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Perspective

Transforming Cities through Water-Sensitive Principles and Practices

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SUMMARY

Many global cities and towns are facing complex and interrelated challenges associated with population growth, resource constraints, aging infrastructure, and degraded environments, exacerbated by increasing climate uncertainty. The United Nation's Agenda 2030 is a global call to action with 17 Sustainable Development Goals (SDGs). Water is the common currency linking nearly every SDG. SDG 11 aspires to "Make cities and human settlements inclusive, safe, resilient, and sustainable" and the water-sensitive city represents an aspirational future state for water management where servicing strategies deliver long-term sustainability, liveability, resilience, and prosperity. This social-technical endeavor is based on three principles of practice proposed in 2009. They have since been operationalized and adapted in many projects globally, and across a range of social, institutional, and biophysical contexts. In this Perspective, we reflect on lessons learned, required actions for mainstreaming water-sensitive practices, the next-wave research agenda, and opportunities to catalyze actions in sectors beyond water.

INTRODUCTION

The twenty-first century marks the point when more people live in urban environments than in rural environments,[1] making cities a critical focal point for sustainable development practices.[2–5] The common currency linking nearly every United Nations' Sustainable Development Goal[6,7] (SDG) is water. It will be a critical determinant of success in achieving targets in most of the 17 SDGs—energy, cities, health, the environment, disaster risk management, food security, poverty, and climate change among others.[8,9] However, the rapid pace and scale of urban growth, combined with the impacts of climate change and economic development, is challenging the capacity of existing water systems to provide the world's cities with clean water and sanitation, and healthy and safe urban environments.[10,11] There is now widespread agreement that conventional water management approaches are ill-equipped to meet the diverse and complex needs of cities.[12] These infrastructure and governance systems remain largely influenced by twentieth century solutions and experience, which are typically characterized by fragmentation and technologically dominant solutions.[13]

Against this backdrop, the United Nation/World Bank High-Level Panel on Water developed an Action Plan based on a more holistic social-technical approach to addressing complex water issues. Indeed, the Action Plan (p. 13) argues that "sustainable solutions require integrated approaches, addressing technical, institutional, financial, social, and environmental issues simultaneously."[8]

In less predictable and "limits to growth" scenarios, water management must be more integrated and adaptive. Reorienting existing infrastructures, institutions, and capacities toward this new integrated approach is the key challenge for developed cities.[13–15] In addition, urban water management must consider related factors that influence broader social and technical issues of urban liveability and efforts to green cities.[16–18] Water initiatives with broader liveability objectives include Australia's Water-Sensitive Cities,[19,20] China's Sponge Cities,[21,22] Singapore's ABC Waters,[23,24] the United States' Low Impact Development,[25] and the recent adoption of such principles in Canada with Vancouver's Rain City Strategy.[26]

The evolution of urban water management over the past 200 years has been defined by an interplay between the social-political drivers for improved services and the technical responses to these drivers. They are framed by progressive evolution of hydro-social contracts, shaped by cultures and value sets, between gove/rnments and communities that manifest in institutional arrangements and regulatory frameworks for urban water service delivery expectations. Brown and colleagues[19] presented a heuristic urban water transitions framework, which describes historical, current, and anticipated future urban hydro-social contracts at the city scale (moving from left to right in the nested continuum characterized in Figure 1).

The water-sensitive city, as the aspirational future state for water management, envisioned at the far right of Figure 1, represents a culmination of water supply, sanitation, flood protection, and environmental protection servicing strategies that ensure long-term sustainability, liveability, resilience, and prosperity.[27] To operationalize this water-sensitive city vision, Wong and Brown[20] proposed three principles for practice (Box 1). While the concepts underpinning these principles (socio-technical approaches, whole water cycle management, context-responsive design, and nature-based solutions) have been developed and framed in many contexts, they were combined for the first time in 2009 to set a coherent pathway for changing urban water management.

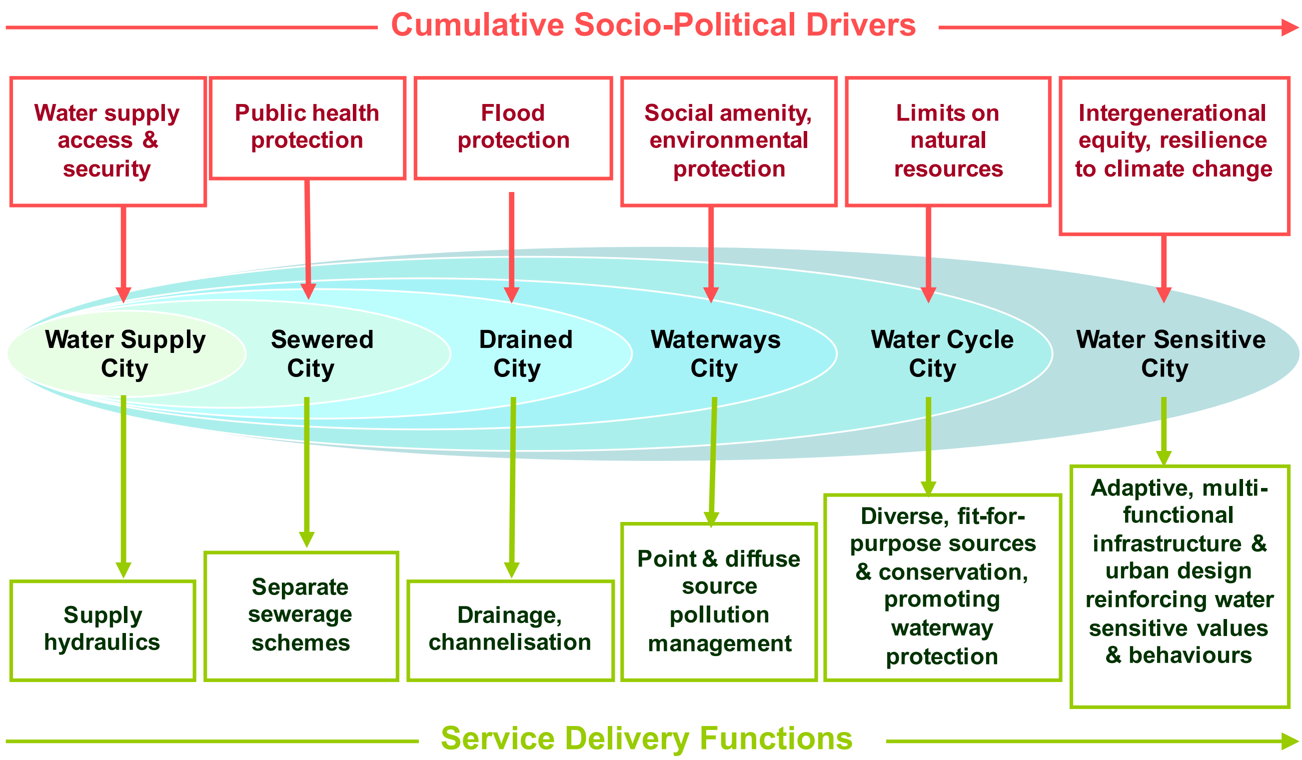

Figure 1. Urban Water Transitions Framework

In a water-sensitive city, each of these three principles would be wholly integrated into the urban environment through urban planning and design.

Since the principles of water-sensitive practice were introduced 10 years ago, significant effort has gone into operationalizing them in cities with diverse social, institutional, and biophysical conditions around the world. This Perspective reviews experiences of applying the principles of water-sensitive practice. While there are similar approaches elsewhere,[21–25] this Perspective is not intended to be comprehensive in recognizing different international interpretations, nor a systematic state-of-the-art review of contemporary urban water management. Instead, it reflects on the lessons learnt over the past 10 years in operationalizing the water-sensitive cities' principles of practice, and sets out research and action agendas that must be pursued over the next decade to mainstream water-sensitive cities. Furthermore, this Perspective presents a preliminary reflection of a conceptual advance on how the experience could help frame expansion of the water-sensitive city agenda to a broader sustainable city and SDG agenda as we commence the "Decade of Action" to deliver the SDGs.

Box 1. WSC Principles of Practice

The water-sensitive city is underpinned by three key pillars of practice[20] that are seamlessly integrated into the urban environment:

1. *Cities as Water Supply Catchments*: access to a diversity of water sources, supplied by an integrated mix of centralized and decentralized infrastructure
2. *Cities Providing Ecosystem Services*: provision of ecosystem services for the built and natural environment
3. *Cities Comprising Water-Sensitive Communities*: socio-political capital for sustainability and water-sensitive decision making and behaviors

Applying the Principles of Water-Sensitive Practice

The first principle, *Cities as Water Supply Catchments*, espouses that cities access a range of water sources that include but go beyond surface water sources that capture rainfall runoff from rural and forested catchments or groundwater.[20] A water-sensitive city has a supply strategy built around multiple water sources and diverse infrastructures for water harvesting, treatment, storage, and delivery. And this portfolio of sources imposes the least cost, including environmental impacts and other externalities. These alternative water sources include managed aquifer (groundwater) recharge schemes, urban stormwater (catchment runoff), rainwater (roof runoff), recycled wastewater, and desalinated water. Many of these sources are provided within city boundaries and each has its own reliability, environmental risk, and cost profile.

In Australia, the Millennium Drought (1997–2009) catalyzed the adoption of this principle, and cities and towns started their transition to become water sensitive.[28] Australia's major coastal cities rapidly diversified their water sources by constructing seawater desalination plants. Although not necessarily optimum, governments considered these plants necessary to make cities resilient to what appeared to be an unending drought. After the drought, significant debates ensued about the decisions to build

Figure 2. Various Scales of Stormwater Bioretention Systems Constructed in Melbourne, Australia
(A–H) (A) Royal Park Wetland, Parkville; (B) Baltusrol Estate, Moorabbin; (C) Lynbrook Boluevard, Lynbrook; (D) Cremorne Street, Richmond; (E) Victoria Harbour, Melbourne Docklands; (F) Baltusrol Estate, Moorabbin; (G) Batman Ave Tree Planters, Melbourne Docklands; (H) NAB Building Forecourt Wetland, Melbourne Docklands.

these expensive plants, many of which were still being constructed. Nevertheless, the water supply security they created gave many governments a window to pursue more sustainable, diffuse, and cost-effective alternatives that take longer to implement and upscale.[29] Examples include stormwater harvesting, wastewater recycling, fit-for-purpose treatment and use of water, and demand management. The Victorian Government, for example, used the "safety net" of its desalination plant to introduce alternative water sources in an effort to avoid building a second desalination plant to support Melbourne's forecast population growth.[15] Often the pursuit of alternative water sources that are diffused throughout a city (e.g., rainwater, stormwater, graywater, and wastewater) led to new infrastructure that serves multiple purposes. For example, stormwater-harvesting projects using nature-based solutions have redefined urban landscapes and streetscapes in many cities. Typical examples include water-sensitive urban design (WSUD) in Australian cities (Figure 2) and the range of nature-based systems in the Chinese city of Kunshan.[30]

Rainwater harvesting has been combined with real-time storm forecasting and control technology to alleviate urban flooding.[31,32] The rainwater capture system in the Star City project in Seoul, Korea, is an example.[33] The 3,000-m^3 tank installed as part of the development saved an average 26,000 m^3 of water annually and reduced by 8.9 MWh the energy consumption associated with transferring water from an external catchment. The downstream drainage system, previously designed for a 10-year Average Recurrence Interval (ARI) storm, had its serviceability increased to 50-year ARI without any upgrades.

The second principle, *Cities Providing Ecosystem Services*, espouses integrating urban landscape design with sustainable urban water management.[20,34,35] This integration incorporates ecological functions and services into urban communities, to buffer the impacts of climate change while increasing natural capital in the urban and nearby natural environments. Landscapes are the product of varying natural and human-induced forces, interacting within a regional and global ecosystem. As well as improving amenity, public open spaces in water-sensitive cities provide ecosystem services to both the built and adjoining natural environments. To ensure that city designs allow for these ecosystem services, we need to bolster our knowledge of the traditional "values" of open spaces and landscape features, to better understand the "ecological functioning" of the urban landscapes that can deliver sustainable water management, influence microclimate, facilitate carbon sinks, and support urban food production. These ecological landscapes are also called *nature-based solutions*, based on preserving or mimicking natural processes to support biodiversity and human needs. The International Union for Conservation of Nature advocated the shift from traditional water management to a blend of green and gray investments, acknowledging the enormous potential for nature-based solutions to help achieve the 2030 Agenda for Sustainable Development.[36] The nature-based solutions approach featured prominently in the 2019 United Nations Secretary General's Climate Summit in New York and in numerous side events in COP25 later that year.

Greener cities are now common in vision statements, reflecting our growing understanding of the significant role of nature-based solutions across a range of scales. These solutions can apply to large regions, focusing on preserving, protecting, and restoring natural systems, such as global efforts to protect wetland and coastal mangrove systems. At a local scale, a combination of public space designs and biomimicry delivers multiple ecosystem services outcomes, including flood management, urban waterway renaturalization, stormwater quality improvement, urban cooling, and general urban area revitalization. There are numerous example projects globally,[37] including those shown in Figure 2 and the many projects by leaders in the field—including German urban designer and water artist Herbert Dreiseitl,[38,39] and Chinese ecological urbanist and Professor of landscape architecture at Peking University, Professor Kongjian Yu.[40,41]

Finally, the third principle, *Cities Comprising Water-Sensitive Communities*, asserts that community values and aspirations should govern urban design decisions and urban water management practices.[20] A water-sensitive city is underpinned by its inherent social and institutional capital, reflected in: (1) communities living an ecologically sustainable lifestyle and recognizing the ongoing balance and tension between consuming and conserving the city's natural capital; (2) industry and professional capacity to innovate and adapt as reflective practitioners in city building; and (3) government policies that facilitate the ongoing adaptive evolution of the water-sensitive city. Brown and colleauges[42,43] analyzed the historical and socio-technical drivers of WSUD across Melbourne. They found that a complex interplay between issue champions (or change agents) and a suite of enabling context variables is important for transitioning toward water-sensitive cities. The enabling context variables relate to the level of socio-political capital for protecting waterway health, opportunities for strategic external funding avenues, and the establishment of bridging organizations to bring scientists and industry together. This interplay of associations and networks helps to formalize the objectives of improving stormwater quality, foster large developers' receptivity to WSUD in the marketplace, and facilitate the development of capacity building tools. These tools include methods for envisioning future water management scenarios, water quality modeling software, and innovative design guidelines. Tan and Wong[44] used this framework of enabling context variables to develop a strategy to institutionalize WSUD in Singapore.

Australian cities' ongoing evolution of urban water management toward water-sensitive cities is now entrenched, through: (1) increasing integration of water services (water supply, sewerage, drainage and flood management, and environmental protection) and (2) increasing integration of water infrastructure planning and design with urban planning and design. Most major Australian cities and local governments have a water-sensitive policy and/or strategy, as well as on-ground water-sensitive projects. The Cooperative Research Center (CRC) for Water-Sensitive Cities[45]—an AU$120M research-to-practice bridging organization (2012–2021)—drove or supported many of these initiatives. Examples include:

- proofs-of-concept for new technologies and urban designs, demonstrations of policy reforms, and pilot-scale and development-scale works-on-ground[46,47]
- a methodology to demonstrate what an "optimum portfolio of water supply options" would look like, based on Greater Melbourne[48,49]
- water policy reforms in local and state governments that reflect research outputs[50]
- water-sensitive city practices implemented in Kunshan, China[30]

Lessons for Operationalizing Water-Sensitive Cities

Looking across the above examples and global experiences of implementing water-sensitive solutions, we can reflect on what we have learnt about how to operationalize the principles of water-sensitive practice. These lessons are universally relevant, although each city's catalyst for change may differ. Often, water system transitions are catalyzed by extreme climatic conditions (such as drought or flood)[15,51] and/or severe pollution of waterways.[43,52]

Water-sensitive practices are not one-size-fits-all. While the principles provide important guidance, their application demands bespoke solutions that are tailored to the local context. Context refers to biophysical conditions, such as a city's geomorphology, hydrology, urban form and microclimate, the local operating environment, and the key social and institutional conditions that influence uptake of new water-sensitive technologies and practices. Operationalizing water-sensitive city principles therefore requires processes that allow local stakeholders to articulate clear objectives, understand their current situation, and develop appropriate and effective responses. We have found that four integrative modes of thinking and working are critical to support these processes: systems, interdisciplinary, design, and collaborative.

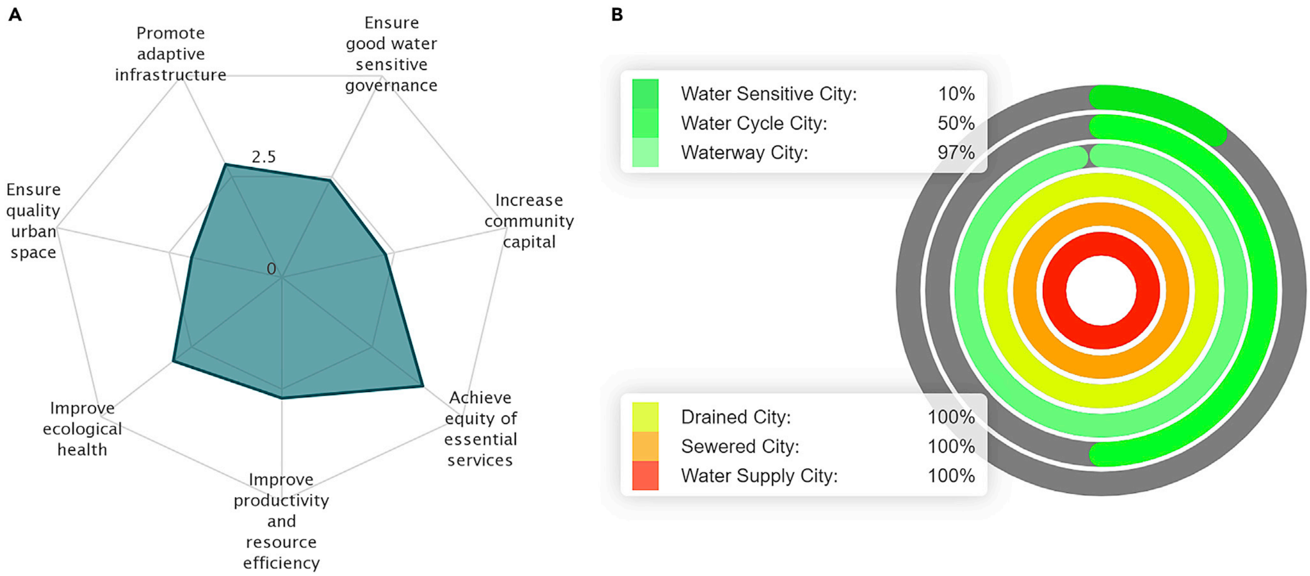

Figure 3. Example WSC Index Results

(A) The aggregate score for each goal's indicators, scored on a spectrum from 1 (low water sensitivity) to 5 (high water sensitivity); the larger the footprint, the higher the water sensitivity.

(B) Interpretation of the WSC Index indicator scores into a percentage attainment of each city state of Brown and colleagues' urban water transition framework.

Systems Thinking

Systems thinking is a holistic approach that focuses on how individual parts of a system interrelate to shape the whole system over time.[53] Operationalizing water-sensitive cities involves recognizing, understanding, and accounting for the complex interrelationships between technological, ecological, and social factors. For example, the success of a streetscape biofilter or constructed wetland depends on it not only performing its intended engineering function of retaining and treating stormwater, but also enhancing urban biodiversity and improving landscape amenity. We need a systems view so that we can understand, plan for, and deliver these multiple benefits.[54,55]

Interdisciplinary Thinking

Sustainable development requires diverse perspectives and disciplinary knowledges that provide depth of insight and robust solutions.[56,57] The biofilter and wetland examples above need engineering knowledge to ensure a biofilter or wetland adequately removes pollution from stormwater. But it also needs social science knowledge to understand the community's esthetic preferences and the governance arrangements needed for long-term maintenance. It also needs knowledge of landscape architecture to develop practical solutions that respond to the community's preferences and can be integrated into the urban form. Processes that facilitate the early and ongoing integration of these different types of knowledge are critical for delivering water-sensitive outcomes.[58,59]

Design Thinking

Design processes bring different perspectives together to analyze a situation and develop integrated solutions for sustainability challenges.[60] For example, the CRC for Water-Sensitive Cities' flagship research synthesis process[46,61]—a facilitated design charrette style intervention—combines latest science from different disciplines with local industry expertise to collaboratively develop and rapidly evaluate practical ideas. Similarly, the water-sensitive cities design studio program led by Monash Art Design and Architecture[62] facilitated postgraduate students through a process to explore design possibilities and develop ideas that use water-sensitive approaches to address real-world problems. Both these examples rely on clarity about the outcomes to be achieved, an understanding and framing of the local context and problem from many different perspectives, and water-sensitive city principles that underpin solutions. This mode of thinking promotes innovative design ideas, such as new urban form configurations, technological interventions, community engagement campaigns, and governance arrangements. [35,59]

Collaborative Thinking

Central to each of the above modes of thinking is a commitment to collaboration: ambitious sustainability objectives cannot be achieved through siloed, single-objective planning, design, and management processes. The CRC for Water-Sensitive Cities' landmark transition strategy development process aims to establish long-term collaborative partnerships that drive transformative action among local stakeholders.[63] These stakeholders often include representatives from policy departments, water utilities, regulatory agencies, local governments, land developers, consultants, academia, and community. Key steps are committing to a shared vision, understanding each other's perspectives, and developing a common mental model of transitional change that informs strategic priorities.[58] Places where such collaborative foundations have been established have seen a much more rapid uptake of water-sensitive principles.[64]

Stakeholders need methodological guidance and associated tools to help them use the systems, interdisciplinary, design, and collaborative modes of thinking that will help them translate aspirational intents into real-world implementation. The CRC for Water-Sensitive Cities has developed several support tools, two

Transition phase	Champions	Platforms for connecting	Knowledge	Projects and applications	Implementation guidance	
					Technical	Administrative
1. Issue emergence	Issue activists		Issue highlighted	Issue examined		
2. Issue definition	Individual champions	Sharing concerns & ideas	Causes & impacts examined	Solutions explored	Data & evidence collected	
3. Shared understanding & issue agreement	Connected champions	Developing a collective voice	Solutions developed	Solutions experimented with	Preliminary practical guidance	Administrative instruments explored
4. Knowledge dissemination	Influential champions	Building broad support	Solutions advanced	Solutions demonstrated at scale	Refined guidance & design tools	Early policy & performance standards
5. Policy and practice diffusion	Government agency champions	Expanding the community of practice	Capacity building	Widespread implementation & learning	Guidance for implementation & cross-sector	Refined policy & standards, early regulation
6. Embedding new practice	Multi-stakeholder networks	Guiding consistent application	Monitoring & evaluation	Standardisation & refinement	Comprehensive standardised guidance	Comprehensive policy & regulation

Figure 4. Transition Dynamics Framework, Setting Out Key Enabling Factors over the Course of a Transition (from Issue Emergence through to the Embedding of a New Practice)

of which have catalyzed collaborative, system-wide shifts in planning, designing, and managing Australia's urban water systems.

First, the Water-Sensitive Cities (WSC) Index[65] benchmarks a city's current water management practice and identifies strengths and weaknesses across social, technical, and ecological domains. Figure 3 shows an example of a city's WSC Index results: Figure 3A displays the aggregate score across 34 indicators organized into seven goals: (1) ensure good water-sensitive governance, (2) increase community capital, (3) achieve equity of essential services, (4) improve productive and resource efficiency, (5) improve ecological health, (6) ensure quality urban space, and (7) promote adaptive infrastructure. Figure 3B interprets the WSC Index goal scores into a percentage attainment of each city state urban water transition framework set out by Brown and colleagues.[19] These goals and indicators reinforce the three principles of water-sensitive practice[20] (Box 1). The WSC Index has now been tested in more than 50 metropolitan and municipal Australian cities and in three south east Asian cities.

Second, the Transition Dynamics Framework (TDF)[66,67] (Figure 4) helps people develop a collective understanding of their local socio-technical context, and identify strategic enablers that drive practice change over time. It sets out six types of enabling factors (champions, platforms for connecting, knowledge, projects and applications, technical guidance, and administrative guidance) that are critical for driving change in water management over different phases of a transition, from issue emergence through to embedding a new practice. The TDF identifies the presence or absence of these key enablers. These insights are then used by and with stakeholders to prioritize and design transition projects and other interventions that most effectively establish these critical enablers and ultimately transform the system.

Both the WSC Index and the TDF can be used for detailed analysis, as well as to support structured dialogue when embedded in a participatory process. Applied together, the tools offer city stakeholders robust evidence and collaborative processes to design their urban water strategies and evaluate their city's system-wide water-sensitive performance over time.[68,69]

The experience of Perth, Western Australia, provides an instructive example. Before 2015, Perth's water sector was perceived as fragmented, with organizations working within their individual mandates and rarely considering broader city outcomes. Facilitated collaborative processes since then have included envisioning, benchmarking with the WSC Index, and developing a transition strategy using the TDF. Out of these processes emerged an informal, organized, and influential network of champions committed to driving Perth's water-sensitive city transition.[70] Five years on, Perth now has a shared water-sensitive city vision, alignment of cross-agency objectives, a government-wide 10-year Waterwise Perth Action Plan, and significant evidence of on-ground adoption of water-sensitive practices.[71,72] While mainstreaming water-sensitive practices in Perth will still take time, the enabling conditions are ripe for their rapid uptake and widespread adoption.

Mainstreaming Water-Sensitive Cities: Next Steps

Water-sensitive cities principles are evident across Australia and globally, whether based on water-sensitive cities framing or alternative aligned concepts. The challenge is now scaling their adoption to make them mainstream. This mainstreaming agenda parallels the scholarship and practice of sustainability transitions in other sectors. Attention has expanded from an initial focus on nurturing and protecting innovative spaces to understanding the processes and mechanisms to accelerate their uptake and stabilize a new regime.[73,74]

The water-sensitive city initiatives implemented over the past decade highlight the interrelationship between the water system and the broader urban fabric—it is clear that efforts to mainstream water-sensitive cities need to engage with wider city-shaping processes. Responding to the challenges and harnessing the opportunities presented by key urban trends will accelerate adoption of water-sensitive solutions.

Urban intensification—through greenfield developments that expand the urban footprint and infill developments that densify existing areas—is an opportunity to introduce new water-sensitive precincts across the city. Capitalizing on this opportunity, however, requires a planning system that drives water-sensitive outcomes.[75] Similarly, we can harness *climate change adaptation* processes, and use water-sensitive cities principles to guide major investments that make cities resilient to climate change impacts. These investments will deliver other benefits, such as improved ecological health and urban amenity. *Technological breakthroughs* may help to rapidly scale the uptake of water-sensitive practices, including digital transformations, such as the Internet of Things, artificial intelligence, blockchain, and augmented and virtual reality.[76] These emerging digital capabilities are particularly important for making available the data needed to manage distributed infrastructures that are integrated with central systems.[77] Digital technologies can also empower communities to adopt and support water-sensitive practices through enriched platforms for *participation and collaboration*.[78] This approach would allow citizens to shape their neighborhoods and cities through placemaking and other people-driven processes.

We can harness these urban trends to accelerate the mainstreaming of water-sensitive cities, provided city and water planners and designers embrace the need for solutions that respond to the complexity and uncertainty of integrated urban environments. This approach, in part, means recognizing that infrastructure needs to deliver multiple functions, through a holistic system approach and aided by new emerging technologies. A new generation of water systems[79] is emerging. Furthermore, we cannot focus on the water sector alone—delivering water-sensitive cities requires explicit attention on the interfaces between water and other key urban sectors, such as energy, waste, food, transport, and the built environment. We can facilitate this integration by combining traditional infrastructure solutions with flexible, decentralized, nature-based, and socio-technical solutions to create, what we term, *hybrid systems*.[80]

Many urban infrastructures are already multi-functional, providing multiple services. Drainage pipes and drains have been an integral part of road systems, and in some cases, roads have been designed for flood conveyance.[81] Many water-sensitive cities and aligned initiatives have introduced nature-based systems for stormwater cleansing and detention, and the design of these landscapes has now been extended to mitigate urban heat and increase urban biodiversity. These approaches to multi-functional infrastructure are early representations of hybrid systems. Over the next decade, we anticipate increasing innovation and sophistication in multi-functionalities of these hybrid systems.

Hybrid water systems can deliver multiple social, economic, and ecological benefits across scales and sectors. For example, higher volumes of wastewater that result from urban intensification can be treated through decentralized technologies that enable low-energy water recycling, reducing water demand and sewage load on existing infrastructure. The waste heat from local energy production can deliver reticulated hot water services to households and disinfect harvested rainwater and stormwater for domestic and industrial use. Nutrient-rich recycled water can irrigate urban food crops, while biosolids and food waste can generate energy. These nexus elements support a circular economy. Other examples of hybrid water systems include nature-based solutions integrated with traditional gray infrastructure in urban landscapes to manage floods, remove air and water pollution, improve people's health and wellbeing by supporting active and passive recreation, cool urban microclimates, and enhance public amenity to increase economic and social value.

Hybrid water systems can be customized and implemented as and when needed. This allows them to: (1) facilitate out-of-sequence urban development, which otherwise challenges the capacity of centralized infrastructure to meet demand growth; (2) defer or avoid investments for major resource development and trunk infrastructure augmentation; (3) service diverse urban contexts to meet local community aspirations and expected levels of service; (4) rapidly respond in changing situations; and (5) adapt to new technologies as they emerge, avoiding stranded systems. Implementing hybrid solutions at a suitable scale can repurpose stranded legacy assets and unlock new private-public co-investments at a time when many governments face increasing resource constraints.

These benefits can reduce the cost of assuring the efficiency, liveability, and health of cities. A real-world example is the proposed Fishermans Bend development in Melbourne, Australia, which will accommodate a projected 120,000 residents and employment for 80,000 people in a former industrial area south of the central business district. Planned hybrid water solutions are expected to reduce the additional demand on existing trunk water supply, sewerage, and drainage infrastructure by up to 45%, significantly deferring or avoiding major capital works for augmentation.[82]

Scaling up the adoption of hybrid water systems is not only a pathway toward mainstreaming water-sensitive cities, it also lays the foundation for *transformative cities*—cities that have the drive and the capability to keep innovating and adapting as circumstances change. We can build on the concepts, methodologies and processes developed through a focus on hybrid water solutions, to support integration with other city-shaping sectors. By providing operational insight on innovation in urban services, water can be a catalyst for city integration through circular economy principles and place-based transformation.

But, realizing this vision requires equipping city stakeholders with new knowledge, skills, and resources that convert aspiration into practice. This leads us to a research agenda that will guide the innovations needed to mainstream water-sensitive cities and lay the foundations for transformative cities. This research agenda consolidates emerging directions in urban water management literature with calls for research and innovation we have heard through deep engagement with industry who have implemented water-sensitive practices.

Creating Integrated Urban Systems

Governments, industries, and communities need new technological and operational capacities to plan, deliver, and evaluate infrastructure systems that maximize community value across sectors and scales.[80] In particular, we need new hybrid technological systems that operate at the nexus between water, energy, food, and waste resources, and integrate with transport systems and other parts of the built environment.[83] Key to operationalizing hybrid systems will be smart infrastructure capabilities—incorporating the Internet of Things—that provide accurate, current, and system-wide information for managing hybrid systems in real-time and monitor their benefits for people and nature.[84,85] Research is needed for the development of low-cost sensors that produce reliable data from harsh environments, coupled with advanced analytics to handle the massive flow of data, including artificial intelligence and machine learning algorithms to enhance prediction and real-time operation. New standards, protocols, and benchmarks are needed to support interoperability and certification of these technologies and tools, ensuring reliable, consistent, and quality data.[77] These capabilities need to be integrated into planning and management tools, for example digital twin[86] and scenario models,[87] that integrate sensor, demographic, climatic, geographic, building, and infrastructure data to simulate diverse systems conditions for use in real-time system optimization, as well as longer-term spatial planning and policy experimentation.

Coupled with new technological capabilities, we need new whole-of-system performance assessment frameworks,[65,88,89] including quantitative indicators of public health, wellbeing, environmental, and economic benefits, to assess integrated outcomes. This would enable us to analyze synergies and tradeoffs across scales, sectors, and time, and identify key system vulnerabilities. We would use these frameworks to benchmark and monitor progress toward the transformative city vision, and evaluate hybrid system policies, plans, and interventions. Using such frameworks for longitudinal monitoring of innovative demonstrations would create evidence of human and ecological health outcomes achieved by implementing hybrid solutions in green, connected, and biodiverse built environments and transport corridors.[90]

Connecting People and Place

Research that explores the practices, values, meanings, motivations, and actions of communities will help us understand the local implications of creating transformative cities.[91] In-depth qualitative work, large-scale quantitative surveys, and social media analysis can generate detailed, place-based, and actionable information about individual and community values, preferences, and practices, and how they relate to urban infrastructure services needs. Engaging with First Nations people is particularly important, to ensure that decisions reflect their knowledge, culture, and priorities.[92,93] These social insights will help city stakeholders plan, design, and manage hybrid systems, and identify points of cooperation and conflict as cities transform. We need new strategies for empowering participation in city shaping, collaborative governance, and climate resilience initiatives.[94,95] We also need new engagement frameworks, processes, and digital technologies to harness the knowledge, skills, and resources of citizens for implementing hybrid solutions.[96] These frameworks need accompanying guidance so that industry can apply them in practice, inform future opportunities for new products and services, and identify where products and policies may need modifying to meet community needs and expectations.

Innovating Funding and Servicing Models

Transformative cities require institutional and business frameworks that guide, deliver, and regulate urban infrastructure services to enable and promote hybrid systems. For example, we need new frameworks and evidence that support comprehensive economic analysis of hybrid systems—including tools to quantify the economic value of their diverse benefits and co-benefits, and new data captured through nonmarket valuation, economic experiments, and econometric analyses.[97] Integrating economic analysis tools with numerical scenario models of city development and infrastructure servicing could allow us to examine the future spatial and community distribution of costs and benefits. Decision makers can use these new evidences and capacities to inform strategies for integrated urban servicing and climate change adaptation. We need innovative policy instruments, including targeted mechanisms to efficiently incentivize residents, industry, local governments, developers, and utilities to optimize their portfolio of hybrid solutions.[80,98] These mechanisms could include pricing, market and regulatory incentives, and innovative finance and insurance products. Trialling these mechanisms through pilot studies, randomized control trials, social surveys, and interactive workshops would give decision makers an expanded portfolio of real options, together with guidelines and protocols for selecting the most suitable mix of strategies for their context. We also need to explore the markets, organizations, jobs, and commercial arrangements that underpin future hybrid systems.[80,99,100] This research will identify regulatory mechanisms, business models, and servicing strategies that can unlock private financing, manage key risks that emerge in reconfigured utility markets, enable more flexible and diverse servicing options for customers, and ensure social equity in delivering hybrid solutions.[90]

Scaling the Uptake of Hybrid Systems

Technical innovations must be coupled with enabling spatial, social, political, and institutional conditions to accelerate their pathway from experiment to mainstream. We need action research to develop practice-led theory of scaling that identifies design principles and processes for maximizing the transformative potential of experiments to enable rapid uptake.[90] We need longitudinal and cross-sectional evidence of the impact of deliberate scaling strategies and initiatives, and conduct place-based case studies of policy implementation for integrated outcomes across key city-shaping sectors to identify opportunities for improvement.[76,80] We can operationalize these insights for governments, industries, and communities through strategy design principles, policy guidance, and tools for sharing knowledge and benchmarking, monitoring, and evaluating mainstreaming progress. By doing so, we can help practitioners to deliver scaling efforts and mainstream innovation. Platforms that facilitate effective advocacy coalitions, promote ready access to knowledge resources and help people, organizations, and cities to learn from each other as they experiment with innovations will also help to scale up the implementation of hybrid solutions.[76]

CONCLUSION

We have come a long way in advancing water-sensitive cities over the past decade. We have demonstrated applications of water-sensitive cities principles at a range of scales and in policy reform. Responding to context is key, so guidance through a set of principles of practice is essential. Pockets of urban innovation focused on particular city challenges and opportunities exist nationally and internationally. Yet nowhere has achieved the cross-sectoral and cross-scale integration of infrastructure services needed for industry to ensure the long-term competitiveness, productivity, and sustainability of cities.

WSUD is a place-based approach to integrating sustainable integrated water management and urban planning and design. Because it is a place-based and context specific, there are no standardized pre-conceived solutions, or solutions that can be readily transposed from one application to another. Only the principles of practice are common to all water-sensitive cities transformation, which means that cities have a limited ability to diffuse standardized solutions widely. As such, the types of obstacles to industry adoption overcome in the past decade largely are related to a lack of place-based enablers, including:

1. technical and design guidance and diagnostic tools for developing context-specific solutions, prioritizing and balancing benefits, and devising suitable structural and non-structural interventions
2. processes for collaborative design across multiple social-technical disciplines
3. investment in collaboration, trials, and experimentation of place-based water-sensitive cities practices across multi-stakeholders
4. policy promoting integrated urban water management with urban planning and design

Some key obstacles remain, particularly in operationalizing water-sensitive city policies. This need is common across the world and must be addressed as we move to the mainstreaming and upscaling phase of water-sensitive cities transformation. The three standout challenges are:

- developing a transparent and rigorous economic valuation basis for determining tangible and non-tangible economic benefits, and in monetizing these benefits
- developing a business model that provides for whole-of-government and public-private sector co-investment of water-sensitive projects
- integrating urban land use planning with water system planning in creating opportunities for water-sensitive solutions through urban development processes

As cities transition to become more water sensitive, the urgency of the complex challenges facing cities means that we must not only develop and experiment with new hybrid solutions, we must rapidly bring them to scale. City stakeholders can already draw on significant actionable knowledge to rapidly progress toward their water-sensitive vision. However, upscaling and mainstreaming of water-sensitive cities practices remains elusive—mainly impeded by institutional factors. Urban planning remains rule-bound to traditional practices that are based on highly fragmented and single-dimension objectives, supported by outdated and narrow economic methods for assessing the benefit-cost of infrastructure investment. Overcoming these impediments and creating the enabling environment for transformations on a broader scale must become our collective mission.

At the heart of our lessons is embracing hybrid measures that can respond to local context. This is an emerging issue in many developed and developing cities as governments strive to augment their system capacity to accommodate increasing urbanization, growing populations, and climate resilience. Infill developments are prominent in urban densification and are often spatially piecewise. These features make them ideal opportunities to combine decentralized solutions with existing trunk infrastructure as integrated hybrid systems. By creating these hybrid solutions, we can ensure that the existing infrastructure is not stranded as we embrace emerging technologies and integrated system thinking. This approach ensures optimal economic returns from past and future infrastructure investments.

We have also learnt that the water-sensitive cities principles of practice are a useful orienting framework for interdisciplinary and integrated approaches to urban water management. They highlight the importance of expanding their use to other urban systems that shape our cities, for example energy, transport, waste, food production, and the built environment. Coupling decentralized water and energy infrastructure with existing trunk infrastructure can increase system robustness and modularity. Architectural built form can be resilient and adaptive to floods. We can also develop infrastructure for waste-to-energy and the broader water-energy-waste systems. All of this infrastructure supports hybrid business models for whole-of-government and private-public sector co-investment and governance.

Experiences from water-sensitive cities point to emerging directions for future research:

- participatory tools and evidence-informed policy, planning and design guidance to co-create hybrid solutions that reflect local values and improve human and ecological health
- leveraging social, policy, regulatory, and economic enablers to create the authorizing environment for accelerating mainstream uptake of hybrid systems
- new business and financing models, incentives and regulatory frameworks to unlock private investment in hybrid systems and encourage their delivery through appropriate sharing of costs, benefits, and risks
- new metrics, technologies, and decision support tools to optimize resources as part of a circular economy and increase infrastructure resilience through system integration
- smart infrastructure enabled through digital technologies

This research agenda is diverse and ambitious. But we should also not ignore the existing knowledge that can already be leveraged, building on the practice changes that have been achieved through efforts to implement water-sensitive cities. The TDF Figure 4 provides the architecture of an action agenda that complements the research agenda proposed in this Perspective. We need champions at all scales of practice to inspire transformative action. We need platforms that bring people together in strong and influential communities of practice that have a common vision and evidence-based strategy for change. We need platforms that integrate interdisciplinary knowledge and make it accessible to the range of actors who must adopt new ways of doing things. We need scalable demonstrations of new solutions as they emerge. These solutions include technological innovations, but also social innovations, such as urban design, collaboration processes, behavior change methods, and policy instruments. Finally, we need to emphasize evaluation and learning that help us understand change processes to drive system transformation from knowledge gained from individual project or practice interventions.

The water-sensitive cities vision has progressed far in the past decade. In another 10 years, we may well see water-sensitive practices becoming mainstream as city stakeholders collectively embrace the action agenda and research frontiers presented in this Perspective. Through this, cities will develop transformative capacities to sustain their broader liveability, resilience, and prosperity over the long term.

REFERENCES

1. Ritchie, H. (2018). Urbanization. https://ourworldindata.org/urbanization.
2. UNEP (2019). Cities and climate change. https://www.unenvironment.org/explore-topics/resource-efficiency/what-we-do/cities/cities-and-climate-change.
3. Kanuri, C., Revi, A., Espey, J., and Kuhle, H. (2016). Getting Started with the SDGs in Cities: A Guide for Stakeholders. Sustainable Development Solutions Network. https://irp-cdn.multiscreensite.com/6f2c9f57/files/uploaded/Cities-SDG-Guide.pdf.
4. United Nations (2016). Habitat III: draft new urban agenda. http://habitat3.org/wp-content/uploads/NUA-English.pdf.
5. International Resources Panel (2018). The Weight of Cities. Resource Requirements of Future Urbanization (United Nations Environment Program).
6. United Nations (2020). Global indicator framework for the sustainable development goals and targets of the 2030 agenda for sustainable development, A/RES/71/313. https://unstats.un.org/sdgs/indicators/indicators-list/.
7. United Nations (2015) Transforming Our World: The 2030 Agenda for Sustainable Development, A/RES/70/1.
8. High-Level Panel on Water (2018). Making Every Drop Count: an Agenda for Water Action, United Nation High-level Panel on Water Outcome Document. https://sustainabledevelopment.un.org/content/documents/17825HLPW_Outcome.pdf.
9. Bhaduri, A., Bogardi, J., Siddiqi, A., Voigt, H., Vörösmarty, C., Pahl-Wostl, C., Bunn, S.E., Shrivastava, P., Lawford, R., Foster, S., et al. (2016). Achieving sustainable development goals from a water perspective. Front. Environ. Sci. *4*, https://doi.org/10.3389/fenvs.2016.00064/full.
10. Asian Development Bank (2016). Asian Water Development Outlook 2016: Strengthening Water Security in Asia and the Pacific. Asian Development Bank, ISBN 978-92-9257-543-4.
11. Pahl-Wostl, C., Gupta, J., and Bhaduri, A. (2016). Water security: a popular but contested concept. Ch. 1. In Handbook on Water Security, C. Pahl-Wostl, A. Bhaduri, J. Gupta, and E. Elgar, eds. (Edward Elgar).
12. de Haan, F.J., Rogers, B.C., Frantzeskaki, N., and Brown, R.R. (2015). Transitions through a lens of urban water. Environ. Innov. Soc. Transit. *15*, 1–10, https://doi.org/10.1016/j.eist.2014.11.005.
13. Pahl-Wostl, C. (2007). Transitions towards adaptive management of water facing climate and global change. Water Resour. Manage. *21*, 49–62.
14. Wong, T.H.F. (2016). Human Settlements—A Framing Paper for the UN/World Bank High-Level Panel on Water (Australian Water Partnership), p. 15, ISBN 978-1-921543-20-3.
15. Ferguson, B.C., Brown, R.R., Frantzeskaki, N., de Haan, F.J., and Deletic, A. (2013). The enabling institutional context for integrated water management: lessons from Melbourne. Water Res. *47*, 7300–7314, https://doi.org/10.1016/j.watres.2013.09.045.
16. de Haan, F.J., Ferguson, B.C., Adamowicz, R.C., Johnstone, P., Brown, R.R., and Wong, T.H.F. (2014). The needs of society: a new understanding of transitions, sustainability and liveability. Technol. Forecast. Soc. Change *85*, 121–132, https://doi.org/10.1016/j.techfore.2013.09.005.
17. Water Services Association of Australia (2019). Urban water update 2019: drought, growth and liveability. https://www.wsaa.asn.au/publication/urban-water-update-2019-drought-growth-and-liveability.
18. Liu, L., and Jensen, M.B. (2018). Green infrastructure for sustainable urban water management: practices of five forerunner cities. Cities *74*, 126–133.
19. Brown, R., Keath, N., and Wong, T. (2009). Urban water management in cities: historical, current and future regimes. Water Sci. Technol. *59*, 847–855.
20. Wong, T., and Brown, R. (2009). The water sensitive city: principles for practice. Water Sci. Technol. *60*, 673–682.
21. Jiang, Y., Zevenbergen, C., and Ma, Y. (2018). Urban pluvial flooding and stormwater management: a contemporary review of China's challenges and "sponge cities" strategy. Environ. Sci. Policy *80*, 132–143.
22. Biswas, A.K., and Hartley, K. (2017). China's 'sponge cities' aim to re-use 70% of rainwater—here's how, China Dialogue. https://chinadialogue.net/en/cities/10063-china-s-sponge-cities-aim-to-re-use-7-of-rainwater-here-s-how-2/?gclid=EAIaIQobChMIjeqbtqnk6QIVMdWWCh3T9gCSEAAYASAAEgLozvD_BwE.
23. Chye, K.T. (2018). The Active, Beautiful, Clean Waters Programme: Water as an Environmental Asset (Centre for Liveable Cities, Urban Systems Studies books). https://www.clc.gov.sg/docs/default-source/urban-systems-studies/rb172978-mnd-abc-water.pdf.
24. Public Utilities Board. https://www.pub.gov.sg/abcwaters.
25. US Department of Housing and Urban Development; NAHB Research Centre (2013). The Practice of Low Impact Development (BiblioGov), ISBN 978-1288919659.
26. City of Vancouver (2019). Rain City Strategy: a green rainwater infrastructure and rainwater management initiative. https://vancouver.ca/files/cov/rain-city-strategy.pdf.
27. Ferguson, B.C., Frantzeskaki, N., and Brown, R.R. (2013). A strategic program for transitioning to a Water Sensitive City. Landsc. Urban Plan. *117*, 32–45.
28. Prime Minister's Science, Engineering and Innovation Council (2007). Water for Our Cities: Building Resilience in a Climate of Uncertainty (Prime Minister's Science, Engineering and Innovation Council, Australia). http://www.dest.gov.au/sectors/science_innovation/publications_resources/profiles/water_for_our_cities.htm.
29. International Water Association (2016). Desalination—the Australian experience. https://iwa-network.org/news/desalination-australian-experience/.
30. CRC for Water Sensitive Cities (2017). CRCWSC receives top industry award for innovation. https://watersensitivecities.org.au/content/crcwsc-receives-top-industry-award-innovation/.
31. Liang, R., Di Matteo, M., Maier, H.R., and Thyer, M.A. (2019). Real-time, smart rainwater storage systems: potential solution to mitigate urban flooding. Water *11*, 2428.
32. Quigley, M., and Brown, C. (2014). Transforming Our Cities: High-Performance Green Infrastructure Report No. INFR1R11 (Water Environment Research Foundation).
33. Han, M.Y., and Mun, J.S. (2011). Operational data of the star city rainwater harvesting system and its role as a climate change adaptation and a social influence. Water Sci. Technol. *63*, 2796–2801. https://pdfs.semanticscholar.org/70ea/076daaa1b5b6b0421d02b572fd61bdef2b53.pdf?_ga=2.174851746.1227376181.1600754028-1389010620.1600754028.
34. Lovell, S.T., and Taylor, J.R. (2013). Supplying urban ecosystem services through multifunctional green infrastructure in the United States. Landsc. Ecol. *28*, 1447–1463.
35. Lund, N.S.V., Borup, M., Madsen, H., Mark, O., Arnbjerg-Nielsen, K., and Mikkelsen, P.S. (2019). Integrated stormwater inflow control for sewers and green structures in urban landscapes. Nature Sustainability *2*, 1003–1010, https://doi.org/10.1038/s41893-019-0392-1.

36. Cohen-Shacham, E., Janzen, C., Maginnis, S., and Walters, G. (2016). Nature-based Solutions to Address Global Societal Challenges (ICUN). https://doi.org/10.2305/IUCN.CH.2016.13.en.

37. Hoyer, J., Dickhaut, W., and Kronawitter, B.W. (2011). Water Sensitive Urban Design: Principles and Inspiration for Sustainable Stormwater Management in the City of the Future (jovis Verlag GmbH), ISBN 978-3-86859-106-4.

38. (2018). C40 cities case study, Singapore: bio-engineering works at Bishan-Ang Mo Kio Park to prevent urban flooding. https://www.c40cities.org/case_studies/singapore-bio-engineering-works-at-bishan-ang-mo-kio-park-to-prevent-urban-flooding.

39. (2018). Projects by Herbert Dreiseitl. http://www.dreiseitl.com/en/portfolio.

40. Turenscape Landscape Architecture. Landezine: landscape architect platform. http://landezine.com/index.php/landscape-architects/turenscape-landscape-architecture/.

41. Yu, K. (2014). Design paths to ecological urbanism: comparative case studies of Zhongshan Shipyard Park and Tianjin Qiaoyuan Park, lecture at MIT ecological urbanism: fall. http://web.mit.edu/nature/projects_14/pdfs/2014-KonjianYuChinaCases-Ma.pdf.

42. Brown, R.R., and Clarke, J. (2007). Transition to Water Sensitive Urban Design: The Story of Melbourne, Report No. 07/1. Facility for Advancing Water Biofiltration (Monash University).

43. Brown, R.R., Farrelly, M.A., and Loorbach, D.A. (2013). Actors working the institutions in sustainability transitions: the case of Melbourne's stormwater management. Glob. Environ. Change *23*, 701–718.

44. Tan, N.S., Wong, T.H.F. (2009). Active, beautiful and clean (ABC) waters programme: towards sustainable stormwater management in Singapore, keynote. Proceedings of the 6th International Water Sensitive Urban Design Conference and Hydropolis #3, 5–8 May, 2009.

45. Cooperative Research Centre for (2019). Water Sensitive Cities https://watersensitivecities.org.au/.

46. Newton, P.W., and Rogers, B.C. (2020). Transforming built environments: towards carbon neutral and blue-green cities. Sustainability *12*, 4745.

47. Cooperative Research Centre for Water Sensitive Cities (2020) https://watersensitivecities.org.au/solutions/water sensitive-cities-case-studies/.

48. CRC for Water Sensitive Cities (2015). What Is the Best Mix for Our Urban Water Supply? (Cooperative Research Centre for Water Sensitive Cities). https://watersensitivecities.org.au/wp-content/uploads/2016/05/IN_A1-1_BestMixUrbanWaterSupply.pdf, Accessed 1 July 2020.

49. Leroux, A.D., and Martin, V.L. (2016). Hedging supply risks: an optimal water portfolio. Am. J. Agric. Econ. *98*, 276–296.

50. CRC for Water Sensitive Cities (2018). Victorian Government endorses stormwater committee recommendations. https://watersensitivecities.org.au/content/victorian-government-endorses-stormwater-committee-recommendations/.

51. Franco-Torres, M., Rogers, B.C., and Ugarelli, R.M. (2020). A framework to explain the role of boundary objects in sustainability transitions. Environ. Innov. Soc. Transit. *36*, 34–48.

52. Wong, T. (2016). How Developing Cities Can Meet the Challenges of the 21st Century (Asian Development Blog). https://blogs.adb.org/blog/how-developing-cities-can-meet-challenges-21st-century.

53. Meadows, D. (1999). Leverage Points: Places to Intervene in a System (The Sustainability Institute). http://donellameadows.org/wp-content/userfiles/Leverage_Points.pdf.

54. Stone, B. (2005). Urban heat and air pollution—an emerging role for planners in the climate change debate. J. Am. Plann. Assoc. *71*, 13–25.

55. Caprotti, F. (2018). Future cities: moving from technical to human needs. Palgrave Commun. *4*, 35.

56. Annan-Diab, F., and Molinari, C. (2017). Interdisciplinarity: practical approach to advancing education for sustainability and for the sustainable development goals. Int. J. Manage. Educ. *15* (2 Part B), 73–83.

57. Bursztyn, M., and Drummon, J. (2014). Sustainability science and the university: pitfalls and bridges to interdisciplinarity. Environ. Educ. Res. *20*, 313–332.

58. Brown, R.R., Deletic, A., and Wong, T.H.F. (2015). How to catalyse collaboration. Nature *525*, 315–317.

59. Rogers, B.C., Bertram, N., Gersonius, B., Gunn, A., Lowe, R., Murphy, C., Pasman, R., Radhakrishnan, M., Urich, C., Wong, T., and Arnbjerg-Nielsen, K. (2020). An interdisciplinary and catchment approach to enhancing urban flood resilience: a Melbourne case. Philos. Trans. A Math. Phys. Eng. Sci *378*, 20190201.

60. Buhl, A., Schmidt-Keilich, M., Muster, V., Blazejewski, S., Schrader, U., Harrach, C., Schäfer, M., and Süßbauer, E. (2019). Design thinking for sustainability: why and how design thinking can foster sustainability-oriented innovation development. J. Clean. Prod. *231*, 1248–1257.

61. CRC for Water Sensitive Cities (2020). Ideas and innovation: research synthesis for industry (CRC for Water Sensitive Cities). https://watersensitivecities.org.au/solutions/research-synthesis/.

62. Bertram, N., and Murphy, C. (2019). In Time with Water: Design Studies of 3 Australian Cities (UWA Publishing).

63. CRC for Water Sensitive Cities (2017). https://watersensitivecities.org.au/content/project-irp1/.

64. Rogers, B., and Hammer, K. (2019). Realising the vision of a water sensitive city, Source Magazine: 15 April 2019, International Water Association https://www.thesourcemagazine.org/realising-the-vision-of-a-water sensitive-city/.

65. Rogers, B.C., Dunn, G., Hammer, K., Novalia, N., de Haan, F.J., Brown, L., Brown, R.R., Lloyd, S., Urich, U., Wong, T.H.F., and Chesterfield, C. (2020). Water Sensitive Cities Index: a diagnostic tool to assess water sensitivity and guide transitions. Water Res. https://doi.org/10.1016/j.watres.2020.116411.

66. Brown, R., Rogers, B., and Werbeloff, L. (2016). Moving toward Water Sensitive Cities: A Guidance Manual for Strategists and Policy Makers (Cooperative Research Centre for Water Sensitive Cities). https://watersensitivecities.org.au/wp-content/uploads/2016/05/TMR_A4-1_MovingTowardWSC.pdf.

67. Brown, R.R., Rogers, B.C., and Werbeloff, L. (2017). A framework to guide transitions to water sensitive cities. In Urban Sustainability Transitions: Australian Cases-International Perspectives. In Theory and Practice of Urban Sustainability Transitions, T. Moore, F.J. Haan, R. Horne, and B. Gleeson, eds. (Springer), pp. 129–148.

68. Rogers, B.C., Gunn, A., Church, E., Hammer, K., and Lindsay, J. (2018). Vision and Transition Strategy for a Water Sensitive Bendigo (Cooperative Research Centre for Water Sensitive Cities).

69. Hammer, K., Rogers, B.C., and Chesterfield, C. (2018). Vision and Transition Strategy for a Water Sensitive Greater Perth (Cooperative Research Centre for Water Sensitive Cities).

70. CRC for Water Sensitive Cities (2018). Achieving a water sensitive Perth: local champions meet with Water Minister. https://watersensitivecities.org.au/content/achieving-water sensitive-perth-local-champions-meet-water-minister/.

71. Department of Water and Environmental Regulation (2019). Waterwise Perth: Two Year Action Plan (Government of Western Australia). https://www.wa.gov.au/sites/default/files/2020-06/Waterwise-perth-action-plan.pdf.

72. Water Sensitive Transition Network (2019). Vision and Transition Strategy for a Water Sensitive Greater Perth—Implementation Plan 2019–2021 (Cooperative Research Centre for Water Sensitive Cities). https://watersensitivecities.org.au/content/vision-and-transition-strategy-for-a-water sensitive-greater-perth-implementation-plan/.

73. Kivimaa, P., Bergek, A., Matschoss, K., and van Lente, H. (2020). Intermediaries in accelerating transitions: introduction to the special issue. Environ. Innov. Sustain. Trans. https://doi.org/10.1016/j.eist.2020.03.004.

74. Markard, J., Geels, F.W., and Raven, R. (2020). Challenges in the acceleration of sustainability transitions. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/ab9468.

75. Chesterfield,C., Tawfik,S., Brotchie,R., Rogers,B., Malekpour,S., Grodach,C., Murphy,C., Bertram,N. (2019). Guiding integrated urban and water planning. In Proceedings of the Ozwater19, Australian Water Association, Melbourne, Australia, 7–9 May 2019.

76. Bai, X., Dawson, R.J., Urge-Vorsatz, D., Delgado, G.C., Barau, A.S., Dhakal, S., Dodman, D., Leonardsen, L., Masson-Delmotte, V., Roberts, D.C., and Schultz, S. (2018). Six research priorities for cities and climate change. Nature *555*, 23–25.

77. Eggimann, S., Mutzner, L., Wani, O., Schneider, M.Y., Spuhler, D., de Vitry, M.M., et al. (2017). The potential of knowing more: a review of data-driven urban water management. Environ. Sci. Technol. *51*, 2538–2553.

78. Vlachokyriakos, V., Crivellaro, C., Le Dantec, C., Gordon, E., Wright, P., Olivier, P. (2016). Digital civics: citizen empowerment with and through technology. Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems, 7 May 2016, pp. 1096–1099.

79. Sedlak, D. (2014). Water 4.0: The Past, Present, and Future of the World's Most Vital Resources (Yale University Press), p. 331pp.

80. Hoffman, S., Feldmann, U., Bach, P.M., Binz, C., Farrelly, M., Frantzeskaki, N., Hiessl, H., Inauen, J., Larsen, T.A., Lienert, J., et al. (2020). A research agenda for the future of urban water management: exploring the potential of nongrid, small-grid, and hybrid solutions. Environ. Sci. Technol. *54*, 5312–5322.
81. Institution of Engineers Australia (2001). Australian Rainfall and Runoff, A Guide to Flood Estimation, Book 8 (Urban Stormwater Management), p. 78.
82. CRC for Water Sensitive Cities (2015). Ideas for Fishermans Bend (Cooperative Research Centre for Water Sensitive Cities). https://watersensitivecities.org.au/wp-content/uploads/2016/04/Ideas-for-FishermansBend-REPORT.pdf.
83. Cai, X., Wallington, K., Shafiee-Jood, M., and Marston, L. (2018). Understanding and managing the food-energy-water nexus—opportunities for water resources research. Adv. Water Resour. *111*, 259–273.
84. Geetha, S., and Gouthami, S. (2017). Internet of things enabled real time water quality monitoring system. Smart Water *2*, 1.
85. Xu, G., Shi, Y., Sun, X., and Shen, W. (2017). Internet of things in marine environment monitoring: a review. Sensors *19*, 1711.
86. Conejos Fuertes, P., Martinez Alxamora, F., Hervas Carot, M., and Alonso Campos, J.C. (2020). Building and exploiting a digital twin for the management of drinking water distribution networks. Urban Water J. https://doi.org/10.1080/1573062X.2020.1771382.
87. Rauch, W., Urich, C., Bach, P.M., Rogers, B.C., de Haan, F.J., Brown, R.R., Mair, M., McCarthy, D.T., Kleidorfer, M., Sitzenfrei, R., and Deletic, A. (2017). Modelling transitions in urban water systems. Water Res. *126*, 501–514.
88. Mori, K., and Christodoulou, A. (2012). Review of sustainability indices and indicators: towards a new City Sustainability Index (CSI). Environ. Impact Assess. Rev. *32*, 94–106.
89. Renouf, M.A., Kenway, S.J., Lam, K.L., Weber, T., Roux, E., Serrao-Neumann, S., Low Choy, D., and Morgan, E.A. (2018). Understanding urban water performance at the city-region scale using an urban water metabolism evaluation framework. Water Res. *137*, 395–406.
90. Frantzeskaki, N., McPhearson, T., Collier, M.J., Kendal, D., Bulkeley, H., Dumitru, A., Walsh, C., Noble, K., van Wyk, E., Ordonez, C., et al. (2019). Nature-based solutions for urban climate change adaptation: linking science, policy, and practice communities for evidence-based decision-making. BioScience *69*, 455–466.
91. Dean, A.J., Lindsay, J., Fielding, K.S., and Smith, L.D.G. (2016). Environ. Sci. Policy *55*, 238–247.
92. Jackson, S., and Moggridge, B. (2019). Indigenous water management. Australas. J. Environ. Manage. *26*, 193–196.
93. Arsenault, R., Diver, S., McGregor, D., Witham, A., and Bourassa, C. (2018). Shifting the framework of Canadian water governance through indigenous research methods: acknowledging the past with an eye on the future. Water *10*, 49.
94. Lindsay, J., Rogers, B.C., Church, E., Gunn, A., Hammer, K., Dean, A.J., and Fielding, K. (2019). The role of community champions in long-term sustainable urban water planning. Water *11*, 476.
95. Mackenzie, J., Tan, P.L., Hovernman, S., and Baldwin, C. (2012). The value and limitations of Participatory Action Research methodology. J. Hydrol. *474*, 11–21.
96. Megdal, S.B., Eden, S., and Shamir, E. (2017). Water governance, stakeholder engagement and sustainable water resources management. Water *9*, 190.
97. Iftekhar, M.S., Gunawardena, A., Fogarty, F., Pannell, D., and Rogers, A. (2019). INFFEWS Value Tool: Guideline (Version 2): IRP2 Comprehensive Economic Evaluation Framework (2017–2019) (Cooperative Research Centre for Water Sensitive Cities).
98. Speight, V.L. (2015). Innovation in the water industry: barriers and opportunities for US and UK utilities. WIREs Water *2*, 301–313.
99. Furlong, K., and Bakker, K. (2010). The contradictions in 'alternative' service delivery: governance, business models, and sustainability in municipal water supply. Environ. Plann. C Polit. Space *28*, 349–368.
100. Sousa-Zomer, T.T., and Miguel, P.A.C. (2018). Sustainable business models as an innovation strategy in the water sector: an empirical investigation of a sustainable product-service system. J. Clean. Prod. *171*, S119–S129.