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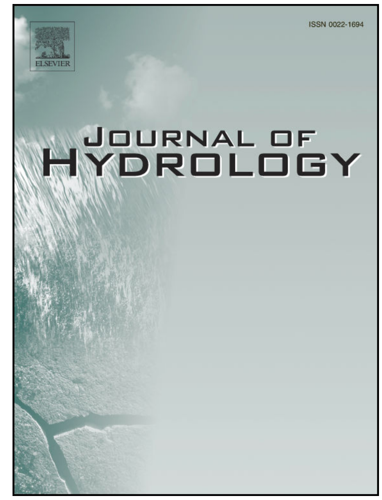

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Urban greening and water strategies are key to adapt Australian cities to climate change and urban growth

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Abstract

Urban greening is increasingly recognized as a key strategy for climate adaptation in cities, particularly in regions with variable climates. This paper explores how Australian cities are pioneering strategies that integrate urban greening with water-sensitive urban design (WSUD), offering valuable lessons for other areas facing similar challenges. Drawing on examples from diverse climate zones, from Darwin's tropics to Melbourne's temperate and Perth's Mediterranean conditions, we analyse how local climate and water availability shape greening strategies and WSUD implementation. The study evaluates technologies such as bioretention basins, tree pits, green roofs, and vertical greening, highlighting successes, limitations, and locally adapted solutions. Key challenges include mismatches between water supply and demand, high maintenance requirements, and the need for community engagement. By reviewing modelling tools and metrics used in Australia to assess the benefits of urban greening, we assess their applicability and limitations. The paper offers valuable lessons from the Australian experience for other regions facing similar climate and water challenges, emphasising that integrating water management is essential for the long-term success of urban greening in building climate-resilient cities.

Highlights

- Strategic urban greening requires climate-specific approaches.
- Water Sensitive Urban Design (WSUD) technologies provide innovative ways to recycle water sources for urban irrigation.
- Effective urban greening requires technology, social insights, and community engagement.

1. Introduction

Greening cities is a global imperative of the 21st century to adapt urban environments to the realities of climate change. As cities worldwide face rapid urbanization (Seto & Shepherd, 2009) and increasing climate variability (Manoli et al., 2019; Xiao et al., 2007), the need for sustainable and resilient urban greening has become increasingly urgent. Urban greenery – such as street trees, lawns and parks, urban forests, green roofs and green wall façades – forms part of broader green infrastructure, which refers to strategically planned networks of natural and semi-natural spaces that deliver ecosystem services and enhance urban resilience. These elements play a crucial role in mitigating various urban environmental challenges (Marchionni et al., 2019). They enhance local thermal comfort (Probst et al., 2022; Zhao et al., 2022), help reduce stormwater runoff (Z. Zhang et al., 2021), improve air quality, and support biodiversity, offering a comprehensive strategy to address the impacts of urbanization and climate change (Marchionni et al., 2019; Yenneti et al., 2020).

However, the effectiveness of these greening efforts is significantly impacted by varying climatic conditions and water availability, which pose substantial challenges to their implementation and long-term sustainability. To address these challenges, securing urban water supplies and utilizing alternative non-potable water sources become critical (Drake et al., 2018; Marchionni et al., 2020). Integrated Urban Water Management (IUWM) and Water Sensitive Urban Design (WSUD) offer essential strategies for this purpose. Specifically, IUWM integrates water management practices to ensure the efficient use and reuse of water resources, while WSUD focuses on mitigating urban runoff impacts on waterways and coastal areas by restoring pre-development flow patterns (Coutts et al., 2013; Fletcher et al., 2013; Livesley et al., 2021; Wiegels et al., 2021).

Tailoring urban greening and WSUD initiatives to cities worldwide is a complex task that requires adapting strategies to suit the unique environmental, climatic, and socio-economic conditions of each location. Cities vary widely in their water availability, vulnerability to flooding, and exposure to heat stress, requiring tailored approaches to urban planning, water management, and greening. For example, arid cities like Phoenix, Arizona and Los Angeles, California focus on drought-resistant vegetation and water-saving strategies to thrive given limited water resources (Vahmani & Ban-Weiss, 2016). In contrast, tropical cities such as Singapore require infrastructure and green spaces designed to manage heavy rainfall and high humidity, reducing flood risks and improving thermal comfort (Lim & Lu, 2016). Beyond climate, socio-economic factors such as available resources, governance structures, legislation, and community priorities also play a crucial role in determining the feasibility and success of these initiatives. Furthermore, the cultural and ecological values of each city shape public perception and support for urban greening and water management projects. Therefore, implementing effective urban greening and WSUD initiatives involves not only technical planning but also an understanding of local needs, challenges, and opportunities.

In Australia, where 86% of the population lives in urban areas, major cities have distinct characteristics shaped by their geography, climate, and growth patterns. Although less densely populated than cities in the USA or Europe, Australia's urban areas are expanding rapidly, leading to increased urban density and sprawl. For instance, Melbourne, Australia's largest urban area in size, covers a similar area to London and Paris but houses less than half their population. Sydney, the densest city, has a population comparable to Barcelona but spans nearly four times the area. Brisbane is a similar size to Milan, with half the population. Australia's major cities experience diverse climatic conditions, from the tropical conditions of Darwin to the subtropical climate of Brisbane, and the more temperate regions of the southern cities. These diverse climates generate specific challenges in managing vegetation and water resources, and influence how cities address the impacts of extreme weather events. Australia's climatic variability is extreme by global standards (Beringer et al., 2022), and as the climate warms further, more heatwaves, long-lasting droughts, floods, and wildfires are expected (Intergovernmental Panel On Climate Change (IPCC), 2023).

In response, Australian cities have led the way in developing innovative strategies to create greener, more water-sensitive urban environments (Australian Conservation Foundation, 2021; Greening Australia, 2023; Hurley et al., 2020). Councils across Melbourne's metropolitan area have set ambitious goals to increase canopy cover to 40% by 2040 (Bayside City Council, 2022; City of Melbourne, 2012; Greening the West Steering Committee, 2020), while implementing various WSUD initiatives, such as Melbourne Water's 2008 program, which aimed to build 10,000 rain gardens by 2013 (City of Port Philip, 2009). Similarly, Greater Sydney aims to achieve a 40% increase in urban tree canopy cover by 2036 (NSW Dept of Planning and Environment, 2023), while implementing initiatives such as "Green Grid", a strategic framework designed to connect the city's green spaces, waterways, and natural landscapes. Adelaide is developing its first Urban Greening Strategy, which leverages cross-sector resources to protect mature trees, green spaces, and urban biodiversity, with the goal of creating a cooler, greener, and more climate-resilient city (Government of South Australia, 2023). In Perth, efforts to increase canopy cover in public areas from 19% to 30% over 30 years are complemented by WSUD initiatives that help managing stormwater during intense, short-duration rainfall events while addressing long periods of drought, also leading to the recharge of shallow aquifers (Bekele et al., 2018; CSIRO, n.d.; Page et al., 2018).

These Australian initiatives align with large-scale investments taking place worldwide. Examples include "one million trees" initiatives in New York City (Rae et al., 2011), London (Gulyani et al., 2018), and Los Angeles (McPherson et al., 2011) and 10,000 Rain Gardens programs in the US and Europe (Green Action Trust, 2024; Riggs, 2008; Stewardship Partners, 2024). Additionally, "sponge-city" efforts have been implemented in multiple cities in China (Hamidi et al., 2021), with similar projects also emerging in European cities (i.e., Sustainable Drainage Systems; SuDS) such as Rotterdam, Copenhagen, and Milan. Satellite observations from 3,037 global cities reveal a greening trend over a 35-year period, driven by tree planting programs and urban warming-enhanced vegetation growth (Wu et al., 2024). Australian cities showed significant increases in greenery between 2001 and 2020, largely due to initiatives like Melbourne's Urban Forest Strategy and Brisbane's 'Greener Suburbs' program. However, greening cities puts additional pressure on urban water resources. It introduces an uneasy tension between increasing green spaces and managing demand for limited water resources required to establish and maintain the city's greenness, especially in drier climates. Managing this tension requires improved understanding of the water demand from urban vegetation, which remains challenging to measure. To address this challenge, long-term urban plans and policies should shift from reactive (mis)management to proactive resilience-building, ensuring that green space expansion is balanced with sustainable water use (Nouri et al., 2019).

This paper aims to advance our understanding of urban greening and WSUD as adaptation measures for environmental changes driven by urbanization and climate change. Through a comprehensive analysis of major Australian cities – which are at the forefront of creating sustainable, climate-adaptive urban landscapes – we examine how varying bioclimatic conditions influence the implementation and effectiveness of integrated urban greening and water management strategies. The Millennium Drought (2001-2009) in Southeast Australia served as a critical catalyst for innovation, forcing cities like Melbourne to develop pioneering approaches to both increase water supply and reduce demand – experiences that have profoundly shaped current urban water management practices (Low et al., 2015). By contextualizing Australian practices within the global urban greening landscape, this work offers valuable insights into best practices and lessons learned that can benefit other regions facing similar challenges in creating water-sensitive, climate-adaptive cities.

The paper makes several key contributions. First, it presents a review of current urban greening and WSUD practices across major Australian cities, examining how they integrate water-sensitive strategies to ensure sustainable and resilient green infrastructure. Second, it identifies and proposes innovative solutions to overcome water management barriers, particularly focusing on advances in rainwater harvesting, stormwater reuse, and irrigation systems that emerged in response to severe drought conditions. Third, it highlights the importance of advanced modelling approaches to effectively evaluate the urban cooling benefits of green infrastructure.

2. Processes and interactions between climate, vegetation, and water in urban environments

2.1 Climate and biophysical characteristics of Australian cities

Rapidly expanding Australian cities are shaped by diverse environmental and climatic factors, reflecting the country's broad geographical range (Figure 1). In the northern regions, cities like Darwin (Figure 1b) and Cairns (Figure 1c) experience a tropical climate with high temperatures and humidity year-round, leading to intense heat and rainfall over 1000 mm during the wet season. Moving south, cities such as Sydney (Figure 1h) and Brisbane (Figure 1d) have subtropical climates, marked by hot, humid summers and mild winters. Further south, cities like Melbourne (Figure 1g) face a temperate climate with significant seasonal variation, including warm summers and cool, wet winters. Perth, on the western coast (Figure 1a), and Adelaide (Figure 1e) have a Mediterranean climate with hot, dry summers and mild, wet winters. Although Perth receives more rainfall than Melbourne - long-term (1993-2023) average rainfall of 732 mm and 568 mm, respectively - the majority falls during winter when potential evapotranspiration is lower, heightening water scarcity risks during the dry months. In contrast, interior cities like Alice Springs face arid conditions, with extreme temperature fluctuations between hot days and cold nights and minimal rainfall throughout the year (Figure 1f). These diverse climatic conditions greatly affect vegetation suitability and water availability (Gill, 2011).

The physical characteristics of urban environments, including building materials, vegetation cover, and urban layout, interact with the climate, influencing the urban heat island (UHI) intensities (K. Nice, 2021; Trlica et al., 2017; Z. Zhang et al., 2022), reducing evapotranspiration (Litvak et al., 2017; Nouri et al., 2020; Voter & Loheide, 2021; Zipper et al., 2017), and increasing pressure on vegetation and water resources (Hill et al., 2021). For instance, in Sydney, urban heat intensifies with increasing distance from the coastline, resulting in a higher average UHI intensity compared to other Australian cities (Yenneti et al., 2020). Perth and Adelaide experience more pronounced night-time UHI due to the release of stored heat from buildings and the ground, while Darwin sees higher daytime UHI, driven by reduced evaporative cooling (Haddad et al., 2020). Water availability, another crucial aspect of urban biophysics, is influenced by rainfall variability and evapotranspiration rates, impacting vegetation growth and the effectiveness of WSUD initiatives. This is especially critical in cities where limited water availability constrains evapotranspiration and heightens the need for effective water management strategies (Voter & Loheide, 2021). Cities like Perth and Adelaide rely on stormwater management and aquifer recharge systems to address water scarcity during the dry months. In these settings, aridity - the ratio of potential evapotranspiration and rainfall - can be used as an indicator of the performance of greening and WSUD interventions, encapsulating the water and energy limiting nature of the prevailing climate, which ultimately influence retention and cooling outcomes (Cuthbert et al., 2022). However, in Mediterranean climates, where water is limited in summer, changes in the seasonality of precipitation influence evaporative demand, and annual aridity metrics often poorly capture this variability (Collignan et al., 2023).

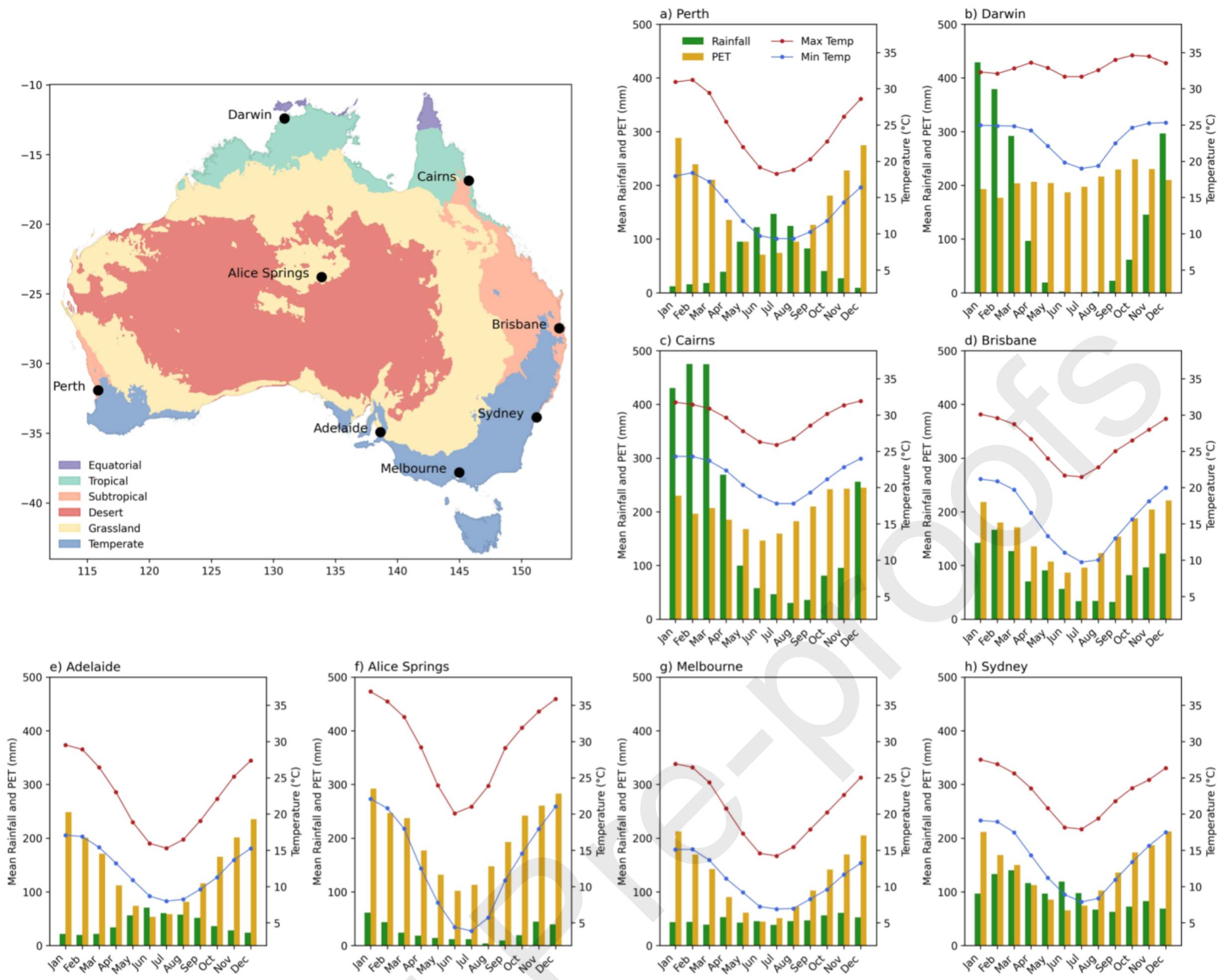

Figure 1. Climate classification for Australia with major cities. Long-term (1993-2023) monthly averages of rainfall, potential evapotranspiration (PET) and temperature (max and min) for a) Perth, b) Darwin, c) Cairns, d) Brisbane, e) Adelaide, f) Alice Springs, g) Melbourne, and h) Sydney (sources: Australian Bureau of Meteorology; Australian Water Outlook: www.awo.bom.gov.au).

2.2 Water use by urban vegetation and its effect on local climate

Water is essential to the health, growth, and cooling capacity of urban vegetation. Through processes such as evapotranspiration and shading, plants moderate urban temperatures, improve microclimatic conditions, and provide essential ecosystem services. Vegetation also plays a role in stormwater management by intercepting and storing rainwater (Carlyle-Moses et al., 2020), particularly during low-intensity events (Rahman et al., 2023), and by reducing surface runoff volumes (Berghuijs et al., 2016; Saadi et al., 2020). However, the benefits of urban greening are often constrained by challenges such as limited water, impervious surfaces, and compacted or shallow soils (Calfapietra et al., 2015; Hatfield & Dold, 2019; Sieghardt et al., 2005). These constraints can inhibit plant establishment and longevity, particularly during periods of drought or high heat stress. Climate change further exacerbates these pressures, with recent studies suggesting that up to 76% of tree species currently planted in cities may be vulnerable to future climate conditions (Esperon-Rodriguez et al., 2022). In response, urban forestry programs are increasingly prioritizing the selection of drought- and heat-tolerant species (Hanley et al., 2021).

Understanding plants' water use, or the combined water use of a green space (Costello & Jones, 2014) is essential for the effective planning, establishment, and maintenance of urban vegetation. This is particularly important in regions where irrigation is required to maintain plant health (Cuthbert et al., 2022; Tan et al., 2020). Strategic planting, appropriate species selection, and water-efficient irrigation practices are all key to supporting urban vegetation, especially in hotter, drier climates (Farrell et al., 2022). Choosing between drought-tolerant species (that can survive extended dry periods) and drought-avoiders (that minimize water loss through specific physiological strategies) can further enhance urban greening success and sustainability in varying climatic conditions (Chen et al., 2022; Tabassum et al., 2021). For this purpose, plant selection tools, such as the Australian *Which Plant Where* (2023), offer valuable guidance by helping identify plant species suited to specific climate and site conditions.

Different urban greening initiatives have distinct impacts on local climate (Brown et al., 2015). For example, irrigated turf lowered daytime mean air temperatures by 0.6°C and surface temperatures by 2.3°C in Melbourne's summer (Cheung et al., 2022). Street trees, especially when well-watered, are highly effective in reducing urban heat through both shading and evapotranspiration, with up to 30% of the cooling effect attributed to the latter (Tan et al., 2018). In Melbourne's urban canyons, tree-lined streets can be 1.5°C cooler than those without (Coutts et al., 2016). Other greening strategies, such as vertical greening systems and green roofs, also contribute to cooling, with green façades reducing wall surface temperatures by up to 7°C on hot days (Bakhshoodeh et al., 2022), and green roofs lowering peak ambient temperatures through latent heat loss, particularly when vegetated with high leaf area index species and irrigated during dry periods (Santamouris, 2014).

Yet, water stress remains a persistent challenge for urban vegetation, driven by factors such as compacted soils, limited soil water availability and restricted rooting volumes. Prolonged periods of water deficit can reduce photosynthesis, increase vulnerability to pests and diseases, and ultimately diminish vegetation health and survival (Meineke & Frank, 2018). This deterioration compromises not only the aesthetic and ecological values of urban greenery but also its capacity to provide cooling benefits. In response, supplementary irrigation has become vital to support plant growth and performance in urban environments.

Irrigation systems, especially those using alternative water sources such as greywater and stormwater, are increasingly valued for supporting vegetation health while enhancing urban water sustainability by removing nutrient pollutants and reducing runoff volumes (Prodanovic et al., 2020; Schütt et al., 2022; Sami et al., 2023). Among these solutions, passively irrigated systems, including raingardens, stormwater tranches and tree pits, are attracting interest for their ability to harvest and store urban runoff without relying on active water supply networks. Directing stormwater into tree pits has been shown to significantly enhance plant growth and transpiration, which in turn supports cooling and runoff mitigation (Thom et al., 2022). However, waterlogging might affect tree performance, making adequate drainage through permeable soils or underdrain systems essential for effective functioning (Grey et al., 2018a).

2.3 Plant responses to climate change

A hotter and drier environment will trigger a range of changes in the urban microclimate and in plant physiology, with results that can be either harmful or beneficial to plants. Higher air temperatures and drier conditions (i.e., less rainfall or longer periods between rainfall events) decrease the relative humidity of the air and increase leaf temperature. These conditions increase vapour pressure deficit (VPD), leading to higher evaporation and plant transpiration rates (Grossiord et al., 2020). Without sufficient plant available water, leaves can become dehydrated, increasing the risk of xylem embolism. Plants may respond to increased VPD by closing stomata when water is limited, which can cause leaf temperatures to rise on warm, sunny days (Jones et al., 2002). A significant increase in leaf temperature can cause tissue damage or even plant death. Conversely, when plant-available water is sufficient, some plants keep stomata open to prevent critical overheating. These strategies and limits on stomatal closure vary among species.

Two primary strategies can enhance plant growth and survival in warming urban environments. The first strategy is to select heat-adapted species to create more resilient urban canopies. A study by Marchin et al. (2022) demonstrated this potential, by exposing 20 Australian tree and shrub species to heatwave conditions for 7 days, with average temperatures of 35°C and daily maxima of 42°C. Heat tolerances across these species ranged from -2.5°C to +12.5°C, showcasing a substantial 15°C range. This diversity in heat tolerance underscores the importance of careful species selection for urban environments to proactively address future heatwaves and warming conditions. The second strategy addresses the critical interplay between drought and thermal stress. When plants experienced both drought conditions and heatwaves, the average heat tolerance of the 20 tested species dropped by about 5 °C, underscoring the pivotal role of water availability in plant resilience (Smith & Boers, 2023). With sufficient water, these plants could withstand heatwaves approximately 5 °C hotter than under drought conditions, highlighting the importance of transpiration in cooling leaves and avoiding catastrophic hydraulic failure or carbon starvation caused by extreme leaf temperatures and water stress. Because many tree species rely on stored soil water from winter precipitation to withstand midsummer drought (Allen et al., 2019), ensuring that urban vegetation has access to rainfall, i.e., through exposed soil, passive irrigation, or other water-sensitive design, is essential for sustaining plant function and survival during extreme heat.

3. Integrating urban water management in green spaces across scales

Combining greening and water management in an urban context is beneficial to address urban and climatic challenges at a range of scales, from building to precinct scale. However, spatial scale can heavily influence the extent of their environmental benefits, requiring integrated planning and analysis of their cumulative impacts (Pataki et al., 2021). WSUD technologies offer diverse solutions to these challenges, by integrating vegetation with water management systems to create multifunctional blue-green infrastructure. These approaches range from localized interventions like bioretention basins and green roofs to comprehensive precinct-scale implementations, each contributing to urban resilience while managing stormwater and supporting urban vegetation. This section examines the various WSUD technologies, their applications across different scales, and the practical considerations that influence their effectiveness in urban environments.

3.1 WSUD Technologies for Urban Greening and Water Management

WSUD technologies refers to the system-level approach used to mitigate stormwater runoff impacts or manage urban water and are also referred to as 'best management practices' or 'stormwater control measures' (Fletcher et al., 2015). These technologies focus on managing urban runoff and recycled wastewater (capture, infiltrate, treat, store, reuse; Figure 2), however due to their multifunctional nature they are often coupled with vegetation, forming blue-green systems (e.g., bioretention, street tree pits, green roofs, etc.). This coupling allows urban greening to be embedded within WSUD technologies and potentially utilize diverse water sources (stormwater, greywater, wastewater, groundwater) for irrigation and to support typical WSUD operation or larger-scale urban greening (e.g., sports fields, golf courses).

Many WSUD technologies exist which can be used both for urban greening and water management. Here, we describe some of the most common technologies used in Australia that explicitly integrate vegetation as a core component. While other widely adopted approaches, such as rainwater tanks or permeable pavements also support urban greening and water management, they are not included here because they do not incorporate vegetation at the system level. The technologies we will discuss are: bioretention basins, street tree pits, green roofs, and vertical greening systems (i.e., green façades and living walls). These diverse technologies also provide opportunities for managing urban water at different scales and locations with the urban form.

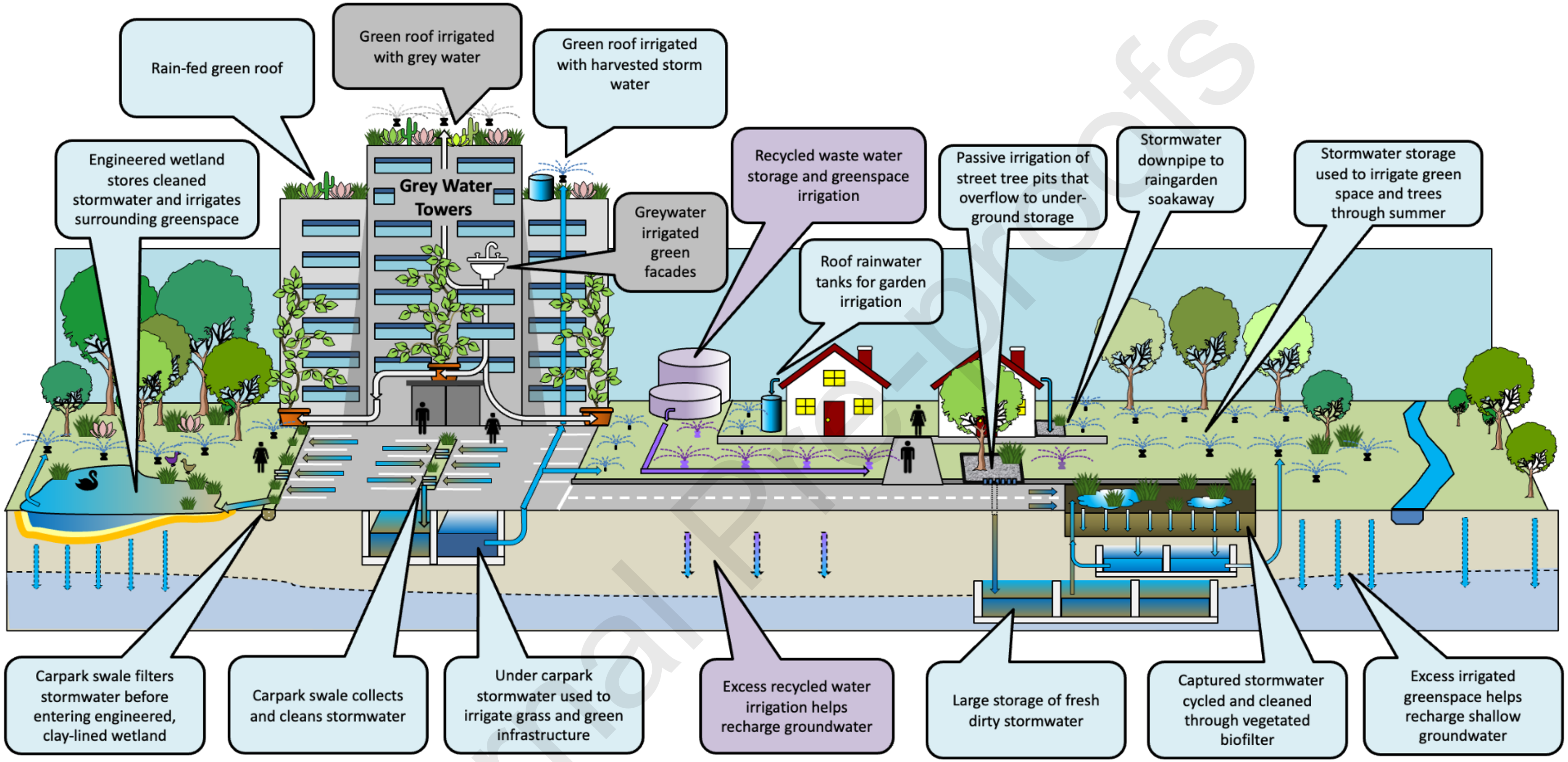

Figure 2. Conceptual diagram of urban greening and WSUD implementation supporting integrated urban water management. This diagram represents an ideal scenario of adopting these practices. Source: Created by the authors.

Figure 3. Urban green spaces at the WSUD technology scale. (a) Bioretention basin in Edinburgh Gardens, Melbourne: the system treats up to 24 ML of runoff per year, supplementing irrigation of sports ovals in the park; (b) Curved green wall project at Adelaide Zoo in South Australia: this vertical greening system is irrigated with harvested stormwater and excess water drains into a bioswale (Water Sensitive SA, 2015); (c) Street tree pit in Melbourne with passively irrigated trees; (d) Green roof in Minifie Park Early Childhood Centre, Melbourne. The green roof was planted to enhance biodiversity. Photo credit: University of Melbourne. All photos were taken by authors or credited to owner with expressed permission for use.

Bioretention basins. Also called rain gardens or biofilters (Figure 3a), these vegetated treatment systems are designed to treat stormwater runoff using filtration and plant and microbial processes (e.g., Bratieres et al., 2008; J. Li & Davis, 2016; Morse et al., 2018; Payne et al., 2014). As the name suggests, bioretention systems can permanently retain, rather than temporarily detain, stormwater runoff 'on site' by exfiltration or evapotranspiration (Bonneau et al., 2018; Hamel et al., 2013), but whether and how infiltration processes contribute to restoring natural catchment hydrology is an ongoing topic of research (Fletcher et al., 2021; Western et al., 2021). Bioretention basins can be used solely to treat and retain storm events, but they can also be used as part of a treatment train for stormwater harvesting to irrigate green spaces, for toilet flushing, or to recharge local groundwater (Hamel et al., 2013). Despite the reported inconsistency of fecal indicator bacteria and reference pathogens removal that meets water recycling standards (e.g., Chandrasena et al., 2016), these systems are used in several harvesting schemes in Australia at a variety of scales (Philp et al., 2008). For example, a 700 m^2 bioretention basin in Edinburgh Gardens (Melbourne, Figure 3a) treats up to 24 million litres of runoff per year, which is stored in an underground storage tank to irrigate the green spaces in the park (Hartmann, 2021).

Removal of emerging contaminants, such as trace organic compounds and microplastics, has been a recent area of investigation in bioretention systems. Biochar used as a filter media amendment improved the removal of trace organics (Ulrich et al., 2017; Rodgers et al., 2024), but not microplastics (Struzak et al., 2024). However, microplastics are generally well removed by bioretention systems (Smyth et al., 2024).

Vertical greening systems. Green walls and green façades (Figure 3b) are either directly planted into substrates or use climbing plants to cover vertical surfaces in the built environment. Both types of vertical greening systems have been shown to provide benefits in terms of habitat for biodiversity (Mayrand et al., 2018), improving local air quality (Perini & Roccotiello, 2018) treating greywater (Fowdar et al., 2017; Prodanovic et al., 2019), and heating and cooling of buildings (Coma et al., 2017). The cooling benefits of green walls are largely due to shading of walls and not through transpiration cooling (Hoelscher et al., 2016). Due to their vertical orientation and limited soil volumes, these systems provide limited opportunities for rainfall interception and retention, unless climbing plants are incorporated into a ground-level bioretention basin (e.g., Tiwary et al., 2018). Typical green wall systems utilize potable water, mixed with nutrients for irrigation, however the high water needs of vertical greening systems (Hoelscher et al., 2016; Pérez-Urrestarazu, 2021) are a major concern in dry regions (such as Australia). In recent years multiple water sources have been used to irrigate these technologies, including harvested stormwater (e.g., Adelaide Zoo curved green wall project, Figure 3b) and greywater. Stormwater harvested from building rooftops and stored in cisterns has been used to irrigate living walls (Kew et al., 2014), however irregularity of supply and space for water storage can be a hindrance, especially where buildings are established and there is limited space at ground level. Recent research demonstrates the potential of irrigating vertical greening systems with greywater, which can provide a consistent irrigation and replace the need for fertilizers (Addo-Bankas et al., 2021; Chung et al., 2021; Fowdar et al., 2017; Pradhan et al., 2019; Prodanovic et al., 2018, 2019, 2020; Sami et al., 2023) and even shows promise for long-term removal of organic compounds in greywater (Abd-ur-Rehman et al., 2025).

Street tree pits (Figure 3c). Passively irrigating the urban forest with stormwater can restore evapotranspiration as a key hydrological process post-development (Berland et al., 2017; V. R. Stovin et al., 2008; Thom et al., 2020). This approach can increase tree growth rates and mitigate drought stress (Grey et al., 2018a; Thom, Fletcher, et al., 2022), though these benefits may be limited to the first two years of establishment (Thom, Fletcher, et al., 2022). Mature trees may not respond if they are already accessing sufficient soil moisture (Szota et al., 2019). Effective streetscape design for stormwater infiltration requires simple inlets, large storage, and drainage for areas with poor exfiltration rates (Figure 3c) (Grey et al., 2018a, 2018b; Scharenbroch et al., 2016; Tu et al., 2020). Tree species differ substantially in water use strategies and drought response, regardless of size (Caplan et al., 2019; Hanley et al., 2023; Scharenbroch et al., 2016; Szota et al., 2018; Thom, Livesley, et al., 2022). Street trees have the potential to remove nutrients from stormwater (Denman et al., 2016). However, where street trees may have the potential to contribute nutrients via litter decomposition, the selection of tree species is particularly important (Hobbie et al., 2014).

Green roofs. Green roofs (Figure 3d) can be a highly effective tool to mitigate stormwater runoff as they retain rainfall from 100% of their catchment and do not compete with ground-level development for space. Annual rainfall retention ranges between 5-80% globally (Carson et al., 2013; Cipolla et al., 2016; Elliott et al., 2016; Y. Li & Babcock, 2013; Locatelli et al., 2014; Mentens et al., 2006; Sims et al., 2016; V. Stovin et al., 2015; Voyde et al., 2010), with greater retention from deeper green roofs and for green roofs in hotter and drier climates. For example, annual rainfall retention for 100 mm deep green roofs in Melbourne (Figure 3d) is approximately 73% (Razzaghmanesh & Beecham, 2014; Z. Zhang et al., 2018). Evapotranspiration dries green roof substrates post-rainfall, suggesting that plant selection is important for retention. However, in climates with small rain event sizes (< 2 mm) and long dry periods, there is consistently high retention of rainfall (Szota et al., 2017). Consequently, species choice (Z. Zhang et al., 2019) and planting density (Soni et al., 2023) do not impact retention or evapotranspiration in these types of climates. Instead, substrate depth impacts retention in these hotter and drier climates (Z. Zhang et al., 2019), which is consistent with cooler climates While increasing substrate depth could also increase retention through promoting the survival of plants with lower drought tolerance, which can have greater evapotranspiration (Farrell et al., 2013; Guo et al., 2021), only one study shows that the relationship between substrate depth and evapotranspiration is not linear (Soni et al., 2022). Irrigating green roofs with captured runoff or greywater has not been explored in Australia to the same extent as in other regions (Van Mechelen et al., 2015). In general, green roofs are more common in North America and Europe than in Australia, but recent efforts in Victoria indicate support for increasing both green roofs and vertical greening systems (Reece & Oke, 2019).

Additional WSUD technologies exist at various scales and degrees of contribution to urban greening (e.g., constructed wetlands, bioretention ponds, etc.). Many of these technologies can be integrated into treatment trains or utilize a variety of water sources to offset potable demand or provide opportunities for greening larger spaces at the precinct scale. Additionally, using real-time monitoring and control of WSUD features as a management strategy (e.g., smart stormwater systems) may improve stormwater harvesting in cities (Kerkez et al., 2016), but this approach to water management apparently has mixed results with respect to enhancing water supply in drought-prone areas, with one showing no significant impact on water supply (Parker et al., 2021) and another showing increased offsets of demand by augmenting non-potable supply (Zhen et al., 2023). The use of real-time control to mitigate urban heat and plant drought stress has not been widely studied but may be a potential benefit to this management strategy.

3.2 Scaling WSUD: From Local Applications to Precinct-Level Integration

In south-eastern Australia, the Millennium Drought - a decade of below average rainfall leading to increased water restrictions - has led to rapid transition to integrated urban water management and an uptake in both recycled wastewater and stormwater harvesting projects. These systems can vary greatly in spatial scale, from single-home systems, to neighbourhood parks, up to metropolitan regions (Furlong et al., 2017).

The City of Melbourne has been a strong advocate for increasing greening and applying best practice sustainable water management practices in the urban landscape, in particular including stormwater harvesting as a climate-sensitive and drought-proofing strategy to support urban vegetation. Stormwater harvesting, storage and reuse systems mainly provide alternative water for irrigating urban green spaces. The iconic Fitzroy Gardens has the largest stormwater harvesting system in the City of Melbourne providing almost 70,000 m^3 annually stored and cycled through subterranean concrete tanks to reduce potable water use in these gardens by 59%.

As rainwater collection and sewage recycling systems become more readily available as part of the water sensitive urban design in old and new residential development in Australia and other parts of the world (Cook et al., 2019), they can provide a sustainable source of water to support active irrigation for urban cooling in private green spaces. For example, Aquarevo is an urban residential development located 42 km south east of central Melbourne (CRC for Water Sensitive Cities, 2017). Each of the 462 houses in the estate is equipped with a 1000-L pressure sewer storage pod to store their sewage, which will then be transferred to an on-site treatment facility. The facility will treat the sewage to provide Class A recycled water for non-potable uses such as public and private green space irrigation and toilet flushing. This type of estate-wide adoption of integrated water cycle management provides an opportunity to strategically store and irrigate public and private green space for timed and targeted urban cooling during high temperature events and at the neighbourhood scale.

In Adelaide, South Australia, the city, state government and water authority have established a climate-proof and climate-sensitive irrigation system throughout the 700 hectares of parkland surrounding the Adelaide city centre. This parkland is dominated by recreational turfgrass areas, but also contains remnant and planted native and exotic vegetation, and it is estimated that 70% of that water applied is taken up and transpired by that urban vegetation (Nouri et al., 2019). The cooling benefits are obvious but hard to quantify, whereas the health and vitality of these inner urban parks is undeniable. Supporting an irrigation system through recycled sewage wastewater means as long as sewage continues to be produced, and the climate remains sunny, warm and dry, then this water supply will always have an end-user, a demand and a purpose.

3.3 Challenges and Limitations of WSUD and Urban Green Spaces

Urban water security is affected by water resources management and climatic factors, and both must be considered when developing urban greening policies (Hoekstra et al., 2018). Extreme temperatures influence plant evapotranspiration and health, with water needs varying widely across plant species and types of green infrastructure. While alternative water sources – such as stormwater, greywater, and treated wastewater – can help meet irrigation demands, most cities lack the high-density distribution networks needed to supply them effectively. Moreover, for increased evapotranspiration to deliver cooling benefits, WSUD and urban green spaces must be strategically located to address local heat vulnerabilities and urban geometry (Cuthbert et al., 2022; Norton et al., 2015; Santamouris & Osmond, 2020; Shaamala et al. 2024).

Matching water availability to plant water requirements is an additional challenge. Seasonal and interannual variability in rainfall often means that peak irrigation demand occurs when water is least available, necessitating storage solutions. These can raise capital and operational costs, while uncertainties in stormwater volume and quality further complicate WSUD spatial planning (Bach et al., 2020; Prodanovic et al., 2022). Compounding this, heat waves and droughts frequently co-occur, diminishing the cooling capacity of vegetation if irrigation cannot be sustained.

Although urban trees are often promoted as a primary strategy for reducing urban heat stress, their cooling performance varies significantly across climates, tree species, and urban forms. In some contexts, dense tree canopies can increase nighttime temperatures by trapping heat, potentially intensifying heat stress for residents during extreme events (Li et al., 2024). In arid regions, the high-water demand of many tree species can make it difficult to maintain their cooling benefits, even with WSUD systems in place. Non-vegetated alternatives - such as shade structures or high-albedo surfaces - could provide complementary or substitute cooling in such settings.

Decentralized WSUD approaches that use alternative water sources at or near the point of generation, (e.g., bioretention basins for dual-mode stormwater and greywater treatment) can reduce the need for energy-intensive pumping from centralized storage or wastewater treatment plants (Zhang et al., 2021). However, by ponding stormwater runoff on the surface, such as in bioretention systems, public exposure to a range of contaminants may be increased as compared to runoff that is conveyed into the stormwater drainage network. Faecal indicator bacteria can well bioretention systems during wetter seasons when there is more runoff (Chandrasena et al., 2014), and cyanobacterial blooms in wetlands can compromize the safety of stored water for irrigation, which can potentially aerosolise neurotoxins associated with algal growth (Plaas and Paerl, 2020).

WSUD systems can have significant drawbacks, as well. For instance, many types of vertical greening systems are costly with pay back periods that exceed their service life (Perini and Rosasco, 2013). Moreover, these systems are most often constructed on private property, where their designs are more difficult to standardize, leading to uncertainty in whether they can achieve the stated benefits. These issues are not unique to vertical greening systems. Most WSUD systems can be a challenge for councils to operate due to their highly distributed nature and requirement of specialist knowledge to inspect and maintain. Additionally, the costs and the engineering for stable green roofs are a major concern with regards to balancing structural safety, cost and environmental benefits. Poorly maintaining WSUD systems can diminish their ecological and cooling benefits and raise safety and fire risks. Often, the systems that require frequent, extensive upkeep are also highly spatially distributed. Innovations like the Zero Additional Maintenance WSUD are designed to alleviate maintenance demands while enhancing urban greening (Prodanovic et al., 2022).

Finally, the integration of WSUD into urban areas is not purely a technical challenge, but it also involves overcoming social and cultural hurdles to blue-green space acceptance (Coyne et al., 2020; Ignatieva et al., 2023; Naserisafavi et al., 2022). Beyond this, urban greening offers significant opportunities for environmental justice in underserved communities (LeFevre et al., 2023). Community involvement in co-designing these spaces is crucial for ensuring their longevity and acceptance, fostering connections between residents and local ecosystems (Dushkova & Haase, 2020; Wendel et al., 2011).

4. Assessing the urban cooling benefits of green infrastructure

Effective urban greening strategies to enhance climate resilience and city liveability require accurate prediction of how green spaces influence microclimates and water management. Cities involve complex interactions between natural and built elements, making modelling a significant challenge. Even in areas with limited vegetation, representing plant and soil processes is essential to simulate surface energy fluxes, which drive urban cooling.

Various metrics can assess the cooling benefits of greenery, with Human Thermal Comfort (HTC) indices being particularly informative. HTC indices integrate multiple environmental factors to reflect human perception of thermal conditions. For instance, the Universal Thermal Climate Index (UTCI) integrates air temperature, mean radiant temperature, humidity, and wind speed, providing a more comprehensive measure of comfort for urban residents. Other metrics, such as air temperature, surface temperature and satellite-derived Land Surface Temperature (LST), offer valuable insights but have limitations. Air temperature is easy to measure but capturing fine-scale variability requires dense networks, often lacking in cities. Surface temperatures, measured on the ground or via aerial or satellite imagery, show greater variability, with shaded areas close to air temperatures but unshaded surfaces reaching 20–30 °C hotter. LST enables rapid, large-scale mapping but reflects only canopy top and specific capture times, potentially misrepresenting conditions experienced within the urban canopy (Coutts et al., 2016; Chakraborty et al., 2022; Naserikia et al., 2023).

Observational studies have documented that urban greening, along with WSUD features and irrigation, can reduce air and surface temperatures while improving HTC (e.g., Bowler et al., 2010, Santamouris et al., 2017). In Australia, Broadbent et al. (2018) looked specifically at WSUD interventions in a mixed residential suburb in Adelaide finding average afternoon air temperature reductions of 1.8 °C near water bodies. However, site-specific conditions and weather variability limit generalization of results from observational studies.

Numerical modelling complements observational studies by allowing controlled experiments and a broader assessment of potential urban cooling impacts. Accurately representing vegetation and soil water processes is critical for realistic simulations of the urban energy balance (Best and Grimmond, 2016), even in neighbourhoods with limited greenery (Grimmond et al., 2010). Present-day models have improved in capturing latent energy fluxes, reflecting the benefits of integrating vegetation and hydrology (Lipson et al., 2024), although challenges remain in accurately representing urban water balances (Jongen et al., 2024).

While many urban models exist, few operate at a scale sufficient to capture the full range of vegetation effects and urban hydrology while explicitly calculating variables relevant to human thermal comfort. In Australia, models such as the Canyon Air Temperature (CAT) and Vegetated Temperatures of Urban Facets-3D (VTUF-3D) have successfully simulated temperature patterns and thermal comfort in cities like Adelaide (Erell & Williamson, 2006) and Melbourne (Nice et al., 2018). These models incorporate detailed simulations of thermal fluxes, urban geometry effects, and energy storage in urban forms. VTUF-3D simulations in Melbourne showed daytime air temperature reductions of up to 5°C through increased vegetation, with even larger reductions in thermal comfort indices such as the UTCI (Nice et al., 2022).

The Air-temperature Response to Green/blue-infrastructure Evaluation Tool (TARGET) reproduces both air and surface temperature patterns from street canyon to block levels, with successful applications in Adelaide (Broadbent et al., 2019), but also in Zurich, Switzerland

(Chen et al., 2024). The Australian Town Energy Budget (ATEB; Thatcher & Hurley, 2012) efficiently represents suburban areas in regional climate simulations and has been used to assess vegetation cooling effects. For example, it estimated urban temperature increases of 2.2–3.8°C under a no vegetation scenario in Brisbane (Chapman et al., 2018) and potential seasonal summer reductions of 0.5–2°C in Melbourne if the city center was replaced with vegetated suburbs and parklands (Chen et al., 2015).

Urban Tethys-Chloris (UT&C), an urban ecohydrological model integrating ecosystem principles with urban canopy schemes, has successfully predicted vegetation effects on air and surface temperatures in Melbourne (Meili et al., 2019). Demuzere et al. (2014) implemented a vegetated biofiltration system combined with rainwater harvesting and urban irrigation in the Community Land Model-Urban (CLM4), demonstrating that such systems can maintain soil moisture, support healthy vegetation, and enhance evapotranspiration. This approach highlights the potential for integrating water-sensitive urban design with advanced urban climate models to optimize vegetation-based cooling strategies.

Krayenhoff et al. (2021) reviewed 146 modelling studies on blue-green infrastructure and reflective surfaces, finding that trees yield a median summer afternoon cooling of 3.3 °C, with additional benefits reported from grass, green roofs, and evaporative methods such as irrigated surfaces. Many models, however, rely on simplified parameterizations or idealized vegetation and urban canyon representations, particularly for generating detailed local-scale time series of energy and water balances. Combining observational and modelling approaches provides a robust framework to assess and optimize the cooling benefits of green infrastructure, with particular attention to healthy vegetation, water management, and accurate representation of local-scale urban processes. Advances in cloud computing, artificial intelligence, and data availability are making high-resolution urban modelling increasingly practical. Initiatives like Digital Twin Victoria provides valuable high-resolution 3D data for Australian cities (Dept of Transport and Planning, 2024).

5. Conclusion and future directions

The integration of urban greening with WSUD has emerged as a critical framework for building resilient cities amidst climate change pressures. Despite advancements in this integration, the urban greening initiatives with the fully integrated urban water management scenario (Figure 2) remain aspirational rather than an operational reality in Australian cities. Through examination of Australian cities' experiences, several actionable insights emerge with broad global applications. While Australia has demonstrated leadership in developing locally adapted strategies, significant challenges persist in operationalizing fully integrated urban water management systems.

Three critical priorities have been identified for resolving the tension between urban greening and water conservation: strategic selection of climate-resilient vegetation, optimized placement of green infrastructure for maximum benefit, and diversification of water sources, including greywater, recycled sewage, and stormwater runoff.

Current challenges extend beyond technological constraints to encompass social, economic, and cultural barriers. The fundamental tension between urban cooling needs and water conservation demands remains particularly acute as climate change intensifies competition among water users. While modelling tools exist to assess urban climate-vegetation interactions, significant gaps persist in integrating hydrological and urban climate models, particularly regarding water-vegetation dynamics in heterogeneous landscapes.

Australia's experience underscores the importance of spatio-temporal, climate-specific planning in urban greening, though crucial knowledge gaps remain regarding irrigation's indirect effects on urban microclimates. The effectiveness of green infrastructure is heavily influenced by local built environment interactions, highlighting the need for context-specific design approaches. The challenges of managing urban water and increasing urban greening are not unique to Australia. Indeed, Australian capital cities represent a diverse range of climates and high competition for land use. However, Australia's response the Millenium Drought – shifting towards a more integrated urban water management approach – can be seen as a good example for similar cities around the world.

As climate change drives more extreme weather patterns, adaptive strategies must include diverse vegetation portfolios, smart irrigation systems, and integrated water resource management. Future research priorities should focus on quantifying urban greening and WSUD performance across different climatic and geographic gradients, developing integrated modelling frameworks that bridge the gap between hydrological and urban climate models, evaluating the effectiveness of alternative water sources for sustainable urban greening, and understanding the complex interactions between urban vegetation, built infrastructure, and local microclimates. These research directions will be crucial for developing evidence-based strategies that can be tailored to specific regional contexts while advancing global urban sustainability goals.

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