7. Nature-based solutions as critical urban infrastructure for water resilience

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THE CASE FOR NATURE-BASED SOLUTIONS FOR WATER RESILIENCE

Since the first human presence on Earth, people have had to contend with water-related natural hazards such as floods, droughts, and storm surges. For a long time, we have sought effective solutions to cultivate resilience by managing these hazards and preventing them from creating disasters. Early solutions used earthen or nature-based materials to manipulate water. One of the earliest recorded water management systems consisted of networks of small dams, ponds, and channels to capture receding floodwaters for both water supply during drought and to support aquaculture in southeast Australia (Jones, 2011). Pre-Inca cultures in the tropical Andes created earthen channels to divert water from headwater streams and encourage it to infiltrate into the ground and recharge groundwater supplies; this helped manage the threat of drought in the dry season (Ochoa-Tocachi et al., 2019). In another example from the Yangtze Delta of China, earthen levees, dams, and ditches were created over 5,000 years ago to prevent floods but also to provide water for irrigation (Liu et al., 2017). In areas where there was growing density of urban development, there was an increasing focus on efficient urban drainage, initially through above-ground conveyance via ditches or canals, and below ground via sewer pipes. In many cases, wastewater and stormwater flowed together in a combined system, creating water quality concerns and human health issues when not properly treated (De Feo et al., 2014).

In the last several decades, there has been growing recognition that rapid conveyance of stormwater that was central to nineteenth- and twentieth-century urban stormwater management has very detrimental effects on downstream water bodies. These effects include increases in peak flows and associated flooding, erosion, pollutant loading, and decreases in various biotic indicators (Walsh et al., 2005). In response, local, state/provincial, and federal governments have increasingly required the implementation of stormwater control measures, i.e., some physical means of detaining, retaining, and/or treating stormwater. In some regions such requirements have been in effect for decades, while in others they are just being considered (McPhillips & Matsler, 2018). In more arid regions, there has been renewed interest in retaining and harvesting stormwater not just to manage downstream impacts of flooding but also to aid in mitigating drought impacts and offsetting demand for imported water (Low et al., 2015).

Options for surface water management can take a wide range of forms and nomenclature. It is helpful to consider the different types in the context of an ecological-to-technological or blue/green/turquoise/brown-to-gray spectrum (Bell et al., 2019; Childers et al., 2019; Matsler et al., 2021; McPhillips & Matsler, 2018). On the technological or gray end are underground storage, infiltration, and filtration devices. Hybrid strategies include some mix of ecological and technological elements, but may be engineered explicitly with water management goals in mind; these include strategies such as bioswales, eco or green roofs, and retention ponds or basins. There are also strategies that have some level of engineering or planning, but are not designed explicitly with stormwater management in mind. However, they may provide surface water management as a co-benefit, defined as “ancillary positive ecological, environmental, and social outcomes that coincide with the installation” (Bell et al., 2019, p. 9). Such features include parks or vacant lots. Moving towards the ecological end of the spectrum, there are modified or managed ecological or natural features that provide water-related benefits, such as a wetland that has had some level of engineering or control retrofit. Finally, there are ecological features in the landscape that can provide water-related benefits; these features could include intact wetlands or forests (McPhearson et al., 2014).

Here, in the context of nature-based solutions (NBS) for water resilience, we consider all features that have multiple interacting ecological elements, or that are less than 100 percent gray or technological in form. These ecological elements include soils, water, vegetation, microbial communities, and other biota. Vegetation provides multiple functions related to water resilience. Vegetation impacts hydraulics of inflowing or conveyed water by decreasing water velocities and associated erosive potential, and by facilitating the settling and capture of entrained particles (Sabokrouhiyeh et al., 2020). Vegetation also transpires water and takes up nutrients and other pollutants from inflowing water (Berland et al., 2017; Bratieres et al., 2008; Hunt et al., 2012; Payne et al., 2014; Vijayaraghavan et al., 2019). Ecological communities can interact in complementary ways that result in desirable (and undesirable) functions.

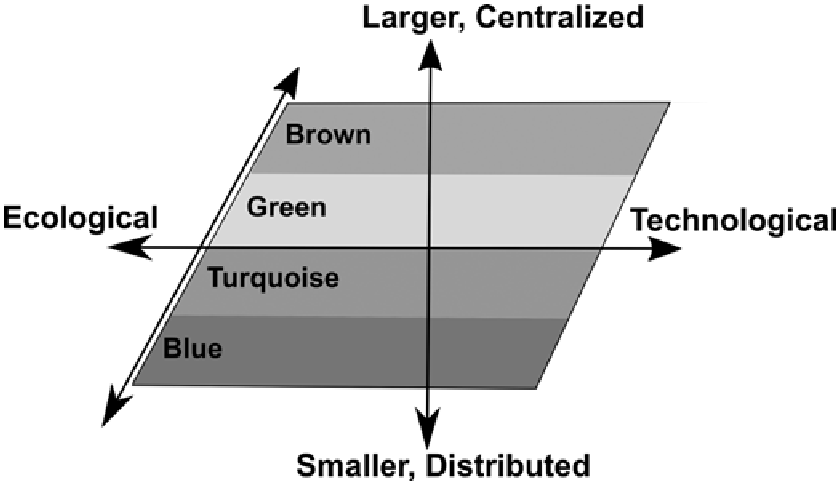
For example, plant species with long, thick roots may facilitate the movement of soil fauna, which can help distribute organic matter to the lower, wetter depths of the soil profile where denitrification is more likely to occur (Levin & Mehring, 2015). Soils provide or facilitate a suite of physical, chemical, and biological processes impacting water quantity and quality. An example of a function dependent on interactions between multiple elements is infiltration. While soil type and structure drive infiltration, incorporation of organic matter from senesced vegetation or development of plant roots affect soil structure and thus infiltration (Gonzalez-Merchan et al., 2014; Le Coustumer et al., 2012). Similarly, interactions between vegetation and microbial communities facilitate improved rates of nutrient removal (Morse et al., 2018). In blue and turquoise NBS, dissolved organic matter and microbial communities can affect the removal of fecal indicator organisms from stormwater runoff (Huang et al., 2018). Interacting ecological elements in NBS are also responsible for many of the co-benefits conveyed beyond water resilience. For example, vegetation can influence urban temperature through shading or evapotranspiration. Potentially, NBS features that are used to retain water in the urban environment may help to cool cities during heat waves when harvested water is used for irrigation, particularly when water restrictions are in place (Coutts et al., 2013).

HOW CAN NBS WORK FOR WATER RESILIENCE?

Given the enormous range in types and associated functions of NBS, it is critical to align desired goals with the choice of NBS, as well as to factor in regulatory, financial, geophysical, or other constraints. Major goals related to water resilience include peak flow reduction to delay and reduce the flood peak in downstream water bodies, runoff volume reduction to reduce flooding in downstream water bodies and to recharge groundwater, rainwater harvesting for beneficial reuse, attenuation of energy associated with flowing surface waters, and water quality improvement to reduce pollutant loading to groundwater or downstream water bodies. Desired co-benefits may also be a factor in the choice of NBS.

There are several axes or dimensions along which NBS can be organized (Figure 7.1). As previously mentioned, the ecological–technological spectrum is a key axis (Matsler et al., 2021; McPhillips & Matsler, 2018). The technological element refers to constructed and non-living components. The ecological element can be categorized using a blue–turquoise–green–brown spectrum (*sensu* Childers et al., 2019). This corresponds to the way that soil, vegetation, and water elements are combined and the hydroperiod, or pattern of water inundation. Blue NBS are aquatic features focused on primarily providing water storage and conveyance (Table 7.1). Green NBS are terrestrial

NBS with soil and vegetation. Key water-related functions of these NBS include infiltration, evapotranspiration, and water quality improvement, and they may provide temporary storage of water during storm events. Brown NBS are not often acknowledged in most NBS classifications, but are terrestrial NBS that include soil-based and minimally vegetated features such as fallow gardens or vacant lots. Brown NBS are more prevalent in arid regions, where most vegetation requires water inputs, and they are still able to provide critical water-related services such as infiltration, temporary storage of water, and water quality improvement. Turquoise NBS are a functional mix of green and blue NBS and include soil, vegetation, and water, with varied hydroperiods, with wetlands being the primary type. Primary water-related functions include storage, infiltration, conveyance, and water quality improvement.



Source: Adapted from Childers et al. (2019) and McPhillips et al. (2020).

Figure 7.1 Dimensions of nature-based solutions for water resilience

Another axis along which NBS can be organized is size and location, particularly with respect to watershed or catchment organization. Decentralized NBS features are often located higher in a watershed closer to points of runoff generation, which may help better mimic pre-development hydrology. They tend to be smaller NBS, but their more distributed nature can make their benefits accessible to more people or fauna. However, there also may be larger decentralized NBS that are primarily designed to provide other ecosystem services (e.g., parks or athletic fields) but may also provide water-related functions (e.g., storage and infiltration) during extreme precipitation events. Centralized

Table 7.1 Examples of nature-based solutions for water resilience with key dimensions and functions characterized

Type of NBS	Dimensions	Designed function	Ancillary function
Bioswale/rain garden	Eco-techno hybrid Green-brown Smaller distributed	Flood management Water quality treatment	Aesthetic benefits Habitat
Rainwater harvesting	Primarily technological Blue Smaller distributed	Flood management Drought management	Aesthetic or recreational benefits
Intact wetland	Ecological Turquoise Smaller or larger	N/A	Flood management Water quality treatment Habitat
Park	Eco-techno hybrid Green Distributed	Recreation	Flood management Habitat Urban heat reduction
Restored floodplain	Ecological Blue-turquoise-green Larger centralized	Flood management	Habitat Recreation

NBS features tend to be larger landscape elements that collect runoff from a larger contributing area and tend to be located closer to a downstream receiving water body (e.g., stream, river, lake, or coast; Table 7.1). They are also often sized to manage larger precipitation events. Additionally, there are NBS that are implemented directly adjacent to or in line with streams and rivers, such as riparian buffers and floodplain or stream areas that have been restored or protected.

A key constraint in choosing the appropriate type of NBS is the regulatory or management framework under which it is being implemented. For example, in the United States, many hybrid engineered NBS (e.g., bioswales) are implemented to satisfy stormwater management goals under the Clean Water Act or local regulations that are often linked to new urban development. Generally, these hybrid NBS features are engineered explicitly to meet a particular required design storm standard, e.g., retention of a two-year, 24-hour storm event. Some states or municipalities may permit incorporation or protection of existing ecosystems into NBS (e.g., forest, wetland, grassland) to satisfy stormwater management regulations with new development, which is often referred to as low-impact development or environmentally sensitive design. However, hybrid NBS features that are designed to primarily provide goals beyond water resilience (e.g., parks) may not satisfy certain stormwater management requirements; reasons may include difficulty in ensuring that the feature satisfies desired design storm requirements, or could be due to challenges in managing and maintaining the facilities relating to governmental agency structure (Matsler, 2019).

Financial constraints can also impact the appropriate choice of NBS. There are almost always multiple NBS that may be able to provide desired benefits. Cost is often a key factor, particularly in less developed countries or regions where finances are tight. In less developed cities, conservation of or slight modification of existing intact NBS may be the most cost-effective option, rather than engineering new NBS for water management. An example of this is provided in the case studies to follow. There may also be constraints based on the types of funding available. For example, particular grants may only be available for certain types of NBS (Zimmerman et al., 2019).

Another key constraint relates to geophysical or climatic factors. Geophysical factors include underlying soil type and associated properties as well as geological formations. For example, poorly draining soils or high water tables can make infiltration-based NBS features impractical. Also problematic can be the presence of karst formations that can lead to sinkhole formation in urban areas if there is targeted infiltration. There can also be anthropogenic karst, created from the process of urbanization and associated use of aging, concrete-dominated, underground infrastructure (Bonneau et al., 2017). Thus, lined or storage-focused NBS might be recommended in these locations, though in some cases, infiltration and groundwater recharge could be facilitated by "urban karst." Climate also influences the appropriate choice and form of NBS, where brown NBS or green NBS using xeric vegetation are more common choices in arid environments.

EXAMPLE CASE STUDIES SHOWCASING NBS FOR WATER RESILIENCE AROUND THE WORLD

Leveraging Existing Wetlands for Stormwater Management

Valdivia and Concepción, two cities in the southern half of Chile, rely heavily on the ability of their coastal, riparian, and inland wetlands to manage coastal, fluvial, and pluvial flooding. These cities feature temperate rainforest ecosystems and riparian (Valdivia) and coastal (Concepción) settings, and also have a shared history of wetlands being generated in an earthquake in 1960. These factors have led to extensive wetland coverage within their urban areas.

Valdivia has conserved many of its wetlands specifically for their use as NBS for stormwater management (Figure 7.2a, b), with some notable exceptions where wetlands were conserved primarily for their cultural services and reasons of environmental justice (Correa et al., 2018). Valdivia has developed its stormwater management system to account for the water management services of its wetland network, and as a result flood risk in the city may change substantially if there are changes in wetland area and characteristics (Sauer et al., 2020). In some cases, urban development in Valdivia has converted either parts of or the entirety of wetlands to urban land uses. Additionally, some wetlands have been channelized to increase rates of water conveyance and to reduce storage levels prior to rainfall events. The lower water levels that result from this channelization in turn alter the ecosystem services the wetlands provide, such as habitat for plants and animals, and species composition may change in undesirable ways.

Notes: (a) A map of Valdivia, Chile with its land cover and drainage system demonstrates its extensive wetlands that are officially incorporated into its stormwater management system model. (b) A photograph demonstrates a channelized wetland that acts as wetland storage for, and conveyance away from, a medium-density residential and commercial area in Valdivia. (c) In Concepción, Chile, Los Batros Urban Wetland Park in San Pedro de la Paz demonstrates efforts to create public access to enjoy the wetlands. (d) The Rocuant-Andalién wetland shows an intact wetland adjacent to urban development.
Source: Jason R. Sauer and Carolina Rojas Quezada.

Figure 7.2 Wetland nature-based solutions in Chilean cities

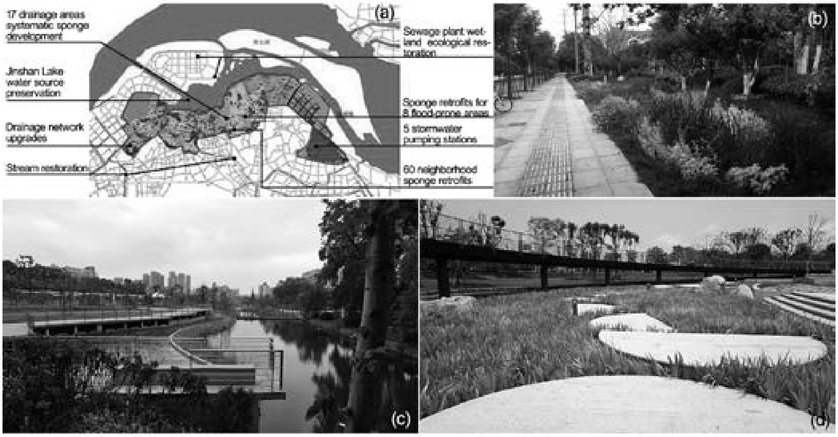
Concepción is undergoing a process of wetland valuation as NBS for flood reduction and other cultural ecosystem services such as recreation. One result of this process is that the city has targeted a series of connected wetlands, called La Ruta del Agua, for protection as stormwater management NBS. Additionally, building permits that would drain or fill small urban wetlands were frozen in 2019, and public space projects were implemented at urban lagoons (Laguna Redonda and Laguna Lo Galindo) to develop and improve access to their cultural services. The city has collaborated with a community to develop Los Batros Urban Wetland Park, which conserved a set of urban wetlands and recognized their utility toward improving stormwater management, increasing urban biodiversity, and aiding in social integration via accessibility to green space for low-income neighborhoods (Figure 7.2c). The coastal wetlands of Rocuant-Andalién in Concepción (Figure 7.2d) have also played a historically important role in protection from tsunami-induced flooding (Rojas et al., 2019) and urban wetlands have supported freshwater provisioning following major earthquakes (Villagra et al., 2014).

Across Chile, concerns about the effects of urban wetland loss on stormwater management, biodiversity, and cultural services, and the environmental injustice it represents for many Chileans, have been elevated to the national level. In January 2020, these concerns led the Chilean legislature to pass a nationwide law protecting urban wetland cover. Whether and how this legislation will help protect the wetland NBS of Valdivia and Concepción remains to be seen.

Large-Scale NBS Implementation in Chinese “Sponge Cities”

Flooding and water quality impairment associated with rapid urbanization and climate change have become one of the most pressing environmental issues in China in recent years. Between 2014 and 2019, the Chinese Central Government implemented an ambitious initiative called Sponge City Development (SCD) to transform cities so that they perform like sponges to store, infiltrate, treat, and convey stormwater (MHURD, 2014), leveraging additional co-benefits of NBS to enhance quality of life (Chan et al., 2018). Promoting a holistic water management regime, SCD emphasizes the application primarily of green and turquoise NBS to facilitate infiltration and water storage. Numerous pilot projects have been implemented in 30 government-funded pilot cities across all the five major climatic zones of China with annual precipitation over 400 mm to test innovative stormwater management strategies.

One of the pilot cities, Zhenjiang, located in Jiangsu province in southeastern China, features an example that employed large-scale hydrological modeling to develop and mandate a stormwater management plan for a 22 km^2 demonstration zone in the Old Town area (Figure 7.3). With annual precipitation of ~1,100 mm, a population of ~3.2 million, and a strong industrial economy, Zhenjiang had suffered from repeated urban flooding, especially in older communities, and severe water pollution before SCD. The stormwater management plan proposed and implemented ~150 pilot projects to achieve the national performance goals of conveying a 30-year storm event with no city flooding while treating 75 percent of annual runoff volume to achieve a 60 percent annual reduction in total suspended solids. Besides upgrades of traditional gray infrastructure, the projects included a variety of NBS (Figure 7.3), including rain gardens, bioswales, bioretention planters, floating wetlands, and a regional terraced filter facility that treats combined sewage and stormwater. Following the pilot period, Zhenjiang adopted a city-scale SCD management ordinance and at least three other design and management guidelines to solidify the regulatory and technical foundations for future implementation efforts (Gu et al., 2019).



Notes: (a) Schematic of the Sponge Development Plan of Zhenjiang's 22 km^2 demonstration zone; (b) examples of a green street; (c) riparian stormwater treatment zone; and (d) a central park treating regional stormwater overflows.
Source: Hong Wu.

Figure 7.3 NBS implementation in the Old Town area of Zhenjiang

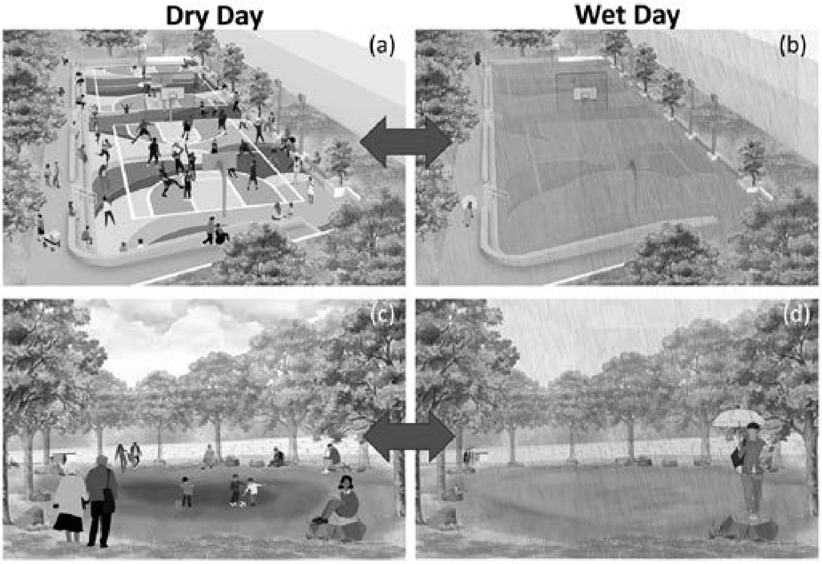
While the initial pilot SCD implementation has been viewed as a success in certain aspects, challenges have already emerged that could impede future implementation efforts (Li et al., 2017). In many cities, NBS were implemented largely individually, rather than taking a system or city-scale approach. Some cities found it challenging to break through traditional disciplinary boundaries, such as integrating engineering and design expertise, to most effectively plan and implement NBS. Additionally, while the Chinese government provided initial financial support for pilot projects, cities are concerned about finding adequate financial support for continued implementation of NBS, but there is hope for leveraging and implementing public–private partnerships in the future (Li et al., 2017).

New York City: Planning for Cloudburst Resilience

New York City's waterscape is diverse and includes canopies of skyscrapers drained by centuries-old combined sewers, subbasins with separated sewer systems, and historic residential communities that remained unsewered until the last decade. Located in the humid northeastern United States, the city has experienced an increase in annual precipitation over the past half-century, after much of its subterranean sewer system had already been built. The city's harbor has historically suffered from very high levels of pollutant and nutrient loading (Rosenzweig et al., 2018a; Taillie et al., 2020) and the city also has a history of frequent flooding, resulting from both coastal and precipitation-driven events (Depietri & McPhearson, 2018). All of these issues will be exacerbated by the more frequent cloudbursts (high-intensity precipitation events) projected for the region due to global climate change in the absence of mitigation efforts (González et al., 2019).

New York City has begun using NBS for stormwater management through several innovative programs – each focused on a different regulatory requirement or management challenge. As an alternative to building out stormwater drainage sewers in neighborhoods at the outskirts of the city, in the 1990s the city initiated its Bluebelt Program (Gumb et al., 2007), which integrates the conservation of existing wetlands with engineered stormwater detention basins. New York City has also broadly implemented primarily decentralized, turquoise and green infrastructure to meet national water quality regulations and reduce discharges from its combined and separate stormwater sewers and, more recently, discharge through separate stormwater systems (Rosenzweig & Fekete, 2018).

While the aforementioned programs have contributed to improved harbor water quality and provided important ecological and societal co-benefits, they are limited in their capacity to address New York City's chronic flooding issues (Rosenzweig et al., 2019). To enhance resilience to pluvial flooding from cloudbursts, the city recently conducted a Cloudburst Resiliency Planning Study, which includes a masterplan for a flood-prone area of the city that utilizes a network of primarily blue NBS to store and convey stormwater following intense rainfall events (NYC DEP & Ramboll, 2017). This study included a full cost–benefit analysis using the results of a dynamic flooding model. Its results demonstrated that the NBS provided flood mitigation and other social benefits that outweighed their capital and operations costs – a benefit–cost ratio of 1.8 over a century. As a first step towards implementation of the full masterplan, blue and green infrastructure projects are being piloted for a low-income public housing development and adjacent to a conventional pumping station within the masterplan study area (Figure 7.4).



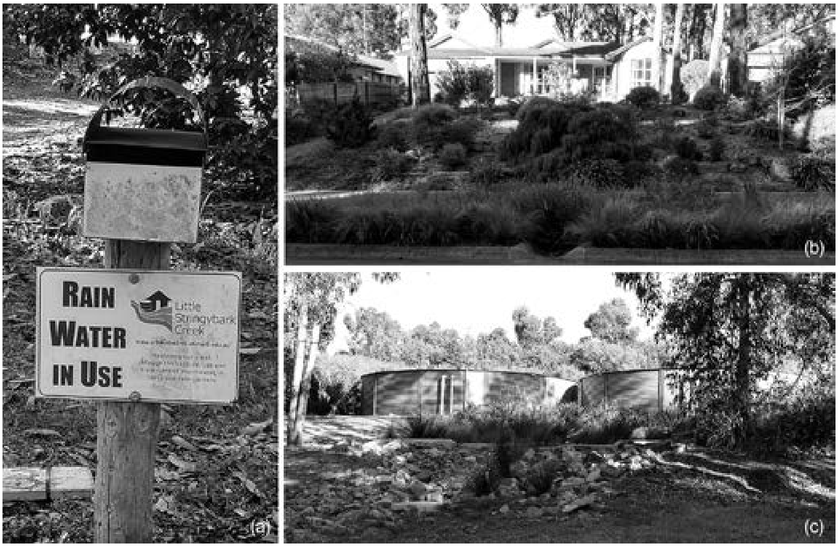
Source: NYC DEP & Ramboll (2017).

Figure 7.4 Future concept vision for cloudburst management at a pilot location in New York City with multi-functional NBS serving as recreation spaces on dry days (a, c) and as stormwater detention spaces on wet days (b, d)

Using Nature-Based Solutions to Manage Severe Drought in Melbourne, Australia

The Melbourne metropolitan area, surrounding the Victorian state capital city of Melbourne, Australia, sits on land traditionally owned by the people of the Kulin Nations. NBS for water resilience were demonstrated by aboriginal people before European colonization in numerous locations in Australia, particularly through a network of weirs and ponds used to capture receding floodwaters and facilitate trapping fish. This managed system also supplied water during drought. The complex network of engineered channels and rock walls near Lake Condah in southwest Victoria, known as the Budj Bim Cultural Landscape, is designated a World Heritage Site by UNESCO on the basis of its representation of cultural values connected to the indigenous group, the Gunditjmara (Bark et al., 2015; Jones, 2011). Today, Melbourne has a population of 5 million and covers roughly 10,000 km^2. Droughts are common in Australian historical records but they appear to be intensifying (Freund et al., 2017). During the Millennium Drought (which occurred from 1996–2010), the most recent and worst drought in the last 400 years (Freund et al., 2017), water supply inflows dropped by 37 percent while the population increased in Melbourne, resulting in a 64 percent reduction in stored water supply between 1996 and 2009 (Grant et al., 2013).

In response to this, water use restrictions, water-sensitive development guidelines, water pricing, wastewater recycling, and finally integrated urban water cycle management projects contributed to reducing per capita water consumption by nearly 50 percent (Low et al., 2015). Several large stormwater harvesting schemes were constructed in the later years of the Millennium Drought in an effort to augment water supply in the city for landscape irrigation. These projects used a range of blue to brown NBS features that are locally referred to as water-sensitive urban design systems (Figure 7.5). In addition to rainwater harvesting, NBS such as stormwater biofilters and wetlands were leveraged to treat runoff before storing it. It was not until the Victorian State Government invested in integrated urban water management in 2012 that treated runoff from biofilters was used as a substitute for potable water use (Low et al., 2015). Perhaps most surprising and unprecedented was the lasting effects the drought had on residents of the city. Average daily water use before the drought was 458l per person. Following the Millennium Drought, water use decreased to 246l per person per day (Grant et al., 2013). Between 2010 and 2020, average water use was 158l per person per day (Melbourne Water, 2021). Although harvested rainwater and stormwater runoff only comprises a small fraction (~3 percent) of the total demand in Melbourne, stormwater runoff available for harvesting comprises about 80 percent of demand (Melbourne Water, 2017). Using treated stormwater runoff to augment potable supply would require a higher level of treatment than current water-sensitive urban design systems are able to provide reliably, particularly for removing pathogens. Currently, researchers are investigating novel soil media amendments and bioinoculants (Palacios et al., 2021), plant species which exude antimicrobial compounds (Galbraith et al., 2019), and real-time control of effluent flow rates and water levels to better and more predictably remove pathogens from runoff in NBS features (Shen et al., 2020). Indeed, NBS such as stormwater biofilters and wetlands are an integral part of utilizing polluted stormwater runoff as a substitute for potable water use in Melbourne (Grant et al., 2013).



Notes: (a) a sign indicating rainwater collection; (b) a street-side bioswale, non-turfgrass yard; and (c) a rainwater collection system and overflow conveyance swale.
Source: Lauren McPhillips.

Figure 7.5 Nature-based solutions in the Little Stringybark Creek catchment in Melbourne, Australia

Making "Room for the River" in the Netherlands

As more engineered and gray infrastructure strategies were implemented around the world to manage water in recent centuries, levees or embankments have been a key flood defense along river corridors. The challenge with this strategy is that it passes the problem downstream, preventing the river from using its floodplain and thus from diffusing its energy or reducing its volume and nutrient or pollutant loads.

In the Netherlands, there has been a recent shift from this "battle against water" to "living with water" and embracing NBS of floodplain restoration and reconnection (de Groot & de Groot, 2009). The €2.2 billion Room for the River program has been a keystone of this effort. This program has involved implementing a suite of strategies to expand the ability of rivers to store water in the floodplain, such as lowering floodplains and relocating embankments (e.g., dykes) inland (Busscher et al., 2019). More than 30 interventions have been implemented along the Rhine River, restoring 4,400 ha of former floodplain.

Recent research is already documenting the reduced consequences of flooding and reduced probability of breach and failure of embankments as a result of these floodplain restoration practices (Klijn et al., 2018). Although this approach inherently takes up more space relative to raising embankments located close to the river, it has provided opportunities for multiple benefits beyond flood management (Busscher et al., 2019). These co-benefits of NBS are discussed more extensively in other chapters of this book (e.g., Chapter 4).

It is important to acknowledge the complex coordination and multi-level governance processes required by this example of large-scale NBS. While clearly challenging, this example demonstrates that it is possible to make such transformative change happen with careful planning, adequate funding, and a mix of centralized and decentralized implementation (Rijke et al., 2012).

CHALLENGES IN MAKING THE CASE FOR NBS FOR WATER RESILIENCE

In general, there is growing evidence documenting the hydrologic and water quality performance of NBS, particularly hybrid NBS designed explicitly for water management. This includes evidence of peak flow reduction, reduction of runoff volumes, infiltration to recharge groundwater, and retention or removal of numerous pollutants (Clary et al., 2017; Liu et al., 2014; Roy-Poirier et al., 2010). There is some documentation of NBS performance at the system scale (i.e., watershed or catchment); this evidence is more sparse than at the site scale, and is dominated by modeling studies (Jefferson et al., 2017; Lintern et al., 2020). Hydrologic metrics that have been evaluated include changes in riverine flooding or flashiness and water quality of downstream water bodies, but evidence of groundwater recharge or reduction in pluvial flooding are lacking (Rosenzweig et al., 2018b).

One knowledge gap is in understanding the function of NBS over time, and based on NBS location(s) in a catchment. Sources of temporal change include the accumulation of sediment and associated pollutants over time, reduction in infiltration, and changes in maintenance that feed back into physical, chemical, or biological processes. Most models assume constant performance over time. The few long-term field studies that exist have demonstrated wide variability, from no change in performance over time to decreases in hydrologic or water quality performance (Amur et al., 2020; Komlos & Traver, 2012; Natarajan & Davis, 2015). While some NBS, particularly those that are more ecological, may be self-maintaining, other more engineered NBS may require maintenance to maintain adequate water resilience functions over time (Conley et al., 2020; Sherk et al., 2020).

Another challenge relates to optimal spatial placement of NBS. In terms of water resilience, this challenge is addressed by catchment science engineering approaches that emphasize placement of NBS based on location of hydrologic hotspots, e.g., for stormwater management, places where concentrated runoff contributions converge (Hewett et al., 2020). With increasingly high-resolution spatial datasets, capabilities to target such hotspots are improving. In terms of stormwater management, the most efficient collection of runoff can occur at more centralized locations with a greater drainage area, but there is some evidence that more distributed NBS can offer greater redundancy and resilience, and better mimic pre-development hydrology and manage floods (Loperfido et al., 2014). Other challenges in this realm are more related to the practical and social-economical-political challenges of land acquisition in these "optimal" locations. For example, planning for large-scale floodplain restoration may require the buy-out of homes and the coordination of many agencies or stakeholders. The placement of NBS is often more opportunistic, leveraging land that is available at any given time.

A further challenge lies in valuing hydrologic and water quality performance of NBS features that are not explicitly engineered for water management. Hybrid NBS or stormwater control measures have target design criteria, such as storage or infiltration capacity or treatment efficiency. How can infiltration and storage benefits of a park or existing wetland be incorporated into existing infrastructure asset management that is often divided between engineered assets and NBS assets, and how do we better integrate these diverse features in our modeling approaches? It is also not always clear how the performance of more engineered NBS compare to more ecological NBS, and more research is needed in this realm.

Although these challenges remain, interest in and implementation of NBS for water resilience continues to grow. A key motivation is the ability to meet water-related goals or regulations while also addressing other goals or providing other benefits. In general, "gray" stormwater control measures provide one or two functions efficiently. As documented here and in other chapters of this book, NBS can offer a wide range of co-benefits. In considering the need to confront climate change and increased incidence of natural hazards such as high-intensity storm events or prolonged drought and extreme heat events, investment in NBS can aid in addressing multiple hazards, in addition to other goals, providing a much more cost-effective investment over simply prioritizing upgrades to existing storm sewer infrastructure.

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