eufala. At the time, no regulations or guidelines for potable reuse existed within the state, although non-potable reuse was common and regulated.

Despite these barriers, the city began developing a permit application to implement technical studies to determine the feasibility of diverting a portion of treated wastewater to Lake Thunderbird, Norman's primary drinking water source. IPR was listed as one of the major strategies in the city's Strategic Water Supply Plan for 2060 (SWSP), released in 2014 [53]. The city was motivated to be the first potable reuse operation in the state because of the severity of the drought, the existing capabilities of the treatment plant, and the desire to have a self-reliant water supply without depending on water imports from Oklahoma City. Norman developed a set of scenarios in their SWSP to compare the costs and benefits of implementing IPR or constructing a new water delivery infrastructure to import water from Oklahoma City. Hearings about the strategic plan resulted in the decision to apply for an IPR permit, despite the lack of regulations. The city commissioned a study to determine the amount of discharge that could be safely diverted to Lake Thunderbird, and the necessary concentration of contaminants to pose minimal risks to the environment and public health. In 2018, the ODEQ approved Norman's application to conduct a pilot study for IPR to determine the feasibility of making IPR a permanent capability of the Norman Water Reclamation Facility, the wastewater treatment plant in Norman. This pilot project is designed to last 2 years and is focused on establishing robust methods for removing nutrients to minimize further contamination of Lake Thunderbird. In 2017, the City of Norman and engineering consulting firm Garver secured a $700,000 USD grant from the US Bureau of Reclamation to conduct the pilot study [54]. One of Norman's challenges was the fact that Lake Thunderbird is a designated Sensitive Water Source (SWS) by ODEQ. The causes of the impairment of the lake include low dissolved oxygen, high Chlorophyll-A, and high turbidity causing the impairment of Lake Thunderbird [55]. The source of this impairment is largely stormwater runoff from surrounding agricultural and residential development. Because this pollution is hard to monitor or regulate, the Norman Reclamation Facility would be required to invest in additional treatment methods, namely nutrient removal, to prevent further impairment of the water source with the addition of treated wastewater.

In addition to water quality concerns, a barrier for IPR through Lake Thunderbird is the fact it is a shared water source. While the proposed project would only divert a portion of Norman's wastewater, the lake is a drinking water source for Midwest City and Del City, two nearby cities Northeast of Norman (Fig. 2). While Norman officials were passionate about the potential for water reuse, Midwest City and Del City officials were much more hesitant. Their hesitancy may be due to an assumed

Fig. 2 Map showing the locations of Lake Thunderbird, Norman, Midwest City, and Del City in Oklahoma, USA. *Source* Author

lack of control of the lake's water quality. There are large camping and fishing events held at the lake, making it a productive ecotourism destination in the state. To better understand public opinion and the social barriers to the project, Norman developed a series of citizen advisory committees to facilitate conversations between water planners and the public. Open and comprehensive communications between these various stakeholders will be an essential part of Norman's plan for IPR and they hope the pilot project will reduce any hesitancy or concerns held by stakeholders dependent on the lake. In 2018, the ODEQ approved Norman's application to conduct a pilot study for IPR to determine the feasibility of making IPR a permanent capability of the City of Norman's Water Reclamation Facility [47].

6 Community Education and Perceptions of Reuse in Norman, OK

Norman is the only city in Oklahoma that requires all water rate increases to be put to a public vote, making it a prime case study for the role of public attitudes towards reuse on project success [56]. The implementation of IPR as a permanent drought control measure will likely increase water rates and thus require public approval, making it a perfect case study to investigate public attitudes of water reuse and the impact of outreach and education on willingness to support the project with a vote. In 2019, a two-phase study was designed by the author to determine baseline acceptance of water reuse in Norman, and investigate the role of community education in the form of wastewater treatment plant tours on acceptance of water reuse.

In phase 1 of the study, 93 participants completed a survey investigating willingness to use reclaimed water for a variety of potable and non-potable uses. Potable uses included drinking, bathing, and cooking. Non-potable uses include cleaning, watering crops, and watering lawns. These uses were chosen to investigate the relationship between proximity to the mouth and willingness to use recycled water. Participants were also surveyed on the extent to which they felt disgusted by using the water for each of these uses. Surveys were randomized to either an experimental or control condition. Those in the experimental condition received a paragraph of information about the IPR project, including the fact that only a small portion of water would be incorporated into Lake Thunderbird and the methods of treatment used before discharging the water. Those in the control group received no information other than basic definitions of water reuse. Participants provided demographic information, including their political affiliation. They were also asked whether they were aware that Norman was planning for IPR.

Results showed no significant difference between the experimental and control groups, indicating that supplying information on paper did not significantly affect willingness to use recycled water or associated disgust. Baseline levels of acceptance were aligned with previous research on willingness to use recycled water for potable and non-potable purposes. Results showed 75% of people were very willing to use water for watering lawns, compared to an average of 70–90%, and 45% of people were very or moderately willing to use recycled water for drinking, compared to composite averages of 30–60% acceptance [3, 4, 37]. In line with previous research, we found a significant correlation between willingness to use recycled water and associated disgust ($p < 0.0001$) and disgust increased with proximity to the mouth, with drinking showing the highest degree of perceived disgust. There was a significant correlation between political affiliation and willingness to use recycled water for drinking ($p < 0.05$). Those that indicated they identified as liberal were more likely to demonstrate a high willingness to use recycled water. The level of education obtained by participants was also significant in our study, however, not much weight is put on this finding due to the discrepancy in literature as to the effect of obtained education on public attitudes of reuse [27]. Interestingly, despite the lack of a relationship between being supplied information about water reuse on disgust or acceptance, those that indicated they had previous knowledge of the IPR project demonstrated, for some uses, higher acceptance and lower disgust associated with using recycled water. This shows that knowledge of water reuse may affect acceptance, even though the provision of information on paper did not produce a significant relationship. This aligns with research showing the type of information and the method of conveying knowledge makes a difference in the trust of public officials and acceptance of water reuse [34, 45].

In light of this finding, for phase 2 of our study, we designed a community education initiative to investigate the mode of knowledge provision on willingness and disgust. Over 3 months in early 2020, 34 participants attended a tour of the Norman Water Reclamation Facility, the wastewater treatment plant in Norman, OK responsible for the planned IPR project. Tours lasted approximately 90 min and were led by the plant supervisor, the Director of Utilities for the city, and the plant manager. During this time, participants could ask any questions they wanted. The education initiative included tours of the water quality lab, control room, and each of the stages of wastewater treatment.

Figure 3 shows an image of the stages of treatment participants witnessed and water samples collected after each stage of treatment. You can imagine how the contrasting image of the first and third bottles, not to mention the difference in odor at the beginning of the tour and the end, had profound sensory impacts on the attendees. Many water professionals believe that this type of education helps participants "flip a switch" from viewing water reuse as something risky or disgusting to something beneficial to the community and environment, and a comprehensive and expensive endeavor overseen by professionals that are committed to their promises. Participants completed two assessments before and after the tour measuring their willingness and self-reported disgust associated with using reclaimed water for the

Fig. 3 An example of the visual educational elements of the tour. From left to right; Norman tap water, plan effluent after treatment and disinfection, wastewater after primary clarifier, wastewater after preliminary treatment. *Source* Author

same uses discussed in phase 1. Participants provided the same sociocultural information collected in phase 1. In addition to measuring willingness and disgust, we were interested in the likelihood of the public to support a project that would give the Norman Water Reclamation Facility the permanent capability to implement IPR in times of drought. Before and after the tour, participants were asked how likely they were to vote "yes" on an eventual ballot initiative for IPR in Norman. They were also asked if they would be willing to support that initiative with a sales tax increase. In reality, the revenue would come from an increase in water rates, but we wanted to expand the willingness to pay to those that are not responsible for their water bill, such as students living in apartments.

Paired t-tests revealed that there was a significant difference in the willingness to drink water containing some reclaimed water before and after the tour. There were significant increases in willingness to use the water because the community education effort successfully increased willingness to vote yes on an eventual ballot initiative to implement IPR as a supplemental water supply strategy. After the tour, 81% of participants indicated "yes" on this question, compared to 56% before the tour resulting in a significant difference within participants ($p < 0.01$). Responses to questions of willingness to bathe, cook, and water crops using reclaimed water also significantly increased ($p < 0.05$). Disgust significantly decreased for drinking, watering crops, cooking, bathing, and cleaning ($p < 0.05$) after the tour. Responses related to watering lawns likely did not have a significant increase due to high initial responses relating to the participants' willingness to use water for watering lawns. These results indicate that wastewater treatment plant tours are a viable method of conveying information about water treatment, increasing the trust of public officials, lowering initial disgust reactions by providing people with cognitive information to combat this emotion, and ultimately increasing support for water reuse in Norman.

Norman is an example of an opportunity for a utility to create a comprehensive stakeholder communication plan from start to finish. The project has been in the works since 2016 and community education efforts have continued throughout that time. Norman Utility Authority (NUA), the agency responsible for creating the strategic water plan and planning for and implementing IPR in Norman, believes the most effective method of community education is through tours of the water reclamation facility in person. Tours of the plant did not begin with our research study but have been a key priority of the education and outreach efforts relating to the IPR project since its inception. Norman Water Reclamation Facility and NUA staff are committed to the power of this in-person education on our perceptions of water reuse, and therefore our attitudes toward water reuse. Because the Water Reclamation Facility is producing such high-quality effluent as it is, this study showed physically being present at the plant helped "flip the switch" in people's minds from being disgusted by the thought of using the water again to being remiss that such clean effluent is traveling downstream to be someone else's drinking water. Education and outreach efforts continue in Norman through treatment plant tours and a series of informative videos. The main limitation of the Norman case study [37] and the main challenge facing the city in regard to public attitudes is getting people to come to the treatment plant. When recruiting for the case study in Norman, the suggestion of spending a

Saturday morning at the wastewater treatment plant was often met with sour faces and very convenient excuses not to be there. One of the problems with measuring the effect of this type of education on attitudes of reuse is that the typical person willing to attend typically already has some interest in water treatment, the environment, or public happenings. Because of this, it may be difficult to generalize findings to the entire community. Multiple types of outreach efforts should be implemented to reach as many different groups in the community as possible.

Water service providers in Norman believe the evolution of water reuse in Oklahoma will be slow, but the demonstration of Norman's IPR project will provide an example for others in the future. IPR in Norman still has barriers to overcome, but they are taking every step to ensure the 2-year pilot program demonstrates that IPR could be a viable strategy for other utilities in the state.

7 Conclusion

Water reuse will be an essential part of future water supply measures in the US, especially in drought-prone states in the West. The scale and frequency of potable water reuse are likely to increase dramatically in the coming decades, as many states, both coastal and inland, have prioritized urban water reuse as a future water supply strategy. As technology for filtration and disinfection continues to evolve and improve in response to new policies, more water service providers will set their sights on reuse. For the United States, as a whole, there are still looming hurdles to overcome with reuse, particularly concerning how inland reuse projects will impact downstream water allocations and environmental flows. A lack of shared research data and coordination between federal and non-federal entities hinders the potential for water reuse projects. However, as more utilities successfully engage the community and demonstrate the benefits of water reuse, there will be many examples that can be looked at. Water reuse can help accomplish goals of water security, environmental sustainability, and the prevention of potentially damaging impediments like dams.

While water reuse is an increasingly viable strategy for obtaining supplemental water supplies, it cannot meet the projected water needs of the country, so it should be planned in conjunction with other water conservation strategies [25]. A full picture of water reuse priorities and future outlooks for the nation can be found in the US EPA's 2019 Water Reuse Action Plan, available at https://www.epa.gov/waterreuse/water-reuse-action-plan. The US EPA and many experienced water managers emphasize the need for an integrated water resource approach. Integrated water management views water holistically and involves the management of supply and demand-side concerns, water quality concerns, public involvement, the reuse of water, and environmental concerns. Implementing multiple, complimenting water management strategies creates more resilient and diverse water plans.

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The Impact of Location on Decentralized Water Use in Urban Agriculture

Tammy E. Parece

Abstract Urban Agriculture is becoming more prevalent across the world because of its ability to provide healthy and nutritious food for urban populations and contribute to urban ecosystem services. Generally, potable water is the main source of irrigation for urban agriculture, and in many regions, this negatively impacts ecosystem services because of the energy required to transport and treat potable water. Rainwater harvesting is a decentralized water strategy and urban agriculture is a decentralized food production method. This chapter reviews the literature on rainwater harvesting for urban agriculture, two decentralized strategies promoting urban sustainability. Four case studies in the Unites States (two are in wet regions and two are in semi-arid regions) are used to analyze rainwater harvesting's ability to irrigate urban agriculture, save energy, and reduce greenhouse gas emissions. Study results show that location does matter because rainfall directly affects the ability for cities in semi-arid regions to harvest rainfall for irrigation. A significant difference is apparent in rainwater availability between arid and wet regions of the US because of the significantly lower amount of precipitation in arid regions, as well as the number of days in arid regions where there is insufficient rainfall to produce runoff.

Results also demonstrate that, even in arid regions, rainwater harvesting has the potential to lower potable water use, save energy, and reduce greenhouse gas emissions.

Keywords Food security · Urban agriculture · Rainwater harvesting · Greenhouse gas emissions · United States

1 Introduction

A United Nations (UN) 2009 report noted that, for the first time in human history, more than 50% of the world's population lived in urban areas [1]. By 2018, that percentage increased to 55% (~4.3 billion people) and is expected to continue

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T. Younos et al. (eds.), *Resilient Water Management Strategies in Urban Settings*,
Springer Water, https://doi.org/10.1007/978-3-030-95844-2_9

increasing to 68% by 2050 [1, 2]. The percentage of people living in urban areas varies by country, from 13% in Burundi to 100% in Kuwait and Singapore [2]. Additionally, as the economic activity of a country increases, the number of people moving into urban areas also increases [3, 4], and those countries, with the lowest percentage of urban versus rural population, are experiencing the highest rates of urban growth [5]. Although moving into urban areas offers the prospects of "*food, employment and security*" [6], in developing countries, almost 1 in 3 people live in a slum household with a lack of access to food, clean drinking water and sanitation services [3].

In 2019, three billion people did not have access to a healthy diet because they could not afford it [7]. The FAO estimates that about two billion people (26.4% of the world's population) face moderate or severe levels of food insecurity [8]. People with moderate levels of food insecurity do not have regular access to nutritious and sufficient food; people with severe food insecurity also face the possibility of persistent hunger [8]. Food insecurity rates have been increasing, not decreasing, since 2015 [8], and significantly increased during the COVID-19 pandemic. Food insecurity can create health issues such as malnutrition, obesity, low birthweight, child stunting, and inability to focus in school, among other things [7].

The FAO [9] estimate that 80% of food produced, worldwide, is consumed in urban areas, and it is widely believed that people residing in rural areas have the greater chance of exposure to food insecurity than urban residents. However, two factors contradict this belief (1) rural residents have access to land in which they grow most of their food, and (2) in low- and middle-income countries, urban residents spend, on average, between 50 to 75% of their household budgets on food [10]. So, while people living in urban areas purchase their food, many urban poor lack the financial resources to make such purchases [6]. The Resource Center for Urban Agriculture and Food Security notes "Malnutrition (both under-nourishment and overweight and obesity) has become a major urban issue, affecting low income and vulnerable residents in particular" [11]. As such, the FAO considers urban agriculture (UA) an essential part of its Special Program for Food Security, yet a complicating factor to implementing UA is access to land and water for food production [12].

Water is essential for food production. The purpose of this chapter is to review the potential of harvesting rainwater for irrigating urban agriculture. Section 2 of this chapter introduces UA and discusses why it is a functioning greenspace with positive impacts on urban sustainability. Section 3 reviews urban water and rainwater harvesting for UA. Section 4 reviews the quantification methods for determining rainwater harvesting volume, energy needs for potable water, and greenhouse gas emissions. Section 4 also introduces the four case study sites. Section 5 discusses the results, the influence rainwater harvesting for UA has on the future of urban sustainability initiatives, and limitations of this study.

2 Urban Agriculture

2.1 Urban Agriculture, Defined

UA is “the growing, processing, and distribution of food and nonfood plants and tree crops and raising of livestock, directly for the urban market, both within and on the fringe of an urban area” [13]. Urban agriculture has been practiced since urban areas were first established [14], but in the United States (U.S.), UA was not initially encouraged. It has, however, gradually intensified over the past 100 years; during periods of national crisis—both World Wars and the Great Depression [15–17], and most recently during the time of COVID-19 [18]. Over the past twenty years, interest in UA has expanded worldwide because of the growing disparity in wealth between the lowest and highest wage earners (affecting access to food), its qualification as locally grown food (decentralized production), the ability to contribute to urban sustainability, and its potential to help alleviate food insecurity for urban residents [16, 17, 19].

2.2 Urban Greenspaces and Urban Sustainability

Urban planning includes initiatives to reduce ecological footprints and increase sustainability, which would result in reduced energy use, enhanced water and air quality, and increased greenspaces. A greenspace is defined as “land that is partly or completely covered with grass, trees, shrubs, or other vegetation” [20], and “functions as productive green areas that are able to deliver useful products (wood, fruits, compost, energy, etc.) as a result of urban green maintenance or construction” [14]. Urban greenspaces provide positive benefits for both humans and wildlife [21–24]. Examples of positive benefits include:

- Increases in ecosystem services [14, 25–28];
- Increases in water infiltration, thus increased groundwater recharge, reduced stormwater runoff, and improved water quality [14, 21, 28, 29];
- Controls air temperature and reduces the urban heat island effect [14, 21, 30];
- Provides an area for increased physical exercise and stress reduction [14, 21, 22]; and
- Increases human social interaction and acts as a place of community for urban residents [14, 18, 22, 31].

2.3 Urban Agriculture Scope

Urban agriculture ranges in size from plants in small containers (see Fig. 1) to large plots as commercial enterprises [32]. The most common form of UA are backyard

Fig. 1 Two container gardens—peppers and squash on the left and strawberries on the right. (Photo by author, 2021)

gardens [33, 34]—people growing food on land next to their home for their own consumption or to share with friends, neighbors and relatives [34] (Fig. 2).

Meso-scale forms of UA include allotment gardens and community gardens [34, 35], see Fig. 3. These gardens normally consist of a plot of land shared by a community—each person cultivates their own plot within the garden and shares the tasks of maintaining the common areas. The major difference between an allotment garden and a community garden is that allotment gardens are provided by the government in lower income areas [36]. The land for a community garden can be provided by any number of entities—churches, governments, private individuals or non-profits

Fig. 2 Backyard garden, shows inter-cropping with corn, beans, tomatoes, and squash. (Photo by author, 2021)

Fig. 3 Mountain view community garden, Roanoke, Virginia. Photo on left as displayed in Google Earth Pro 2019, photo on right by author, 2015

and the individual gardeners pay a small annual fee for participating [18, 34, 35]. Community gardens can also include schoolyard gardens [31].

UA's largest forms (by area) are urban farms (see Fig. 4), and in many instances are identified as a for-profit business [33]. Urban farms are not limited to row crops, they can include greenhouses, aquaculture, rooftop gardens, and hoop houses (as noted in Fig. 4 and seen in Fig. 5). Exceptions to the for-profit characteristic are

Fig. 4 Wilson Street Urban Farm, Buffalo, New York, 2018, as displayed in Google Earth

Fig. 5 Examples of hoop houses. Wilson Street Urban Farm on left (as displayed in Google Earth Street View, 2020) and Colorado Mesa University in Grand Junction on right. (Photo on right by author, 2021)

found, especially in areas undergoing mass emigration, such as Detroit, Michigan [16].

While each form of UA has specific characteristics, characteristics are not exclusive for any specific form. For example, produce from community gardens, home gardens and patio gardens are frequently sold; food forests can be planted by governments for consumption by their citizens; and some urban farms are owned by non-profits food banks (for example Growing Goodwill Garden in Roanoke, Virginia and the Rob and Melani Walton Urban Farm in Phoenix, Arizona).

UA qualifies as a greenspace but also provides benefits beyond most other urban greenspaces (parks and urban trees). These benefits include provisioning of fresh, nutritious fruits and vegetables, economic opportunities from selling agricultural products [33, 37], and nurturing a sense of land/environmental stewardship and ownership [38, 39]. Additionally, since UA uses space and water more efficiently (not just horizontal but also vertical, and in smaller plots), produces shorter life-cycle crops, and uses inter-cropping [33, 40, 41], it can produce a greater output (kilograms per unit area) than traditional agriculture [42, 43]. It reduces food miles (the distance food travels from where it is grown to where it is ultimately consumed) and provides urban residents access to locally grown food [2]. Urban agriculture is also widely recognized as an important social aspect of urban environments, one which political ecologists argue embodies social justice issues found in most urban areas [44].

3 Urban Water

Current water infrastructure is based on twentieth century technology; for urban areas, this means water is stored in reservoirs and then energy is used to collect, transport and then treat to potable standards for urban residents [45]. In a study of 11 US water companies, Young reports that the energy use to treat, convey and distribute potable water ranges from 500 to 3500 kWh per million gallons (0.132 to 0.925 kWh per m^3), with an average of 2,300 kWh per million gallons (0.608 kWh per m^3) [46]. (See Chapter 1 of this book for more information.)

The amount of energy used is highly dependent on whether transporting water from source to city is gravity fed. Although New York City obtains the majority of its potable water from a watershed over 100 miles north of the city [47], it is gravity fed. The town of Blacksburg, Virginia's water source is the New River and while transport only occurs over a distance of 2 miles, it is uphill the entire way. Thus, energy per cubic meter is significantly higher for Blacksburg than New York City.

Urban water use includes water used for consumption (residential and commercial), irrigating greenspaces (lawns, flowers, ornamental bushes, gardens), washing real and personal property, and in manufacturing. Additionally, it includes construction and maintenance of the infrastructure to support these activities and to remove wastewater and stormwater runoff.

As discussed in the Introduction (Sect. 1), human populations in urban areas will continue to increase. Along with this population growth, comes conversion of open lands into the built environment, and increasing demands for municipal services, including water for domestic consumption and other uses. Competing demands for urban water are complicated by lack of available water resources, especially in arid or semi-arid regions, and increasing costs for new infrastructure, or for maintenance and repair of aging infrastructure [48]. Harvesting rainwater as a substitute for some uses can help alleviate pressures on overall water demand (See Chap. 5 of this book for a specific case study).

3.1 Rainwater Harvesting in Urban Areas

Impervious surfaces in urban areas—building rooftops, sidewalks, roads and parking lots—reduce underground infiltration and increase stormwater runoff. Runoff from sidewalks, parking lots and roads create stormwater that could be a source of human-health risks to those consuming food produced, and from working in contaminated soils [49–52], as such, "Rainwater harvesting captures, diverts, and stores rainwater from ***rooftops*** [emphasis added]" [53]. Harvesting rainwater in urban areas has many applications. For this purpose of this chapter, only one use is discussed in the next sub-section—for urban agriculture. (See Chap. 7 of this book for more uses.)

3.2 Water for Urban Agriculture

The FAO recommends two specific alternative water sources for UA water use—(1) reusing treated or partially treated wastewater and (2) harvesting rainwater [54]. Literature on rainwater harvesting in urban areas is plentiful and many researchers reference the possibilities of rainwater harvesting for irrigation purposes (e.g. [6, 31, 55], but case studies calculating rainwater harvesting potential for UA are recent phenomena. The following studies relate to rainwater harvesting for urban agriculture:

- Ward et al. [48] estimated water demand for a hypothetical garden using the water requirements and crop yields from traditional agriculture in Australia. Their results showed household potable water demand would have a significant increase with a related increase in household expenses. They opined that alternative sources of water for UA, such as rainwater harvesting, should be considered.
- Redwood et al. [56] completed a cost/benefit analysis of actual rainwater harvesting and greywater use for urban farms using a local school as a test site in Tunisia. Their results produced economic benefits for urban farmers. After the success of the case study, rainwater harvesting systems were installed at 20 urban farms.

- Lupia & Pulighe [57] quantified water demand for existing home gardens and calculated the potential rainwater harvesting volume that could be used for irrigation water in Rome Italy. Their results estimated that (with the exception of vineyards and olive groves) harvested rainwater from roof areas would adequately meet water needs for all existing home gardens.
- Richards et al. [58] constructed two vegetable raingardens (one lined and one unlined) and two control sites on the Burnley Campus of the University of Melbourne in Australia. In their study, 2/3 of harvested rainwater was directed to raingardens and 1/3 stored for supplemental irrigation. Their results showed lined raingardens needed no additional irrigation during dry periods.
- Parece et al. [59] identified existing locations of UA, and calculated rooftop areas of adjacent buildings and rainwater harvesting potential for the city of Roanoke, Virginia, USA. Their results calculated the potential volume of rainwater harvested and reduction in energy and greenhouse gas emissions when using that rainwater, in place of potable water, for irrigation.
- Petit-Boix et al. [60] used a hypothetical family home with a 40 m^2 garden, and estimated rainwater harvesting for toilet flushing, laundry, and lettuce production and precipitation volumes of 21different cities in the USA, Europe, and India. They used three different scenarios—no food production, only food production and a combination. Their results were averaged over all cities, and showed that rainwater harvesting supplied the water demand—no food production (60%), food production only (84%), both (47%).
- For Rome Italy, Lupia et al. [61] estimated water needs for 2,631 gardens and rainwater harvesting potential from building rooftops to identify self-sustaining gardens vs. gardens with supplemental water needs by land use type (horticulture, mixed crops, olive groves, orchards and vineyards). Their results demonstrated that rainwater harvesting could provide between 19 and 33% of water needs in irrigated landscapes, depending on the efficiency of the irrigation system; and between 22 and 44% of water needs in non-irrigated gardens.
- Weidner and Yang [62] completed a comparative analysis between Lyon, France and Glasgow, Scotland. They evaluated a food-water-energy-waste nexus, including seasonal and greenhouses and no rainwater harvesting and rainwater harvesting with short term and reservoir storage. Their results revealed that with rainwater harvesting, potable water input was reduced to zero when storage is included (for hydroponics—rainwater harvesting produced more water than was needed). They noted that the difference documented between the two cities was related to the amount of annual rainfall.

The studies identified above have quantified and demonstrated that rainwater can be harvested and used for UA production. All rainwater harvesting studies described only harvesting from rooftops, not from any other type of impervious surface. The question is whether rainwater harvesting is a viable method for all urban areas (both water-rich and arid environments), and if so, what impact would it have on energy use and greenhouse gas emissions.

4 Methods and Study Sites

This section reviews how rainwater volume, energy needs for potable water, and greenhouse gas emissions are quantified, and introduces the four urban study sites in the U.S. For this comparative analysis: two sites are in the water rich east—Roanoke, Virginia and Buffalo, New York, and two sites are in the arid west—Grand Junction, Colorado and Phoenix, Arizona (Fig. 6). For each location, the urban area and urban agriculture for that city are described, and water and energy sources introduced. The results—rainwater harvesting potential and reductions in energy and greenhouse gas emissions are presented in Sect. 5 (Results and Discussion).

4.1 Equations and Data Inputs

This section discusses the three equations to be used for the analysis of each city. This section also defines the variables that are used in each equation.

Fig. 6 Reference map of study sites. Tiger line shapefiles from [63] overlaid on Landsat satellite imagery in ArcGIS Pro

4.1.1 Equation 1: Usable Rainwater Volume

To quantify the amount of rainwater that can be harvested and used for irrigation (hereinafter referred to as usable rainwater volume or URV), Eq. 1 (from [64]) is used.

$$\mathrm{URV}\left(\mathrm{m}^3/\mathrm{timeperiod}\right) = \mathrm{RoofArea}\left(\mathrm{m}^2\right) \times \mathrm{AverageRainfall}(\mathrm{m}/\mathrm{timeperiod}) \times \mathrm{C} \tag{1}$$

The variable C is collection efficiency, which allows for splash and evaporation. The amount of splash varies based on roof materials and pitch. The amount of evaporation depends on air temperature, time of day (impacts roof temperature), and humidity. Variable C can range from 0.75 to 0.9, so an average of 0.8 is normally used in rainwater harvesting calculations [64].

For rooftop areas (the rainwater harvesting collection site) are calculated from aerial photos (e.g. [59, 61]), or using the building footprint (area) from municipal GIS files. The method used for each city in this analysis will be addressed under each city site below. Additionally, with the exception of Roanoke, Virginia (as discussed under Sect. 4.2.1), two analyses will be completed for each city—a microscale analysis using a few existing locations of urban agriculture (and related buildings), and a macroscale analysis for potential backyard gardens using one-family dwellings (for roof areas).

The input for average rainfall are precipitation rates, which are recorded by the U.S. National Weather Service (NWS). The NWS has climate records for over 100 years, including daily, monthly, and annual rates along with normal rates. Annual rates are the amount of rainfall recorded for a specific year. Normal rates are averages calculated on a 30-year basis; the most recent available is for 1991—2020 [65].

The results from Eq. 1 estimates the potential volume of rainwater that can be harvested and the potential reduction in both stormwater runoff and potable water use. Equation 1 can be used with a microscale (e.g. [60]) or a macroscale analysis (e.g. [59, 61]).

4.1.2 Equation 2: Energy Used Per Volume of Potable Water

To calculate the energy saved from reducing potable water use, Eq. 2 from [64] is used:

$$\begin{aligned}&\mathrm{EnergyConserved}(\mathrm{kWh})\\ &= \mathrm{PotableWaterSavings}\left(\mathrm{m}^3\right) \times \mathrm{EstimatedEnergyUse}\left(\mathrm{kWh}/\mathrm{m}^3\right))\\ &\quad - \mathrm{Indoor}/\mathrm{OutdoorPumpEnergyNeed}(\mathrm{kWh})\end{aligned} \tag{2}$$

URV (from Eq. 1) is used as the input for the potable water savings. If available, the estimated energy use will be gathered from the annual reports from the local water authority for each location. If not available, the energy use (from [46]), will be used.

The energy needs for pumping the harvested rainwater varies substantially and depends on multiple factors. These include if the pump is “on demand” (in constant ready mode), the size of pump, pump power, water pressure to be delivered, the distance water travels, the purpose of the water (indoor, outdoor, irrigation, multi-use, etc.) and volume of water [66, 67]. An additional factor is whether a pump is actually needed or not, for example, a pump is not needed for a system wherein rainwater is harvested from a rooftop, caught in a “rainbarrel,” and used for an adjacent garden (water flow is handled by gravity).

The results from this equation is the energy not needed if rainwater is used in place of potable water, thus is the energy conserved.

4.1.3 Equation 3: Reduction in CO_2 Emissions Related to Reduction in Energy Use

The final equation (from [64]), calculates the reduction in greenhouse gas (GHG) emissions:

$$\begin{aligned} &\mathrm{CO_2 emissions(kilograms)} \\ &= \mathrm{EnergyConserved(kWh)} \times \mathrm{CO_2 outputrate(kilograms/kWh)} \end{aligned} \tag{3}$$

The input for energy conserved is the result from Eq. 2. The carbon dioxide output rate depends on the fuel source for the electricity [68]. The fuel source will be gathered from the annual reports for the energy company for each location. The CO_2 output rate is calculated using the values in Table 1.

Table 1 Carbon dioxide emissions from electric power generation

Fuel type	CO_2 output rate (kilograms per kWh)
Coal*	1.0
Natural gas*	0.41
Hydroelectric**	0.018
Nuclear**	0.012

* [68] reports pounds per kWh; converted to kilograms per kWh (1 pound = 0.454 kg). ** [69] reports these as a global average in grams, converted here to kilograms

4.2 Urban Study Sites

4.2.1 Roanoke, Virginia USA

Roanoke is located in a valley in southwest Virginia (Fig. 6) and was established in 1852 as a railway hub [70]. It is the largest city in southwest Virginia with a population of 99,143 over 110 km^2 [71], a density of 900 persons per km^2. Its current commercial activity includes as a hub for railway and road traffic, finance, manufacturing, trade, and healthcare with a school of medicine.

Roanoke's greenspaces include tree canopy cover, park land (city and national), and UA (including home gardens, community gardens (an example is Fig. 3) and urban farms) [59]. Review of the UA in Roanoke (through the American Community Garden Website, the Roanoke Community Garden website, and Google Earth and Maps) shows that, since 2016, although one urban farm has expanded (Lick Run Urban Farm) and some gardens have not changed (Growing Goodwill, Mountain View and Hurt Park), others have either reduced the area under cultivation (Heritage Point Farm) or suspended operations (Frank Roupas Community Garden).

Rainwater harvesting is permissible in Virginia, without restrictions. While rainwater harvesting is available at some community gardens (see Fig. 3 as an example), most locations use potable water for irrigation. As noted in Sect. 3.2, Parece et al. [59] completed a macroscale rainwater harvesting evaluation of existing UA for the entire city with a microscale analysis for two specific sites (Growing Goodwill Community Garden and Heritage Point Farm).

The amount of electricity used for potable water varies as the city has five different sources of water—Carvin's Cove Reservoir, Crystal Spring, Spring Hollow, Falling Creek and private wells [72], Fig. 15 in [59]. Whereas Parece et al. [59] were able to obtain the energy usage for each water source that information has not been updated on the water authority documents, so this chapter will use the same breakdown as in [59].

Electricity for Roanoke is provided by the Appalachian Power Company, Inc. (an American Electric Power company (AEP), a conglomerate of local power companies in several U.S. states). However, AEP's annual report does not separate the individual companies' fuel use for energy generation, so this analysis uses the breakdown for the entire corporation. The Annual report does identify the renewables used by each company, and for Appalachian Power, the renewables include only hydro (solar is under development). The breakdown in fuels are coal (44.8%), natural gas (31.1%), nuclear (8.2%), renewables (hydro, solar and wind—13.2%), and other (2.7%) [73], these data for their current fuel sources are a significant change from that used in [59].

Roanoke's normal annual precipitation is 1,048 mm (41.25 inches) of precipitation [65]. Normal precipitation (averages calculated on a 30-year basis) is relatively unchanged from that reported in [59] as 1,097 mm. Normal by month is shown in Table 2 and shows that precipitation is prolific in all months.

Table 2 Roanoke, Virginia normal precipitation (cm) by month [65]

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
(cm)	7.42	7.34	8.79	8.56	10.31	9.73	10.26	9.04	9.88	7.34	8.64	7.47

For Roanoke, the macro-scale analysis in this chapter will use the rooftop area already calculated and subdivided by water source in [59].

4.2.2 Buffalo, New York USA

Buffalo is located in the western part of New York State and adjacent to Lake Erie (Fig. 6). Buffalo began as a small trading post in 1789. As a transportation hub, it grew rapidly during the 1800s industrialization boom [74]. Its current population is 255,284 over 105 km^2 [75], a density of 2,431 persons per km^2. It is dominated by service industries such as health, finance and sales [74].

Urban agriculture in Buffalo is extensive with at least four urban farms and 17 community gardens (when using those terms in the Google Search Engine and the American Community Garden Association website [76]), and in 2020, the University of Buffalo received a grant to expand UA in the city [77]. Buffalo's microscale analysis will include three urban farms—Common Roots Urban Farm, Growing Green Urban Farm and Wilson Street Urban Farm.

Common Roots Urban Farm was established in 2012 as a neighborhood cooperative farm. It occupies 4,047 m^2 (1 acre) but only ½ is cultivated [78]. Many of the lots surrounding the farm are vacant (Fig. 7), thus there are only five buildings that can be used for rooftop rainwater harvesting, including a pavilion and a hoop house on the farm.

Growing Green Urban Farm was established by neighborhood residents in 1992, and incorporated as a non-profit in 2000 [79]. It has greatly expanded over several vacant lots. Their farm includes two large greenhouse and solar panels on the main building (Fig. 8). It is in a densely built-up area of Buffalo and surrounded by many building, mostly residential structures. All buildings surrounding the farm (except the area concealed by solar panels), and the two greenhouses will be used as rooftop areas for harvesting rainwater.

Wilson Street Urban Farm has also expanded substantially, from an empty lot in 2009. Figure 9 shows the farm expansion from 2009–2018 [80]. In the top image (2009), it is mostly vacant land with two hoop houses within the red oval (and on the left in Fig. 5). Within the center image (2011), some cultivated fields are seen within the white box and new clearing in the black box. The bottom image shows that by 2018, most of the location is under cultivation. Adjacent to the farm is the Family Dollar Store on the south and several residential lots on the west. The rooftops of the Family Dollar, the residences to the west, and the hoop houses on the farm will be used to calculate rooftop areas for rainwater harvesting. The residential areas across

Fig. 7 Common Roots Urban Farm displayed in Google Earth

the street will not be used since the street creates an impediment to safely moving water.

Rainwater harvesting in New York State is permissible and promoted by all levels of government. The water source for Buffalo is Lake Erie [81]. Water is transported by gravity through an initial phase of chemical treatment, and thereafter, lift pumps are used to transport the water through final phases of chemical treatment and fine particle deposition [82]. After water is treated to potable standards, pumps transport the water through 800 miles of pipes and to over 80,000 individual service connections [81]. Examination of Buffalo Water's financial reports (available at https://buffalowater.org/) does not identify the energy use for treating and transporting water. As such, the US average per kWh (from [46]) for treating and transporting water will be used.

Energy is deregulated in New York State, as such users choose their own company if more than one company provides service (as in Buffalo). National Grid is the largest supplier in the state and for the city of Buffalo. National Grid provides service in two countries—the United Kingdom and the United States. Within the United States, it services Massachusetts, New York and Rhode Island [83]. Their annual report does not specifically list the breakdown in energy source for their electricity generation neither by country, nor in the US by state. The report does note that the company has reduced their CO_2 emissions by 70% since 1990. The total emissions are reported as

Fig. 8 Growing Green Urban Farm displayed in Google Earth, top and Google Earth Street View, bottom

6.5 million tonnes of CO_2 for 28,223 GWh of total power generated. This converts to 230.3 tonnes per GWh, or 0.23 kg per kWh.

Buffalo's annual normal precipitation is 1,033 mm (40.68 inches) per year [65]. Normal by month is shown in Table 3 and shows that precipitation is prolific in all months.

For the microscale analysis of the specific UA locations identified above, aerial photos displayed in Google Earth will be used for rooftop areas of adjacent buildings. For the macroscale analysis of the rainwater harvesting potential for backyard gardens, building footprint areas (from [84]), will be used as a substitute for rooftop areas.

Fig. 9 Wilson Street Urban Farm. Aerial photos as displayed in Google Earth (2009 top, 2011 center, 2018 bottom)

Table 3 Normal Precipitation (cm) by month for Buffalo, New York [65]

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
(cm)	8.51	6.32	7.34	8.56	8.56	8.56	8.20	8.13	10.41	10.24	8.89	9.53

4.2.3 Grand Junction, Colorado USA

Grand Junction (GJ) is located in the western part of Colorado, about 40 km from the Utah border, and in an area generally called the Grand Valley of Colorado (Figs. 6 and 10). GJ was established in 1882 at the confluence of the Colorado and Gunnison Rivers [85]. It is the largest urban area on the western slope of Colorado. Total population in the Grand Valley is 147,803. GJ's population is 63,597 over 99 km^2 [86], a density of 642 persons per km^2. This region is a semi-arid to arid climate situated on high desert lands and considered an important agriculture area for Colorado (as noted in inset map in Fig. 10 and [87, 88]. Additionally, Grand Junction is home to the largest university in western Colorado—Colorado Mesa University.

GJ has a significant amount of greenspace (as seen in Fig. 10), which includes city and state parks and extensive agricultural lands (mostly commercial). Urban

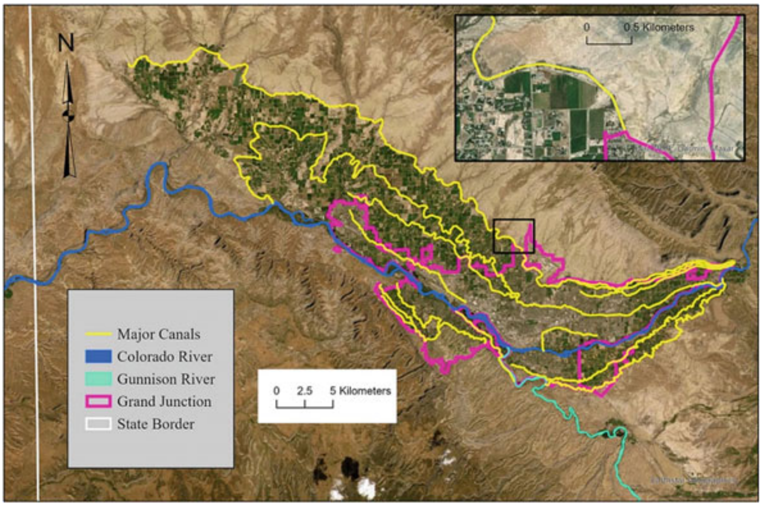

Fig. 10 The Grand Valley in western Colorado—Landsat image, 2021, as displayed in ArcGIS Pro; GIS files from [63, 89]

agriculture includes mostly home gardens and one community supported agricultural farm—Rooted Gypsy Farms. Community gardens are rare in GJ, only three have been personally identified by the author (two are shown in Fig. 11—Copper Creek Homeowners Association and Colorado Mesa University), and none are found when using the Google Search Engine or the American Community Garden website [76].

Rainwater harvesting is prohibited in Colorado except for single family (or up to 4-unit multi-family) residences, and limited to two containers with a total maximum capacity of 110 gallons (0.416 m^3). Rainwater can only be harvested from rooftops and only for outdoor uses on the same property where it is collected (with minor exceptions) [90]. The Ute Water Conservancy District provides potable water for the

Fig. 11 Copper Creek community garden (left), Colorado Mesa University community garden (right). Photos by author (2021)

Fig. 12 A major canal extending from the Colorado River into the Grand Valley (left), a minor canal extending to individual parcels (right). Photos by author 2021

region, and it is the District's policy that "it will not sell taps solely for irrigation or landscape maintenance purposes" [91], p. 28. As such, irrigation canals extend from both the Colorado and Gunnison Rivers. The canal network is extensive, with 328.7 km (as calculated from Mesa County's GIS files [89]) of major canals (Fig. 10 and on left in Fig. 12), and an unknown number of smaller canals (right in Fig. 12) extending river water to individual parcels of property. Both community gardens and the urban farm, identified in the previous paragraph, are irrigated with canal water.

Pumps transport irrigation water from the canals. Figure 13 shows a variety of pumps used in GJ. Image A shows the intake valve from a major canal and Image B shows the related pump house required for pumping water into a neighborhood (photo of equipment is not available). Image C shows the pump required from a minor canal which services the Copper Creek Community and its community garden (mentioned above). Image D shows the use of a solar panel to run a pump for water from a minor canal and used to irrigate a small common area in the Copper Creek North 2 community.

Electricity for GJ is provided by Xcel Energy. Xcel also provides energy to other locations in Colorado and many other states. Xcel's 2020 Annual Report identifies fuel use for energy generation, but does not break down its energy generation by location. The report does note, for Colorado, by 2030, they plan to retire or replace their remaining coal generating plants and add additional wind and solar generation. The 2020 breakdown in fuels are coal (21%), natural gas (32%), nuclear (13%), renewables (hydro, solar and wind—34%) [92]. In the US, there is an increasing trend toward renewable use.

GJ's normal annual precipitation is 230 mm (9.06 inches) per year [65]. However, it is well known that the Colorado River Basin is undergoing a mega-drought [93].

Fig. 13 Types of irrigation pumps used in the Grand Valley. (Photos by author 2021)

Precipitation totals for each year, 2016–2019, are shown in Table 4 and shows substantial variability year to year. Normals by month are shown in Table 5, again showing substantial variability. The NWS tracks daily rainfall amounts in multiple categories including the number of days less than 0.01 inches (0.25 mm) and for GJ, 69.2% of those days where precipitation occurs (71.6 of 103.5 days), less than 0.25 mm (0.01 inches) is received [65], thus runoff does not occur, so normal annual precipitation amounts cannot be used in this analysis. Table 6 lists the precipita-

Table 4 Grand Junction, Colorado normal per annum precipitation (cm), 5 years [65]

Year	2020	2019	2018	2017	2016
Amount	13.0	21.7	20.9	12.9	22.4

Table 5 Grand Junction, Colorado normal precipitation (cm) by month [65]

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Amount	1.55	1.35	2.03	2.49	2.11	1.04	1.5	2.34	3.02	2.51	1.55	1.52

Table 6 Grand Junction, Colorado precipitation (cm) by month for January–May, 2021 and June–December, 2020 [65]

Year	2021					2020						
Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Total	0.91	0.81	1.35	0.76	1.35	1.30	0.13	0.18	2.87	1.5	0.28	0.81
Usable*	0.53	0.46	1.12	0.66	1.19	0.91	0	0	2.79	1.5	0	0.58
Days**	1	1	3	1	2	2	0	0	2	2	0	1

* rainfall rates $\geq$ 0.25 mm. ** number of days that rainfall rates $\geq$ 0.25 mm

tion by month for 12 months (January—May, 2021 and June—December, 2020), including the number of days precipitation was greater than or equal to 0.25 mm and the total precipitation for only those days. These amounts in Table 6 would equate to the amount of precipitation that actually could be harvested for irrigation and this total (97.4 mm) will be used as the average rainfall input for Eq. 1.

The microscale analysis of for GJ will be an analysis of a single-family home. Manual measurement of the building's footprint will be used for roof area as the collection point and to determine if harvested rainwater will even meet the maximum harvest allowed under Colorado law (two barrels totaling 0.416 m^3). For the macroscale analysis of the rainwater harvesting potential, single family residential building footprints (from [89]) will be used as a substitute for rooftop area.

4.2.4 Phoenix, Arizona USA

Phoenix is located in southwest Arizona within the Salt River Valley (Fig. 6). It has ancient roots, having been previously settled by the Pueblo for approximately 700 years (700–1400 A.D.). By 1868, it was established as a town (incorporated as a city in 1881) and irrigation canals were dug to provide water from the Salt River [94]. Currently, Phoenix is known as a corporate and industrial center of the southwestern US and has a population of 1,680,992 over 1,341 km^2 [95], and is one of many cities within a greater metropolitan area (which includes Tempe, Scottsdale, Peoria, among others) (Fig. 14).

The largest employers in Phoenix are healthcare, sales, and multiple universities. Phoenix is home to extensive recreational facilities including tennis, pickleball and other sports courts, golf courses, parks (playgrounds, dog, and skate, among others), swimming pools, community centers, and walking trails [96] (see Fig. 14 for examples).

UA in Phoenix is extensive, at least eight community gardens were identified in the city alone from the American Community Garden website [76], and many more were identified within the greater metropolitan area. Community gardens include Coronado Neighborhood Community Garden (Fig. 15a), Growing Together Garden (Fig. 15b), and Cartwright Community Garden (Fig. 15c).

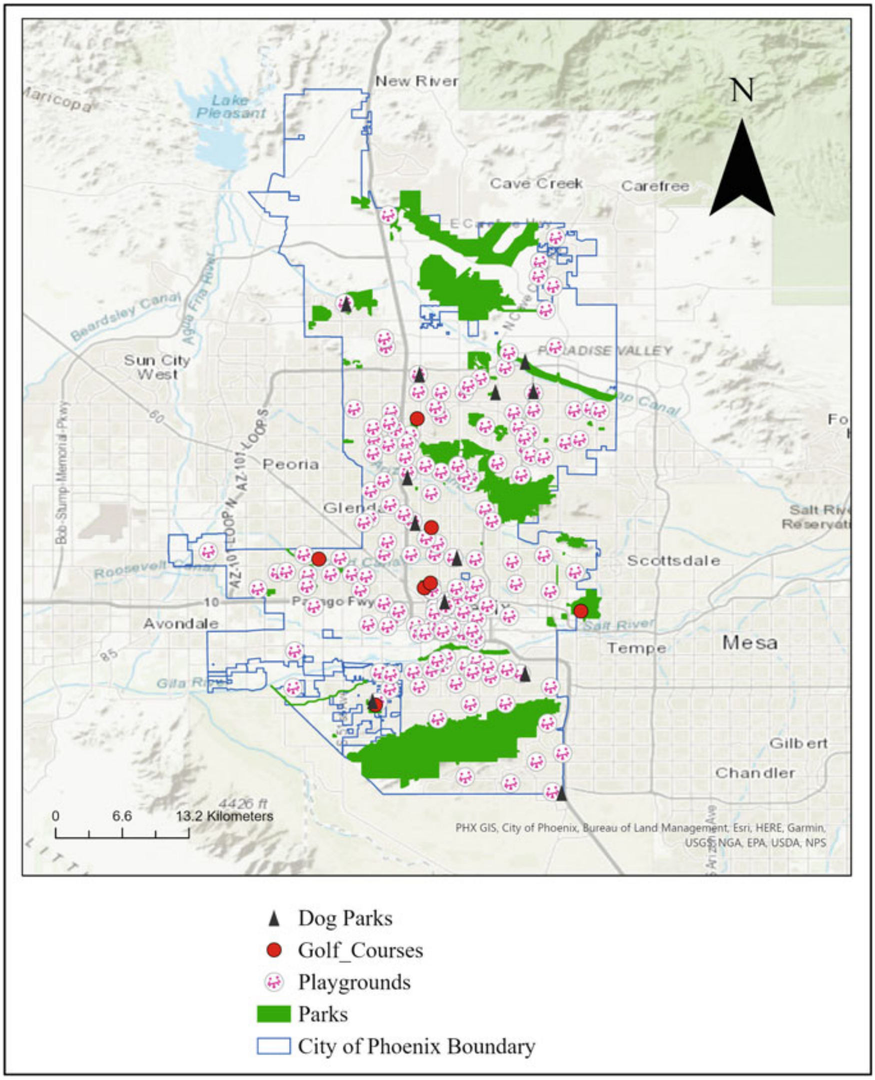

Fig. 14 Phoenix' location in the greater metropolitan area, including recreation facilities within the city (GIS files from [96] as overlaid on topographic maps in ArcGIS Pro)

Coronado Neighborhood Community Garden is for members of the Coronado Neighborhood Homeowners Association [97]. As can be seen in Fig. 15a, the location has substantial rooftop area for harvesting rainwater from its community center and a large home located adjacent to the garden, on the east.

Growing Together Garden was initially established in 2009 and moved to its current location at the Living Streams Church in 2017. The site provides food to local charities but also acts as a place of education and community unity [98]. This

Fig. 15 Community gardens in Phoenix Arizona, as displayed in Google Earth

garden also has potential for rainwater harvesting from using the adjacent buildings, including the roof of the church (Fig. 15b).

Cartwright Community Garden does not have a website and its Facebook page only has a few pictures. By using the Historical Imagery in Google Earth, the garden plots first start showing up in aerial photos from December of 2017. As can be seen in Fig. 15c, with the exception of a small rooftop just south of the garden, no other buildings are present within the confines of the parcel (it is surrounded by roads).

Only one urban farm was located—the Rob and Melani Walton Urban Farm (indicated by the red arrow in Fig. 16), which is part of The Society of St. Vincent de Paul. The farm opened in 2018 and has one acre under cultivation [99]. It several adjacent buildings, and The Society of St. Vincent de Paul includes the substantial white rooftop in the lower part of Fig. 16, from which to harvest rainwater.

In Arizona, it is legal to harvest rainwater on one's own property [100]. Potable water in Phoenix is provided by the City of Phoenix Water Services. Potable water sources for the region include the Salt and Verde Rivers (treated at 3 different plants) and approximately 50% of the water supply, the Colorado River (treated at 2 plants) and 47% of the supply, and groundwater wells for 3% [101]. At least one treatment plant uses solar power. No prohibitions on using potable water for irrigation was identified. No information was located on the city's website as to the electricity usage to treat and transport the water from the various treatment plants.

Salt River Project (SRP) provides electricity in addition to canal water for the region. Canal water is used for various irrigation purposes and for supplies to the city for treating water to potable standards. Nine major canals are in the valley and were established between 1898 and 1968. Over 1,000 miles of smaller canals take

Fig. 16 Rob and Melani Walton Urban Farm, top of the image, as displayed in Google Earth

canal water to delivery points for irrigation [102]. No information was found on the SRP website with regards to locations served with canal water.

Energy is provided by a variety of fuel sources through SRP. SRP reports its carbon footprint, "As of April 30, 202a carbon intensity of 934 lbs CO_2 per MWh. (Includes clean energy products from *large customers* and opt-in *carbon-reducing energy products* for residential customers)" [103]. This converts to 0.4237 kg/kWh.

Phoenix' annual normal precipitation is 183 mm (7.22 inches) per year [65]. However, Phoenix is in the lower basin of the Colorado River and is included in the mega-drought region [93]; and recent reports indicate that "massive water restrictions" will limit to the flow in the lower Colorado River basin in 2022 [104]. Normal monthly precipitation is listed in Table 7, but in 60% of those days where precipitation occurs (33.4 out of 55.6 days), less than 0.25 mm (0.01 inches) is received, thus runoff does not occur [65]. Table 8 lists the precipitation by month for 12 months (January—May 2021 and June—December 2020), including the number of days precipitation exceeded 0.25 mm and the total precipitation for only those days. Since

Table 7 Phoenix, Arizona normal precipitation (cm) by month [65]

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
(cm)	2.21	2.21	2.11	0.56	0.33	0.05	2.31	2.36	1.45	1.43	1.45	1.88

Table 8 Phoenix, Arizona precipitation (cm) by month for January–May, 2021 and June–December, 2020 [65]

Year	2021					2020						
Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Total	1.73	Trace	0.94	0.03	Trace	Trace	0.25	2.29	Trace	0	Trace	1.14
Usable*	1.68	0	0.89	0	0	0	0	2.29	0	0	0	1.14
Days**	3	0	2	0	0	0	0	2	0	0	0	1

* rainfall rates $\geq$ 0.25 mm. ** number of days that rainfall rates $\geq$ 0.25 mm

normal annual precipitation cannot be used, the amounts in Table 8 would equate to the amount of precipitation that actually could be harvested, and this total (60 mm) will be used as the average rainfall input for Eq. 1.

For the microscale analysis of the specific UA locations, aerial photos displayed in Google Earth will be used for rooftop areas of adjacent buildings. For the macroscale analysis of the rainwater harvesting potential, single family residential building footprints (from [96]) will be used as a substitute for rooftop area.

5 Results

5.1 *Roanoke, Virginia*

Table 9 provides the Eqs. 1 and 2 results for the macroscale analysis, similar to that was accomplished by [59]. Table 9 includes the breakdown in URV by water source; total URV (using the same roof area as [59]) is 69,423.88 m^3. This amount would also constitute the amount of potable water saved if rainwater were harvested from these rooftops. These URV results are then used as the input into Eq. 2, along with the energy usage by water source (from [59]) to provide the total kWh by water source used to treat and transport potable water equivalent to the amount of URV. The total energy usage is 23,506.77 kWh, and represents the amount of energy savings if

Table 9 Roanoke, Virginia roof areas, usable rainwater volume and total energy use by water source

Water source*	Roof area (m^2)*	URV (m^3) (Eq. 1)	kWh/m^3*	Total kWh (Eq. 2)
Carvin's cove	40,390.7	33,863.56	0.081	2,742.95
Carvin's cove	13,463.6	12,126.28	0.345	4,183.57
Crystal spring	21,113.0	17,701.14	0.463	8,195.63
Spring hollow	6,837.9	5,732.90	1.513	8,673.87
City total	81,805.2	69,423.88		23,506.77

* from [59]

Table 10 Roanoke, Virginia potential reduction in energy use and CO_2 emissions, annually

Fuel source for roanoke (from Sect. 4.2.1)	Total kWh (Eq. 2)	CO_2 emissions (kg) (Eq. 3)
Coal (44.8%)	10,531.03	10,531.03
Natural Gas (31.1%)	7,310.61	2,997.35
Hydroelectric (13.2%)	3,102.89	55.85
Nuclear (8.2%)	1,927.56	23.13
Other (not specified—2.7%)		
Total		13,607.36

that amount of water was harvested and not treated to potable standards. For Eq. 2, the energy usage for any irrigation pumps is assumed as zero for reasons noted in Sect. 4.1 and further discussed in Sect. 6.

Table 10 provides the Eq. 3 results. As the inputs, total energy savings for the entire city was used, the breakdown in fuel source is from AEP Annual Report [73], and the CO_2 emissions by fuel source in kilograms from Table 1. Total CO_2 emissions from the energy to treat and transport 69,423.88 m^3 of water is 13,607.36 kg, which equates to the reduction in CO_2 emissions if this amount of water was harvested instead of treated to potable standards.

The amount of CO_2 emissions calculated using the current normal precipitation amounts and the current fuel sources for AEP show a significant reduction from [59]. The value of CO_2 emissions from [59] was 19,971.0 kg. The result obtained from this current analysis shows ~ 32% reduction in GHG emissions. The most significant change that impacts these results was in fuel usage of coal, a reduction from 75.5% of all fuel sources to 44.8%.

5.2 *Buffalo, New York*

Table 11 provides the results of the microscale analysis for the three urban farms identified under Sect. 4.2.2. The adjacent roof areas were calculated using Google Earth. Average rainfall input into Eq. 1 was the normal annual precipitation. This URV result was used as an input to Eq. 2. Since Buffalo does not report its energy use for water transport and treatment, the kWh energy input was the average reported by [46], 0.608 kWh/m^3. For Eq. 2, the energy usage for any irrigation pumps is assumed as zero for reasons noted in Sect. 4.1 and further discussed in Sect. 6. The results from Eq. 2 were then used as inputs to Eq. 3 along with National Grid's total CO_2 emissions (0.23 kg/kWh).

Table 11 Buffalo, New York results for urban farms from all 3 Equations

Farm	Roof area (m^2)	URV (m^3) (Eq. 1)	kWh/m^3 [46]	Total kWh (Eq. 2)	Total emissions (kg) (Eq. 3)
Common Roots	570	471.0	0.608	286.4	66.0
Growing Green	2,221	1,835.4	0.608	1,115.9	257.0
Wilson Street	3,570	2,950.3	0.608	1,793.8	413.1
Total	6,361	5,256.7	0.608	3,196.1	736.1

Table 12 Buffalo, New York results for potential home gardens from all 3 equations

Roof area (m^2)	URV m^3 (Eq. 1)	kWh/m^3 [46]	Total kWh (Eq. 2)	Total emissions (kg) (Eq. 3)
348,377	287,898.4	0.608	175,042.2	40,312.2

The total for these three urban farms equated to 5,256.7 m^3 of URV, harvested from rooftops adjacent to the gardens. If this amount were harvested instead of using potable water, then 3,196.1 kWh of energy would be reduced and 736.1 kg of CO_2 emissions eliminated.

For the macroscale backyard garden analysis, the tax assessment files for Buffalo [84] contained information on one-family dwellings along with the square footage for the 1st floor (or the only floor in ranch style homes). There are 37,885 one-family dwellings with a footprint of 3,483,765.8 m^2. Since it is unreasonable to assume that all residences would contain a backyard garden (or want to implement backyard gardens), 10% of this roof area is used as impervious surface area for rainwater harvesting.

Table 12 provides the results of the macroscale analysis. If 10% of the one-family dwellings implemented rainwater harvesting, a total of 287,898.4 m^3 reduction in potable water use would occur. Again, using the average energy from [46] and the emissions rate from National Grid, a reduction of 175,042.2 kWh in energy and 40,312.2 kg of CO_2 emissions would be achieved if the URV harvested were used instead of that same volume of potable water.

5.3 *Grand Junction, Colorado*

The microscale analysis for this city does not include any urban farms, since farms are not allowed to harvest rainwater (canal water use only). And, in consideration of the small amount of precipitation in this arid region, the first question to ask—is there sufficient precipitation to fill two 55-gallon vessels (0.416 m^3) for use in backyard gardens? To determine this, the backyard garden in Fig. 2 was used to explore

Table 13 Grand Junction, Colorado rainwater harvesting potential for one dwelling

Roof area (m^2)	Total annual precipitation (m)	Annual URV m^3 (Eq. 1)
161.9	0.0974	12.6

rainwater harvesting potential for usable precipitation (from Table 6). The roof area was manually measured at 161.9 m^2. Average rainfall rate used was 97.4 mm. These two figures were used as inputs to Eq. 1. The results in Table 13 demonstrate that rainwater harvesting is possible and sufficient enough to fill two containers totaling 0.416 m^3, several times over.

For the macroscale backyard garden analysis, two GIS files—*Parcels* to identify residential parcels that were zoned as one-family dwellings, and *Buildings* for the area of the building footprint [89]. For the city of Grand Junction only (not the entire Grand Valley or all of Mesa County), there are 31,759 residences with a building footprint of 7,314,619 m^2. As with the Buffalo assessment, 10% of this area was used as the roof area and, as with the microscale analysis, annual usable precipitation of 97.4 mm (from Table 6) as the input annual rainfall inputs to Eq. 1. Since Ute Water does not report energy use by water source, 0.608 kWh/m^3 was used from [46] as the energy input into Eq. 2. The Eq. 1 results are reported in Table 14. Total URV is 56,995.5 m^3, which represents the potential reduction in potable water use if 10% of one-family dwellings in Grand Junction harvested rainwater for backyard gardens. This reduction in potable water use results in a reduction in energy use of 34,653.3 kWh (Eq. 2).

The energy use total from Table 14 was used as an input into Eq. 3. Xcel does report its fuel source, so the kilograms per kWh by fuel source, from Table 1, was used as the other input into Eq. 3. Table 15 reveals the total CO_2 emissions that

Table 14 Grand Junction, Colorado results for URV (Eq. 1) and Energy (Eq. 2) for potential backyard gardens

Roof area (m^2)	URV m^3 (Eq. 1)	kWh/m^3 [46]	Total kWh (Eq. 2)
731,461.9	56,995.5	0.608	34,653.3

Table 15 Grand Junction, Colorado potential reduction in CO_2 emissions, annually

Fuel source for GJ (from Sect. 4.2.3)	kg per kWh (from Table 2)	CO_2 emissions (kg) (Eq. 3)
Coal (21%)	1002.4	7,294.7
Natural Gas (32%)	412.8	4,577.6
Renewables (34%)	18.5*	218.0
Nuclear (13%)	12.0	54.1
Total		12,144.2

*Since Xcel does not split its renewables between solar, hydro and wind, the hydro emissions output from Table 1 was used could be reduced is 12,144.2 kg if 10% of the homes in Grand Junction harvested the rainwater from their dwellings' rooftops.

5.4 Phoenix, Arizona

Table 16 provides the results of the microscale analysis for the three of the existing UA locations identified under Sect. 4.2.4. Cartwright Community Garden is not included in Table 16 since there are no adjacent buildings available for rainwater harvesting. Total roof area, as calculated from Google Earth, is 17,655.38 m^2 (Growing Together Garden—4,619.0 m^2, Coronado Neighborhood Community Garden—346.8 m^2, and Rob and Melani Walton Urban Farm—12,689.5 m^2). The normal annual rainfall was not used as an input because, for some days, rainfall is insufficient to produce runoff. Instead usable precipitation from Table 8 was used as the average rainfall input (60 mm) into Eq. 1. The total URV for all three sites is 847.4 m^3.

The URV results obtained from Eq. 1 was used as the input for annual rainfall into Eq. 2. The energy usage for any irrigation pumps is assumed as zero for reasons noted in Sect. 4.1 and further discussed in Sect. 6. Since Phoenix does not report its energy usage for potable water, the average from [46] was used, 0.608 kWh/m^3 as the final input into Eq. 2. The individual results from Eq. 2 and the total for all three gardens (515.2 kWh) were then used as the energy input into Eq. 3. Since SAP does not report its fuel type breakdown but does report its total CO_2 emissions, 0.4237 kg/kWh was used as the second input into Eq. 3, giving a reduction of 218.3 kg in CO_2 emissions for all three locations.

GIS files for parcels nor buildings are not available for download from the City of Phoenix, or any other related site. The two counties that contain Phoenix are Maricopa and Pinal. The total population of these two counties is 4,948,203, thus Phoenix represents 34% of the population (1,680,992/4,948,203) [95, 105, 106]. "There are about 1.414 million single-family homes across the two counties that make up Greater Phoenix" [107]. Thus, I estimated the number of single-family

Table 16 Phoenix, Arizona URV (Eq. 1) and Energy (Eq. 2) results for microscale analysis on specific UA sites

UA site	Roof area (m^2)	URV (m^3) (Eq. 1)	kWh/m^3 [46]	Total kWh (Eq. 2)	Total emissions (kg) (Eq. 3)
Growing Together	4,619.0	221.7	0.608	134.8	57.1
Coronado Neighborhood	346.8	16.6	0.608	10.1	4.3
Rob and Melani Walton Urban Farm	12,689.5	609.1	0.608	370.3	156.9
Total	17,655.3	847.4	0.608	515.2	218.3

Table 17 Phoenix, Arizona results for potential home gardens from all 3 Equations

Precipitation Rates	Roof area (m^2)	URV m^3 (Eq. 1)	Total kWh (Eq. 2)	Total emissions (kg) (Eq. 3)
Usable	7,076,787	339,685.8	206,529.0	87,506.3

homes in Phoenix at 480,760 (34% of total single-family homes). The average home size in Phoenix, depending on which real estate website is consulted, ranges from 1,584 ft^2 (147.2 m^2) [108] to 2,386 ft^2 (221.7 m^2) for new builds [109]. For this analysis, I used 147.2 m^2 because this allows for multi-story homes (roof area is less than a multi-floor dwellings' total area), which results in 70,767,872 m^2 (480,760 × 147.2 m^2). As with the Buffalo and Grand Junction analyses, I used 10% of the roof area to assume that either 10% of single-family homes have a backyard garden (or would implement a backyard garden).

Using the same inputs as noted under the micro-scale analysis for average rainfall, energy usage and emissions, the results are displayed in Table 17. Total possible URV is 339,685.8 m^3, which equates to a possible reduction in amount of potable water use. If that amount of potable water was reduced, energy saved would be 206,529.0 kWh and CO_2 emissions of 87,506.3 kg would be reduced.

5.5 *Limitations of This Research*

Normal rainfall rates used were from the National Weather Service Stations at each city's airport, which affects this analysis. Rainfall across an urban area can be extremely variable [110], and while many urban areas have more weather stations than those just located at airports, they are often unevenly distributed and precipitation can even vary between the stations. To include such variation in rainfall, identification of weather stations adjacent to each garden would need to be accomplished. Furthermore, normal precipitation values are averages over 30 years and are not updated but once every decade (e.g., 1980, 1990, 2000, 2010, 2020). The analyses within this chapter have benefited from the most recent update, however, it is noted the climate change has had the greatest impact on temperature and rainfall patterns in the past 20 years, so the normal values will not likely reflect this impact until the 2030 or 2040 updates.

Using 10% of available roof areas assumes that 10% of the population would be convinced that this is a viable source of water and would participate in urban agriculture. This rate could be lower or higher dependent upon the population residing within the city, including political affiliation, knowledge of agricultural practices, and funds available to acquire needed equipment. Additionally, the 10% to estimate for all parcels only included those single-family homes (which Buffalo termed one-family dwellings). Multi-family homes, such as condos and townhouses, also have the potential to harvest rainwater but the specific ability to do so depends on homeowners' associations' covenants and bylaws and available land in common areas (or as in the State of Colorado, if it is allowed at all). Additionally, this analysis only looks at rainwater harvesting for urban agriculture. Rainwater harvesting has additionally applications for non-potable uses—irrigation for lawns, flowers and bushes; car washing and other external home uses; and for toilet flushing (additionally uses are discussed in Chap. 5). Other uses require harvested rainwater to be treated to potable standards, thus additional energy is used.

For three of the locations, Buffalo, Grand Junction and Phoenix, the exact amount of energy used to transport and treatment water to potable standards was not available. Thus, the US average from [46] was used as a substitute for this value. Using this average likely had an effect on the final results. If these three locations' energy use is less than average, then ultimately the reduction in greenhouse gas emissions has been over calculated.

The amount of energy used for irrigation pumps is also not calculated as part of this analysis because of the variation in pumps sizes, energy use and amount of water pumped, among other variables, as noted in Sect. 4.1. For many community gardens large rain vessels are being used (see Fig. 3), and the pressure created by the large volume of water (especially their height) in such vessels alleviates the need for pumps to move the water to garden areas. Sufficient rainfall would need to occur to "fill up" such large vessels, a likelihood only in rain rich areas such as Buffalo and Roanoke. Pump energy use would need to be included in calculations for community gardens and urban farms in both Phoenix and in Grand Junction where canal water is used. However, using solar power for the pumps, as seen in Fig. 13D and as noted in Sect. 4.2.4 for Phoenix, would alleviate the need for including pump energy use in calculation energy and emissions savings.

Additionally, these analyses do not address if rainwater harvesting is adequate source for the irrigation of urban agriculture. Agriculture water use is dependent upon crop type, local humidity levels, and timing of rainfall, among other things. Roanoke and Buffalo are located in water and agriculturally rich areas, so the potential diversity of crops produced puts such estimates beyond these analyses, but does present future avenues of research. Grand Junction is also an agriculturally rich area, but uses canal water for irrigation purposes; the calculations would need to include replacing traditional energy pumps with solar-powered (or wind-powered) irrigation pumps.

Finally, these analyses did not include any calculations for virtual water. Virtual water is water used in the manufacture and transport of products, and in the delivery of services (such as fast food restaurants) [111]. Virtual water is considered "hidden" water because it is water that is used in the background. Virtual water use impacts production of any irrigation pumps, solar panels, and has a significant impact on water used for commercial agriculture. This impact should be calculated whether infrastructure is centralized or decentralized and represents a very broad range of future research opportunities.

6 Conclusions and Recommendations for Additional Research

These analyses demonstrate that, even in arid regions, rainwater harvesting has the potential to lower potable water use, save energy, and reduce greenhouse gas emissions. A significant difference is apparent in rainwater availability between arid and wet regions of the US because of the significantly lower amount of precipitation in arid regions, as well as the number of days in arid regions where there is insufficient rainfall to produce runoff (70% of those days in Grand Junction and 60% in Phoenix). A significant difference also exists between the two cities in the arid west–Phoenix does not have the same restrictions as Grand Junction for rainwater harvesting.

For the macroscale analysis of Roanoke, Virginia, a significant reduction occurred in CO_2 emissions between 2016 [59] and this current analysis (2020 values). This reduction is related to the change in fuel type used by American Electric Power, a reduction in coal use of 30.7%. National Grid (Buffalo) reports a similar change in fuel type, which resulted in a 70% reduction in CO_2 emissions since 1990 (2021). Furthermore, Xcel (2021) (Grand Junction) plans to retire their remaining coal generating plants by 2028 and reduce their emissions by 80% by 2030. The Salt River Project (2019) (Phoenix) is already using solar power to treat and transport treated water in at least one of their treatment plants. Moreover, SRP plans on reducing their CO_2 emissions 65% (from 2005 levels) by 2035 and 90% by 2050. These efforts not only impact the sustainability efforts of the four cities in this analysis but all cities, states, and countries served by these energy companies.

Rainwater harvesting and urban agriculture are both decentralized methods to aid in decreasing the ecological footprint of individuals (microscale analyses) and for an entire city (macroscale analyses), even when just targeted for backyard gardens. Decentralized methods are important not just for reducing energy use but to assist in prevention of either terrorist attacks or cyber-attacks on centralized infrastructure which cause wide-spread service interruptions (such as those seen in 2021 on JBS Meat Supplier and the Colonial Pipeline), and represent national security issues.

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Water Sector Reconstruction for Post-disaster Housing Settlements: A Tale of Two Governance Models

Luke Juran, Robert D. Oliver, and Dustin C. Read

Abstract The 2004 tsunami impacted coastal India resulting in thousands of mortalities and hundreds of thousands displaced. The aftermath elicited the largest reconstruction effort in India's history. This study investigates reconstruction in the adjacent territories of Nagapattinam District (Tamil Nadu) and Karaikal District (Puducherry). While both territories deployed virtually identical public–private partnership frameworks consisting of Memoranda of Understandings between the governments and humanitarian organizations, the models deployed to manage reconstruction differed. In Nagapattinam, a collaborative model was executed in which various public agencies were responsible for their respective reconstruction activities. Meanwhile, Karaikal exercised a single agency model under which a standalone public agency assumed responsibility for reconstruction activities. By linking primary data to the theoretical literature, this study examines outcomes of the two governance models through the lens of water. In this case, findings suggest that the collaborative approach—while seemingly more holistic and participatory—produced inferior outcomes due to issues of coordination, bureaucratic layering, and project organization. This outcome, which is incongruent with many theories on governance, development, and project management, is problematized and discussed as are strategies to better integrate the water sector into disaster and urban planning.

Keywords Disaster policy · Disaster reconstruction · Housing development · Urban infrastructure · Urban morphology · Water management

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T. Younos et al. (eds.), *Resilient Water Management Strategies in Urban Settings*,
Springer Water, https://doi.org/10.1007/978-3-030-95844-2_10

1 Introduction

December 26, 2004 remains a day of infamy for much of Asia, particularly in southeastern India where thousands perished and hundreds of thousands were displaced by a massive tsunami. Entire coastal settlements necessitated reconstruction and recovery of transportation, electricity, housing, water, and other critical infrastructure systems as the unforeseen mega-disaster set in motion the largest reconstruction project in the country's history. While much has been written on post-tsunami reconstruction [1–4], little has been written on the water components. This study examines the outcomes of water sector reconstruction for newly built permanent housing settlements in the two adjacent and similarly affected territories of Nagapattinam District and Karaikal District, India. Each territory employed the same reconstruction framework, but deployed it in different ways in practice—one more top-down and centralized using a single agency model, and one more holistic and participatory using a collaborative governance model. Contrary to theoretical expectations, the former generally produced better outcomes than the latter, begging empirical analysis as to why this was the case.

2 Setting the Stage: The Models for Reconstruction

The 2004 tsunami impacted 15 countries, resulting in the death of approximately 200,000 persons and displacement of roughly 1.7 million. After the immediate response phase, attention turned to rehousing affected populations. In India, reconstruction was not executed under the purview of preexisting central, state, or local disaster management plans or policies because no national or local disaster management agencies existed. Rather, the unexpected nature of the event, compounded by its magnitude and geographic scope, spawned a liminal process for reconstruction that was both *sui generis* and ad hoc given the policy and agency vacuum. Governments scrambled to respond to the unprecedented event by creating new departments, extending and expanding the powers of existing departments, and exercising authorities already established in various related plans that lie within the bounds of local administrative powers. State and local governments—thrusted by media attention and citizen demand for political action—sought to mollify the post-disaster situation with a multitude of fresh government orders, temporary measures (e.g., relief camps, transitional housing), and financial assistance to families that experienced a fatality. To address reconstruction and recovery, Nagapattinam District (in the state of Tamil Nadu) created the Tsunami District Implementation Unit (TDIU) while the adjacent affected territory of Karaikal District (in the Union Territory of Puducherry) created the Project Implementation Agency (PIA). Both agencies were established and appointed administrative heads to officially manage reconstruction activities in their locales.

As humanitarian need swelled, the Government of India sought financial assistance from external actors in order to reconstruct well over 100,000 damaged and destroyed homes. In Nagapattinam and Karaikal, external aid was formalized through prototypical memoranda of understandings (MoUs) drafted by the State of Tamil Nadu and Union Territory of Puducherry, respectively. The MoUs were duly signed by the District Collectors (county supervisor in the United States) and the nonprofits that had promised to construct a settlement or specified number of housing units along with associated infrastructure. Three days shy of the tsunami's one-year anniversary, the Government of India passed the "Disaster Management Act, 2005," which created the National Disaster Management Authority (akin to the Federal Emergency Management Agency in the United States), as well as state and local level disaster management agencies. The Act further permitted and explicitly encouraged the acquisition of external aid in times of disaster, stating in Section 30(xxvii) that districts should "encourage the involvement of non-governmental organisations" [5, p. 17] while being sure to "provide rehabilitation and reconstruction assistance to the victims of any disaster" [5, p. 23]. Thus, the post-tsunami reconstruction canvas—including the water sector—emanated from a lack of pre-tsunami disaster planning, creation of the MoU framework to access external assistance, and the subsequent encouragement of MoUs by the new Disaster Management Act and National Disaster Management Authority.

The MoU frameworks employed in Nagapattinam District (under G.O.Ms.No.25) and Karaikal District (under G.O.Ms.29) are virtually identical. Each MoU signified an official agreement between the district level governments and non-governmental organizations (NGOs) that all housing settlements would be jointly constructed and must include:

> [G]ood roads preferably cement roads with side drains with RWH [rain water harvesting] facility, good water supply, sanitation, schools, noon meal centers, solid waste disposal facilities, street lights etc. [6, Annexure 1].

In terms of responsibilities, each government (through the newly created TDIU or PIA) was responsible for land acquisition and preparation, hard surface roads, electrical connections, and connection to a water supply. Meanwhile, NGOs were responsible for constructing disaster-resistant concrete homes, a latrine and septic tank or leach pit for every household, and water access points. Drainage infrastructure was optional but "should also be focused upon" [6, Annexure 1] in Nagapattinam, while it was required as a government task in Karaikal—this is the only practical difference between the MoUs. However, as noted, while the MoU framework employed in each political territory was virtually identical, Nagapattinam deployed it through a collaborative governance approach while Karaikal exercised a single agency approach. This presents a natural social/policy/governance experiment in that political units with similar social, economic, cultural, climatological, and geophysical attributes experienced the same disruption and employed the same responsive framework, but deployed it through different governance models in practice. Thus, this study examines the outcomes of water sector reconstruction in adjacent *de jure* territories that were affected by the same event and subsequently enacted similar policy responses, but in different ways. Outcomes of the diverging models are discussed and several strategies are provided to better integrate the water sector into larger urban, disaster, and ecological planning processes.

3 Study Area and Data Collection

This study investigates outcomes of post-tsunami reconstruction in the neighboring districts of Nagapattinam and Karaikal, India, through the lens of water. The study area lies at the mouth of the Cauvery River with a flat, low-lying topography that is perennially exposed to monsoon and multi-hazard risk. The coastal and deltaic region also exhibits a history rife with water supply and sanitation issues [7, 8]. Fourteen newly constructed housing settlements (randomly selected from 35) were investigated across eight field visits from 2008–2018 (Fig. 1). The permanently recon-

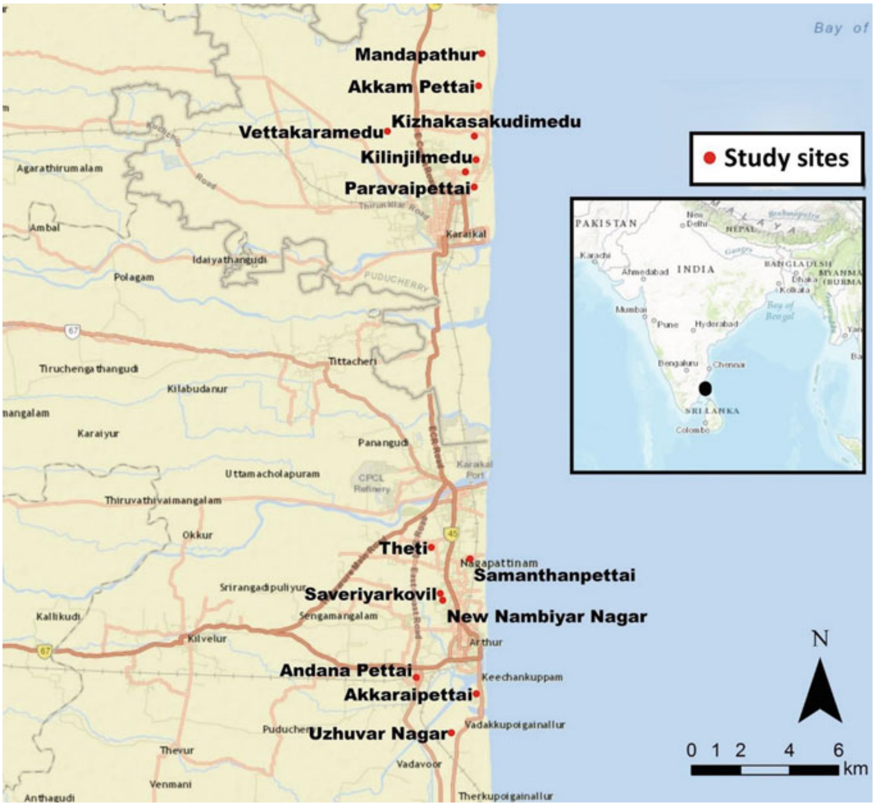

Fig. 1 The 14 study sites in Nagapattinam District, Tamil Nadu (southern set of sites), and Karaikal District, Puducherry (northern set of sites). *Source* Luke Juran's (author) photo

Fig. 2 A view of a typical study site (Andana Pettai in Nagapattinam District). *Source* Luke Juran's (author) photo

structed settlements, seven in each district, average roughly 200 households and have been inhabited since approximately 2007 (Fig. 2). The settlements are both rural and urban (demarcated by jurisdiction and governance structure) and are inclusive in terms of religion (e.g., Hindu, Muslim, Christian), livelihood (e.g., fishers, service industry, daily labor), and social location (e.g., low income, middle income, scheduled caste). Twelve settlements were relocated due to the creation of a 500 m Coastal Regulation Zone (CRZ) implemented to mitigate future hazard risk, while two were reconstructed in situ (one in each district). Each settlement was visited at least three times, and visits encompassed both the dry (May–August) and monsoon (October–December) seasons to address issues of water scarcity, monsoon seasonality, and management of and adaptations to the water infrastructure over time.

Data were acquired through a mixed methods approach comprised of 66 key informant interviews with government officials, NGOs, and individuals with specialized knowledge on water and reconstruction; 14 focus group discussions (one at each study site); and 74 semi-structured interviews with settlement residents [9, 10]. Interviews with residents were conducted as mobile interviews, which enabled interviewees to escort the interviewer to waterscape features, discuss tangible issues in real space, and 'teach' the interviewer about their lived experiences [11]. This approach also facilitated the application of observational theories while attempting to cultivate rapport by placing interviewees in command [12, 13]. Furthermore, this study elicits insights from over one decade of fieldwork in which practice theory, extensive survey data, hundreds of water quality tests, and ongoing community conversations have permitted a longitudinal and triangulated perspective. These data, combined with emergent post-tsunami policies and primary government documents, are used to construct a critical narrative on how the same reconstruction framework was deployed differently in two similarly affected territories, effectively serving to create two different post-disaster waterscapes.

4 Deployment of the Reconstruction Models

The framework for reconstructing housing settlements, including water infrastructure, was virtually identical in Nagapattinam and Karaikal Districts. Each government formalized reconstruction activities in MoU agreements with NGOs. However, while responsibilities of governments and NGOs in each MoU were essentially the same, the governments managed those responsibilities differently: Nagapattinam through a collaborative governance approach, and Karaikal through a more centralized, single agency approach. The two models will be described in this section followed by a discussion of the outcomes produced by the models.

4.1 The Model for Reconstruction in Nagapattinam District

After surveying damage to housing settlements, the State of Tamil Nadu, in which Nagapattinam is located, enacted its first reconstruction-based directive in G.O.Ms.No.25. The government order officially established the MoU framework and collaborative governance approach for post-tsunami reconstruction in all districts of the state. The order begins by stating:

> Many non-government organisations, voluntary agencies, corporate houses, charities, public and private sector enterprises etc. have been in contact with the State Government to participate for the permanent relocation and rehabilitation of people affected by this calamity. The Government has considered these requests from such agencies and has decided to set out the framework for partnering with the State Government for permanent relocation and rehabilitation of the affected persons [6, Sect. 3].

Next, the directive details responsibilities of both the district governments throughout the state (via newly created TDIUs) and partnering NGOs. The MoU obligates Nagapattinam District to purchase or secure the land required for reconstruction activities at no cost to NGOs. Thus, the government first selected and finalized sites for housing reconstruction and paid for or transferred ownership (in cases of public land) via a newly appointed administrator housed in the Revenue Department. Next, the government carried out site preparation through the Tamil Nadu Public Works Department (TNPWD) and then TDIU presented the prepared, developable land to NGOs to erect an agreed upon number of disaster-resistant houses in a layout comprised of:

> [A]ssociated infrastructural facilities such as Water Supply, Sanitation, Waste Water/Solid Water Management, Rain Water Harvesting facilities, other ecological features, Roads, Community Centres, School Buildings, Fish and Farm Produce Market Yards, Village Information/communication Centres, etc. in consultation with the beneficiaries especially women [6, Sect. 1].

In practice, the MoU required NGOs to construct reinforced concrete houses, shared/public water access points, sewerage infrastructure for each house (i.e., pour-flush latrine with septic tank or leach pit), rainwater harvesting systems (i.e., groundwater recharge by conveying rooftop water to the subsurface via pipes), and a community hall at each settlement. Drainage infrastructure was optional, as were facilities such as livelihood training centers, libraries, commercial stalls, *anganwadis* (government childcare and nutrition centers), and parks.

Upon completion of MoU-defined tasks by an NGO, the District Collector was charged with inspecting the settlement and, upon satisfaction, took "ownership of the building and infrastructure" with a "handing/taking over certificate in writing and signed by both the parts" [6, Sect. 14]. TDIU then oversaw the completion of remaining government requirements, specifically laying pipes to connect community standposts to a water supply, providing hard surface roads, and connecting all houses to electricity. TDIU delegated these tasks to three state-level agencies: Tamil Nadu Water Supply and Drainage Board (TWAD) was responsible for water supply, Tamil Nadu Public Works Department (TNPWD) was in charge of roads, and Tamil Nadu Electricity Board (TNEB) was accountable for electrical connections. Upon completion of these tasks, the settlement was deemed complete. Each tsunami-affected community was settled *en masse* into the newly created settlements with houses allotted to families via a lottery to ensure fairness.

Additionally, given the chaos that surrounded the tsunami and the fact that thousands were living in transitional shelters awaiting permanent housing, the government arranged weekly Shelter Advisory Committee (SAC) meetings. The meetings were open to the public (i.e., housing beneficiaries) and aimed to communicate emerging information and up-to-date construction timelines for each settlement. Furthermore, questions were answered, suggestions were fielded, and the government sought to build a level of rapport through a process that was arguably participatory and transparent. SAC meetings were attended by the District Collector, officials from TDIU and relevant government departments, and representatives from NGOs involved in reconstruction.

The model for managing reconstruction in Nagapattinam District can be defined as one that utilized a collaborative governance approach [14, 15]. Although reconstruction activities operated under the auspices of a newly created, standalone agency for dealing with a specific disaster (i.e., TDIU), various agencies such as the Revenue Department, TWAD, TNPWD, and TNEB worked together and were each accountable for separate aspects of reconstruction. This collaborative and arguably holistic, participatory, and transparent model (given weekly SAC meetings) contrasts with that employed in Karaikal District.

4.2 The Model for Reconstruction in Karaikal District

The reconstruction framework in Karaikal District is essentially a mirror image of that utilized in Nagapattinam District. However, the model used to manage reconstruction in practice, including water, was notably different. First, an almost identical MoU process was conceived by the Government of Puducherry in GO.Ms.No.29 for all of its districts to follow. The MoU had the same requirements for local governments and NGOs, including a 500 m CRZ, and notes in Sect. 7 which party was responsible for various facets of reconstruction [16]. Next, the Revenue Department was renamed to Department of Revenue and Disaster Management, a name that remains to the present day, to facilitate the pass-through of government funds for land purchases. Finally, the establishment of TDIU in Nagapattinam was paralleled by creation of the Project Implementation Agency (PIA). However, PIA in Karaikal District varied from its counterpart in that it exists at the Union Territory of Puducherry level (i.e., state level) with appointed officials working directly at the district level. Thus, PIA was designated as the single agency across the territory for completing all government reconstruction tasks in the new housing settlements: water pipelines, roads, electrical infrastructure, as well as site selection and preparation. Karaikal therefore adopted a more centralized, single agency approach to reconstruction [17, 18] that deviates considerably from the collaborative approach adopted in Nagapattinam where separate departments were responsible for niche roles.

In Karaikal District, the reconstruction process began with PIA creating a Site Selection Committee. An executive at the Revenue and Disaster Management Department described the process:

> A Site Selection Committee was formed made up of nine officials: District Collector as the Committee Chairman, Deputy Collector, Commissioner of Karaikal Municipality, Executive Engineer of PWD [Public Works Department], Irrigation and Public Health section of PWD, Building and Roads section of PWD, Executive Engineer of the Electricity Board, Medical Superintendent, and a Commune *Panchayat* representative [government representative from a rural section of the district]. First, the Site Selection Committee would visit unoccupied land to see if it was suitable for development. All members of the Committee had to approve the land based on their own relevant background. If all found it suitable, then the Revenue Department would transfer the land if it was government-owned land, or approach the owners—usually individuals or temples—to purchase the land. Then it was ready for preparation and landfill [infill] [19].

It must be noted here that Karaikal's approach for site selection was more comprehensive than that of Nagapattinam, where an appointed official in the Revenue Department selected reconstruction sites.

Once sites were prepped by PIA, NGOs took over and fulfilled their requirements in a manner akin to those in Nagapattinam. When NGOs completed their work, an inspection was conducted by PIA and, upon a satisfactory review, NGOs transferred ownership of all infrastructure to the government and their duties were complete. Next, PIA—as a single entity—implemented a water supply connection, drainage channels along roadsides, hard surface roads, and electrical connections to all houses. Following the introduction of this critical infrastructure, the reconstruction process for a settlement was complete and houses were allotted to families via a lottery as was done in Nagapattinam.

5 Results and Discussion: A Deconstruction of the Reconstruction Models

Having outlined the MoU framework for reconstruction after the 2004 tsunami and the models deployed to manage reconstruction in Nagapattinam and Karaikal Districts, it is useful to document and contrast the actual results that ensued. Based on the literature on project management and good governance [20–23], it is reasonable to assume that disaster recovery efforts that adopt more collaborative, participatory, and transparent models produce superior outcomes compared to those that do not. However, as demonstrated by empirical research in the study area that examined post-tsunami water infrastructure management [24], the introduction of latrines [25], and comparative analyses based on water quality tests and statistical and geospatial analyses [26], this is a tenuous assumption.

These qualitative and quantitative studies reveal that the more top-down, single agency approach of Karaikal produced a relatively better waterscape considering a host of attributes. Additionally, water services were generally introduced more quickly at the study sites in Karaikal while waterlogging and monsoon floods are less of a problem due to site choice and the presence of drainage infrastructure. For example, a Water Poverty Index that surveyed 300 households from the 14 study sites established statistically significant differences between water services in Nagapattinam and Karaikal in terms of water quality, liters per capita per day, number of households supported per tap, distance to collect water, flow rate, and several related variables [27]. In fact, settlements in Karaikal outperformed those in Nagapattinam in every water comparison, where individuals in the latter secured 43.1% or 21.6 fewer liters per capita per day and 77.5% of public taps tested positive for fecal coliform [27, p. 963]. Prince et al. recently expanded the study with 10 additional reconstructed settlements in Nagapattinam and Karaikal (five in each district) and 207 more households. Similarly, comparisons of all water-related indicators were statistically significant with Karaikal outperforming in each case [26]. Furthermore, spatial analyses via Global Moran's I tests indicated that statistically significant differences between the indicators are not random but rather a determinant of spatial organization [26]. In other words, positive spatial autocorrelation exists in which similar indicator and Water Poverty Index scores cluster in space. The clusters are divided by district lines and are, at least in part, an etiology of the reconstruction processes that generated their existence.

5.1 Deconstruction Junction: How the Models Functioned

Although the adoption of a relatively collaborative and participatory approach in Nagapattinam is commendable, such efforts were hindered by the lack of a coherent vision and development strategy. The absence of vision was first exposed during site selection and carried through subsequent phases of the reconstruction process. These phases will be narrated with the goal of dissecting and ultimately learning from the intricacies of this case study to foster enhanced integration of water into reconstruction and other politico-developmental processes.

In Nagapattinam District, the first compounding issue was site choice. An appointed official at the Revenue Department was in charge of selecting and securing land for all reconstruction sites. While there was informal input from other officials and all land purchases and transfers were approved by the District Collector, sites were ultimately selected based on financial and construction ease [28]. That is, land already owned by the government and land that was cheap, flat, and easy to prepare and develop were (inadvertently) privileged in selection. As declared by an Executive Engineer at TDIU, "geography wasn't a concern because the government would prepare the land and it would be inspected" [29], suggesting that any precursory issues would be fully rectified at the site preparation stage. However, as will be demonstrated, price and physical developability do not necessarily translate into good outcomes in the water sector.

Next, upon taking over settlements from NGOs, issues arose in coordinating the remainder of government tasks. Participating agencies (i.e., TWAD for water supply, TNPWD for roads, and TNEB for electricity) were alerted by TDIU when a site was ready for public services, but the order of introducing services was not prioritized. In practice, this led to settlements being constructed haphazardly. For example, one study site with a newly introduced water supply had several major pipes broken during the subsequent introduction of roads by TNPWD. Upon the site being inhabited, residents complained that there was no water. TWAD insisted that water supply lines were installed and that they had dutifully done their job, but after several more complaints the broken pipes were finally identified and fixed. Meanwhile, TNPWD stated that they were simply doing their job by laying the roads where they needed to be. At another site the water supply was implemented after the introduction of roads. In this case, TWAD tore up sections of roads to lay pipes but failed to patch the roads or contact TNPWD to return for remedial work. The torn up sections of road were eventually filled in with pieces of broken bricks by settlement residents. Further, there were multiple cases of road construction resulting in broken septic tanks and leach pits from heavy machinery that got too close as operators failed to pay attention to or were unaware of the subsurface infrastructure. Another issue is that some sites were complete except for one remaining critical service. These sites would sometimes remain vacant for months until the service—often connection to a water supply—was finally provided. Such sites were not prioritized as agencies merely went site to site to provide their service without harnessing a coordinated and more holistic view. A final example of inefficiency and ineffectiveness emerged once settlements were declared complete and inhabited. Here, the lack of attention paid to drainage (optional for NGOs and thus rarely introduced due to cost) portended to floods and persistent sanitation issues as standing water negatively interacted with sewerage infrastructure, degraded water quality when retrieving water from public taps, and created stagnant bodies to support mosquito habitats in a region combatting several mosquito-borne diseases (e.g., chikungunya, dengue, malaria, and zika).

In Nagapattinam District, the model for reconstruction was collaborative as well as relatively participatory and transparent through organized SAC meetings, but the approach ultimately lacked coordination. Despite operating with a spirit of openness, the agencies operated in silos, were tripped up by bureaucracy, and produced inequitable infrastructure across space through the fabrication of fragmented settlements that lacked a unified vision. A primary example of these heterogeneous outcomes can be observed in Arlikatti and Andrew's study documenting uneven housing recovery in rural Nagapattinam District, particularly among low caste communities (i.e., bottom rung of the Hindu hierarchy) and non-fisher communities who perceived that fishers were privileged in the doling of humanitarian aid [30]. Ultimately, cumbersome coordination and the absence of a shared vision served to limit the speed, scale, and scope of recovery. This also led to settlements, on average, taking longer to both build and populate in Nagapattinam compared to Karaikal. Dr. J. Radhakrishnan, District Collector of Nagapattinam at the time of the tsunami, is quite frank and humble in agreement:

> All of the water solutions were short-sighted and not visionary. The government and NGOs were rushing development in order to finish the reconstruction there was no cohesion or long-term planning. The entire reconstruction process was not given the importance it was due. It was put through strenuous approvals through various government levels, but not for reconstruction purposes, only for following rules and to do your job [31].

Thus, in practice, there was an absence of a true collaborative culture or ecosystem approach to address the intractable issues of housing, disasters, and water. Annie George of Building and Enabling the Disaster Resilience of Coastal Communities, an NGO that helped to coordinate other NGOs involved in reconstruction activities, is even more direct:

> Reconstruction results seem Helter Skelter [disorder or chaos] and not an improvement of the previous scenario. The government had funds to produce better, more well planned, and more sustainable results, but they chose not to. They intentionally got the bare minimum done and swept the rest under the rug [32].

Therefore, the great potentials for water sector reconstruction, as well as for other sectors, were subjugated by a systemic business-as-usual approach that failed to break down inflexible traditions of governance. Even Radhakrishnan readily admitted that "we need to move to a higher plane" to address future issues more holistically and collaboratively rather than "simply pushing papers for the sake of performing work" [31]. Here, the demand for development expedience without various groups/agencies having been versed in collaborative decision-making resulted in a hybridized governing arrangement that although well intentioned, may not have been fully equipped to swiftly navigate the myriad challenges (economically, socially, politically, etc.) of a post-disaster landscape. This echoes the findings of Prater et al., who argue that Nagapattinam's initial ability to develop a vertically and horizontally integrated response plan was lacking [33].

In Karaikal District, the more top-down, centralized, and single agency approach was ultimately more coordinated and produced relatively better and cohesive outcomes. The PIA—a union territory (i.e., state) agency unlike the lower district level TDIU in Nagapattinam—began with site selection. While PIA was in charge of all reconstruction activities, it formed a comprehensive nine-person committee to consider various facets of settlement construction, including those relevant to the water sector such as PWD (water service provider), the Irrigation and Public Health section of PWD, and the Medical Superintendent. Therefore, site selection in Karaikal was founded upon unanimous approval from numerous sector-specific agencies and utility providers, thereby forcing a lens of holistic long-term settlement sustainability into the process. After site preparation overseen by PIA, NGOs completed their infrastructural tasks and handed sites back over to PIA for introduction of water supply, drainage, roads, and electricity. Here, each government task was directed by PIA including what was to be done and when and where it was to be performed. This more command-oriented process—which was less collaborative, participatory, and transparent—resulted in settlements being constructed not only with fewer bungles and bureaucratic delays, but also with more consistent and standardized infrastructure across space. Furthermore, on average, sites were completed and populated more quickly while containing relatively superior waterscape attributes (e.g., quality, quantity, and less flooding due to drainage) relative to Nagapattinam.

Compared to collaborative governance models, single agency models are often contended to be less effective in theory based on, among other things, their encumbered ability to consider the wider picture, build institutional capacity, and engage stakeholders and the broader citizenry [15, 34–36]. Likewise, top-down management is eschewed in today's activist and community-based participatory research (CBPR) as an approach that decontextualizes projects, relies on prototypical and/or technocratic 'solutions,' and further marginalizes subaltern populations [37–39]. However, in the case of Nagapattinam and Karaikal, the top-down, single agency model spawned relatively better results in practice. This outcome begs several rhetorical questions: how does this inform conventional notions of 'good' governance, what does this challenge in a theoretical and practical sense, and—more broadly—how does one make sense of the outcome as a simultaneous advocate for both communities and effective process?

First, we argue that findings of this study should not be instrumentalized as convenient rationale to institute exclusive and non-participatory governance as there is value in harnessing a comprehensive view, promoting transparency, and establishing a robust trust ecology among stakeholders and citizens. However, this must be accomplished not only in theory and on paper, *but in practice*. Next, and as argued by Sørenson and Torfing, much deliberation occurs during the 'upstream' design of collaborative approaches in terms of representation and agreeing upon tasks [40]. However, many problems to be confronted are located ‘downstream,’ thus warranting additional time to be spent on examining the impacts of upstream decisions and jointly agreed solutions upon actual outcomes.

A pragmatic consideration of three approaches developed by water and disaster scholars may better integrate the water sector into reconstruction processes in the study area and writ large. Camron and Shamir’s Water-Sensitive Planning (WSP) approach to sustainable development integrates the water sector into larger urban and regional planning based on an overarching principle of ‘multiple goals and common means’ [41]. Important regarding the case of Nagapattinam and Karaikal, the WSP approach calls for interdisciplinarity in planning and acknowledges various planning scales all the way from the building site to the entire catchment area. These principles may have assisted in fashioning a more holistic process with more consistent outcomes across the projects. Juran’s Water Resources Reconstruction (WRR) framework, borne from several longitudinal studies on post-tsunami reconstruction in Nagapattinam and Karaikal, provides additional guiding principles to integrate water into the reconstruction arena [28]. In this case, the WRR framework’s principles on designing an effective organizational structure, managing scalar issues of governance and land-use change, and integrating water as a dual component of both disaster recovery and long-term sustainable development may have served to enhance project management, improve coordination among agencies, and avert future water problems that arose due to upstream decision making. Finally, Kreamer’s ten allegories on how humanitarian water development can actually injure communities may have proven valuable to reconstruction actors as collaborative governance in Nagapattinam appears to have suffered from a synthesis of not seeing the big picture (Antonie van Leeuwenhoek View), nearsightedness and poor long-term planning (Mr. Magoo Myopia), and doing the bare minimum (Neville Chamberlain Approach) [42].

6 Limitations and Critical Considerations

It would be remiss to omit several limitations in our comparison of water sector reconstruction in Nagapattinam and Karaikal. First, it must be stated that the districts—while extremely similar in culture, livelihood, climate, physical geography, and disaster affectedness—exhibit notable differences. For example, Karaikal had a smaller population, more (internal) green space available for reconstruction, and fewer settlements to reconstruct as a function of its shorter coastline. Conversely, Nagapattinam had a larger population and less land available for reconstruction given its narrow shape and elongated coastline. In fact, Radhakrishnan posits that, second only to magnitude of the event, “the linearity of the district was the biggest obstacle” [31]. He continues:

> Land was at a premium because much of the district was destroyed due to its geographic linearity. There was not enough space to put up such a large concentration of new houses, especially with the CRZ [500 m coastal buffer] regulations [31].

A second limitation stems from the fact that newly created government agencies were charged with overseeing reconstruction activities in an extremely raw and chaotic post-disaster setting. Such an approach has been shown to exhibit delays and jurisdictional confusion [43]. Further, the disaster was both unprecedented and unforeseen; as stated by Murugesan, “it was the first time we had such a big problem” [19]. In fact, the 2004 tsunami ranks as the largest single reconstruction effort in India’s history to date. Thus, one wonders, as somewhat postulated by Jordan et al. [44], if the collaborative model may have worked better at a smaller scale and/or under a more flexible timeline that did not entail external actors, media attention, and mass homelessness.

Yet another limitation relates to the inability to refute claims that outcomes could have been worse in Nagapattinam had a collaborative governance model not been deployed. That is, albeit with flaws, perhaps the collaborative and relatively participatory model produced better results than otherwise would have been attained. For example, SAC meetings did at the very least offer an opportunity for citizen engagement, even if the opportunity or its impact were not particularly robust. Further, Lawther has claimed that as the scale of disaster increases, so does the difficulty in implementing popular input as a foundation of reconstruction [45]. This has led some to argue that while community participation can take on a number of forms and be implemented at various stages, there is no single theoretical model for participation that automatically affords better results, specifically noting that reconstruction models without popular input can also be successful [46–48]. Rather, as contended by Lizarralde and Massyn, the organizational structure—not inclusion of the affected community per se—is often the biggest indicator of project success [47]. Finally, it would be misleading to assume that Karaikal’s single agency model operated without flaw or that it represents a beacon to strive for. Rather, similar problems also surfaced in Karaikal regarding water sector reconstruction and management of the newly introduced infrastructure [see 24, 28]. However, the frequency, magnitude, and community impact of such issues were markedly less when comparing the two territories.

Ultimately, we concur with Mulligan and Nadarajah that “there is a need for good physical and social planning in the development of new permanent settlements” [49, p. 362], and this work highlights ramifications of this ongoing disconnect between local communities, government agencies, NGOs and other stakeholders in the arena of disaster reconstruction. Given that organization and orchestration of the development community unfolds differently in different locations, it remains important to highlight how various locations mobilize following a disaster and to learn from such processes.

7 Conclusion

This study critiqued post-tsunami water sector reconstruction in the adjacent and similarly affected districts of Nagapattinam and Karaikal. While the political territories employed virtually identical frameworks consisting of MoUs with humanitarian organizations, the practical model each government deployed to manage reconstruction activities diverged. Contrary to governance theories, as well as practical approaches rooted in activist and community-based participatory research, outcomes generated under the relatively top-down and centralized single agency model produced better outcomes. Moving forward, this result warrants a serious theoretical and pragmatic discourse. The discourse should not focus on discrediting, dismantling, or prescribing a specific approach, but rather on how to produce optimal short- and long-term results given multiple constraints (e.g., geographic, temporal, resources) and often competing objectives. As evidenced in the cases of Nagapattinam and Karaikal, this dialogue is particularly significant for the water sector because water not only sustains the residential, commercial, and industrial sectors, but also represents a crucial component of urban planning, disaster management, and long-term human and ecological development.

Acknowledgements This research was supported by a Fulbright-Nehru Fellowship. The authors greatly thank the research participants in Nagapattinam and Karaikal, without whom this research would be impossible. The authors also thank Annie George, BEDROC, Prema Rajagopalan, Ligy Philip, Rajagopal Chidambaram, E. Nagarajan, and N. Kalyani for logistical support.

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