Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Water Sensitive Cities Index: A diagnostic tool to assess water sensitivity and guide management actions

B.C. Rogers, G. Dunn, W. Novalia, F.J. de Haan, L. Brown, R.R. Brown, K. Hammer, S. Lloyd, C. Urich, T.H.F. Wong, C. Chesterfield

PII: S2589-9147(20)30023-2
DOI: https://doi.org/10.1016/j.wroa.2020.100063
Reference: WROA 100063

To appear in: Water Research X

Received Date: 30 March 2020
Revised Date: 23 July 2020
Accepted Date: 16 August 2020

Please cite this article as: Rogers, B.C., Dunn, G., Novalia, W., de Haan, F.J., Brown, L., Brown, R.R., Hammer, K., Lloyd, S., Urich, C., Wong, T.H.F., Chesterfield, C., Water Sensitive Cities Index: A diagnostic tool to assess water sensitivity and guide management actions, Water Research X (2020), doi: https://doi.org/10.1016/j.wroa.2020.100063.

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2020 Published by Elsevier Ltd.
A benchmarking and diagnostic tool to assess the water sensitivity of cities and guide the development of management responses

Bring stakeholders together in a deliberative process

Assess city’s water sensitive performance using the WSC Index

Design management responses for priority indicators

Learn from the experiences and successes of other benchmarked cities

- Target
- Action
- Action
- Target
- Action
- Action
- Target
- Action
- Action
Water Sensitive Cities Index:
A diagnostic tool to assess water sensitivity and guide management actions

B.C. Rogers*1,2,3, G. Dunn1,2,4, W. Novalia1,2, F.J. de Haan1,2, L. Brown1,5, R.R. Brown1,3, K. Hammer1,2, S. Lloyd1,6, C. Urich1,7, T.H.F. Wong1, C. Chesterfield1

1 Cooperative Research Centre for Water Sensitive Cities, Melbourne, Australia
2 School of Social Sciences, Monash University, Melbourne, Australia
3 Monash Sustainable Development Institute, Monash University, Melbourne, Australia
4 Uisce Consulting International, Vancouver, Canada
5 Foundry Associates, Melbourne, Australia
6 e2designlab, Melbourne, Australia
7 Department of Civil Engineering, Monash University, Melbourne, Australia

* Corresponding author: email briony.rogers@monash.edu, phone +61 3 99052581

Abstract:
Cities are wrestling with the practical challenges of transitioning urban water services to become water sensitive; capable of enhancing liveability, sustainability, resilience and productivity in the face of climate change, rapid urbanisation, degraded ecosystems and ageing infrastructure. Indicators can be valuable for guiding actions for improvement, but there is not yet an established index that measures the full suite of attributes that constitute water sensitive performance. This paper therefore presents the Water Sensitive Cities (WSC) Index, a new benchmarking and diagnostic tool to assess the water sensitivity of a municipal or metropolitan city, set aspirational targets and inform management responses to improve water sensitive practices. Its 34 indicators are organised into seven goals: ensure good water sensitive governance, increase community capital, achieve equity of essential services, improve productivity and resource efficiency, improve ecological health, ensure quality urban spaces, and promote adaptive infrastructure. The WSC Index design as a quantitative framework based on qualitative rating descriptions and a participatory assessment methodology enables local contextual interpretations of the indicators, while
maintaining a robust universal framework for city comparison and benchmarking. The paper
demonstrates its application on three illustrative cases. Rapid uptake of the WSC Index in
Australia highlights its value in helping stakeholders develop collective commitment and
evidence-based priorities for action to accelerate their city’s water sensitive transition. Early
testing in cities in Asia and the Pacific has also showed the potential of the WSC Index
internationally.

**Key words:**

benchmarking; integrated water management; nature-based solutions; performance
indicators; sustainability assessment; transitions
1. Introduction

There is growing emphasis globally on the importance of urban water services in enhancing a city’s liveability, sustainability, resilience and productivity (Farrelly and Brown 2011; Rijke et al., 2013). Achieving these outcomes, particularly against the backdrop of climate change (Vorosmarty, 2010; Hoekstra et al. 2012), rapid urbanisation (Eliasson, 2012), degraded ecosystems (Bouleau et. al., 2009), and ageing infrastructure (OECD, 2015; Vaux 2015), requires a fundamental shift in the way water system services are planned, designed and delivered (Ashley et al., 2013; Brown et al., 2009). There is now broad scholarly consensus that integrated and adaptive approaches to urban water services are needed to improve flexibility and agility for coping with unpredictability and change, while delivering multi-functional benefits that support social wellbeing, healthy ecosystems and strong economies.

While different terms are used in water management literature to represent combinations of these attributes, in this paper, we refer to them as water sensitive.

Despite this consensus, cities around the world are wrestling with the practical challenges of shifting urban water services in a water sensitive direction. Guiding and motivating action for change is difficult, as existing structures and processes often reinforce conventional practices (Farrelly and Brown 2011; Van de Meene et al., 2011). Even when there are good intentions and policy aspirations, it can be difficult to achieve coordinated and aligned action across multiple organisations (Ferguson et al. 2013a). Decisions-makers within water utilities and city governments are in need of more targeted and tailored insight to guide collective local efforts to overcome existing institutional and infrastructure challenges as cities transition from conventional to water sensitive practices (Ferguson et al. 2013a). How should activities and investments be prioritised? What measures and targets can be used to
monitor and assess progress? Which structures and processes support and enable cross-sectoral collaboration and inclusive planning and design solutions?

Indicators have been shown to be valuable for guiding system changes by: reducing ambiguity and enabling effective and clear communication amongst diverse interests (McCool and Stankey, 2004); assessing and quantifying performance (Spiller 2016); providing early warnings (Spiller 2016); giving feedback on the effects of policies (Chiras and Corson, 1997; Swanson et al., 2010), and co-constructing visions and evaluating pathways towards desired societal change (Lehtonen et al., 2016). However, the assessment of city sustainability is not a well-established practice (Marques et al., 2012), the conditions for assessing city sustainability are ambiguous (Mori & Christodoulou, 2012), and there is misalignment between future city visions and available performance indicators (Renouf et al., 2017). Moreover, complex urban challenges and stakeholder interests means processes for identifying priorities, negotiating trade-offs and tracking progress, are important aspects of sustainable water management, but often overlooked in the development and application of indicators.

Against this background, our paper presents the development of the Water Sensitive Cities (WSC) Index, a new benchmarking and diagnostic tool developed by the Cooperative Research Centre for Water Sensitive Cities¹ (CRCWSC). The WSC Index is designed to facilitate assessment of the water sensitivity of a city (from the scale of local municipality to large metropolitan centre), set targets based on best available research, and inform

¹ An interdisciplinary research program funded by the Australian Government and industry partners, 2012-2021, AUD 120 million (www.watersensitivecities.org.au)
management responses to improve water sensitive practices. The tool can support strategic
planning and decision-making, foster inter-city learning and enable governments to assess
their cities’ urban water management trajectories in relation to other cities.

The theoretical underpinning of the WSC Index framework is presented in Section 2,
followed by a summary of the development approach in Section 3. The WSC Index goals and
indicators are outlined in Section 4. A case study application of the WSC Index in three
diverse Australian cities is illustrated in Section 5. Insights from applications of the WSC
Index to date and further development needs are discussed in Section 6, followed by a
conclusion in Section 7. This paper will be of interest to scholars, policy-makers and
practitioners of urban water management, and sustainability assessment more broadly.

2. Background

In setting out to develop a WSC Index that can meaningfully guide policy and action for
driving water sensitive transitions, it is important to define what attributes of a water
system will need measurement, as well as to learn from the experiences of existing indicator
initiatives.

The WSC vision is underpinned by three principles of practices (Wong and Brown, 2009): (1)
Understanding cities as catchments to provide resources at different scales in fit-for-
purpose applications; (2) Cities providing ecosystem services to integrate urban water
management into the urban landscape, providing multiple benefits such as heat mitigation,
ecological health and landscape amenity; and (3) Water-conscious communities, where
citizens value and are connected to their water environments and engage in water-
conscious behaviours, and water, planning and design professionals work collaboratively to deliver water sensitive outcomes.

The heuristic in Figure 1 demonstrates the transitions in water service delivery functions that are needed to respond to evolving socio-political drivers, culminating in the WSC. The first three stages of the embedded continuum describe the evolution of the water system to provide essential services such as secure access to potable water (water supply city), public health protection (sewered city) and flood protection (drained city). These are followed by the waterways city, water cycle city and ultimately a WSC, which describe the anticipated and aspirational evolution of the urban water system to deliver higher order services such as social amenity and environmental protection, provide reliable water services under constrained resources, and ensure intergenerational equity and resilience to climate change. Defining features of the WSC that go beyond the pollution management function of the waterways city, and integrated water cycle management function of the water cycle city include: water infrastructure designed sensitively into the urban landscape to deliver multi-functional liveability and ecological benefits, adaptive planning and management based on flexible, hybrid solutions to increase resilience, and communities that are active in caring for their water resources and environments.
While cities and metropolitan areas are awash in indicators, which have proliferated since the 1987 Brundtland Commission report (Böhringer and Jochem, 2007; Dunn and Bakker, 2011), there are not yet agreed metrics that define the WSC concept and its constituent collection of attributes. Without such measures, stakeholders will struggle to operationalise their shared WSC vision, lack comprehensive insight on current system performance, and receive limited guidance on priorities for action to progress their water sensitive transition.

As a crosscutting issue, water-related metrics are found in indicator initiatives for sustainability, urban greening, city governance, vulnerability, resilience and liveability. These provide a useful starting point for considering the assessment of a city’s water sensitive performance. Table 1 highlights the components of water sensitivity in notable water-related indicators, mapped against the six city-states in Figure 1.

Figure 1. Urban Water Transitions Framework (Brown et al., 2009, reproduced with permission from journal)
Table 1: Notable water-related indicators

| Index and indicator examples                                                                 |
|---------------------------------------------------------------------------------------------|
| Water Supply City                                                                           |
| Sewered City                                                                               |
| Drained City                                                                               |
| Waterways City                                                                             |
| Water Cycle City                                                                           |
| Water Sensitive City                                                                        |
| Water Stress Index (Falkenmark, 1989)                                                       |
| Drinking Water Quality Index (e.g., UN, WHO and CCME)                                       |
| Water Availability Index (Jiménez-Cisneros, 1996)                                           |
| Climate Vulnerability Index (Sullivan and Meigh, 2005)                                      |
| Green-Blue Water Scarcity Index (Gerten et al., 2011)                                       |
| Percentage of city population served by wastewater collection and treatment (e.g. UN and OECD Statistics) |
| Basic Human Needs Index (Gleick, 2009)                                                      |
| International Wealth Index (Smits and Steendijk, 2013)                                      |
| The Water, Economy, Investment and Learning Assessment Indicator (WEILAI) (Cohen and Sullivan, 2010) |
| The Green City Index (Economist Intelligence Unit and Siemens AG)                           |
| Sustainable Society Index                                                                  |
| Swedish Sustainability Index for Municipal Water and Wastewater Services                    |
| Global reporting Initiative 303: Water and Effluents (2018)                                 |
| Canadian Environmental Sustainability Indicators (2019)                                     |
| Environmental Vulnerability Index (UNEP)                                                    |
| Environmental Performance Index (Yale University)                                          |
| The Watershed Sustainability Index (Chaves and Alipaz, 2006)                               |
| Index of Watershed Indicators (US EPA 2002)                                                |
| Sustainable Development of Energy, Water, and Environment Systems (SDEWES) City Index       |
| Water Poverty Index (Sullivan, 2002; Sullivan et al., 2003)                                |
| Water Security Status Indicators (Norman et al. 2012)                                      |
| Flood Vulnerability Index (Hara et al., 2009)                                              |
| Flood risk indicator (e.g. HM Land Registry, UK)                                           |
| Global Flood Risk Index (Okazawa et al., 2011)                                             |
| Aqueduct Water Risk Atlas (World Resources Institute)                                     |
| Canadian Water Sustainability Index (PRI, 2007)                                             |
| Wellbeing/Stress Index (IUCN)                                                              |
| Indicators of Urban Green Infrastructure (European Environment Agency 2017)                |
| Sustainable Cities Water Index (Arcadis)                                                    |
| Clean and Safe Water - Ecocity Standards Level 1                                            |
| City Resilience Index (Arup and the Rockefeller Foundation)                               |
| City Blueprint (van Leeuwen 2013; Feingold et al., 2016)                                   |
Table 1 shows that while many established indices measure multiple aspects of water service performance, they have not been designed to assess the full suite of attributes that constitute water sensitive performance. They typically either focus too specifically on a particular water servicing attribute (e.g. compliance with drinking water quality standards, level of wastewater treatment) for effective evaluation of water sensitive city policies and practices, or they are too broad in scope to pay significant attention to water. There are several notable gaps in available measures that would be important for assessing water sensitivity: a dearth of indicators for nature-based solutions, which are widely seen as important elements of urban sustainability, climate change adaptation, and land use planning (EPA, 2014); limited green or grey-green infrastructure indicators (e.g. De Ridder et al 2004); and, while stormwater is often implied within wastewater quality indicators, there are few indicators of physical, hydrological or biological changes to measure the cumulative effects of urban runoff.

Within the past decade, a handful of frameworks have been developed that facilitate a broader understanding of sustainable urban water management or have relevance to water sensitive principle (see bottom rows of Table 1). The Ecocity Standards ‘Clean and Safe Water’ examines water demand in relation to supply, emphasising resource constraints, the importance of integrated water management (including stormwater as a resource), pricing and ecological health. However the Ecocity Standards does not provide tools, guidance or methodology to enable practitioners to benchmark progress toward the ten levels proposed, which the standards recognise are context specific. The Sustainable Cities Water

---

2 The most prominent are the two indicators developed by the European Environment Agency (EEA) to capture the range of benefits that green infrastructure afford urban areas. These include climate adaptation and mitigation, multiple ecosystem services (e.g. biodiversity), and improvements to public health and wellbeing through proximity to green urban spaces.
Index (SCWI) developed by Arcadis is intended to be a global ranking tool. The Index centres around three key sub-indices for water sustainability: resiliency, efficiency, and quality, which are further supported by a series of sub-indices and indicators such as disaster risk, water charges, green space and pollution. SCWI focuses on resources, public health and the economic dimensions of water but does not include social and governance aspects of integrated water management. Arup’s City Resilience Index comprises 52 indicators (across 12 goals) that measure and assess multiple factors contributing to urban resilience, including water and sanitation services, flood resilience and ecosystem stewardship (Arup, 2019). There are additional indicators for leadership and strategy; economy and society; health and wellbeing, although these are broader city resilience indicators that are not specific to water. The City Blueprint Approach comprises three frameworks: Trends and Pressures Framework (TPF) with 12 descriptive trends and pressure indicators, the City Blueprint Framework (CBF) with 7 categories and 25 indicators, and the Governance Capacity Framework (GCF) (van Leeuwen et al., 2016; Feingold et al. 2018). The CBF enables a baseline assessment of the sustainability of urban water resources management and is intended as a first step or quick-scan to benchmark the sustainability of the urban water cycle and facilitate awareness of current water challenges (Koop and van Leeuwen 2015).

Whilst each of the above frameworks provide valuable insights for improving water system planning and management, none covers the full range of social, governance, economic, liveability, multi-functional and adaptive attributes that are defining attributes of water sensitivity.
Beyond these thematic gaps in existing water-related metrics in relation to water sensitive objectives, there are emerging critical perspectives on indicators highlighting their limited uptake and impact on policy and practice (Boyko et al., 2012; Lehtonen, 2013; Turnpenny et al., 2014; Diehl et al. 2016). There are various explanations for this disconnect. First, indicators often fail to meet the needs of policy and decisions-makers, as the development process does not adequately engage them or identify their information requirements (Brennin, 2007; Dunn and Bakker, 2011, Norman et al. 2012). Second, data collection methods vary between government agencies and across sectors, which can impact on the scale of assessment that is possible, and is further compounded by the scalar mismatch between administrative and hydrological boundaries (van der Zaag and Gupta, 2008; Brandeler et al., 2018). Third, spatial and temporal data gaps can make indicators difficult to calculate and limit the ability to develop baselines and threshold values, monitor trends, or understand the broader impacts of climate change and land-use practices (Hak et al., 2007). Fourth, indicator projects require long-term commitment of resources (both financial and staff) to ensure continued relevance and provide end-user support (Mayer, 2008; Dunn and Bakker, 2009). Other limitations of indicators include inadequately capturing the system’s complexity with its associated subjectivity and inherent biases (Barnett et al., 2008; Pintér et al., 2005; Sagar and Najam 1998; Mayer, 2008), as well as overlooking processes of negotiation and prioritisation that are critical for sustainability planning (Starkl et al., 2013). Furthermore, poorly constructed indicators can be misinterpreted, risking misleading or overly simplistic policy messages (OECD, 2003). These interrelated challenges mean that multifaceted indicators are often unwieldy, impractical and costly in terms of both the time

---

3 Existing datasets can be incomplete, have different parameters, and use different sampling standards and frequencies. Inconsistent data collection methods and data storage protocols limit the usability of datasets and impede data sharing and integration of datasets between different users.
and resources needed to gain valuable insights and improve decision making (Norman et al., 2012).

Drawing on these insights, and in a quest to address the identified challenges through design features to support its uptake in practice, the development of the WSC Index aimed to create a tool that: (1) is reliable and scientifically robust, (2) takes a holistic and integrative approach to assessing water sensitivity; (3) is applicable at both metropolitan and municipal council scales; (4) enables benchmarking and comparison across diverse contexts, and (5) has clear benefits and meets the practical needs of decision-makers, policy-makers and practitioners.

3. Development of the WSC Index

The WSC Index was developed over a two-year period (2014-2016) in the phases depicted in Figure 2: prototyping, refinement and piloting, trialing and industry release. The development process was guided by an industry steering committee and an internal working group consisting of CRCWSC leaders and key researchers from across the range of disciplines covered by the WSC Index. These inputs aimed to ensure that both scientific and end user considerations informed and shaped the tool.

The prototype framework for the WSC Index was developed drawing on existing water indicators and supplemented with emerging knowledge from CRCWSC research, including insights from water sensitive city envisioning processes (Ferguson et al., 2013). The inventory and analysis of existing indicators identified more than 230 individual indicators
from over 50 frameworks, organisational initiatives (e.g. the Global Indicator Facility⁴) and academic research (e.g. Sullivan, 2003). These spanned multiple scales, from global assessments (e.g. Vörösmarty et al., 2012), national measures (e.g. PRI, 2007), to municipal level initiatives (such as city report cards). The indicators most closely aligned with attributes of the WSC are shown in Table 1. For WSC performance objectives that did not have an existing associated indicator that adequately represented its intent (particularly for those more closely aligned with the water cycle city and water sensitive city), we developed a new measure that could be used to qualitatively distinguish between low and high water sensitive performance. Scientific expertise and emerging knowledge from the CRCWSC’s research network and projects were drawn on to develop these new indicators and integrated them into the prototype framework for the WSC Index.

The prototype was tested with two councils (City of Knox and City of Port Phillip) located in Melbourne, Australia. This provided detailed feedback on its usability, functionality, benefits and reliability, which led to a range of refinements and enhancements. Numerous indicators were consolidated to reduce the overall number and therefore the time and effort burden for assessment. We refined the assessment methodology in consultation with our industry partners, whose feedback was that a data-driven approach was unwieldy, inefficient and unlikely to be broadly adopted in practice—reconfirming earlier insights from literature that time-intensive and costly benchmarking processes impede uptake (Norman et al., 2012). Instead, we judged that practitioners—equipped with system knowledge and available evidence, and guided by a well-facilitated assessment process—would reach a sufficiently robust score for the purposes of benchmarking, prioritisation and action planning.

---

⁴ Source: https://www.iso.org/organization/660833.html
To this end, we developed an assessment methodology based on deliberation by local experts of available evidence to determine indicator scores. The indicator descriptions were clarified through rewording to simplify language in accordance with the prototyping participant feedback; ease of understanding was considered particularly crucial for an assessment methodology based on facilitated discussion to ensure a reliable and consistent approach to scoring across diverse cities. We developed the conceptual basis for analysing results through a number of different frameworks that would support the development of management responses. We also developed web-based software to support visualisation and interpretation of the WSC Index results.

The revised WSC Index was piloted in three locations within Greater Perth as a single metropolitan area in Australia (one case at the metropolitan scale and two cases of municipal Council areas). An 18-month industry trial period followed the pilot cases (2016-2018), during which time the WSC Index was applied to an additional 11 Australian cities. Assessments were conducted by members of the research team, who had in-depth knowledge of the framework and indicators and could provide consistent guidance to workshop participants in helping them understand the indicators and decide on the most appropriate scores. Again, minor refinements were made to the indicator rating descriptions over this period to provide greater clarity in response to participant feedback. In preparation for broad industry release of the WSC Index in early 2018, a training program and facilitation guidance were prepared. Eight industry practitioners were trained by the research team to become accredited WSC Index providers (see Supplementary Material for details on the training and accreditation process). To date, WSC Index workshops have been
facilitated by accredited providers to assess water sensitive performance and develop management responses in more than 50 cities (see Supplementary Material for the list of cities that have been benchmarked).

**Figure 2: Steps taken to develop the Water Sensitive Cities Index**

4. Presenting the WSC Index

The WSC Index offers users the ability to benchmark cities at the metropolitan or municipal scale, based on performance against a range of urban water indicators across the societal, biophysical and ecological dimensions that characterise a WSC. These insights enable cities around the world to be ranked according to their water sensitivity, as well as diagnose key areas of strength and weakness. This enables governments to assess their cities’ urban water management trajectories in relation to other cities, identify priorities for management actions and learn from other cities that are experiencing similar challenges or opportunities. The WSC Index is accessed through a web interface that provides
visualisations of the results to facilitate understanding and support communication with
broad audiences, including policy-makers, service providers and community.

4.1 WSC Index Goals and Indicators

The seven WSC Index goals are: (1) Ensure good water sensitive governance, (2) Increase
community capital, (3) Achieve equity of essential services, (4) Improve productivity and
resource efficiency, (5) Improve ecological health, (6) Ensure quality urban spaces, and (7)
Promote adaptive infrastructure. 34 indicators span these goals, collectively representing
the full suite of WSC objectives that have emerged over the last ten years in the Australian
water context\(^5\) (Table 2).

Scoring for each indicator is based on a rating from 1 to 5, assigned according to the
description that best fits the city’s current situation. Half scores (1.5, 2.5, ...) can be assigned
where the conditions are between the integer descriptions. However, scores of finer
granularity (1.1, 1.2, ...) are not assigned, since the degree of accuracy that would be implied
by such scores has little meaning in the context of the WSC Index’s key purpose of
identifying a city’s relative strengths and weaknesses to inform priorities for management
actions.

While some indicators use quantitative thresholds to inform the score (3.1, 3.2, 3.3, 4.2, 4.3,
6.3), the majority are based on qualitative thresholds. This enables assessment through

\(^5\) Early testing internationally shows that the suite of indicators is relevant in
other contexts, although potentially with some refinements. This is discussed further in
Section 6.
evidence-based judgement and provides opportunity for local expression of how the indicator may manifest in different contexts. Once priority indicators for action have been identified through the assessment process, attention can be given to defining quantitative measures relevant to the local context that correspond to its 1-5 rating so that more accurate tracking of progress can be done. As further WSCs research is conducted, including city and water practitioners testing and applying their own measures, it is anticipated that further indicator ratings descriptions could be updated to be more quantitative.

This measurement approach relies on clear methodological structure and detailed scoring guidance to ensure consistency of application for diverse conditions. Table 3 provides an example of an indicator rating description and associated scoring guidance that has been developed to prompt due consideration of relevant evidence, and to limit ambiguity when deciding on a score. The full rating descriptions for each indicator are provided as Supplementary Material.
| Table 2. WSC Index goals, indicators and strategic objectives |
|--------------------------------------------------------------|
| **Goal 1: Ensure good water sensitive governance**          |
| 1.1 Knowledge, skills and organisational capacity          |
| Strengthen the capabilities of individuals and organisations to adopt water sensitive practices through science, experimentation, learning and training. |
| 1.2 Water is key element in city planning and design       |
| Improve urban planning and design frameworks and processes to drive the implementation of water sensitive solutions through urban development. |
| 1.3 Cross-sector institutional arrangements and processes   |
| Encourage collaboration and coordination across organisations, sectors and levels of government to plan and implement water sensitive solutions. |
| 1.4 Public engagement, participation and transparency       |
| Communicate effectively with citizens and encourage their meaningful involvement of citizens in planning, decision-making and design processes. |
| 1.5 Leadership, long-term vision and commitment             |
| Articulate a water sensitive vision that links to broader city aspirations, and commit to delivering the vision through policy, strategic plans and investment. |
| 1.6 Water resourcing and funding to deliver broad societal value |
| Invest in water sensitive practices that will deliver the highest community value, including consideration of externalities and non-market values. |
| 1.7 Equitable representation of perspectives               |
| Ensure inclusiveness and representation of a diversity of perspectives in governance arrangements and decision-making |
| **Goal 2: Increase community capital**                      |
| 2.1 Water literacy                                         |
| Improve community knowledge about the water cycle and water issues so they can adopt water sensitive behaviours and participate in decision-making. |
| 2.2 Connection with water                                  |
| Foster pride and connectedness of people with water through improved understanding and appreciation of water's role in landscape. |
| 2.3 Shared ownership, management & responsibility          |
| Empower community to be an active participant in creating, operating and maintaining decentralised parts of the water system. |
| 2.4 Community preparedness and response to extreme events  |
| Support citizens to cope with and recover from impacts associated with storms, floods, drought and heatwaves. |
| 2.5 Indigenous involvement in water planning               |
| Recognise Indigenous water values and interests in water system planning and management and involve Indigenous people in water system governance. |
| **Goal 3: Achieve equity of essential services**            |
| 3.1 Equitable access to safe and secure water supply       |
| Provide safe, secure and affordable water supply services that meet the World Health Organization’s (WHO) standards for drinking water quality. |
| 3.2 Equitable access to safe and reliable sanitation       |
| Provide safe, reliable and affordable sanitation services that meet the standards for sanitation defined by the WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation. |
| 3.3 Equitable access to flood protection                    |
| Manage flood risk in a way that is affordable, including reducing nuisance flooding and protecting citizens and infrastructure from major floods. |
| 3.4 Equitable and affordable access to amenity values of    |
| Enhance amenity values associated with urban landscapes through water sensitive solutions and provide affordable access |
| Goal 4: Improve productivity & resource efficiency |  |
|-------------------------------------------------|-------------------------------------------------|
| **4.1 Optimised resource recovery** | Optimise the recovery of water, energy, heat and nutrients through circular design of water systems. |
| **4.2 Low GHG emission in water sector** | Maximise the use of alternatives to high carbon emitting energy sources in water system infrastructure. |
| **4.3 Water-related business opportunities** | Stimulate investment in new business opportunities through innovation in the water sector. |
| **4.4 Low end-user potable water demand** | Support low end-user potable water demand relative to the local scarcity or abundance of water. |
| **4.5 Broad community benefits from water services** | Stimulate beneficial outcomes of water-related services for other sectors beyond water. |

| Goal 5: Improve ecological health |  |
|---------------------------------|-------------------------------------------------|
| **5.1 Healthy and biodiverse habitat** | Design water systems to help protect, restore and create well-functioning ecosystems that contribute to ecological resilience. |
| **5.2 Surface water quality and flows** | Improve and protect the quality of surface waters and marine environments. |
| **5.3 Groundwater quality and replenishment** | Improve and protect the quality of groundwater-connected environments. |
| **5.4 Protect existing areas of high ecological value** | Protect existing areas of high ecological value from the impacts of catchment urbanisation. |

| Goal 6: Ensure quality urban space |  |
|---------------------------------|-------------------------------------------------|
| **6.1 Activating connected green-blue space** | Plan and design the urban form to create many distributed, connected and well-maintained green spaces and waterways. |
| **6.2 Urban elements functioning as part of the urban water system** | Plan and design the urban form (such as green walls, roofs, retarding basins in parks) to function as an integral part of the water system. |
| **6.3 Vegetation coverage** | Provide significant vegetation coverage (e.g. tree canopies) supported by the water system. |

| Goal 7: Promote adaptive infrastructure |  |
|---------------------------------|-------------------------------------------------|
| **7.1 Diverse fit-for-purpose water supply** | Provide a flexible and adaptive water supply system appropriate to the quality water and demand requirements of the end user. |
| **7.2 Multi-functional water infrastructure** | Provide multi-functional water infrastructure that seamlessly integrates into the urban landscape. |
| **7.3 Integration and intelligent control** | Optimise water system network performance through the use of intelligent control systems. |
| **7.4 Robust infrastructure** | Remove sensitivities and vulnerabilities in the water system network through redundancy measures and by-pass systems. |
| **7.5 Infrastructure and ownership at multiple scales** | Optimise water system performance through the integration of centralised and decentralised infrastructure. |
| **7.6 Adequate maintenance** | Improve maintenance policies and practices to ensure the long-term integrity of all water system infrastructure, including natural and green infrastructure assets. |
### Table 3. Example indicator rating descriptions and scoring guidance

| Goal | Indicator | Description |
|------|-----------|-------------|
| 3    | 3.4       | Equitable and affordable access to amenity values of water-related assets |

**Ratings:**

1: Water-related assets do not provide amenity benefits in most areas of the city. Enjoyment of available amenity benefits of assets comes at a relatively high cost for some households.

2: Water-related assets provide amenity values in some areas of the city. These areas are not easily accessible and enjoyment of these benefits comes at a relatively high cost for some households.

3: Water-related assets provide amenity values in large areas of the city. These areas are mostly accessible and come at a moderate cost for some households.

4: Water-related assets provide amenity values in most areas of the city. These areas are highly accessible and enjoyment of these benefits comes at low cost.

5: Water-related assets provide amenity values in all areas of the city and are implemented to improve lower socio-economic areas. These areas are highly accessible and enjoyment of these benefits comes at no cost.

**Key definitions**

- **Water-related assets**: natural assets (e.g. rivers, creeks, bays, beaches) and built assets (e.g. constructed wetlands, retarding basins, reservoirs, biofilters, cycle paths and walking trails beside water assets)

- **Accessibility**: people can readily access the amenity in terms of location (distribution and distance to travel), affordability (financial and time cost), universality (all people including those with a disability)

**Guiding questions**

- What amenity values are associated with water-related assets? Where are they located? Are they easily accessible?

- Are the amenity values of most water-related assets accessible to different income groups? Are there admission costs?

- How are the relative costs to enjoy such amenities distributed between different income groups?

**Examples of relevant features that may be observed**

- Waterways and water-related assets that are channelised may have few attractive elements and exclude people

- Retarding/detention basins may be single purpose and protected by fencing or alternatively, may be landscaped and incorporate community facilities such as trails and shelters

- Water reservoirs may incorporate parklands

- Coastline or inlets backing onto private property with no public access means low accessibility

**Examples of evidence**

- Policy documents and strategic plans

- GIS maps of the distribution of water assets with high amenity values

### 4.2 Assessment Methodology

While the WSC Index framework can be applied in diverse ways to provide value to city stakeholders, the CRCWSC has developed and certified a workshop process methodology for using it to benchmark the water sensitive performance of cities. It has trained and
accredited providers in this methodology (see Supplementary Material for details on the accreditation process) to ensure that the assessment approach—including how discussion amongst workshop participants is facilitated and how final indicator scores are decided on—will be consistent, regardless of who is facilitating the workshop. Cities that are assessed by an accredited provider are considered to have official benchmarks and have their scores included in the database of WSC Index results. This is creating an invaluable dataset for enabling consistent benchmarking and comparison, helping cities learn from each other as they implement management actions and supporting meta-analysis across cities to inform new research insights.

The certified assessment methodology requires involvement of at least 15 and up to 50 participants who represent different interests, functions and responsibilities from various relevant organisations— and different departments within those organisations—with water-related responsibilities in the geographic and/or socio-political area being benchmarked. Participant organisations in applications to date have included local municipalities, water utilities, consultants, developers, research institutes, and government departments including planning, environment, water, health, sports and recreation, parks and wildlife.

Figure 3 presents an overview of the assessment methodology. Prior to the workshop, participants are provided with the framework and definitions of the indicators in the WSC Index framework. They are asked to consider indicators they have particular knowledge on and to collect relevant evidence to contribute in workshop discussions; providers will often engage with their main client contact to suggest an appropriate distribution of indicators among participants. While full preparation by participants is not necessary for a successful
workshop, and the robustness of the scoring is not compromised if there has been less
preparation for some indicators, workshop discussions are enriched if participants have
done this pre-thinking.

During the workshop, scoring is done goal by goal. A workshop duration of one-day requires
some of the goals to be scored concurrently by splitting the participant group in two
separate rooms, with participants freely choosing which goals they can best contribute to
the assessment of. Within each goal, approximately 15 minutes is spent per indicator. The
facilitator introduces the indicator, explaining its intent and providing any local
interpretations and examples needed to provide clarity. Participants initially individually
score the indicator using a live polling system, drawing on their own tacit knowledge,
understanding of evidence, or opinion if they do not have access to relevant information.
Through facilitated discussion, participants then explain their scores and substantiate their
view with supporting evidence. Participants deliberate the insights and information
provided and decide on the final score based on (near-)consensus. There may be some
disagreement amongst participants on the final score, although rarely by more than 0.5
difference in the applications to date. This is not considered problematic, however, as
accuracy of the score itself is less important than having a sound basis for identifying a city’s
relative strengths and weaknesses, and understanding the issues that need to be addressed
through management actions. At this point, the degree of confidence in the score is noted
for reference in the development of management actions and WSC Index applications in the
future: ‘high’ means consensus and supported by strong evidence, ‘medium’ means
consensus but lack of evidence, and ‘low’ means lack of both consensus and evidence.
The assessment method allows a diversity of perspectives and opinions to be revealed and explored, while inviting critical reflection on the available evidence to then lead to a collective decision on the score. At the end of the workshop, overall results are shared with the participants and preliminary reflection amongst the group is facilitated to begin the process of collective sense-making and identification of priorities. This process is typically expanded after the workshop by the WSC Index provider, who may prepare a report that provides more in-depth analysis of the results and recommended strategies and actions.

![Figure 3: Participatory process for applying the Water Sensitive Cities Index](image)

Instead of the collaborative workshop process described above, the scoring could be undertaken by an informed individual or expert panel, for example. However, a cautionary note: a single individual is unlikely to have the necessary in-depth understanding or access to evidence across all goals and indicators to provide a reliable assessment, and there is a risk that the results would not be considered valid amongst key stakeholders without wider participation. An expert-driven assessment also means that city stakeholders miss out on participating in the dialogue that leads to the scoring, which applications of the WSC Index
to date have shown to be an effective way to share knowledge and generate commitment to action to improve scores.

5. Illustrative case study applications

We now demonstrate the application of the WSC Index by presenting three case study cities in contrasting contexts, ranging from metropolitan scale (Greater Sydney; Hammer et al. 2018), regional city (City of Greater Bendigo; Rogers et al., 2018), to municipal council (Moonee Valley City Council; Lloyd et al., 2016).

5.1 Comparing WSC Index results

Table 4 briefly outlines the context of each city and compares their WSC Index results in order to highlight key insights the tool was able to reveal, leading to discussion of how these insights supported the development of specific management responses across the different contexts. The radar charts show the cities’ performances against the seven WSC goals.
Table 4. WSC Index results for three illustrative case studies

| Greater Sydney | City of Greater Bendigo | Moonee Valley City Council |
|----------------|-------------------------|---------------------------|
| **Context**    | Large coastal metropolitan area inhabited by 4.7 million people, forecast to grow to 8 million by 2050 (Greater Sydney Commission, 2018) | Regional inland city inhabited by 93,000 people, forecast to grow to over 170,000 by 2050 (Department of Environment, Land, Water and Planning, 2016b). | Inner city suburbs covering 43 km², inhabited by 124,700 people, forecast to grow to 180,000 by 2040 (Moonee Valley City Council, 2017). |
| **WSC Index application** | July 2017 as part of the validation period. Involved 50 government and non-government participants from water, planning, environment and development sectors. | October 2017 as part of the validation period. Involved 36 participants from the local council, water utility, state government department, catchment management authority, private developers, and Indigenous community representatives. | April 2016 as part of the validation period. Participants represented a diverse range of internal stakeholders as well as external stakeholders (including representation from the local council, water utilities and state government department). |

**Radar results**

Note: The scores in the radar diagrams range from 0 (lowest performance, centre of the radar) to 5 (highest performance, outer edge of the radar). The midpoint value of 2.5 is indicated as a grey line in the middle of the radar to show the relative performance of a city to this midpoint score across the different goals. The shaded blue areas show the overall performance of the city—the larger the shaded area the higher water sensitive performance.
5.2 Interpreting WSC Index results

When interpreting the results in Table 4, it is important to remember that the purpose of the WSC Index and the intent of the assessment methodology is not to determine precise scores. Rather, it is to understand the water sensitive performance of the system relative to an aspirational benchmark or other comparable cities, so that opportunities for management responses can be identified. Hence, while the results may be expressed with a precise number between 0-5, where 0 indicates the lowest and 5 the highest performance relative to the water sensitive city aspirations, it is important to attribute meaning from the results with careful reference to the specific indicators that are diagnosed to be performance enhancing or inhibiting. Comparing performance across cities will require analysis of the types of ongoing challenges and potential management responses for specific indicators, rather than drawing sweeping insights based on their aggregated scores. The following analysis will show how such comparison can reveal valuable detail on key aspects of a city’s urban water services.

The WSC Index goal scores (averaged across component indicators) in the three cities ranged from 2 to 4, indicating a moderate level of overall performance. However, looking at the scores on the individual goal and indicator level reveals contrasting performances.

All three cities scored highest on Achieve equity of essential services, which is not surprising given the generally high performance of Australian water utilities in the provision of basic water supply and sanitation services. Greater Bendigo is reliably serviced by a network of drainage systems managed by the local government agency. On this aspect, Greater Bendigo performed slightly better than Greater Sydney and Moonee Valley. Greater
Sydney’s lower drainage performance reflects an uneven distribution of flood protection across the city, with some inhabitants at greater risk of flooding (Hammer et al., 2018). While a range of flood-related risk analyses and strategies were being implemented at the municipal or sub-catchment levels, they were not strategically aligned with one another, limiting opportunities for learning and scaling up at the catchment level. Meanwhile, in Moonee Valley, rainfall events generally do not disrupt everyday activities, although there are known localised flooding issues and inconsistent planning controls, which has resulted in some overland flow paths being built over.

Greater Sydney demonstrated higher performance for Improve ecological health than Bendigo and Moonee Valley. While point-source pollution in Bendigo is well-managed, and there is growing acknowledgement of the need to manage diffuse-source pollution, adoption of new industry standards for stormwater management are yet to be mainstreamed in established suburbs. Similarly, in Moonee Valley compliance to best practice stormwater discharge guidelines can also be improved. While major waterway corridors are accessible to community, active recreation infrastructures such as bicycle and walking paths can be increased along smaller blue-green assets (e.g. ponds, wetlands).

Moonee Valley shows the highest relative performance for Improve productivity and resource efficiency compared to Greater Sydney and Bendigo. This reflects a range of efforts by the municipality to implement decentralised alternative supplies, stormwater harvesting projects for reuse in local parks, and ongoing WSUD working groups with multidisciplinary representation. Whilst these achievements are encouraging, there remains significant room for improvement to reach a high level of water cycle performance in the municipality.
Volume of water reuse, for instance, remains low compared to mains water. Greater Sydney has diversified its water sources, although significant challenges remain in implementing stormwater harvesting and other recycling measures as a viable option at scale. Bendigo has also promoted diversification of water sources, including rainwater tanks, bores and wastewater recycling and reuse. However, water demands in Bendigo have grown in recent years and remain quite high.

Despite evidence of some improvement in water management and urban design approaches, attainment of an ideal WSC state across the three cases remained elusive. In Sydney, although the overall score for water security and public health was high, there is a clear need to integrate governance innovations to increase the city’s overall water sensitivity. For Bendigo, while there is evidence of strategic city greening and investments in stormwater harvesting projects, there remains relatively few examples of other water sensitive infrastructure, such as raingardens. The benefit of nature-based solutions for mitigating urban heat, for instance, has not been understood by many residents and overall tree canopy cover appears to have been reduced. In Moonee Valley, evidence showed that the municipality’s approach in advancing water sensitive practices has been driven by demand management following Australia’s Millennium Drought (1997-2010). While this period saw widespread installation of water saving fittings, fixtures and appliances, water usage has since bounced back to 200-250 litres/person/day across residential and industrial sectors. To reach a WSC state, management actions that lead to multi-functional outcomes need to be implemented more widely across the three cities.
5.3 Using WSC Index results

Experience in assessing the water sensitive performance of 45 cities to date, including five international applications (Bogor, Indonesia; Suva, Fiji; Mandalay, Myanmar; Kunshan and Jiaxiang, China), shows the WSC Index results can be used in a variety of ways to inform the development of management actions and strategies in response to key priorities. Examples from this paper’s three illustrative cases are given here.

Application of the WSC Index in Greater Sydney generated high-level strategic recommendations that identified priority issues for the short- to medium-term. The city-wide benchmarking, informed by perspectives from a range of municipal council areas, enabled a systematic understanding of the drivers, challenges and opportunities for improved water sensitivity. The process also strengthened relationships among participants through engaging in new types of discussions with different people and organisations and sharing lessons and experiences from different parts of the city. While it was useful to have a metropolitan-wide WSC Index result, participants and facilitators of the Greater Sydney application reflected that the aggregated scores at the metropolitan level disguised a high degree of variation in performance across the large geographical and administrative region. Participants therefore saw value in follow-up applications of the WSC Index at the sub-city and/or municipal scale to derive more tailored management actions in response to local issues.

Bendigo participants engaged in a further process to prioritise indicators for strategic action following the benchmarking workshop. Stakeholders have since committed to an ongoing
network of WSC champions who meet regularly and follow up on agreed actions. The WSC Index and associated processes has led the leaders of key agencies to establish a clear mandate for implementing the changes needed to improve the scores of these priority indicators. They plan to reassess Bendigo in three years to monitor their progress towards their water sensitive aspirations.

For Moonee Valley, a nine-point action plan was developed using the WSC Index results, which has provided an overarching framework to guide initiatives across the municipality to advance towards the WSC. These actions span on-ground practices, enabling structures, and socio-political capital.

6. Discussion

Applications to date, including both municipal and metropolitan cities, have shown that the WSC Index can provide reliable, meaningful insight across different contexts—including coastal and inland locations, temperate and tropical climates, dense and sparse populations, major cities and regional centres. While workshop participants in different cities found that some indicators were less relevant at the municipal scale and some were more challenging to uniformly apply at the metropolitan scale, there was value in scoring all indicators for the selected scale of application to lead to meaningful insights about the area’s water sensitivity and point to management actions to improve scores.

The design of the WSC Index as a quantitative framework with qualitative rating descriptions and a process-based assessment methodology has helped it be applicable across diverse contexts. The indicator descriptions allow for contextual interpretations of
the indicators, while maintaining a robust universal framework that enables city comparison and benchmarking. The scoring approach means it is feasible to benchmark any city where there is sufficient stakeholder interest, even in situations where there is a lack of quantitative data. This is because the evidence needed to determine the WSC Index scores is typically readily accessible—for example, in the form of organisational policies, strategies and reports, or in the tacit knowledge of key individuals.

Early testing in Indonesia, China, Fiji and Myanmar showed the potential value of the WSC Index for developing cities. Elaboration on this is beyond the scope of this paper, beyond suggesting that refinement through further international testing may be necessary to ensure the indicator and rating descriptions are sufficiently robust for universal application. For example, it may be that finer granularity is needed in the lower rating scores for some indicators, or that additional indicators may be needed to suit the particular conditions of developing city contexts (for example, informal settlements).

The participatory assessment methodology became a central focus for the WSC Index’s development and application—a novel finding of this research. Emphasis on a well-facilitated process was initially to ensure providers were consistent in how they engaged participants in scoring deliberations. However, applications of the WSC Index to date have revealed a range of unanticipated benefits from the assessment process that would not have been achieved through a desktop assessment methodology. Workshop participants consistently report that the WSC Index framework and workshop process: (a) increased their understanding of WSC principles, concepts, solutions and practices, (b) introduced them to people who would be important to collaborate and coordinate with to achieve
water sensitive outcomes, (c) facilitated new cross-sectoral conversations between stakeholders, (d) helped the group develop a collective understanding of their water system context and key drivers, (e) led the group to articulate a shared set of aspirational outcomes for their future water system, and (f) gave them insight into relevant policies, programs and other initiatives from other departments and external organisations. These insights reinforce findings from studies on the value of participatory processes (e.g. Olsson et al., 2006, Rijke et al., 2013) and point to a promising direction for the design of other indicator initiatives beyond water—particularly those aiming to drive system change through collaboration and learning across multi-sectoral policy-makers, strategists and practitioners.

Further development of the WSC Index could integrate diagnostic filters that interpret the goal and indicator scores in different ways, depending on the interest, perspective and communication needs of the end user. For example, the indicator scores could be analysed through the urban water transition framework (Figure 1, Brown et al., 2009) to determine a city-state benchmark. This would allow a city’s results to be interpreted with respect to their progress towards the water supply city, sewered city, drained city, waterways city, water cycle city and, ultimately, the WSC, helping to give meaning to their results in relation to city-state aspirations. Another potential diagnostic filter is the United Nations Sustainable Development Goals (SDGs) (United Nations, 2019), with which the WSC Index has many points of alignment. Their integration could help city stakeholders assess how improvements to their city’s water sensitive performance may contribute to the achievement of SDG targets, and vice versa. These and other diagnostic filters would support users to gain critical insights into the current state of the urban water services and develop management actions that will address key priorities.
Finally, meta-analysis of city data collected through the assessment process, beyond simple overlaying of results for visual interpretation and ranking of aggregate scores, would help to gain comparative insight the water sensitive strengths and weaknesses of cities in diverse contexts. Meta-analysis of data collected longitudinally would also generate insight on the effectiveness of management actions in improving a city’s water sensitivity, providing an invaluable database for research into water sensitive city transitions.

7. Conclusion

This paper presents, for the first time, a framework for defining water sensitive performance across the full range of technical, social, ecological, governance, economic, liveability, multi-functional and adaptive attributes that are becoming recognised as important features of future water systems. In building on established indicators and developing new measures that address gaps in existing water-related metrics, the WSC Index offers a robust and industry-relevant tool and process for diagnosing a city’s strengths and weaknesses in relation to its water sensitive aspirations, and guiding management responses that will help improve a city’s water sensitivity. Rapid uptake of the WSC Index in Australia highlights its value in helping stakeholders develop a collective commitment and evidence-based priorities for action to accelerate their city’s water sensitive transition.

We have demonstrated application of the WSC Index through three illustrative case studies, showing how it can be used to generate insights for benchmarking a city’s water sensitive performance, setting operational targets for improvement, developing management responses, and monitoring progress towards its water sensitive aspirations. Comparing the
case study results across the seven WSC Index goals reveals which specific aspects of urban
water servicing and management responses can be enhanced to strengthen water sensitive
principles. The case applications also show the suitability of the WSC Index tool across a
range of biophysical and socio-political contexts, including large metropolitan scale, regional
city, and municipality with different climates and demography.

The outlook for the WSC Index as a valuable benchmarking and diagnostic tool to support
the assessment of urban water services in practice appears positive, with applications
continuing across Australia. There has also been increasing interest from international cities;
further testing and refinement of the WSC Index in diverse contexts will help realise its full
potential as a global tool. There may also be additional diagnostic filters that would provide
new ways of interpreting and communicating the WSC Index results. Innovation in the
assessment methodology may present opportunity to increase the flexibility of application,
for example by utilising online collaboration platforms, especially relevant in the current
COVID-19 pandemic. Finally, there would be value in complementing the WSC Index’s focus
on material outcomes of water sensitive practices with transitions-focused frameworks that
can provide guidance on the process of change itself, such as how to drive organisational
cultural change, enhance collaborative practices, and establish enabling institutional
structures.

Acknowledgements

The support of the Commonwealth of Australia through the Cooperative Research Centre
program is acknowledged. We are grateful to the many industry stakeholders who have
been engaged in the WSC Index development and testing process, particularly staff from the
City of Knox, City of Port Phillip, City of Subiaco, City of Swan and water-related
organisations for Perth’s greater metropolitan area. We also thank members of the steering
committee and working groups for their time and input.

References

Arcadis. (2016). Sustainable Cities Water Index. Retrieved from
https://www.arcadis.com/media/4/6/2/%7B462EFA0A-4278-49DF-9943-C067182CA682%7DArcadis_Sustainable_Cities_Water_Index-Web.pdf

Arup. (2015). City Resilience Index (CRI): Understanding and measuring city resilience.
Retrieved from New York, New York: https://www.rockefellerfoundation.org/report/city-resilience-index/

Ashley, R., Lundy, L., Ward, S., Shaffer, P., Walker, L., Morgan, C., . . . Moore, S. (2013). Water-sensitive urban design: opportunities for the UK. Proceedings of the Institution of Civil Engineers - Municipal Engineer, 166(2), 65-76. doi:10.1680/muen.12.00046

Barnett, J., Lambert, S., & Fry, I. (2008). The Hazards of Indicators: Insights from the Environmental Vulnerability Index. Annals of the Association of American Geographers, 98(1), 102-119. doi:10.1080/00045600701734315

Böhringer, C., & Jochem, P. E. P. (2007). Measuring the immeasurable — A survey of sustainability indices. Ecological Economics, 63(1), 1-8. doi:10.1016/j.ecolecon.2007.03.008

Bouleau, G., Argillier, C., Souchon, Y., Barthélémy, C., & Babut, M. (2009). How ecological indicators construction reveals social changes—The case of lakes and rivers in France. Ecological Indicators, 9(6), 1198-1205. doi:10.1016/j.ecolind.2009.03.010

Boyko, C. T., Gaterell, M. R., Barber, A. R. G., Brown, J., Bryson, J. R., Butler, D., . . . Rogers, C. D. F. (2012). Benchmarking sustainability in cities: The role of indicators and future scenarios. Global Environmental Change, 22(1), 245-254. doi:10.1016/j.gloenvcha.2011.10.004

Brennин, R. (2007). Linking indicator information to the policy process for sustainable development. Lessons learned from relevant international examples. A report prepared for the Strategic Information Integration Directorate, Environment Canada. 30 pp.

Brown, R. R., Keath, N., & Wong, T. H. (2009). Urban water management in cities: historical, current and future regimes. Water Science & Technology, 59(5), 847-855. doi:10.2166/wst.2009.029
Brown, R. R., & Farrelly, M. A. (2009). Delivering sustainable urban water management: a review of the hurdles we face. *Water Science & Technology, 59*(5), 839-846. doi:10.2166/wst.2009.028

Chaves, H. M. L., & Alipaz, S. (2006). An Integrated Indicator Based on Basin Hydrology, Environment, Life, and Policy: The Watershed Sustainability Index. *Water Resources Management, 21*(5), 883-895. doi:10.1007/s11269-006-9107-2

Chiras, D. D., & W. H. Corson. 1997. Indicators of sustainability and quality of life: Translating vision into reality. *Journal of Environmental Science and Health* 15(1):61-82. https://doi.org/10.1080/10590509709373490

Cohen, A., & Sullivan, C., A. (2010). Water and poverty in rural China: Developing an instrument to assess the multiple dimensions of water and poverty. *Ecological Economics, 69*(5), 999-1009. doi:https://doi.org/10.1016/j.ecolecon.2010.01.004

De Ridder, K., Adamec, V., Bañuelos, A., Bruse, M., Bürger, M., Damsgaard, O., Dufek, J., Hirsch, J., Lefebre, F., Pérez-Lacorzana, J.M., Thierry, A., and Weber, C. 2004, An integrated methodology to assess the benefits of urban green space. *Science of the Total Environment* vol. 334–335, p 489–497.

Diehl, K., Burkhard, B., & Jacob, K. (2016). Should the ecosystem services concept be used in European Commission impact assessment? *Ecological Indicators, 61*, 6-17. doi:10.1016/j.ecolind.2015.07.013

Dunn, G., & Bakker, K. (2009). *Canadian Approaches to Assessing Water Security: an Inventory of Indicators. (Policy Report).* Vancouver, BC: UBC Program on Water Governance.

Dunn, G., & Bakker, K. (2011). Fresh water-related indicators in Canada: An inventory and analysis. *Canadian Water Resources Journal, 36*(2), 135-148.

Eliasson, J. (2015). The rising pressure of global water shortages. *Nature, 517*(6). doi:10.1038/517006a

EPA (U.S. Environmental Protection Agency) (2014). *Enhancing Sustainable Communities with Green Infrastructure.* EPA Report 100-R-14-006. https://www.epa.gov/sites/production/files/2014-10/documents/green-infrastructure.pdf.

Falkenmark, M., Lundqvist, J., & Widstrand, C. (1989). Macro-scale water scarcity requires micro-scale approaches. *Natural Resources Forum.

Farrelly, M., & Brown, R. (2011). Rethinking urban water management: Experimentation as a way forward? *Global Environmental Change, 21*(2), 721-732. doi:10.1016/j.gloenvcha.2011.01.007
Feingold, D., Koop, S., & van Leeuwen, K. (2018). The City Blueprint Approach: Urban Water Management and Governance in Cities in the U.S. *Environmental Management, 61*(1), 9-23. doi:10.1007/s00267-017-0952-y

Ferguson, B. C., Brown, R. R., Frantzeskaki, N., de Haan, F. J., & Deletic, A. (2013a). The enabling institutional context for integrated water management: lessons from Melbourne. *Water Research, 47*(20), 7300-7314. doi:10.1016/j.watres.2013.09.045

Ferguson, B. C., Frantzeskaki, N., & Brown, R. R. (2013b). A strategic program for transitioning to a Water Sensitive City. *Landscape and Urban Planning, 117*, 32-45. doi:10.1016/j.landurbplan.2013.04.016

Gerten, D., Heinke, J., Hoff, H., Biemans, H., Fader, M., & Waha, K. (2011). Global Water Availability and Requirements for Future Food Production. *Journal of Hydrometeorology, 12*(5), 885-899. doi:10.1175/2011jhm1328.1

Gleick, P. H. (2009). Basic Water Requirements for Human Activities: Meeting Basic Needs. *Water International, 21*(2), 83-92. doi:10.1080/02508069608686494

Hák, T., Moldan, B., & Dahl, A. L. (2007). *Sustainability Indicators: A Scientific Assessment*. SCOPE 67. Island Press.

Hammer, K., Rogers, B.C., Chesterfield, C., Church, E. K. and Gunn, A. W. (2018). *Benchmarking, Envisioning and Transition Planning for a Water Sensitive Greater Sydney: Final Case Report*. Melbourne, Australia: Cooperative Research Centre for Water Sensitive Cities.

Hara, Y., Umemura, K., Kato, K., Connor, R. F., & Sato, Y. (2009). The Development of Flood Vulnerability Index applied to 114 Major River Basins around the World. *Journal of Japan Society of Hydrology and Water Resources, 22*(1), 10-23. doi:https://doi.org/10.3178/jjshwr.22.10

Hoekstra, A. Y., & Mekonnen, M. M. (2012). The water footprint of humanity. *Proceedings of the National Academy of Science USA, 109*(9), 3232-3237. doi:10.1073/pnas.1109936109

Jiménez-Cisneros, B. (1996). Water availability index based on quality and quantity: Its application in Mexico. *Water Science and Technology, 34*(12), 165-172. doi:https://doi.org/10.1016/S0273-1223(96)00866-9

Lehtonen, M. (2013). The non-use and influence of UK Energy Sector Indicators. *Ecological Indicators, 35*, 24-34. doi:10.1016/j.ecolind.2012.10.026

Lehtonen, M., Sébastien, L., & Bauler, T. (2016). The multiple roles of sustainability indicators in informational governance: between intended use and unanticipated influence. *Current Opinion in Environmental Sustainability, 18*, 1-9. doi:10.1016/j.cosust.2015.05.009
Lloyd, Roberts and Beck (2016) *Water Sensitive Cities Benchmarking and Assessment: Moonee Valley City Council*. Melbourne, Australia: Cooperative Research Centre for Water Sensitive Cities.

Marques, R. C., da Cruz, N. F., & Pires, J. (2015). Measuring the sustainability of urban water services. *Environmental Science & Policy, 54*, 142-151. doi:10.1016/j.envsci.2015.07.003

Mayer, A. L. (2008). Strengths and weaknesses of common sustainability indices for multidimensional systems. *Environmental International, 34*(2), 277-291. doi:10.1016/j.envint.2007.09.004

McCool, S. F., & Stankey, G. H. (2004). Indicators of sustainability: challenges and opportunities at the interface of science and policy. *Environmental Management, 33*(3), 294-305. doi:10.1007/s00267-003-0084-4

Mori, K., & Christodoulou, A. (2012). Review of sustainability indices and indicators: Towards a new City Sustainability Index (CSI). *Environmental Impact Assessment Review, 32*(1), 94-106. doi:10.1016/j.eiar.2011.06.001

Norman, E., Dunn, G., Bakker, K. Allen, and D., R. Cavalcanti de Albuquerque (2012). *Water Security Assessment: Integrating Governance and Freshwater Indicators*. Water Resources Management 27: 535-551. doi: 10.1007/s11269-012-0200-4.

Okazawa, Y., Yeh, P., Kanae, S. & Oki, T. (2011) Development of a global flood risk index based on natural and socioeconomic factors. *Hydrological Sciences Journal 56*(5), 789–804.

Olsson, P., Gunderson, L.H., Carpenter, S.R., Ryan, P., Lebel, L., Folke, C., & Holling, C.S. (2006). Shooting the rapids: Navigating transitions to adaptive governance of social-ecological systems. *Ecology and Society, 11*(1), 18.

Organisation for Economic Cooperation and Development. (2003). *OECD Environmental Indicators: Development, Measurement and Use*. Paris, France: Organisation for Economic Cooperation and Development.

Organisation for Economic Cooperation and Development. (2014). *Managing Water for Future Cities*. ENV/EPOC/WPBWE(2014)5. Retrieved from Paris, France: Organisation for Economic Cooperation and Development.

Pintér, L., Hardi, P., & Bartelmus, P. (2005). *Indicators of Sustainable Development: Proposals for a way forward. Discussion Paper Prepared under a Consulting Agreement on behalf of the UN Division for Sustainable Development*. New York, New York: United Nations Division for Sustainable Development

Policy Research Institute (PRI) (2007). *Canadian Water Sustainability Index (CWSI): project report*. Policy Research Initiative, Ottawa.
Renouf, M. A., Serrao-Neumann, S., Kenway, S. J., Morgan, E. A., & Low Choy, D. (2017). Urban water metabolism indicators derived from a water mass balance - Bridging the gap between visions and performance assessment of urban water resource management. *Water Research, 122, 669-677*. doi:10.1016/j.watres.2017.05.060

Rijke, J., Farrelly, M., Brown, R., & Zevenbergen, C. (2013). Configuring transformative governance to enhance resilient urban water systems. *Environmental Science & Policy, 25*, 62-72. doi:10.1016/j.envsci.2012.09.012

Rogers, B.C., Gunn, A., Church, E., Hammer, K., and Lindsay, J. (2018). Benchmarking, *Envisioning and Transition Planning for a Water Sensitive Bendigo: Final Case Report*. Melbourne, Australia: Cooperative Research Centre for Water Sensitive Cities.

Sagar, A. D., & Najam, A. (1998). The human development index: a critical review. *Ecological Economics, 25*, 249-264.

Smits, J., & Steedndijk, R. (2013). *The International Wealth Index (IWI)*, NiCE Working Paper 12-107. Nijmegen, The Netherlands: Nijmegen Center for Economics (NiCE) Institute for Management Research Radboud University Nijmegen.

Spiller, M., McIntosh, B. S., Seaton, R. A. F., & Jeffrey, P. J. (2012). An organisational innovation perspective on change in water and wastewater systems – the implementation of the Water Framework Directive in England and Wales. *Urban Water Journal, 9*(2), 113-128. doi:10.1080/1573062x.2011.652129

Starkl, M., Brunner, N., Lopez, E. & Martinez-Ruiz, J.L. (2013) A planning-oriented sustainability assessment framework for peri-urban water management in developing countries. *Water Research, 47*(20), 7175-7183.

Sullivan C.A. (2002). Calculating a water poverty index. World Dev 30(7):1195–1210

Sullivan, C.A., Meigh, J.R. and Giacomello, A.M. (2003). The Water Poverty Index: Development and application at the community scale. *Natural Resources Forum, 27*(3): 189-199.

Sullivan, C. A., & Meigh, J. (2006). Integration of the biophysical and social sciences using an indicator approach: Addressing water problems at different scales. *Water Resources Management, 21*(1), 111-128. doi:10.1007/s11269-006-9044-0

Swanson, D., Barg, S., Tyler, S., Venema, H., Tomar, S., Bhadwal, S., . . . Drexhage, J. (2010). Seven tools for creating adaptive policies. *Technological Forecasting and Social Change, 77*(6), 924-939. doi:10.1016/j.techfore.2010.04.005

Turnpenny, J., Russel, D., Jordan, A. (2014). The challenge of embedding an ecosystem services approach: patterns of knowledge utilisation in public policy appraisal. *Environmental Planning C: Government and Policy, 32*, pp. 247-262, 10.1068/c1317j
van den Brandeler, F., Gupta, J., & Hordijk, M. (2019). Megacities and rivers: Scalar mismatches between urban water management and river basin management. *Journal of Hydrology, 573*, 1067-1074. doi:10.1016/j.jhydrol.2018.01.001

van de Meene, S. J., Brown, R. R., & Farrelly, M. A. (2011). Towards understanding governance for sustainable urban water management. *Global Environmental Change, 21*(3), 1117-1127. doi:10.1016/j.gloenvcha.2011.04.003

van der Zaag, P., & Gupta, J. (2008). Scale issues in the governance of water storage projects. *Water Resources Research, 44*(10). doi:10.1029/2007wr006364

van Leeuwen, C. J. (2013). City Blueprints: Baseline Assessments of Sustainable Water Management in 11 Cities of the Future. *Water Resources Management, 27*(15), 5191-5206. doi:10.1007/s11269-013-0462-5

Vaux Jr H (2015). An overview of urban water management and problems in the U.S.A. In: Lopardo RA, Bernex N (eds) *Urban water: Challenges in the Americas: A perspective from the Academies of Sciences*. Inter-American Network of Academies of Sciences, Mexico, p 506–523

Vorosmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., . . . Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature, 467*(7315), 555-561. doi:10.1038/nature09440s
Highlights:

- Presents the Water Sensitive Cities Index, a new benchmarking and diagnostic tool
- Used to define, assess and operationalize a city’s water sensitive performance
- Novel assessment methodology is based on a collaborative stakeholder process
- Application is demonstrated for three diverse Australian cities
- Helps develop collective commitment and evidence-based priorities for action
Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: