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Approaches to Water Sensitive Urban Design

Potential, Design, Ecological Health, Urban Greening, Economics, Policies, and Community Perceptions

Edited By
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Preface

Conventional stormwater systems in cities were designed to quickly drain the stormwater runoff from urban areas to minimize flooding. However, this hydrologically efficient system of gutters and big pipes was also very efficient in transferring contaminants and sediment to receiving creeks and waterways. This invariably caused a substantial reduction in their ecological health, and a destruction of their stream morphology by erosion and/or sediment smothering. Stormwater is essentially a diffuse pollution source and, as such, it is much more challenging to manage than point sources such as the discharge from sewage treatment plants and factories.

Over the last few decades Australia has invested many hundreds of millions of dollars into sewage treatment to reduce the contaminant loads into the bays and estuaries that surrounded most of its major cities. The attention of society is now turning to urban creeks and rivers that provide such important ecosystem services to their communities. Many of these waterways have been straightened and lined with concrete to make them more efficient conduits to transport the extra rainfall runoff from rapid urbanization.

Urban society has also developed the aspiration to be more locally self-sufficient and to protect the remaining natural urban ecosystem, involving effluent reuse, stormwater capture and reuse, rainwater tanks, combined with more energy-efficient technologies. Hence the concept of water sensitive urban design (WSUD) started to take off in Australia in the 1990s, with new ways of designing and building suburbs, which do not rely on the direct drainage of runoff from impervious surfaces to waterways. Moreover, there was an emphasis on alternative urban water supplies, renaturalization of water courses and associated riparian areas, and installing vegetative technologies that not only looked attractive in the urban street, but also delivered a much-improved stormwater quality.

Given the connectedness of the global community, it’s not surprising that this WSUD concept emerged in other countries of the world, although each had their own nomenclature and drivers. Hence the terms: best management practices (BMPs), green infrastructure (GI), integrated urban water management (IUWM), low impact development (LID), low impact urban design and development (LIUDD), source control (SC), stormwater control measures (SCMs), sustainable urban drainage systems (SUDS), Sponge City, and experimental sewer systems (ESS). The specific drivers for this innovation also varied between countries, with North America initially focusing on water quality improvement, while much of Europe was driven by the need to reduce local flooding and overflows from their “combined sewers,” which carry both stormwater and sewage. Australia focused on water quality protection, waterway ecosystem protection, and littoral zone conservation, while other countries, such as China, are facing urban water shortages that somewhat perversely are accompanied by regular flooding, and impaired stormwater quality.

Even though these approaches are comparatively new, we find ourselves today with a wide range of WSUD technologies, design models, descriptive terms, driving objectives, guidelines, regulations, effectiveness metrics, and economic values as part of societies’ journey to urban sustainability.

WSUD approaches are implemented in existing and new developments to address impacts from climate change, urbanization, and population growth. Incorporating WSUD as a mainstream practice in urban developments can play a significant role in the transition from the current water, wastewater, and stormwater systems to a more sustainable paradigm including mitigating impacts from climate change and urbanization. WSUD systems can deliver multiple benefits including water supply, stormwater quality improvements, flood control, landscape amenity, healthy living environment, and ecosystem health improvement of urban waterways.

So, if we know so much about WSUD, why do we need to write another book on it? The answer we think is in the vast store of data, information, and social drivers that can make distilling “the knowledge” a very difficult task for the student, the water practitioner, and the urban planner.

It is also important to understand what WSUD cannot do, especially for protection from low-frequency flooding events and the high erosion losses and stream degradation that can occur during civil construction before WSUD measures are implemented. The challenge is getting the right mix of hydrology with water quality and design aesthetics to protect, or restore, the natural functioning of a complex urban water ecosystem, which helps create a sense of place for new urban communities.

In this book, we aim to provide a holistic overview of WSUD technologies, their applications, and successes using Australian and international studies (mainly North America and Northern Europe). The book has 27 chapters, each written by different authors, and has been divided into several themes. These chapters are described in brief to provide overview of the associated themes.

1. HISTORY OF WSUD AND WSUD APPROACHES

Chapter 1 sets the scene for water sensitive urban development, both historically and geographically. It considers the evolution of ecologically sustainable stormwater management in Europe, North America, United Kingdom, Asia, Australia/NZ and introduces terms used in those countries, such as LID, SuDS, Sponge City, and GI. A key underlying principle of WSUD/LID is to emulate the natural hydrology of a site by using decentralized management measures. However, the drivers for adopting WSUD can be quite different between countries, and includes: sewer overflow protection, flood management, access to green space, water quality protection, waterway ecosystem protection and littoral zone conservation, and stormwater harvesting and reuse.

Chapter 2 focuses on the WSUD technologies used in Australia. Avoidance measures (such as permeable pavement) avoid the generation of contaminated stormwater runoff from allotments. Mitigation measures (including gross pollutant traps, swales, bioretention basins, wetlands, and smart street trees) are typically implemented to detain and treat stormwater runoff. The selection of technologies is heavily influenced by the preferences of local authorities and site-specific considerations such as soil type and slope and existing assets. Despite over 20 years of WSUD practice in Australia, there is still much to be learned about the performance of many of the treatment technologies, as installed in the field. Nonetheless, simple visual assessment of healthy plant growth is a very useful criterion of the operational effectiveness of vegetated, treatment devices.

2. STORMWATER QUALITY

Chapter 3 discusses the chemical and microbiological characteristics of stormwater and the types and efficacies of typical stormwater quality mitigation measures. Catchment characteristics including stormwater and wastewater infrastructure, land-use activities, traffic characteristics, and climate are key influencers of water quality. The authors give a detailed description of pollutants' build up and wash off processes, and how these may be modeled. Detections of pharmaceuticals, human pathogens, and human-specific biomarkers in stormwater from catchments with **separate** sewers highlight the need for further research on pollutant transport processes.

3. DESIGN GUIDELINES AND REGULATIONS

Chapter 4 discusses the international, national, regional, and local planning and design guidelines that have been developed by various agencies for the sustainable implementation of WSUD/LID systems. These guidelines help water professionals to plan, design, and implement these approaches based on urban development requirements, water quality and hydrology criteria, catchment characteristics, local climatic conditions, local regulations, and environmental and community considerations.

Chapter 5 reviews WSUD policy and regulation in Australia and internationally. Case studies from Australia, Europe, the United States, and Singapore show how the mix of policies, incentives, regulation, capacity building, and institutional perceptions at various levels impact the institutional culture and context in each jurisdiction. Municipal government has typically been the key agent for WSUD implementation. However, collaboration is required across discipline areas and stakeholders to support and empower local government and community in the implementation of WSUD.

4. POTENTIAL FOR WSUD

Chapter 6 reminds us that most WSUD features are designed to be multifunctional elements that provide benefits to runoff volume, peak flow rate, water quality, and stream ecology. The systems are also intended to reduce flooding and peak flows from small and frequent storms. Critical parameters for successful flood mitigation performance are detention storage size, the portion of catchment impervious area connected to the storage, and the rate at which the storage is emptied. Their efficacy to reduce flooding and peak flows from larger, less frequent storms at the broader catchment scale has yet to be confirmed.

Chapter 7 discusses the use of GI stormwater controls such as rain gardens, swales, and porous pavement to alleviate the magnitude and frequency of combined sewer overflows (CSO). Although many modeling studies have demonstrated the potential of large-scale use of these controls for CSO reduction, there have been few monitoring efforts. This chapter reviews two such large-scale projects in the United States, which monitored the performance of retrofitted GI in combined sewer catchments with areas of 8—40 ha.

Chapter 8 examines the impacts and magnitude of sediment loads generated during the construction phase of subdivision and compares this with the loads generated during the operational phase of development—traditionally the major focus of WSUD in Australia. Without application of erosion and sediment control measures, sediment export from the construction phase is orders of magnitude greater than the sediment export from unmitigated operational-phase runoff. Even with application of conventional best practice measures, the construction-phase loads are still equivalent to nearly a decade of operational-phase sediment exports. The author recommends that much greater emphasis should be placed on the construction phase in regulation and research.

Chapter 9 introduces the role of stormwater and roof water harvesting for beneficial use as part of an integrated WSUD approach to urban development. An effective scheme must combine sufficient rainfall, a suitable catchment, opportunities for diversion and storage, adequate demands, and water treatment suitable for the proposed end uses. Other issues discussed include stormwater contamination, validation and verification, and governance issues. However, the main impediments for operators to develop harvesting schemes with regulatory and financial confidence are the uncertainties with the long-term operation, governance, and compliance requirements.

5. ECOLOGICAL HEALTH COVERING IMPACTS AND BENEFITS FROM WSUD

Urban development changes the hydrology of catchments (including runoff volume, frequency, and peak flow) and the transport of sediment, nutrients, and pollutants. Consequently, it has a degrading impact on urban stream morphology and in-stream biota. A key question is whether, and to what extent, WSUD can prevent these changes. Chapter 10 suggests that WSUD can restore hydrology at small scales; however, restoration at the catchment scale is much more challenging, and there is limited evidence that existing techniques are effective. Chapter 11 finds that even when WSUD measures are implemented to help restore more natural flow patterns, degraded water quality can have an overriding influence on stream ecosystem health.

Chapter 12 discusses the changes to stream morphology and the opportunities for WSUD to ameliorate the impact. WSUD has been successful in reducing pollutant loads and providing some reductions in flow volume. However, current practice has commonly failed to arrest the geomorphic degradation of streams, due in part to the fact that WSUD has rarely been applied at a catchment scale, sufficient to mitigate the increased magnitude and frequency of runoff from connected impervious areas.

In Chapter 13 we learn that engineered urban lakes primarily increase amenity and property values and provide a flood-mitigation purpose. The failure of many urban lakes to remain in a healthy ecosystem usually stems from poor design and a lack of runoff pretreatment. Once a lake changes to a degraded state, it is very difficult to recover the initial healthy state.

6. WSUD ECONOMICS AND OPTIMIZATION

Economic assessment of WSUD investments is challenging. Data shortages and the broad range of nonfinancial benefits provided by WSUD make it difficult to rigorously quantify economic benefit. Chapter 14 provides a framework to overcome these difficulties. Cost—benefit analysis (CBA) transparently provides a decision-maker with a decision metric for proceeding with an investment, or otherwise. Total Economic Value (TEV) identifies and categorizes all benefits accruing from an investment, including environmental and social benefits that may be difficult to quantify. A remaining challenge to rigorous economic assessment is the data availability of environmental and social benefits produced by WSUD investments.

Chapter 15 discusses how optimization methods can be used to plan and design WSUD schemes to achieve the best outcomes and identify system trade-offs between a range of economic, social, and environmental indicators. Two case studies consider the selection, sizing, and layout of WSUD components for water quality improvement and stormwater harvesting. Future developments in optimization are also discussed.

7. WSUD IN INTEGRATED URBAN WATER MANAGEMENT AND URBAN PLANNING

Chapter 16 outlines a case study from Melbourne, Australia, where water industry experts discuss the practical infrastructure and urban planning processes to achieve the vision of IUWM and WSUD. Effective coordination of policy development, strategy, planning, and implementation of WSUD approaches is required to overcome the primary barriers to achieving these visions.

Chapter 17 focuses on the lessons from South Africa in WSUD and GI, planning, application, and implementation. It describes the need for context-driven design guidelines and for emerging middle class South Africa to become familiar with WSUD approaches, the importance of social benefits, and the integration of WSUD into mainstream spatial planning.

WSUD is currently applied at the local municipal level, with much of the current planning and design-related WSUD material focused on stormwater harvesting, management, and maintenance-related issues such as greening roads and street verges, open space areas, and a cities' landscape features. Chapter 18 highlights the opportunity for WSUD to contribute to and enhance urban sustainability through the relatively new concepts of healthy and liveable cities, which can be used to promote sustainability and provide economic and social benefits to communities.

8. URBAN HEAT ISLAND AND GREENING THE CITY

Urbanization can lead to the development of the urban heat island effect, whereby public health and thermal comfort are adversely affected. Chapter 19 provides examples from various climates to illustrate how the application of GI (including parks, street trees, green roofs, and green walls) and WSUD approaches can be effective in mitigating increased urban air temperature.

Chapter 20 reviews the key elements of resilient green roof and living wall systems. Green roofs and living walls are becoming an important component of WSUD systems and provide many environmental, economic, and social benefits such as: reduced temperatures both inside and outside of buildings, reduce building energy usage, improved air quality, and reduced pollution levels. This chapter will assist urban planners and designers in developing resilient GI for cities, particularly those located in dry climates.

Chapter 21 provides a European perspective on the use of novel urban water systems in greening and cooling the urban environment. Although WSUD design principles usually focus on stormwater management, this chapter provides examples of the integration of urban wastewater into WSUD.

9. CAPACITY BUILDING AND COMMUNITY PERCEPTION FOR WSUD

As the stormwater components of WSUD have gained traction, large numbers of SCMs have been constructed as new assets. However, failure to appropriately maintain and operate these WSUD assets runs the risk of reducing public support for the implementation and adoption of WSUD approaches. Chapter 22 describes the challenges, operation, and maintenance requirements, and an eight-step process is described to develop WSUD asset management plans for the ongoing operation and maintenance of SCMs as a mainstream activity in local authorities.

Capacity-building programs are a critical component for the successful delivery and operation of WSUD systems. As WSUD systems are comparatively new, different skills for their planning, design, operation, and maintenance are required, and the associated capacity building programs are still evolving. Chapter 23 uses a case study from South Australia to follow the process of developing a business case and implementing a capacity building program. Successful capacity building results in the efficient delivery of assets, an improved return on the investment, and reduces the risk of asset failure.

The community can easily recognize the improved aesthetics, greenspace, and recreational amenity features of above ground WSUD systems. However, there is a need to educate the community about the benefits of other less visual outcomes such as water quality improvement and flood mitigation. Chapter 24 explores five dimensions of people's attitudes to, and engagement with, WSUD systems: visibility; recreation and other amenity; economic benefits for residents; place attachment; and social capital and community engagement. Interventions that increase awareness of WSUD benefits strengthen social capital within a community and helps support WSUD over the long term.

10. WSUD POST IMPLEMENTATION ASSESSMENT AND CASE STUDIES

Postimplementation assessment of developments designed with WSUD features is essential to learn from on-ground implementation of such systems to better inform future developments. Chapter 25 describes a case study from Kansas City, Missouri, USA, where a linear regression model was developed and verified with field data using a limited palette of SCM installations. The model was demonstrated to reliably estimate stormwater removal/capture by SCMs in the catchment. The performance of SCMs over a range of rainfall events during a 3-year monitoring period was shown to be effective in preventing CSO and supported the efficacy of green solutions in reducing urban runoff.

Chapter 26 provides a precinct-scale case study of an infill development near Perth, Western Australia. The development implemented a range of sustainable water, energy, and urban greening initiatives in a medium density site of mixed building typologies. Understanding the delivery process and learnings from the on-ground implementation experience are an important factor for the success of future such developments.

Chapter 27 provides Australian and international case studies of some leading edge WSUD approaches and discusses the challenges and benefits from implementing WSUD. The findings reinforce the importance of WSUD being integrated across different urban functions, stakeholders, and levels of government. The benefits of WSUD often extend beyond the primary objective of improved urban stormwater management, reflecting the multifunctional nature of many WSUD approaches. Case study findings can be used to refine standards and guidelines, build confidence in the WSUD approaches, and help build public understanding and engagement in the benefits of WSUD. The studies also identified the importance of using economic instruments that reflect the true cost of different stormwater management approaches, thereby helping create financial incentives for the adoption of WSUD.

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Chapter 20

The Role of Green Roofs and Living Walls as WSUD Approaches in a Dry Climate

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Chapter Outline

ABSTRACT
The addition of green infrastructure, including green roofs and living walls, into buildings is part of a new approach to urban design aimed at resolving current problems associated with built environments. Green roofs and living walls are becoming an important component of water sensitive urban design systems, and their use around the world has increased in recent years. Green roofs can cover the impermeable roof areas that densely populate our urban areas, and through doing so, can provide many environmental, economic, and social benefits. In addition to roofs, there are a number of bare walls that have the potential to be transformed into vegetated, living walls. Living walls can potentially improve air quality, reduce pollution levels, reduce temperatures inside and outside of buildings, reduce building energy usage, and improve human health. Despite such benefits, both green roofs and living walls are relatively new technologies, and there are several research gaps and practical barriers to overcome before these systems can be applied more widely. Furthermore, specific design criteria need to be developed for a range of climatic conditions to develop resilient green infrastructure. Consequently, several field experiments comprising both intensive and extensive green roof test beds, as well as living walls, have been

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recently established. In these recent research studies, stormwater quality and quantity, hydrological behavior, plant performance, and thermal benefit have been investigated. The findings of these studies can be used to identify the key elements of resilient green roof and living wall systems.

Keywords: Green Infrastructure; Green Roofs; Green Roof Hydrology; Living Wall; Low Impact Development; Stormwater Quality; Water Sensitive Urban Design; Thermal Performance.

This chapter will describe several experimental and modeling studies that have been conducted on both living walls and green roofs. In terms of field experiments, the quality and quantity of runoff from both intensive and extensive green roofs are discussed, as is the use of fertilizers in green roof and living wall systems. In terms of modeling applications, the effects of different scenarios of adding green roofs to a typical urban environment are explained using industry available tools such as the commonly used ENVI-met software (Huttner and Bruse, 2009). Finally, in terms of green roof and living wall design, methods of optimizing plant performance are described including plant selection, media type and depth, irrigation management, and other important design factors. In addition, opportunities to recycle and reuse outflow water from green roofs and living walls for end uses such as irrigation and toilet flushing are explored using current design standards.

This chapter should assist urban planners and designers in developing resilient green infrastructure models for cities with dry climates around the world.

20.1 WATER SENSITIVE URBAN DESIGN

Over recent decades, the hydrologic cycle of water has changed significantly because of continuous changes in Australian green spaces from forest or similar vegetation to urban environments (ANZECC, 2000). Australia is one of the most urbanized countries in the world with 85% of its inhabitants living in towns or cities (Skinner, 2006). The growth rate of urbanization has led to changes of green spaces with large impervious areas such as roofs, car parks, roads, highways, and paving. This in turn has led to changes in the urban hydrologic cycle. In an investigation by Razzaghmanesh et al. (2012), various studies from Europe, North America, Asia, Australia, and New Zealand were compared to understand how green roofs could be adapted to meet water sensitive urban design (WSUD) objectives in Australia. It was found that green roofs are used as an important WSUD infrastructure around the world, but that this technology is very much in its infancy in Australia. Furthermore, specific design criteria needs to be developed for the wide range of climate conditions found in Australia. WSUD, however, is not a single technology but rather it is a systems approach (Beecham, 2003). Australian cities have developed guidelines on developing water-sensitive cities. For example, the Adelaide 30-year Plan (South Australia Government, 2010) articulates a vision for the Adelaide community beyond 2037. The purpose of the plan is to promote Adelaide as a city that is recognized worldwide as livable, competitive, and resilient to climate change. Generally, WSUD can be used as a strategy for incorporation across a wide range of urban development scales, including residential homes, roads, vehicle parking areas, subdivisions, multistorey units, commercial and industrial areas, and public land. Green roofs, living walls, permeable pavements, and wetlands are some of the commonly used WSUD technologies that aim to improve water quality reduce flood risk, and enhance biodiversity in urban areas (Fig. 20.1). There is also a concept

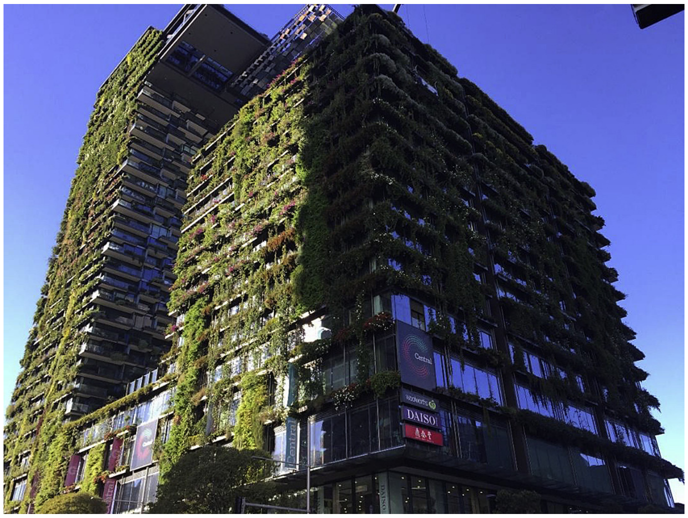

FIGURE 20.1 One Central Park in Sydney Australia with its 1200 m^2 of living wall.

known as *blue roofs* which is an unvegetated system designed to retain water above an impermeable membrane, either temporarily or permanently. Blue roofs can provide a number of benefits including storage of rainfall to reduce runoff impacts, and storage for reuse purposes such as toilet flushing and irrigation. Because of the risk and consequences of leakage into buildings, blue roofs are seldom used in practice, and are considered beyond the scope of this chapter.

20.2 GREEN ROOF AND LIVING WALL CONCEPTS

20.2.1 Extensive green roofs

Extensive green roofs are those in which the depth of the growing media is generally <150 mm, although Table 20.1 provides different definitions of green roof depth from various authors (Berndtsson et al., 2010; Fassman and Simcock, 2012). Extensive green roofs are lightweight structures with drought-tolerant, self-seeding vegetated cover. The vegetation has to cope with little or no irrigation during the roof's operational life. Generally, they are constructed on roofs with slopes up to 33%. Because of their relatively low weight, it is often possible to retrofit them on existing structures without installing extrastructural support. Fig. 20.3(a) shows a schematic of a typical extensive green roof.

20.2.2 Intensive green roofs

Intensive green roofs are those where the growing media depth is generally >150 mm and are often covered with shrubs, grassed areas, and occasional trees (FLL, 2002). They are usually installed on flat roofs (Fig. 20.2). Regular maintenance, such as watering, weeding, and fertilizing, is needed to keep intensive green roofs alive (Berndtsson et al., 2008). They can also be used as amenity areas. Fig. 20.3(b) shows a schematic of a typical intensive green roof.

20.2.3 Categorization of green walls

Green wall is a general term for a vertical wall covered in vegetation. Other terms for plants grown on vertical landscaping include vertical greenery system, vertical garden, green vertical system, vertical green, bioshader, and vertical landscaping. It is commonly agreed that these can be divided into two categories according to the installation and growing methods for these systems. These categories are green façades and living walls (Dunnett and Kingsbury, 2008; Köhler, 2008; Manso and Castro-Gomes, 2015; Safikhani et al., 2014a) (see Fig. 20.4).

In direct green façades, the vegetation is rooted in the ground and grows vertically on the wall. For indirect green façades, climbing plants grow vertically on trellises, cables, or mesh support systems without attaching to the surface of the building (Fig. 20.5). A living wall on the other hand is a building envelope system where plants are planted and irrigated on a structure attached to the wall without relying on a ground level rooting media (Fig. 20.6). Popular systems include living walls with modular boxes, felt pockets, planter boxes, and hydroponic systems. Green façades have received more attention in Europe (Dunnett and Kingsbury, 2008; Pérez et al., 2014), whereas living walls are generally more popular in Asia (Pérez et al., 2014).

TABLE 20.1 Green Roof Nomenclature Based on Media Thickness, as Described by Various Authors

Intensive (mm)	Extensive (mm)	References
>150	≤150	Fassman-Beck et al. (2013) and Fassman and Simcock (2012)
150–1200	50–150	Kosareo and Ries (2007)
>500	–	Köhler et al. (2002)
150–350	30–140	Mentens et al. (2006)
>100	<100	Hien et al. (2007)
>300	–	Berndtsson et al. (2006)
>100	20–100	Graham and Kim (2005)

Modified from Berndtsson, J.C., Bengtsson, L., Jinno, K., 2010. Runoff water quality from intensive and extensive vegetated roofs. Ecological Engineering, 35, 369–380.

FIGURE 20.2 Intensive green roof at the Fairmont hotel in Singapore.

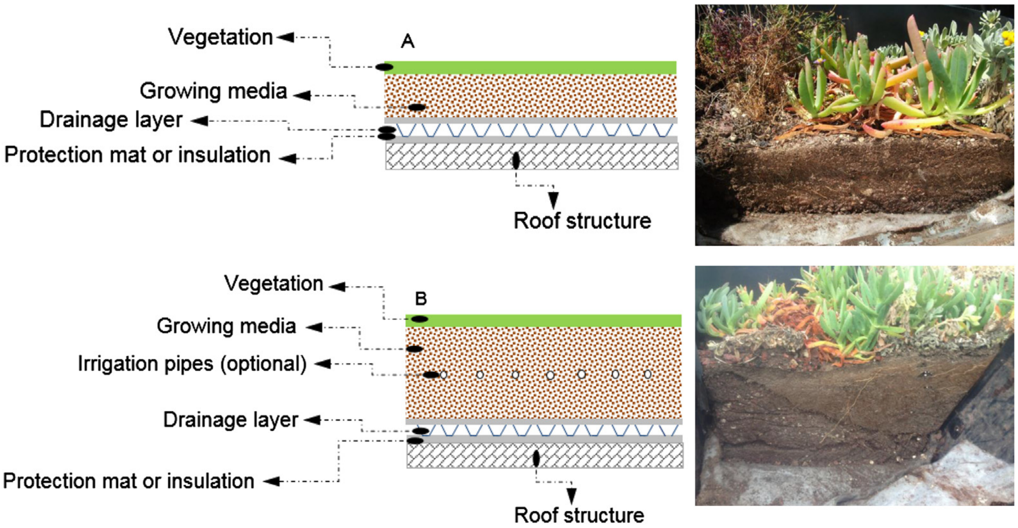

FIGURE 20.3 Schematics and photos of (a) an extensive (depth ≤ 150 mm) green roof profile and (b) an intensive (depth > 150 mm) green roof profile (Razzaghmanesh, 2015).

Apart from being aesthetically pleasing, green walls provide environmental, social, and economic benefits which are attributed to their design, plant choice, density of vegetation, and location. Examples of these environmental, social, and economic benefits are listed in Table 20.2.

Investigations into green façades have taken place since the 19th century, but there has been an increasing number of guidelines and other publications since the 1980s (Köhler, 2008). It has only been since the early 2000s that studies have

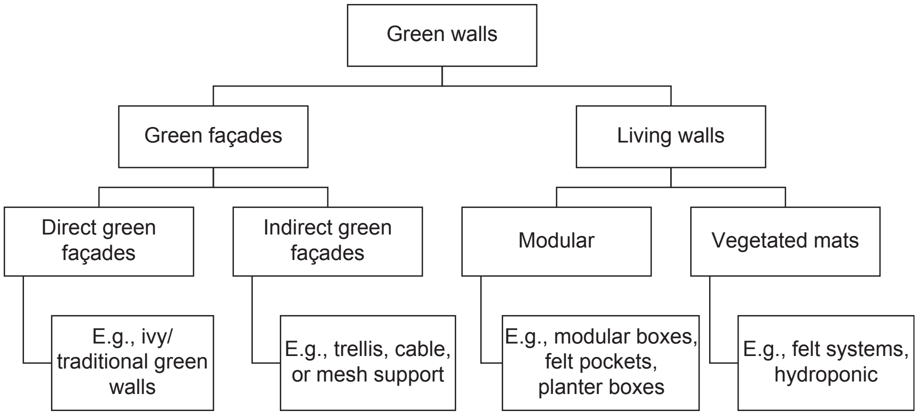

FIGURE 20.4 Types of green walls.

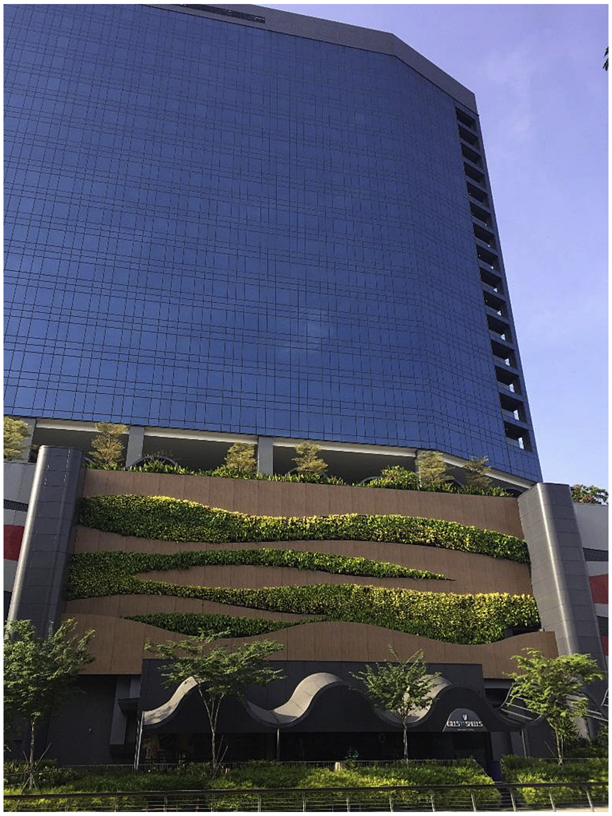

FIGURE 20.5 Green façade at the Hotel Boss in Singapore.

begun into living walls. There are a number of factors to consider in selecting a suitable green wall. Initial installation and maintenance costs for green façades are lower than for living walls, making them a more economical choice. However, living walls offer a wider selection of plants and are often considered more aesthetically pleasing than green façades. Living walls also have the capacity to provide instant cooling upon their installation, whereas green façades may take several years to colonise the entire wall (Dunnett and Kingsbury, 2008; Ottelé et al., 2011; Perini and Rosasco, 2013).

Recent studies have confirmed that both green façades and living walls can mitigate the urban heat island (UHI) effect by creating a microclimate. One of the key benefits of green walls over other shading devices is the capability of plants to repartition solar radiation and sensible heat into latent heat during the transpiration process (Scarpa et al., 2014). In addition, green walls act as a layer of insulation, thereby reducing building heating demand in cooler climates.

FIGURE 20.6 Living wall at the Marina Barrage in Singapore.

TABLE 20.2 Environmental, Economic, and Social Benefits of Green Walls

Category	Benefits
Environmental	Temperature reduction from shading Improved air quality Carbon dioxide sequestration from photosynthesis Sound attenuation Improved flora biodiversity in urban areas
Economic	Reduced energy demand and increased energy efficiency of buildings Suitable for retrofitting projects
Social	Increased human health and well-being Improved building esthetic

Hui, S.C.M., Zhao, Z., 2013. Thermal regulation performance of green living walls in buildings. In: Joint Symposium 2013: Innovation and Technology for Built Environment, Hong Kong, pp. 1—10; Safikhani, T., Abdullah, A.M., Ossen, D.R., Baharvand, M., 2014a. A review of energy characteristic of vertical greenery systems. Renewable and Sustainable Energy Reviews 40, 450—462; Sheweka, S., Magdy, A.N., 2011. Living walls as an approach for a healthy urban environment. Energy Procedia 6, 592—599.

In various green façade studies, the maximum surface temperature differences between a green façade and a bare control wall were 15.2°C in Lleida, Spain (Pérez et al., 2011), 11.3°C in Nagoya, Japan (Koyama et al., 2013), 12.6°C in Chicago, USA (Susorova et al., 2014), and 9.9°C in Bangkok, Thailand (Sunakorn and Yimprayoon, 2011). Similar positive temperature differences have also been measured for living walls compared with bare control walls. For example, in the Mediterranean climate of Adelaide, South Australia (Fig. 20.7), the maximum temperature difference recorded between a living wall and a control wall was 14.9°C in the summer of 2015 (Razzaghmanesh and Razzaghmanesh, 2017). In experiments conducted in Italy a maximum temperature difference of 20°C was recorded between a living wall and its bare control wall (Mazzali et al., 2013).

Both experimental and modeling studies have shown that living walls provide more cooling benefits compared with green façades, including providing instant cooling to the building surface following its installation (Jaafar et al., 2013; Ottelé et al., 2011; Perini and Rosasco, 2013; Safikhani et al., 2014b; Wong et al., 2010). In humid, tropical Singapore, living walls were up to 7°C cooler than green façades (regardless of the percentage of green cover) (Wong et al., 2010), whereas in Malaysia living walls were 0.5—1.5°C cooler than a green façade (Safikhani et al., 2014b).

A simulation exercise for Mediterranean climates showed that green façades/living walls could save up to 43% of the cooling energy costs. It was shown also that a living wall with planter boxes could reduce heating energy demand by up to 6% compared with only a 1% saving for green façades (Ottelé et al., 2011).

Mazzali et al. (2013) demonstrated that a living wall's overall outgoing heat flux was measured at $-87\ \mathrm{W/m^2}$ compared with the incoming heat flux of $30\ \mathrm{W/m^2}$ on its bare wall. This measured difference in net energy flux from the wall is presumably due to the significant shielding effect of the green cladding that reduces the amount of incoming energy from

FIGURE 20.7 Experimental living wall at the University of South Australia.

FIGURE 20.8 Modular box-type living wall in Xi'an, China.

the sun. It is also due to other factors, including the type of vegetation, the latent heat of evaporation, and the reflection coefficient for solar radiation. In a Mediterranean climate, their experiment recorded a 12–20°C surface temperature reduction on sunny days and a 1–2°C temperature reduction on cloudy days. This demonstrated yet again the potential of green walls to mitigate the UHI effect, at least locally.

The installation and maintenance costs of green wall systems can be expensive, as confirmed by cost-benefit analyses undertaken by several researchers. Installing and maintaining living walls costs approximately US\$150/m^2 compared with US\$45/m^2 (in today's costs) for green facades (Perini and Rosasco, 2013). However, some unquantifiable benefits such as increased flora biodiversity, aesthetic values, and UHI mitigation, were not included in the analysis.

A lifecycle assessment by Ottelé et al. (2011) for different green wall types indicated that direct green façades are the most economically sustainable, followed by modular pot living wall systems (Fig. 20.8).

20.3 GREEN ROOF ELEMENTS

The outer layer of a green roof system consists of vegetation. In theory, almost any plant species could be used for green roof applications, providing they are suited to the climatic region, grown in a suitable substrate, and are given adequate irrigation (Oberndorfer et al., 2007; Rowe et al., 2012). Wind stress resulting from eddy formation around tall buildings may need to be accounted for in the selection of plants. Visibility and accessibility are other selection criteria. Although *Sedum* remains the most commonly used genus for green roofs in cold climates, the range of green roof vegetation is wide. Researchers have tested many herbaceous and woody taxa under various rooftop conditions since the 1980s (Durhman et al., 2004; Monterusso et al., 2005).

Heinze (1985) compared combinations of various *Sedum* species, grasses, and herbaceous perennials, planted in two substrate depths in simulated roof platforms. Slow-growing sedum performed well in thin substrates. Grass and herbs had better performance in deeper substrates. It should be noted that *Sedum* is classified as a weed in many states of Australia.

20.3.1 Growing media

Growing media is the supporting layer for vegetation in a green roof system. The media should be lightweight, well drained, have good moisture storage capacity, and should be able to resist biological breakdown over time (Getter and Rowe, 2006). An optimum growing media is: 80%−90% (by volume), of lightweight inorganic aggregate (LWA), and 10%−20% organic matter (OM). LWA provides a porous media for water and gas exchange, whereas the OM provides nutrient supply and retention, as well as promoting a rootzone ecology essential for plant growth (Friedrich, 2005; Fassman and Simcock, 2012).

A commonly used standard for growing media properties is the FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau) guideline (FLL, 2002). Other standards for various countries are listed in Table 20.3. Note that the inorganic matrix can include scoria, ash, pumice, sand, coir, pine bark, chemically inert porous foams, and recycled materials such as crushed bricks and roof tiles.

20.3.2 Root barrier

Root barriers are often used in green roofs to protect the roof's waterproofing membrane (Fig. 20.9) from plant root growth. The most common type of root barrier is a thin polyethylene sheet, laid over the waterproofing membrane. This may not be required if the waterproofing membrane is certified as root-resistant. The root barrier must also be resistant to the humic acids produced when plants decompose. Separation sheets are sometimes installed between the waterproofing layer and root barrier to provide additional protection and to separate materials that are not compatible (Green Roof Australia, 2010; Carpenter, 2014).

20.3.3 Drainage layer

The primary role of a green roof drainage layer is to remove the excess water from rainfall as quickly as possible, and to refill external storages for future irrigation use. Basically, green roof drainage systems can be divided into two classes: aggregate drains and geocomposite drains. These may be combined or used separately in conjunction with the drain outlets (Wingfield, 2005). Aggregate drainage layers less than 100 mm in depth should be freely drained. With deeper layers, drainage restriction (by textural layering) can be used to increase the water-holding capacity of the overlying media. A number of granular materials considered suitable include gravel, lava and pumice, expanded clay and slate, and recycled materials such as crushed roofing tiles or bricks.

Geocomposite drains are any drains composed of two or more materials, one of which is a geosynthetic (Carpenter, 2014; Wingfield, 2005). Geocomposite drains may also include heavy duty high-density polyethylene with excellent load-bearing capacity to retain and drain water (Fig. 20.10). Depending on the product chosen, the drainage layer can often take the weight of a pedestrian or even vehicular traffic, with a design life of 50 years.

20.3.4 Insulation layer or protection mat

Protection mats are often used to protect the building's waterproof membrane from damage during installation of the green roof. The most common materials used are water-permeable, hard-wearing, and dense synthetic fibers, polyester, and polypropylene. Protection matting is installed directly on top of the waterproofing layer for root-resistant membranes or on top of the root barrier layer, providing further protection against root penetration, as well as doubling as a separation sheet (Green Roof Australia, 2010).

TABLE 20.3 Tests for Developing Local Recycled Growing Media in Different Climates

Researchers	Country	Purpose	Materials	Tests or Targets	Standards
Molineux et al. (2009)[a]	United Kingdom	Characterizing alternative recycled waste materials for use as green roof growing media in the United Kingdom	Crushed red brick, clay and sewage sludge, paper ash, carbonated limestone	• pH • Particle size distribution • Loose bulk density • Particle density • Leachate analyses	1. Particle size distribution: BS EN 933-2:1996 2. Loose bulk density and void spaces: BS EN 1097-3:1998 3. Particle density and water-holding capacity: (BS EN 13055-1:2002) 4. Leachate analysis: BS EN 12457-3:2002
Fassman and Simcock (2008, 2012)	New Zealand	Development and implementation of locally sourced extensive green roof substrate in New Zealand Moisture measurements as performance criteria for extensive green roof substrates	Blend of 70% 4–10 mm pumice, 10% 1–3 mm zeolite, 15% pine bark fines plus mushroom farm waste, and 5% peat and installed at a depth of 70 mm 70% v/v 4–10 mm pumice, 10% v/v 1–3 mm zeolite, and 20% organic matter at a 100 mm depth are recommended to maintain plants without irrigation (excluding drought conditions) and minimize weeds while preventing runoff from storms with less than 25 mm of rainfall	• Retention of a design storm • Wet system weight • Dry bulk density • Minimum target permeability • Minimum plant cover	1. FLL (2002, 2008): German guidelines for green roofs 2. AS/NZS 1170
Rayner (2010)	Australia	Choosing substrates for Australian green roofs	Gravels, sands, topsoil, scoria (various grades), crushed clay brick, bottom ash (enviroagg) products, pumice, perlite, recycled plastics (chips and beads), light expanded clay granules, foam flakes (urea formaldehyde) and vermiculite	• Porosity (air-filled porosity) • Permeability/ hydraulic conductivity • Water-holding capacity • Particle size distribution	1. Australian Standards: AS 3743 Potting Mixes 2. FLL Guidelines (2002, 2008): German guidelines for green roofs

[a] *The addition of organics also significantly reduced the pH of the recycled aggregates making growing conditions for plants more favorable in these substrates.*

FIGURE 20.9 Installation of a roof barrier sheet in an experimental green roof in Australia. The drainage layer is the black open matrix.

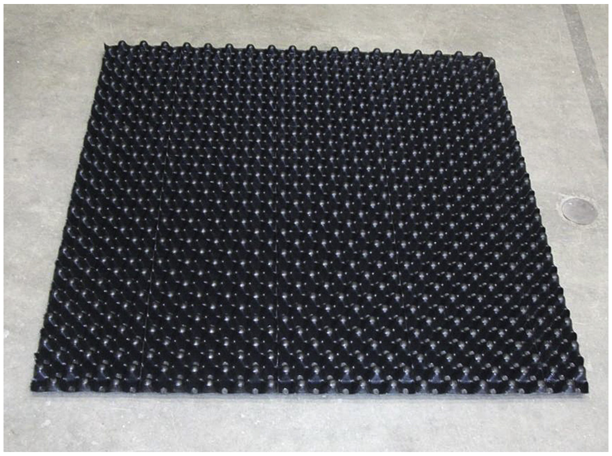

FIGURE 20.10 Example of a synthetic green roof drainage material showing the raised 3D structure creating drainage channels. The material is high-density polyethylene.

20.3.5 Roof structure

It is generally possible to install a green roof on any roof type irrespective of the material and slope, subject to safety and load-bearing considerations. However, green roofs are generally installed on concrete roof decks because of structural integrity, ease of design, durability, and amenity considerations (Carpenter, 2014). As described by Munby (2005), it is often quite difficult to obtain as-constructed structural drawings for existing buildings, especially for those over 10 years old. A structural survey is therefore recommended in the majority of cases to determine a building's roof load-bearing capacity before designing the retrofit of a green roof (Castleton et al., 2010).

20.4 LIVING WALL ELEMENTS

There are several factors to be considered in determining the choice of green wall, especially in dry climates. This includes their design and performance, as well as installation and maintenance costs. The choice of green wall type (green façades or living walls) will very much affect installation and maintenance costs. Perini and Rosasco (2013) took into consideration the yearly maintenance costs of pruning and irrigation. They found that annual pruning of green façades will generally begin 4 years after installation. However, the environmental and social benefits of living walls were found to start immediately on installation. Selection of plant species and growing media are among the core considerations in designing green wall structures. These have to be carefully evaluated to suit the location and environment of the green wall, thus maximizing the benefits delivered by the system.

Installation and maintenance of green façades are generally less complicated than living walls; therefore, the following sections will briefly discuss green façades but will focus more heavily on living wall elements.

20.4.1 Vegetation

Vegetation plays the critical role in any green wall system. While nonvegetative building cladding only contributes to shading, the thickness of vegetation combined with transpiration processes contribute to both shading and temperature regulation of a building and its microclimate. Plant selection depends largely on the building orientation and climatic conditions including local weather. Evergreen and native plants are often preferred for minimum maintenance and to prolong the lifetime of the system. The canopy cover, canopy thickness, and plant morphology are among the factors contributing to the cooling benefits of green walls (Cameron et al., 2014; Manso and Castro-Gomes, 2015; Stav and Lawson, 2012). Other associated variables that contribute to thermal cooling benefits include vegetation height, leaf reflectivity, and leaf emissivity (Stav and Lawson, 2012).

Flexibility in plant selection allows the creation of attractive patterns, colors, texture, and thickness (Manso and Castro-Gomes, 2015). Such systems are generally more popular with designers and building residents. Living walls offer a wide selection of growing methods and plants, unlike green façades, which are limited to climbing plants. Perennial and native plants usually minimize maintenance and irrigation needs for living wall installations (Perini and Rosasco, 2013; Mårtensson et al., 2014). A living wall system with low water usage is often preferable in terms of its lifecycle performance (Natarajan et al., 2014).

Drought-tolerant succulent carpets have also been used in living wall applications following their successful use in green roofs (Manso and Castro-Gomes, 2015). However, as living walls are vertically orientated they are not well suited for succulent plants, which often require near horizontal growing surfaces. A "decision tree" developed by Perini et al. (2013) recommended evergreen shrubs for living walls, while evergreen climbing species were preferred for green façades.

20.4.2 Growing substrate

Research into the selection of growing media in living walls is limited. Selection of a substrate media is important because it influences plant root growth and the subsequent growth of the living wall plants (Jørgensen et al., 2014; Weinmaster, 2009). Popular substrates for living walls include rock wool, coir, peat, and potting soil (Weinmaster, 2009), as well as hydroponic media, which supply nutrients through the irrigation water. Lightweight materials are generally preferred because of the increasing weight of growing vegetation.

20.5 GREEN ROOF HYDROLOGY

An important strategy in sustainable urban drainage systems and WSUD is "at-source" runoff control (Berndtsson et al., 2010; Roehr and Fassman-Beck, 2015). Green roofs are viewed as a best management practice to attenuate peak runoff flows in urban areas (Palla et al., 2010). Therefore, one of the more important issues in green roof studies is their hydrology. The following section describes recommendations on green roof hydrology based on previous studies.

20.5.1 Rainfall and runoff relationship in green roofs

Most researchers have used the water mass balance equation to study the hydrologic behavior of green roofs (Mentens et al., 2003). A steady state form is given by (Vilareal and Bengtsson, 2005)

$$P + I - E - Q - D + \Delta S = 0 \tag{20.1}$$

where, P, precipitation, E, evapotranspiration, Q, runoff, D, deep percolation, ΔS, water storage in the system, and I, irrigation (summer irrigation if need be).

By neglecting D, as deep percolation rarely occurs in green roof systems, the equation becomes

$$Q = P + I - E - \Delta S \tag{20.2}$$

In most water balance studies of green roofs, the main objective is to estimate the various components of this equation.

20.5.2 Runoff comparison between green and conventional roofs

Green roofs provide a substantial opportunity to reduce both runoff volume and peak discharge from roofs (Fassman-Beck et al., 2013). The most significant differences between the outflow hydrographs from conventional roofs and green roofs are the peak flow and the time of runoff movement on the surface (Berndtsson et al., 2010). Fig. 20.11 shows the rainfall and conventional roof and green roof runoff as measured by Razzaghmanesh and Beecham (2014) from an experiment in Adelaide, Australia.

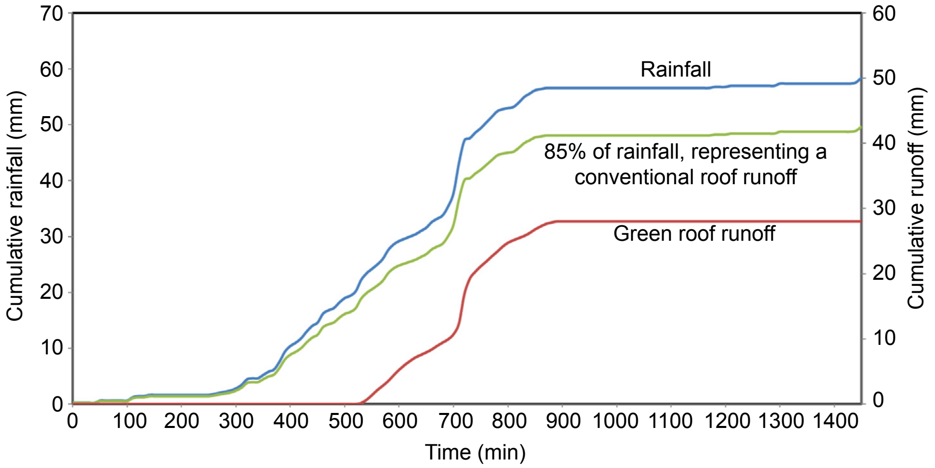

FIGURE 20.11 Cumulative rainfall together with conventional roof and green roof runoff hydrographs.

20.5.3 Retention capacity of green roofs

Hydrological studies of green roofs, especially studies focusing on water retention in green roofs, began in Germany several decades ago (Mentens et al., 2006). There has since been rapid growth of the green roof industries in both Germany and North America. In a study of two green roofs undertaken in Portland, Oregon, USA, by Hutchinson et al. (2003) the precipitation retention was calculated as 100% in the (non snow) warm seasons and 69% on average.

Voyde et al. (2010) studied the hydrology of a green roof in Auckland (NZ) and found, a 66% retention of precipitation over a one year period. They concluded that, regardless of rainfall properties, green roofs can significantly reduce runoff and in particular the maximum runoff rate. For some rainfall events green roofs could retain 82% of average rainfall and reduce peak flows by up to 93%.

Four extensive green roofs and three conventional (control) roofs were investigated by Fassman-Beck et al. (2013) in Auckland, New Zealand, over a 2-year period. Runoff reductions of over 50% were measured from green roofs with substrate depths of 50−150 mm and >80% plant coverage. Runoff rarely occurred from storms with <25 mm of rainfall. Peak discharge rates were 60%−90% less than those from conventional roofs, and did not vary seasonally.

20.5.4 Rainfall events

Rainfall is one of the most important factors in the water mass balance equation. In this section, rainfall characteristics such as design rainfall intensity, duration, and frequency are discussed. As Mentens et al. (2006) discussed, according to the German guideline (FLL, 2002), a design rainstorm is defined as an event having rainfall of 300 L/s/ ha during 15 min, equivalent to 27 mm in 15 min. Furthermore, peak runoff during design rainstorm events is defined as the amount of runoff during the last 5 min of rainfall (FLL, 2002).

Carter and Rasmussen (2006) found an inverse relationship between the depth of rainfall and the percentage of rain retained. For small storms (<25 mm), 88% was retained, for medium storms (25−75 mm), 54% was retained, whereas for large storms (>75 mm), 48% was retained. The moisture conditions of the roof materials before the storms were not given. Similarly, Simmons et al. (2008) found that all small rain events (<10 mm) were completely retained by the green roofs. However retention also depends on rainfall intensity.

Villarreal-Gonzalez and Bengtsson (2005) found that water retention by green roofs depended to a large extent on rainfall intensity. The lower the intensity, the larger the retention. For a rainfall intensity of 24 mm/h and roof slopes of 2 and 14 degrees, retention was 60% and 40% of the simulated precipitation, respectively. As rainfall intensity increased to 80 mm/h, the retention reduced to 21% and 10%, respectively. Considering the high permeability of the green roof media, this response was unexpected. However, Bengtsson (2005) also found that the water storage capacity of a green roof was related to the rainfall intensity and that the vertical percolation process through the growth media dominated the rainfall−runoff relationship. In a 24-month study by Razzaghmanesh and Beecham (2014) in Adelaide, Australia, the experimental intensive and extensive green roofs were able to retain 100% of all the rainfall from 1-year Average Recurrence Interval (ARI) events with a duration of less than 7 h (Fig. 20.12).

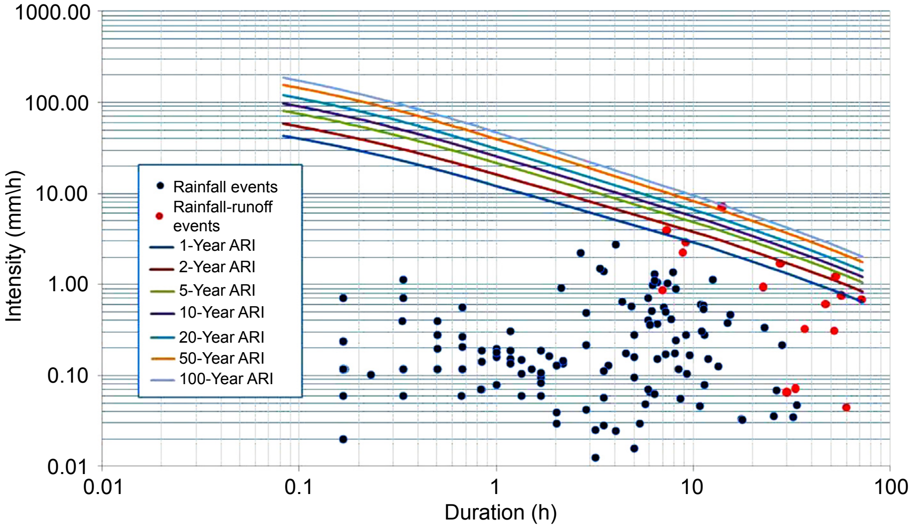

FIGURE 20.12 Monitored rainfall-runoff events compared with Adelaide's Intensity-Duration-Frequency curve (IDF curves).

20.5.5 Effect of design parameters on green roof hydrological performance

In this section, the influence of parameters such as slope, substrate material and depth, and vegetation cover on green roof hydrology is discussed, based on published studies from various countries with different climates.

20.5.5.1 Slope

The published literature is inconclusive regarding the effects of slope on green roof hydrology. Some researchers argue that an increase in slope can cause an increase in green roof runoff. Others posit there is no relationship between slope and water retention in green roofs (Berndtsson et al., 2006; Mentens et al., 2006). On the other hand, others believe higher roof slopes reduce outflow and improve the water retention properties of green roof systems (Köhler et al., 2002). Generally, studies on the effect of slope on green roofs have been combined with examining the effect of other factors. VanWoert et al. (2005) tested the effects of two slopes, 2% and 6.5%, and growing media with 2.5, 4.0, and 6.0 cm depths for a range of rainfall events. The test beds with 2% slope and 4 cm media depth had the greatest mean retention at 87%. They concluded that outflow runoff is decreased with less slope and deeper growing media. Similar results were reported by Getter et al. (2007) who constructed green roof beds with four slopes (2%, 7%, 15%, and 25%) and found the maximum retention value (86%) was in the 2% slope roof. Moreover, time for runoff initiation increased and peak discharges reduced for all slopes.

20.5.5.2 Vegetation

The amount of transpiration from green roofs depends on the local climate and the type of vegetation. Some studies have been undertaken to examine the plant species and/or their combinations to improve the performance of green roofs. Dunnett et al. (2008) examined the influence of vegetation composition on runoff in two green roof experiments. In the first experiment, an outdoor lysimeter was used to investigate the quantity of runoff and evapotranspiration from trays containing 100 mm growing media, and a combination of grasses and forbs with bare substrate. In their second experiment, conducted in a laboratory, simulated rainfall was used to understand how much water was retained by different vegetation types. In both cases, a combination of vegetation worked best in terms of water retention. In another study, Schroll et al. (2010) monitored runoff from conventional roofs with impervious surfaces, roofs with a half-impervious surface area, and a vegetated roof. During winter rainfall events, vegetation had no influence on roof water retention. In contrast, in summer periods, vegetated roofs retained more water than the other two roof types.

20.5.5.3 Substrate

Substrates or growing media are another important factor in the design of green roofs in that they can improve the water retention performance of these systems.

Beck et al. (2011) evaluated changes in water discharge quality and quantity from an extensive green roof after adding biochar, which is a carbon-based soil amendment promoted for its ability to retain nutrients in soils. Green roof trays with and without biochar were planted with *Sedum* or ryegrass and subjected to two sequential 74 mm/h rainfall events using a rainfall simulator. The 7% biochar treatment showed increased water retention, reduced peak runoff rates, and a significant decreases in the discharge of nitrogen, phosphorus, and dissolved organic carbon.

20.5.6 Hydrological modeling of green roofs

Carter and Jackson (2007) observed that there were few studies that have examined the impact of green roof applications on the hydrology of an urban catchment. Consequently, they used local green roof rainwater retention data to model the hydrologic effects of green roofs in an urban catchment at a variety of spatial scales. Spatial analysis identified areas of the catchment where green roofs would significantly reduce the fraction of total impervious area. Subsequent hydrological modeling demonstrated that appropriately located green roof implementation could significantly reduce peak runoff rates, particularly for small storm events.

Palla et al. (2012) developed a conceptual linear reservoir using a simple mechanistic (HYDRUS-1D) model to simulate the hydrologic behavior of green roof systems in an urban environment at the University of Genova, Italy. This model was calibrated and validated using data collected from an experimental green roof site. The hydrographs from the hydrologic model reproduced, with acceptable accuracy, the experimental measurements, as confirmed by the Nash–Sutcliffe efficiency index being generally greater than 0.60. Indeed, they concluded that the layered roof structure and each green roof component could be designed to improve the hydrologic process. The mechanistic model, based on a single porosity approach, was able to adequately describe the variably saturated flow within the thin stratigraphy.

20.6 STORMWATER QUALITY

The quality of discharges from green roofs is important as it is often reused or discharged to receiving waters. Previous studies have shown that stormwater quality can be a major challenge for green roof designers. This section summarizes the results of previous studies that have investigated green roof water quality.

20.6.1 Green roof water quality

A green roof can act as a sink for the contaminants that occur in rainfall such as nitrogen and phosphorus species. An investigation of water quality in the outflows from green roofs was started in Germany some time ago and continued by other researchers. NO, NO_2, NO_3, NH_3, TKN, TN, and NH_4 are various forms of nitrogen which are often investigated in green roof systems. For green roofs, the PO_4 forms of total phosphorus (Tot-P) are often studied because PO_4 is the most bioavailable form. Anions, cations, and OM are examples of other commonly studied constituents, as shown in Table 20.4. The growing media of green roofs, applied fertilizers, applied water for summer irrigation, and air pollutants are the major sources of green roof pollutants.

20.6.2 Factors affecting water quality

Berndtsson et al. (2010) concluded that the factors potentially influencing green roof runoff quality can be summarized as follows:

- Type of material used (composition of soil, material of drainage and/or underlying hard roof material, pipe material);
- Soil thickness;

TABLE 20.4 Summary of the Water Quality Constituents Measured in Green Roof Outflows Across the World

Region	Country	Researcher	Nutrients	Cations	Anions	Heavy Metals	Organic Matter
Europe	Sweden	Berndtsson et al. (2006, 2008), Berndtsson et al. (2010)	NO_3, NH_4, PO_4, Tot-N, Tot-P	Cr, Fe, K, Mn		Cd, Cu, Pb, Zn	DOC
	Germany	Steusloff (1998)				Cd, Cu, Pb, Zn	
		Köhler et al. (2002)	NO_3, PO_4			Pb, Cd	
	Estonia	Teemusk and Mander (2007)	Tot-P, Tot-N, PO_4, NO_3, NH_4	Ca, Mg	SO_4		BOD, COD
North America	USA	Monterusso et al. (2004)	NO_3, Tot-P				
		Hathaway et al. (2008)	TKN, NO_3, NO_2, NH_3, Tot-N, Tot-P, and OP				
		Bliss et al. (2009)	P, Tot-N		SO_4	Pb, Zn, Cd	COD
		Alsup et al. (2010)		Cu, Fe, Mn		Cr, Ni, Pb, Zn, Cd	
		Carpenter and Kaluvakolanu (2011)	NO_2, P, TSS				
		Gregoire and Clausen (2011)	TKN, $NO_3 + NO_2$, NH_3, Tot-P, and PO_4			Cd, Cr, Pb, Zn	
	Canada	Van Seters et al. (2009)	Tot-P, PAH	Ca, Mg			
Australia	Australia	Razzaghmanesh et al. (2014a), Beecham and Razzaghmanesh (2015)	NO_3, NO_2, NH_3, PO_4	B, Ca, K, Mg, Fe	Na, Cl	Cd, Cu, Pb, Mn, Mo and Zn	

- Type of drainage;
- Maintenance/chemicals used (including fertilizers);
- Type of vegetation and seasonal growth pattern;
- Dynamics of precipitation;
- Wind direction;
- Local pollution sources; and
- Physicochemical properties of pollutants.

20.7 GREEN ROOF VEGETATION GROWTH FACTORS

20.7.1 Vegetation diversity

Green roofs often provide a harsh and stressful growing environment which only a limited range of plant species are able to tolerate. However, ecological theory suggests that highly diverse or species-rich vegetation might be more resistant and resilient to severe environmental stress (Nagase and Dunnett, 2010). To assess this hypothesis, a complex experiment was set up to investigate the influence of vegetation diversity on plant survival following an imposed drought. Twelve species were selected from the three major taxonomic plant groups commonly used for green roofs (forbs, *Sedums*, and grasses) and planted in combinations of increasing diversity and complexity, overlaid with three watering regimes. Greater survivability and higher visual rating occurred with a diverse plant mix under dry conditions (irrigated every 3 weeks). Drought tolerance in *Sedums* was superior to that of forbs and grasses, which in turn were little different to each other. It was recommended that irrigation may be unnecessary if *Sedum* species alone are used for an extensive green roof, as they can survive more than 3 weeks without watering, in UK growing conditions. However, if forbs or grasses are used, frequent irrigation is required to maintain good visual quality.

Oberndorfer et al. (2007) explained that climatic condition is also one of the major factors influencing selection of green roof plants. The nature of rainfall and extreme temperatures may restrict the use of certain species or it may necessitate the use of irrigation. Native plants are generally considered ideal choices for landscapes because of their adaptations to local climates. However, many native plants appear to be unsuitable for conventional extensive green roof systems because of the harsh environmental conditions, and typically shallow substrate depths. Local policies for biodiversity and nature conservation may affect the establishment of locally distinctive and representative plant communities. Monterusso et al. (2005) found only 4 of the original 18 native prairie perennial species remained growing in the 10 cm substrate after 3 years. In comparison, all nine nonnative species of *Sedum* thrived. In addition, Dunnett et al. (2008) reported that the most commonly used green roof vegetation is a mix of predominantly exotic (nonnative) *Sedum* (stonecrop) species that have very low maintenance requirements. The species used were generally low growing carpeting plants that were drought-resistant and capable of growing on thin substrate depths. They concluded that green roof vegetation with greater structural and species diversity may provide different benefits than *Sedum*-dominated roofs.

20.7.2 Substrates

Oberndorfer et al. (2007) argued that the depth of the substrate has a significant effect on vegetation diversity and the range of suitable species. Substrate depths between 20 and 50 mm have rapid rates of desiccation and high diurnal temperature variations. However, they can still support simple *Sedum*—moss communities. Increasing substrate depths to 70—150 mm supported a more diverse mixture of grasses, geophytes, alpines, and drought-tolerant herbaceous perennials, but these were also more vulnerable to weed invasion.

In another study by Rowe et al. (2012), the effect of green roof media depth on *Crassulacean* plant succession was investigated over 7 years in south central Michigan, USA. 25 succulents (various species of *Graptopetalum*, *Phedimus*, *Rhodiola*, and *Sedum*) were grown in three media depths (25, 50, and 75 mm). Deeper media depths generally produced greater survival rates and better coverage (Bates et al., 2013).

20.7.3 Suitable plants for Australian green roofs

Williams et al. (2010) suggested that a major barrier to the widespread uptake of green roofs in Australia, and regions with similar dry climates, is the lack of plants that can both survive and be aesthetically attractive under local climatic conditions. To survive in temperate northern hemisphere climates, green roof plants need to be adapted to heat, cold, sun, wind, and water deficit, and be tolerant to some root inundation (Snodgrass and Snodgrass, 2006). Similar criteria will apply to roofs in southern hemisphere cities, although the plants will generally not be required to tolerate freezing conditions. However, plants will often be required to have much greater tolerance to longer, and more extreme, periods of water-deficit stress. While *Sedums* are widely used in northern hemisphere green roofs, there are concerns about their suitability for southern hemisphere countries. Some *Sedum* species can switch their photosynthetic pathway from C3 to a C4 crassulacean acid metabolism (CAM) during periods of water stress (Borland and Griffiths, 1990; Castillo, 1996). This allows the plants to open their stomata at night and store carbon dioxide for subsequent photosynthesis during the day. This reduces water loss and increases water use efficiency. However, *Sedum* species have a relatively weak CAM potential (Castillo, 1996; Razzaghmanesh et al., 2014b,c) and may need relatively low temperatures, either during the day or at night, to perform CO_2 exchange when water stressed (Kluge, 1977).

In recommending suitable plants for south eastern Australian climates, Farrell et al. (2012) evaluated the effects of severe drought (113 days without water) on the growth, water use, and survival of five succulent species (*Sedum pachyphyllum*, *Sedum clavatum*, *Sedum spurium*, *Disphyma crassifolium*, and *Carpobrotus modestus*) planted in three different green roof growing media with different water-holding capacities. Water use determined survival under severe drought conditions, with the higher water use species (*D. crassifolium* and *C. modestus*) dying at least 15 days earlier than *Sedum* species, which are conservative water users. Farrell et al. (2012) found that to maximize survival, green roofs in continuous or seasonally hot and dry climates should be planted with species that have high leaf succulence and low water use, in substrates with high water-holding capacity.

In the tropical climate of Queensland, Australia, Perkins and Joyce (2010) found that the native plants *Myoporum parvifolium* (creeping myoporum) and *Eremophila debilis* (winter apple) and the exotic plant, *Sedum sexangulare* (tasteless stonecrop), displayed the greatest survival rates and coverage on an extensive green roof.

20.8 THERMAL PERFORMANCE OF GREEN ROOFS

In urban environments, vegetation has largely been replaced by dark and impervious surfaces such as asphalt, road highways, and roofs (Oberndorfer et al., 2007). This brings more serious environmental problems such as flooding and UHI effects (Carter, 2011). The UHI effect is expressed as higher urban temperatures due to the repartitioning of solar radiation into sensible heat rather than the latent heat emboded in evapotranspiration (Bacci and Maugeri, 1992). Consequently, towns and cities are significantly warmer than their surrounding suburban and rural areas, particularly at night. The UHI effect depends principally on the modification of energy balance, as well as the effect of urban canyons (Landsberg, 1981), the thermal properties of building materials (Montávez et al., 2000), the substitution of green areas with impervious surfaces that limit evapotranspiration (Takebayashi and Moriyama, 2007; Imhoff et al., 2010), and decreases in the urban albedo (Akbari and Konopacki, 2005).

Many studies have established a correlation between an increase in green areas and a reduction in local temperatures (Takebayashi and Moriyama, 2007), suggesting the augmentation of urban vegetation as a possible mitigation strategy for the UHI effect. As densely urbanized areas have few residual spaces that can be converted into green areas, one solution is to convert conventional dark, flat roofs into vegetated areas. Approximately 20%−40% of the impervious area in an urban environment is occupied by roofs (Akbari et al., 2003; Carter and Jackson, 2007; Kingsbury and Dunnett, 2008).

Increasing the fraction of vegetated surfaces in urban areas is associated with increasing albedo (Solecki et al., 2005), which is the reflection of incoming short-wave radiation away from a surface. A regional simulation model using a uniformly distributed green roof coverage of 50% showed temperature reductions as great as 2°C in some areas of Toronto, Canada (Bass et al., 2002).

20.8.1 Urban heat island effects

UHI effects have a significant impact on building energy consumption and outdoor air quality (Mirzae and Haghighat, 2010). There are several approaches to study the UHI effect, including multiscale models, empirical observations, and simulation techniques. Because of the complexity of UHI effects, multiscale modeling is not generally feasible. Instead, observations or theoretical approaches have most often been employed. However, the causes of UHI effects differ in different climates, and even with different city features. Therefore, general conclusions cannot be made based on limited empirical monitoring data. With recent progress in computational tools, simulation methods have often been used to study UHI effects.

20.8.2 Available numerical models

There are two common numerical models used for urban microclimate studies and particularly UHI investigations namely: RayMan (Matzarakis et al., 2007) and ENVI-met (Huttner and Bruse, 2009). ENVI-met is a three-dimensional non-hydrostatic model for the simulation of surface—plant—air interactions. It is often used to simulate urban environments and to assess the effects of green infrastructure on urban and built environments. It is designed for microscale applications with a typical horizontal resolution of 0.5—10 m and a typical temporal resolution of 24—48 h, with a time step of 1—5 s. This resolution enables the analysis of small-scale interactions between individual buildings, surfaces, and plants. The RayMan model estimates the radiation fluxes and the effects of clouds and solid obstacles on short-wave radiation fluxes. The model, which takes complex structures into account, is suitable for utilization and planning purposes at both the local and regional scales.

20.8.3 Green roof mitigation of urban heat island effects

Susca et al. (2011) evaluated the thermal effects of vegetation at both the urban and building scales. The UHI effect was monitored in four areas of New York City, USA, and an average temperature difference of 2°C was found between the most vegetated and the least vegetated areas. Green roofs showed a potential for decreasing the use of energy for cooling and heating and, as a consequence, reducing peak energy demands.

In another study by Alexandri and Jones (2008), a two-dimensional microscale model was used to study the thermal effects of covering the building envelope with vegetation for various climates and urban canyon geometries. The effect of temperature decreases on outdoor thermal comfort, and energy savings were investigated and it was found that plants on the building envelope can be used to ameliorate the UHI effect. From this quantitative research, it was shown that there is potential for lowering urban temperatures when the building envelope is covered with vegetation. It was also shown that air temperature decreases at roof level can be up to 26.0°C with an average daytime decrease of 12.8°C. At ground level, decreases in temperature reached up to 11.3°C maximum with an average daytime decrease of 9.1°C. Overall the hotter and drier a climate is, the greater the effect of vegetation on urban temperatures. However, it has been pointed out that humid climates can also benefit from green surfaces, especially when both walls and roofs are covered with vegetation. For example, Alexandri and Jones (2008) recorded an 8.4°C maximum temperature decrease for humid Hong Kong. Temperature decreases due to vegetation are primarily affected by the amount and geometry of the vegetation itself rather than by the building orientation in street canyons, in hot periods. If applied to the whole city scale, green roofs can mitigate increased urban temperatures and, especially for hot climates, bring temperatures down to more comfortable levels. They can also reduce energy cooling costs for buildings by 30%—100%.

Skelhorn et al. (2014) tested seven green space scenarios that might be applied at a block or neighborhood level and investigated the resulting microclimate changes that can be achieved through such applications for Manchester, a city in temperate North West England. The research employed ENVI-met to compare the changes in air and surface temperatures on a warm summer's day in July 2010. The modeling demonstrated that, even in in temperate cities, a 5% increase in mature deciduous trees can reduce mean hourly surface temperatures by 1°C over the course of a summer's day.

Perini and Magliocco (2014) investigated the effects of several variables that contribute to the UHI effect and outdoor thermal comfort in dense urban environments. The study was conducted using the three-dimensional ENVI-met model. The effects of building density (% of built area) and canyon effect (building height) on potential mean radiant temperature and Predicted Mean Vote (PMV) distribution were quantified. PMV is a method of describing thermal comfort. The influence of several types of green areas (vegetation on the ground and on roofs) on temperature mitigation and on comfort improvements was investigated for different atmospheric conditions and latitudes in a Mediterranean climate. It was found that vegetation on the ground and on roofs mitigated summer temperatures, decreased the indoor cooling load demand, and improved outdoor comfort. The results of this study also showed that vegetation is more effective in environments with higher temperatures and lower relative humidity.

Coutts et al. (2012) explained how the combination of excessive heating driven by urban development, low water availability, and future climate change impacts could threaten human health and amenity for urban dwellers. They reviewed the literature to demonstrate the potential of WSUD to help improve outdoor human thermal comfort in urban areas and support climate sensitive urban design (CSUD) objectives within the Australian context. They further argued that WSUD provides a mechanism for retaining water in the urban landscape through stormwater harvesting and reuse while also reducing urban temperatures through enhanced evapotranspiration and surface cooling. It was also shown that WSUD features are broadly capable of lowering temperatures and improving human thermal comfort and, when integrated with vegetation, have the potential to meet CSUD objectives. However, the degree of benefit (the intensity of cooling and improvements to human thermal comfort) depends on a multitude of factors including local environmental conditions, the design and placement of the systems, and the nature of the surrounding urban landscape.

The ability of two types of extensive and intensive green roofs to reduce the surrounding microclimate temperature was monitored by Razzaghmanesh et al. (2016). The results showed that green roofs have significant cooling effects in summer time and could behave as an insulation layer to keep buildings warmer in the winter. Furthermore, different scenarios of adding green roofs to the Adelaide urban environment were investigated using the ENVI-met model. The scenario modeling of adding green roofs in a typical urban area supported the hypothesis that this can lead to reductions in energy consumption in the Adelaide urban environment. In addition, an increased use of other WSUD technologies, such as green walls and street trees, together with the adoption of high-albedo materials is recommended for achieving the optimum efficiency in terms of reducing urban temperatures and mitigating UHI effects.

20.9 CONCLUSION

Green roofs and living walls are increasingly important components of WSUD systems and have become widely used around the world in recent years. Green roofs can cover current impermeable roofs that densely populate our urban areas and by so doing, can provide many environmental, economic, and social benefits. Despite such benefits, green roofs are relatively new in regions with a dry climate, and there are several research gaps and practical barriers to overcome before these systems can be applied more widely. Furthermore, specific design criteria need to be developed for both green roofs and living walls for a range of weather conditions to develop climate-resilient systems. Improving water quality is one of the objectives of WSUD. However, some WSUD components, including green roofs and living walls, might indeed act as pollutant sources particularly during the early years of plant establishment. Nitrogen, phosphorus, potassium, chloride, and heavy metals have all been detected in both green roof and living wall outflow samples collected in several studies. These are believed to be largely sourced from applied fertilizers, the growing media components, or irrigation water application. Even so, pollutant concentrations in the outflow from green roofs and living walls are normally within the recommended ranges for nonpotable reuse such as toilet flushing and urban irrigation, but are seldom within the guideline ranges for potable consumption. Some of the environmental and social benefits of green roofs and living walls derive from the selection of aesthetically pleasing plants.

In the design of green roof systems in a dry climate, the size of the plants, the combinations of green roof layers, and the time of planting should all be taken into consideration. Stormwater quantity control is another main objective of WSUD. Regardless of the configuration, both extensive and intensive roof profiles can retain significant volumes of stormwater runoff. The peak attenuation of the recorded events is usually in the range of 15%−100%. This indicates that green roofs can, if designed appropriately, serve as effective source control structures. Intensive green roofs have generally displayed more capacity for retaining water, which is important in dry climates where the retained water may reduce the need for supplementary irrigation.

Both green roofs and living walls are able to mitigate the UHI phenomenon. In various macroscale studies, the addition of green roof areas reduced electricity consumption. This is a very important strategy with respect to developing low carbon, resilient, and livable cities. A longitudinal study over a 5−10-year period would be ideal for examining the changing performance over time of green roofs and living walls. In addition to better understand plant growth mechanisms, further investigations using monoculture plantings might provide important information to understand individual plant water requirements, water use efficiencies, evapotranspiration rates, and cooling potential.

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