Title
Adapting Urban Water Systems to a Changing Climate: Lessons from the Millennium Drought in Southeast Australia

Journal
Environmental Science and Technology, 47(19)

ISSN
0013-936X

Authors
Grant, Stanley B
Fletcher, Tim D
Feldman, David
et al.

Publication Date
2013-10-01

DOI
10.1021/es400618z

Peer reviewed

Environmental Science & Technology

Feature

pubs.acs.org/est

Adapting Urban Water Systems to a Changing Climate: Lessons from the Millennium Drought in Southeast Australia

Stanley B. Grant,*[,†,‡] Tim D. Fletcher,[⊥] David Feldman,[§] Jean-Daniel Saphores,[†,§] Perran L. M. Cook,[#] Mike Stewardson,[‡] Kathleen Low,[†] Kristal Burry,[∇] and Andrew J. Hamilton[‖]

[†]Department of Civil and Environmental Engineering, E4130 Engineering Gateway, University of California, Irvine, Irvine, California 92697-2175, United States

[‡]Department of Infrastructure Engineering, Melbourne School of Engineering, Engineering Block D, The University of Melbourne, Parkville 3010, Victoria, Australia

[§]Department of Planning, Policy, and Design, 300G Social Ecology I, University of California, Irvine, Irvine, California 92697-7075, United States

[‖]Department of Agriculture and Food Systems, The University of Melbourne, 940 Dookie−Nalinga Road, Dookie College, Victoria 3647, Australia

[⊥]Melbourne School of Land and Environment, The University of Melbourne, Burnley Campus, 500 Yarra Boulevard, Richmond, Victoria 3121, Australia

[#]Water Studies Centre, School of Chemistry, Monash University, Victoria 3800, Australia

[∇]Melbourne School of Land and Environment, The University of Melbourne, Parkville Campus, 207 Bouverie Street, Victoria 3052, Australia

A LONG HISTORY OF DROUGHT IN MELBOURNE

Australia is the world's driest inhabited continent, and its population is one of the most urban. As of 2010, 89% of Australia's 21 million inhabitants lived in urban areas.[1] Finding adequate water resources to sustain Australia's cities is an ongoing challenge.[2] Nowhere is that more apparent than in Melbourne, a coastal city of approximately 4 million people located on the country's southeastern coast. Over its 166-year history, Melbourne has experienced eight major droughts. The most recent one, known as the Millennium Drought, started in 1997 and lasted more than a decade. By 2009, below-average precipitation and above-average temperatures drained the city's drinking-water reservoirs and stoked bush fires, including the "Black Saturday" fire that damaged 30% of the city's water supply catchment and claimed 173 lives.[3] The Millennium Drought also altered public perceptions about global climate change, water conservation, and water-use behaviors, and energized city managers and politicians to adopt a wide range of approaches for augmenting water supplies and conserving water resources, although the contribution of climate change to the Millennium drought, while plausible, remains unproven.[4] In this paper, we explore how the Millennium Drought changed the way Melburnians source and use their water resources and discuss what these changes may portend for other large cities in water-scarce and climate-change-vulnerable regions of the world, in particular, the Southwest region of the United States.

MELBOURNE'S WATER SUPPLY

Melbourne sources most of its water from protected stream catchments located in uninhabited mountain ash (*Eucalyptus regnans*) forests to the north and northeast of the city (Figure 1). Runoff from these protected catchments flows by gravity into ten harvesting reservoirs and, from there, through a network of aqueducts and pipelines to storage reservoirs where it is distributed, after minimal treatment, to local service reservoirs. Since the first harvesting reservoir was built in the mid-1800s, Melbourne's protected catchments have provided the city with a safe, low-energy, and mostly reliable source of high quality drinking water. However, they have also left the city vulnerable to water shortages during periods of very low precipitation.[5]

To buffer against water shortages, Melbourne recently invested in various water supply augmentation schemes, including an interbasin transfer pipeline (the North−South or Sugarloaf Pipeline) and the largest desalination plant in the Southern Hemisphere (the Wonthaggi Desalination Plant) (Figure 1). These two projects were built at a capital cost of approximately AU$700 million [6] and AU$6 billion,[7] respectively, and can deliver annually up to 75 and 150 GL of water to Melbourne; combined, that equates to about 40% of the city's present day municipal water demand.

However, since their completion in 2010 (Sugarloaf Pipeline) and 2012 (Wonthaggi Desalination Plant), neither

Special Issue: Design Options for More Sustainable Urban Water Environment

Published: May 3, 2013

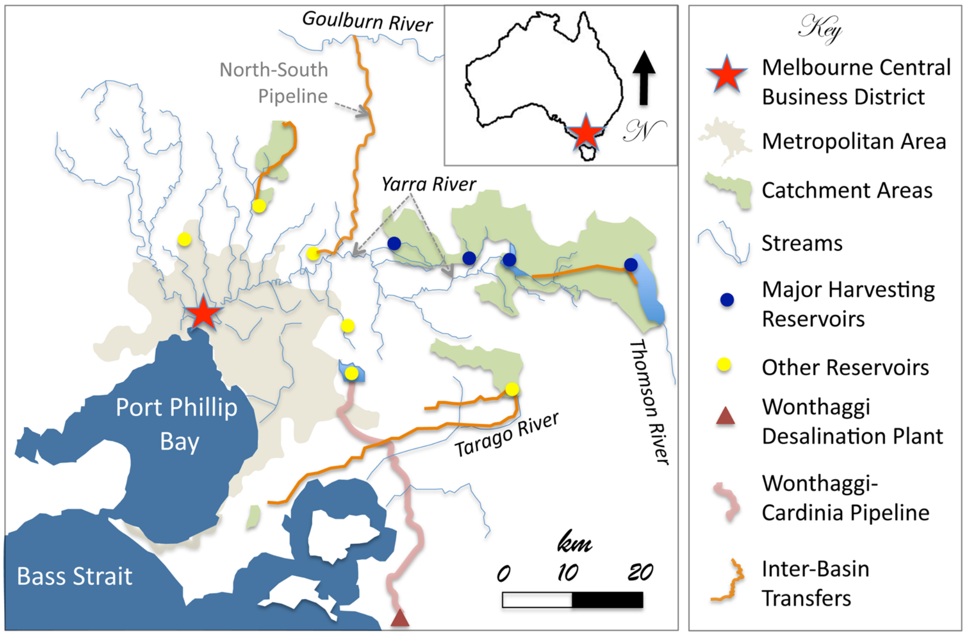

Figure 1. Drinking water supply system for Melbourne, Australia. Most of the drinking water comes from protected catchments located in the mountains, which drain into four major harvesting reservoirs (Thomson, Upper Yarra, O'Shannassy, Maroondah) and six other harvesting reservoirs (Tarago, Yan Yean, Silvan, Greenvale, Cardinia, Sugarloaf). Recent water supply augmentation schemes include a pipeline that transfers water to Melbourne from the Goulburn River (North−South or Sugarloaf Pipeline) and the largest desalination plant in the Southern Hemisphere (Wonthaggi Desalination Plant).

project has provided water to Melbourne. There are several reasons for this outcome. Both projects were commissioned during the Millennium Drought but completed after the drought ended. With water no longer in short supply, public concern has mounted over the cost and carbon footprint of producing water from the desalination plant, while the Sugarloaf Pipeline has proved politically unpopular because it transfers water from already water-stressed rural areas.[7] The purchase price of the desalinated water, which was negotiated during a period of extreme water scarcity, depends on the quantity of water purchased and is currently significantly higher than the cost of water from conventional sources.

The fraught history of these two water supply augmentation schemes illustrates the complexities that can arise when climate alternates between periods of relative water scarcity (when the exigency to augment water supply holds sway) and periods of water abundance (when financial, environmental, and equity concerns dominate). For the Melbourne area, global climate change models forecast long-term decreases in average annual precipitation and an overall increase in climate variability.[8] Thus, climate change—and increasing climate variability, in particular—will likely play a starring role in Melbourne's water supply challenges for the foreseeable future.

■ INFLOW FROM CATCHMENTS DURING THE MILLENNIUM DROUGHT

An analysis of the water flowing into and out of the city's reservoir system reveals how the Millennium Drought affected Melbourne's water budget (Figure 2). Until 1997, annual net inflow to Melbourne's four major harvesting reservoirs fluctuated around a long-term average of 615 GL per year (GL = 10^9 L) (blue line in Figure 2A). After 1997, reduced precipitation associated with the drought caused annual net inflow to drop to approximately 390 GL/year, a 37% decline relative to the long-term average (red line in Figure 2A). Even after the Millennium Drought ended in 2010, annual net inflow remained below its long-term average, due to the impacts of prolonged dry conditions and fire damage to forested catchments.[5] The Millennium Drought also reduced average inflow during the critically important normally wet months of October to December (Figure 2B), causing the volume of water stored in Melbourne's reservoirs to drop by 64%, from 1700 GL in October of 1996 to 611 GL in October of 2009, an average rate of decline of over 90 GL per year (Figure 2C). Had this trend continued past 2008, the city's reservoirs could have dried up in less than seven years.

■ MUNICIPAL DEMAND DURING THE MILLENNIUM DROUGHT

Approximately one-half to three-quarters of Melbourne's water supply is used to satisfy municipal demand, which includes water for residential, commercial, landscaping, and agricultural activities within the urban and peri-urban areas of the city. During the Millennium Drought, municipal demand declined 25%, from a predrought average of 40 GL per month to a postdrought average of 30 GL per month (Figure 2D). Because the Greater Melbourne area population increased from 2.87 to 4 million over the same period,[1] the per capita municipal demand declined 46% over 12 years, from 458 to 246 L per person per day.

What accounts for this precipitous decline in municipal demand? In general, a city subjected to drought conditions can use its drinking water more effectively through a number of complementary approaches.[9] Here, we focus on four approaches that worked well in Melbourne: public education campaigns, restrictions on water use, substitution targets, and water pricing.

Public Education. Public education was perhaps the most effective tool government agencies adopted to reduce municipal demand during the drought. The Victorian Government and

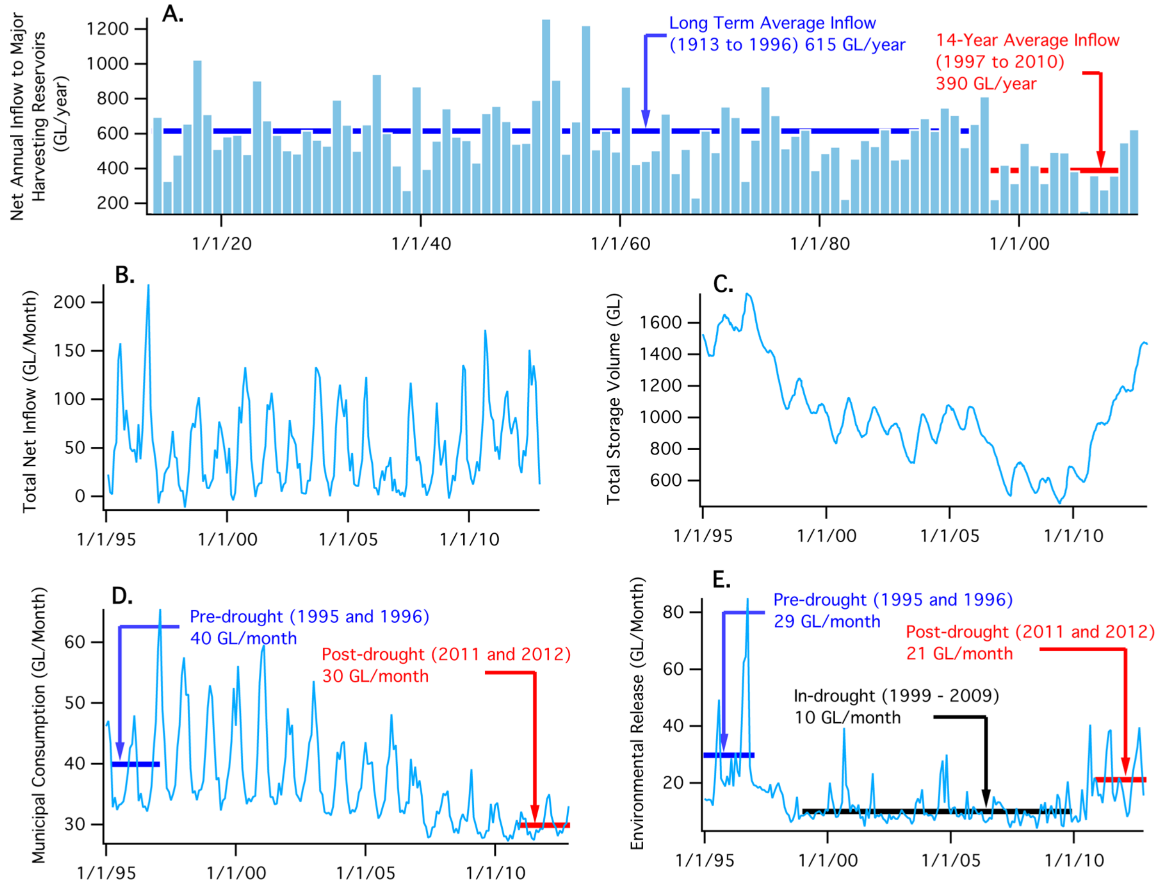

Figure 2. Water budget for the Greater Melbourne Region. Annual net inflows (inflow minus evaporation from the reservoirs) to the four major harvesting reservoirs for the past 100 years (Panel A). Monthly time series of total net inflow to the water system (Panel B), total stored water (Panel C), municipal consumption (Panel D), and environmental releases via outlet structures or spills (Panel E) for the past 17 years, including the Millennium Drought (1997−2010). Data for Panels A, C, D, and E provided by Melbourne Water; monthly total net inflows (Panel B) calculated by volume balance.

the Melbourne water industry broadcast water storage levels on TV, radio, and print news services, and installed billboards that summarized the latest water storage data, weekly rainfall and inflows, and provided advice on how to save water. Education extended to commercial and industrial water users as well, with water authorities assisting major water users to develop water conservation plans.

Restrictions. Together with the State of Victoria, Melbourne developed clearly delineated water restriction plans.[10] For residential areas, these start at Level 1 (minor restrictions on garden watering) and progress to Level 4 (no outdoor water use at all). In addition to mandatory restrictions, Victorians were urged to respect a voluntary target of 150 L water consumption per person per day, for example by showering no longer than 3 min, capturing rainwater from roofs for toilet flushing and gardening, and using gray water from sinks for gardening.[9] Reported compliance with both mandatory and voluntary restrictions was very high.[11] For industrial and commercial water users, the Victorian government introduced *WaterMAP*, which required each major user to set water conservation targets and to report on them as part of annual reporting requirements.[12] Deliveries of water for agricultural use also decreased during the drought, causing a decrease in crop yields.[4]

Substitution Targets. The Victorian government set a statewide target to reuse 20% of all wastewater inflows to its treatment plants by 2010; this was exceeded, with 24.1% of wastewater inflows recycled by 2009/10 (22.8% in Melbourne alone).[13] By 2010, the city was also capturing and reusing large volumes of stormwater and rainwater.[14] These together provided an additional 10 GL, or approximately 3% of Melbourne's annual municipal demand. Critical to such ambitious reuse was tight regulation around water quality and protection of public health. The Victorian Department of Health is charged with managing public health risks associated with reuse, and it does this through aligning its approval process to both State and Federal guidelines. There has been much activity at both levels of government, such that virtually all reuse options are covered by quite specific and comprehensive guidelines, including those for recycled water use in general,[15,16] on-site reuse,[17] recycled water dual-pipe (third-pipe or purple-pipe) developments,[18] direct stormwater reuse (including roof water),[19] and managed aquifer recharge with recycled and stormwater.[20]

Pricing. Water prices rose during the Millennium Drought, including the introduction of a 5% "environmental levy" and the modification of the block tariff price structure from two- to three-tiers. These changes had the dual objective of signaling the scarcity of water and of helping pay for the major investments in water substitution and supply augmentation described.

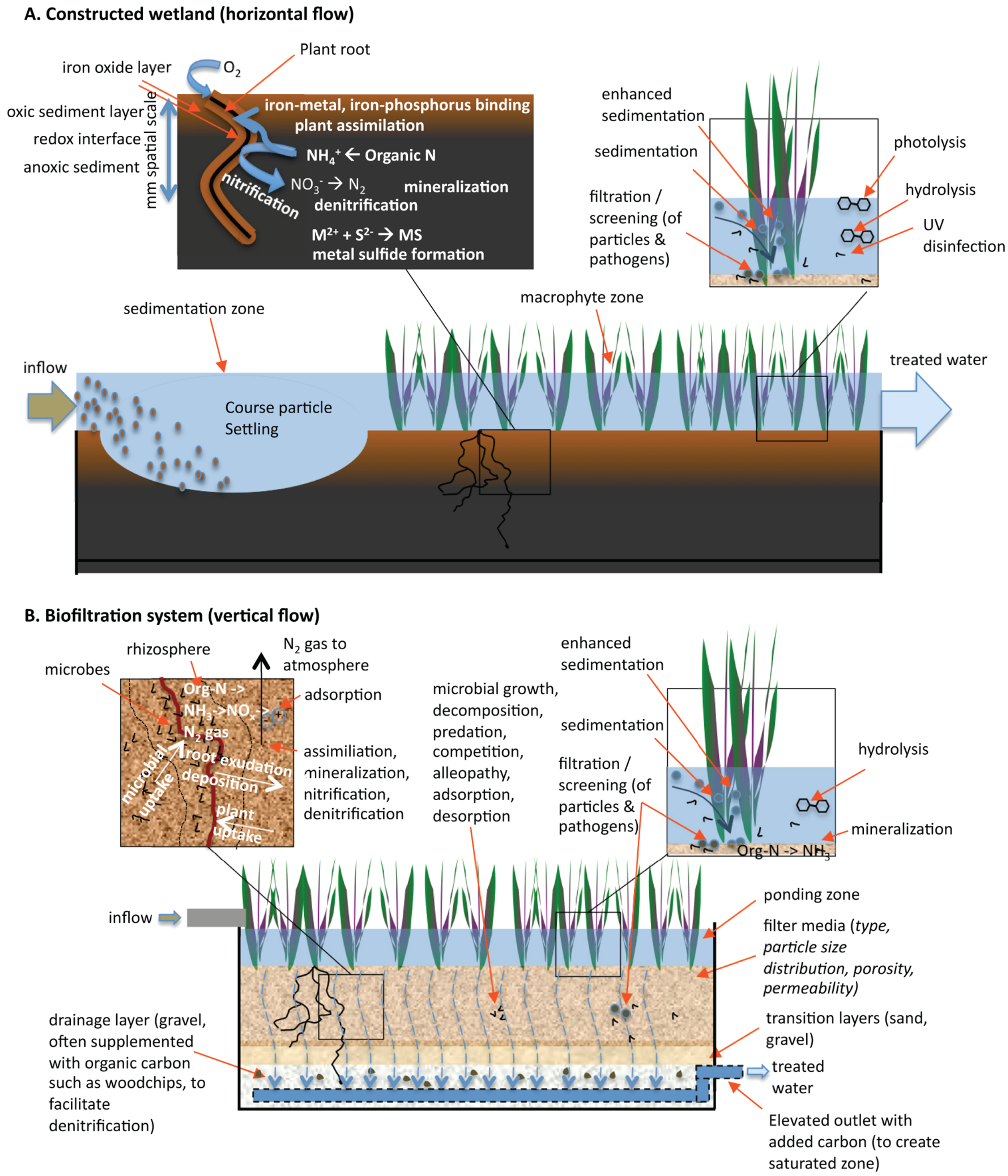

Figure 3. Pollutant removal, retention, and transformation processes in low-energy treatment systems. Constructed wetlands (Panel A): within the sedimentation zone, sedimentation, screening, and photolysis remove particles, while sunlight breaks down pollutant molecules through hydrolysis and kills bacteria through UV disinfection. Within the sediment, biogeochemical processes, such as denitrification, remove nitrogen, while phosphorus and metals are removed through sorption and the formation of insoluble minerals. Plants enhance these processes through the input of both organic carbon and oxygen into the sediment. The dominant flow pathway is horizontal with a gradient in redox potential occurring between the sediment and water. Biofiltration systems (Panel B): within the ponding zone, processes such as sedimentation and adhesion to plants remove particles. Physical screening and chemical adsorption in the filter media play important roles (particularly for phosphorus, heavy metals and pathogens), while the combination of plant roots, microbes, and soil media support plant and microbial uptake of nutrients, along with the transformations and potential removal of nitrogen through denitrification.

ENVIRONMENTAL RELEASES DURING THE MILLENNIUM DROUGHT

Environmental Releases are the other major "consumer" of water resources in Melbourne. During the Millennium Drought, riverine and riparian ecosystems downstream of water diversions suffered from significant streamflow reductions.[21] Melbourne has ten water supply reservoirs and several diversion weirs on tributary streams that reduce streamflows across the Yarra Catchment and in neighboring Thomson, Goulburn, and Tarago Rivers from which water is diverted to Melbourne via interbasin transfers (Figure 1). In October 1996, all of the main reservoirs were close to full, and an average of 29 GL/month was released to the environment (Figure 2E; environmental releases include flow through outlet structures and spillways). While it took several years for the Millennium

Drought to affect environmental releases, by 1999 they dropped 66% to an average of 10 GL per month (Figure 2E). These low environmental releases persisted for a full decade following 1999. Environmental releases were reduced in both absolute terms and as a proportion of inflows, and both seasonal and event-based variations in flow were similarly attenuated. The disproportionate impact of the Millennium Drought on streamflows in regulated rivers has also been observed across the Murray-Darling Basin in southeastern Australia.[21,22]

In an ironic twist, the Millennium Drought coincided with the implementation of national water reforms, which produced legally mandated environmental entitlements that require increasing environmental releases to the major rivers impacted by Melbourne's water supply. Because these mandated increases coincided with Stage 3 water restrictions in Melbourne, the new environmental entitlements were suspended from the time of their publication in 2007 until Melbourne's water restrictions eased in 2009/10.[23] The Victorian Government estimated that the suspension of environmental entitlements provided an additional 148 GL of water (or five months supply) for Melbourne, avoiding the need to introduce more severe (Stage 4) water use restrictions.[24]

When the Millennium Drought ended, environmental releases increased with inflows; in particular, in the two years following the end of the drought (2011 and 2012), environmental releases averaged 21 GL per month (Figure 2E). By the end of 2012, however, environmental releases were still less than predrought levels, despite the implementation of environmental water entitlements. Reduced storage levels, and infrastructure or operational changes implemented during the drought, may have contributed to the persisting effect of the drought on downstream flows.

■ THE LAST FRONTIER: CAPTURE AND REUSE OF STORMWATER RUNOFF

Looking forward, Melbourne hopes to become a world leader in the capture and reuse of stormwater runoff, one of the last untapped sources of water available to the city.[14] While most projects are still in planning stages, with 57 estimated to be in operation by 2015,[14] there have already been a few schemes successfully commissioned, such as the first stormwater third-pipe residential development, Avenview, in eastern Melbourne.[3] To put the potential of stormwater reuse in perspective, Melbourne's municipal demand in 2010 (356 GL) is significantly less than the average annual volume of stormwater runoff generated by the city (463 GL).[14] Stormwater reuse can take many forms, with different energy requirements (e.g., for treatment), human and ecosystem health implications, and economic and social considerations. Broadly speaking, low-energy stormwater reuse schemes work by (1) capturing water before it becomes contaminated by contact with the urban landscape; (2) relying on low-energy processes for removing contaminants; and (3) treating water only to the extent necessary for its intended use. Residential irrigation from rainwater tanks satisfies the first and last criteria, by capturing runoff from relatively less-polluted surfaces (e.g., roofs[25]) before it comes into contact with the broader urban landscape and by using the water for a quality-appropriate activity. Stormwater wetlands and bioretention (also referred to as biofiltration) systems can be effective for the treatment of stormwater for nonpotable uses, or for pretreatment upstream of more traditional treatment technologies (Figure 3). Wetlands have commonly been used for stormwater harvesting and pretreatment, for example prior to storage and subsequent recovery in aquifers.[26] Bioretention systems, which filter water through a planted soil or sand-based media, are a newer approach. They are easily integrated into the urban landscape at a range of scales and can remove sediment, nutrients, and heavy metals typically present in urban runoff.[2,27]

Stormwater reuse also comes with many potential ecosystem benefits, such as the opportunity to restore predevelopment flow regimes and retain nutrients and pollutants in a catchment. Capturing, retaining, and treating runoff, rather than facilitating its rapid delivery to streams, can effectively 'disconnect' impervious areas from receiving waters, thus returning frequency, magnitude, timing, and quality of streamflows to more natural levels (e.g., ref 28). This approach is consistent with the 'natural flow paradigm', which aims to restore ecologically important aspects of the hydrograph to a predevelopment state.[29] Stormwater retention and treatment systems should be designed to mimic natural retention capacity prior to development [30] and to ensure that they allow infiltrated or filtered flows to the stream to support predevelopment baseflow conditions, whether perennial or ephemeral. In retaining water within low-energy retention and treatment systems, urban soil moisture is also restored, with potential benefits for the urban microclimate.[31] These approaches mitigate channel modification due to erosion (with its ecological, social and economic impacts), minimize flooding, and help protect sensitive taxa such as amphibians.[9]

■ BIG-PICTURE LESSONS AND FUTURE CHALLENGES

Melbourne's experience has shown that a severe water shortage can drive behavior change,[32] especially when water storage levels are communicated to the public.[33] A major challenge, however, will be to keep long-term consumption low because there is evidence that per capita water use in Melbourne is back on the rise.[34]

Despite literature dating back decades showing that urbanization increases runoff volumes,[35] the scientific community has taken a surprisingly long time to recognize the environmental benefits of stormwater harvesting. This situation has been rectified, however, and scientific frameworks are now available for estimating the volume of water that should be harvested in a given catchment, to both satisfy reasonable levels of water demand and return urban watersheds to a more natural flow regime.[36]

A clear lesson from the implementation of wastewater recycling and stormwater harvesting in Melbourne has been the integration of centralized and decentralized solutions. Decentralized solutions increase resilience and adaptability,[37−39] although Hughes et al. [40] showed that the centralized governance arrangements in Australia allowed setting region-wide performance targets (e.g., the percentage of wastewater recycling), which are more difficult to achieve under weak centralized control. The challenge is to balance these two approaches, particularly when retrofits of areas that have already been developed are required.[41,42]

Finally, water substitution, such as stormwater harvesting and wastewater reuse, can present a potential risk to human and ecosystem health. Establishing a sufficient number of treatment barriers and adequate real-time monitoring is necessary to ensure that the water produced is consistently suitable for its intended end use, despite the inherent variability at the point of harvesting,[43] and to demonstrate that centralized and decentralized treatment schemes pose small chemical or microbiological risks.[44] Developing a regulatory framework that encourages water substitution and minimizes human health risk is therefore a critical challenge. This framework also needs to clarify rights to substitute sources, since a lack of security over water entitlements will hamper private investment in such schemes.

PARALLELS TO WATER SCARCITY IN THE SOUTHWEST U.S.

Lessons from the Millennium Drought in Southeast Australia invite at least four comparisons with the experience of water scarcity in the Southwest U.S. First, the Southwest U.S. has long experienced chronic water scarcity and highly variable water availability.[45] Unlike Southeast Australia, however, it has experienced more dramatic population growth, which has strained water supplies[46,47] and sparked the adoption of reforms. This led to improvements in the water infrastructure, as well as institutional innovations to cushion the region against endemic water conflicts.

Throughout the 20th Century, water supply infrastructure was funded mostly by the federal government. Major dams authorized by Congress ensured that portions of the upper and lower Colorado basins could provide dependable supplies as well as flood control and hydropower for many of the region's cities, and for irrigated agriculture in California's Imperial and Central Valleys, Central Arizona, Utah, and New Mexico.[48−52] In addition, laws and policies favoring senior appropriators were passed by states, and water markets permitting transfers to higher-valued uses were established.[45,46,53] These innovations focused largely on augmenting supply and only rarely on attenuating demand or encouraging more efficient water uses.

Second, since the 1970s, proactive municipalities in the region have adopted additional innovations in response to chronic drought. They introduced tiered pricing, promoted metering, provided incentives for drought-tolerant landscaping, created aggressive public outreach programs, and mandated water appliance standards—complementing measures adopted in the region's agriculture sector, including drip irrigation and water accounting systems.[53−55] These innovations were introduced unevenly within the region, however, and enthusiasm for their adoption often waned after drought ended.

Following severe droughts in 1976−7 and the early 1990s increasing block rate pricing schemes were introduced in coastal and near-coastal communities in California. At the same time, fast-growing inland desert regions in the Mojave Desert and the Sonoran Desert's Coachella Valley, adopted mandatory drought-tolerant landscaping on public properties while encouraging residential landscaping replacement programs inspired from successful models in neighboring states (e.g., Las Vegas, Nevada, or Tucson, Arizona). Following the end of the early-1990s drought, however, further impetus for adopting increasing block rates pricing structures and other innovations declined.[55]

Third, unlike Southeast Australia's exemplary interagency and interjurisdictional collaboration, the Southwest U.S. has traditionally experienced fragmentation and competition in water management. Recent years have witnessed improved cooperation, especially for identifying the information decision-makers need to avoid disruptions, fostering communication between scientists and water managers,[56,57] and enhancing coordination among local jurisdictions within states.

In California, for instance, where water marketing has long been practiced, the state legislature encouraged, after the late 1970s drought, greater marketing to reduce scarcity, modify long-term demand patterns, and acquire water for environmental needs.[58−60] An emergency drought water bank was established, and in 1992, Congressional action gave impetus for using water markets to protect in-streamflow.[61] In Arizona, the introduction in 1980 of a novel Groundwater Protection Act compelled interjurisdictional local cooperation to better allocate limited groundwater in response to urban growth, and encouraged aquifer recharge through use of reclaimed wastewater. The Act furthered intergovernmental collaboration by establishing integrated groundwater management protection areas extending across entire metropolitan areas.[62]

Fourth, while numerous lessons from Southeast Australia's experience are relevant to the Southwest's drought-adaptation efforts, constraints in applying them abound. One critical set of lessons emerges from Melbourne's public engagement process associated with its integrated water-cycle management efforts. The foremost of these are the concerted efforts to help establish a culture promoting community-level engagement in identifying, prioritizing, and implementing supply- and demand-side water management options including off-stream catchment, reducing household water use, incorporating plans for using low-quality treated water for nonpotable needs, capturing stormwater runoff through biofiltration, and reclaiming wastewater. The visioning effort associated with this process encouraged bottom-up collaboration among stakeholders, enhanced social learning among the public regarding the severity of drought, and helped generate a broad public consensus, which, in turn, empowered city officials to embrace a wide and diverse range of vetted strategies.[63]

Like Southeast Australia, the Southwest U.S. is subjected to recurring cycles of drought and faces increasing weather variability (e.g., ref 57). Given dire long-term drought projections, conservation and reuse appear inevitable—and are becoming increasingly acceptable—for improving supply reliability and meeting in-stream and societal needs.[64,65] However, while some Australian strategies may appear attractive, U.S. water management traditions, which are especially pronounced in the Southwest, make adoption of these reforms difficult—if not impossible. Impediments include fragmented authority for water management scattered among numerous jurisdictions and agencies, institutional conservatism resistant to innovation, and top-down agency-driven agendas that discourage broad-based public engagement.[63] In short, while enhanced coordination has occurred, more local-scale engagement and visioning remain future challenges.

AUTHOR INFORMATION

Corresponding Author

*Phone: (949) 824-8277. Fax: (949) 824-2541. E-mail: sbgrant@uci.edu.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors gratefully acknowledge data provided by Melbourne Water, comments on the manuscript from A. Deletic and R. Brown, and financial support from the U.S.

National Science Foundation Partnerships for International Research and Education (OISE-1243543). Fletcher is supported by an ARC Future Fellowship (FT100100144).

REFERENCES

(1) CIA World Factbook, 2013; https://www.cia.gov/library/publications/the-world-factbook/fields/2212.html (accessed:).

(2) Fletcher, T. D.; Deletic, A.; Mitchell, V.; Hatt, B. E. Reuse of urban runoff—A review of recent Australian advances and remaining challenges. *J. Environ. Quality* **2008**, *37* (5), 116−127.

(3) Barker, F.; Faggian, R.; Hamilton, A. J. A history of wastewater irrigation in Melbourne, Australia. *J. Water Sustainability* **2011**, *1*, 31−50.

(4) van Dijk, A. I. J. M.; Beck, H. E.; Crosbie, R. S.; de Jeu, R. A. M.; Liu, Y. Y.; Podger, G. M.; Timbal, B.; Viney, N. R. The Millennium Drought in southeast Australia (2001−2009): Natural and human causes and implications for water resources, ecosystems, economy, and society. *Water Resour. Res.* **2013**, *49*, 1040−1057, DOI: doi:10.1002/wrcr.20123.

(5) Rhodes, B. G.; Fagan, J. E.; Tan, K. S. Responding to a rapid climate shift—Experiences from Melbourne Australia. *Proceedings of the World Congress on Climate and Energy, International Water Association*, Dublin, Ireland, May 13−18, 2012.

(6) Irrigation efficiency programs; http://www.audit.vic.gov.au/reports__publications/reports_by_year/2009-10/20100906_irrigation_efficiency.aspx (accessed:).

(7) Edwards, G. The desalination plant, the north−south pipeline and the welfare of Melburnians. *56th annual conference of Australian Agricultural and Resource Economics Society*, Esplanade Hotel, Fremantle, Western Australia, Feb. 9−10, 2012.

(8) Howe, C.; Jones, R. N.; Maheepala, S.; Rhodes, B. *Implications of Potential Climate Change for Melbourne's Water Resources*: Melbourne Water CSIRO: Melbourne, Victoria, 2005; http://www.melbournewater.com.au/content/publications/reports/climate_change_study.asp

(9) Grant, S. B.; Saphores, J. D.; Feldman, D. L.; Hamilton, A. J.; Fletcher, T. D.; Cook, P. L. M.; Stewardson, M.; Sanders, B. F.; Levin, L. A.; Ambrose, R. F.; Deletic, A.; Brown, R.; Jiang, S. C.; Rosso, D.; Cooper, W. J.; Marusic, I. Taking the "waste" out of "Wastewater" for human water security and ecosystem sustainability. *Science* **2012**, *337*, 681−686.

(10) Using and saving water: Water restrictions; www.water.vic.gov.au/saving/restrictions (accessed:).

(11) Dolnicar, S.; Hurlimann, A. Water alternatives—Who and what influences public acceptance? *J. Public Affairs* **2010**, *11* (1), 49−59.

(12) Using and saving water: WaterMAP; www.water.vic.gov.au/saving/industry/watermap (accessed:).

(13) *Progress Against the National Target of 30% Of Australia's Wastewater Being Recycled by 2015*, Report prepared for the Department of Sustainability, Environment, Water, Population, and Communities (DSEWPaC), Commonwealth of Australia; Marsden Jacob Associates: Canberra, Australia, 2012; available online: http://www.environment.gov.au/water/publications/urban/pubs/recycled-water-target-final-report.pdf.

(14) *Living Melbourne, Living Victoria Roadmap*; Living Victoria Ministerial Advisory Council, Department of Sustainability and Environment, Victorian Government: Australia, 2011.

(15) EPA Victoria. *Guidelines for Environmental Management: Use of Reclaimed Water*; Environmental Protection Agency Victoria: Southbank, Victoria2003.

(16) *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 1)*; Natural Resource Management Ministerial Council, Environment Protection and Heritage Council, and the Australian Health Ministers' Conference: Canberra, Australia, 2006.

(17) *Guidelines for Environmental Management: Code of Practice Onsite Wastewater Management*; Environmental Protection Agency Victoria: Southback, Victoria, 2008.

(18) *Guidelines for Environmental Management: Dual-Pipe Water Recycling Schemes—Health and Environment Risk Management.* Environmental Protection Agency Victoria: Southback, Victoria, 2005.

(19) *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2): Stormwater Harvesting and Reuse*; Natural Resource Management Ministerial Council, Environment Protection and Heritage Council, and the Australian Health Ministers' Conference: Canberra, Australia, 2009.

(20) *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2): Managed Aquifer Recharge*; Natural Resource Management Ministerial Council, Environment Protection and Heritage Council, and the Australian Health Ministers' Conference: Canberra, Australia, 2009a.

(21) Finkel, E.; Normile, D. River basin management plan secures water for the environment. *Science* **2012**, *338*, 1272−1273.

(22) Davies, P. E.; Stewardson, M.; Hillman, T. J.; Roberts, J. R.; Thoms, M. C. *Sustainable Rivers Audit 2: The ecological health of rivers in the Murray− Darling Basin at the end of the Millennium Drought (2008−2010)*, Vol. *1*; Murray Darling Basin Authority: Canberra, Australia, 2012; available online: http://www.mdba.gov.au/files/SRA2-REPORT-VOL-1.pdf.

(23) O'Donnell, E. Institutional reform in environmental water management: The new Victorian Environmental Water Holder. *J. Water Law* **2011**, *22.2*, 73−84.

(24) *Victorian Water Accounts 2010−2011: A Statement of Victorian Water Resources*; Department of Sustainability: Victoria, Australia, 2011; http://www.water.vic.gov.au/__data/assets/pdf_file/0009/147753/VWA-2010-2011_Final.pdf

(25) Gilbert, J. K.; Clausen, J. C. Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut. *Water Res.* **2006**, *40* (4), 826−832.

(26) Dillon, P. Future management of aquifer recharge. *Hydrogeol. J.* **2005**, *13* (1), 313−316.

(27) Hatt, B. E.; Siriwardene, N.; Deletic, A.; Fletcher, T. D. Filter media for stormwater treatment and recycling: The influence of hydraulic properties of flow on pollutant removal. *Water Sci. Technol.* **2006**, *54* (6−7), 263−271.

(28) Burns, M.; Fletcher, T. D.; Hatt, B. E.; Ladson, A.; Walsh, C. J. Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. *Landscape Urban Plan.* **2012**, *105*, 230−240.

(29) Poff, N. L.; Allan, J. D.; Bain, M. B.; Karr, J. R.; Prestegaard, K. L.; Richter, B. D.; Sparks, R. E.; Stromber, J. C. The natural flow regime—A paradigm for river conservation and restoration. *BioScience* **1997**, *47* (11), 769−784.

(30) Walsh, C. J.; Fletcher, T. D.; Ladson, A. R. Retention capacity: A metric to link stream ecology and stormwater management. *J. Hydrol. Eng.* **2009**, *14* (4), 399−406.

(31) Gomez, F.; Jabaloyes, J.; Vano, E. Green zones in the future of urban planning. *J. Urban Plan. Dev.—ASCE* **2004**, *130*, 94−100.

(32) Barnes, D.; Mollenkopf, T. Effluent recycling in Australia rapid development as a major component of water management. *Proc. Water Environ. Federation* **2010**, *9*, 6626−6636.

(33) Hurlimann, A.; Dolnicar, S. Newspaper coverage of water issues in Australia. *Water Res.* **2012**, *46* (19), 6497−6507.

(34) Dowling, J. Is the wally back? Melbourne water use surges. *The Age*; Jan. 18, 2013; available online: http://www.theage.com.au/victoria/is-the-wally-back-melbourne-water-use-surges-20130117-2cwan.html.

(35) Leopold, L. B. *Hydrology for Urban Land Planning: a Guidebook on the Hydrological Effects of Urban Land Use*, Circular No. 554; U.S. Geological Survey: Washington, DC, 1968.

(36) Walsh, C. J.; Fletcher, T. D.; Burns, M. Urban stormwater runoff: A new class of environmental flow problem. *PLoS One* **2012**, *7* (9), e45814.

(37) Norton, J. W. Decentralized Systems. *Water Environ. Res.* **2009**, *81* (10), 1440−1450.

(38) Sieker, F. On-site stormwater management as an alternative to conventional sewer systems: A new concept spreading in Germany. *Water Sci. Technol.* **1998**, *38* (10), 65−71.
(39) Wong, T. H. F. An overview of water sensitive urban design practices in Australia. *Water Pract. Technol.* **2006**, *1* (1), DOI: 10.2166/WPT.2006018.
(40) Hughes, S. Authority structures and service reform in multilevel urban governance: The case of wastewater recycling in California and Australia. *Urban Affairs Rev.* **2012**, DOI: 10.1177/1078087412458762.
(41) Fletcher, T. D.; Deletic, A.; Mitchell, V.; Hatt, B. E. Reuse of urban runoff—A review of recent Australian advances and remaining challenges. *J. Environ. Quality* **2008**, *37* (5), 116−127.
(42) Wong, T. H. F. Water sensitive urban design; The journey thus far. *Australian J. Water Resour.* **2007**, *110* (3), 213−222.
(43) McCarthy, D.; Hathaway, J.; Hunt, W.; Deletic, A. Intra-event variability of *Escherichia coli* and total suspended solids in urban stormwater runoff. *Water Res.* **2012**, *46* (20), 6661−6670.
(44) *Water Reuse: Expanding the Nation's Water Supply Through Reuse of Municipal Wastewater*. National Academy of Sciences: Washington, DC, 2011.
(45) Gleick, P. H.; Heberger, M. The Coming Mega Drought. *Sci. Am.* **2012**, *306*, 1−14.
(46) MacDonnell, L. J.; Fort, D. *Policy Report −A New Western Water Agenda: Opportunities for Action in an Era of Growth and Climate Change*; University of New Mexico Law School: Albuquerque, NM, Feb. 2008.
(47) Hoerling, M.; Eischeid, J. Past peak water in the Southwest. *SW Hydrol.* **2007**, No. January−February, 18−35.
(48) Boulder Canyon Project Act, 45 Stat. 1057, 1928.
(49) Boulder Canyon Project Adjustment Acts, 54 Stat. 774, 1940.
(50) Colorado River Storage Project Act, 70 Stat. 105, 1956.
(51) Colorado River Basin Project Act, 82 Stat. 885-6, 1968.
(52) U.S. Department of the Interior, Bureau of Reclamation, 2008. http://www.usbr.gov/uc/rm/crsp/lor.html (accessed:).
(53) Gleick, P. H. Water use. *Ann. Rev. Environ. Resour.* **2003**, *28*, 275−314, DOI: 10.1146/annurev.energy.28.040202.122849.
(54) *Securing L.A.'s Water Supply*; City of Los Angeles Department of Water and Power: Los Angeles, CA, 2008
(55) Hanak, E.; Lund, J.; Dinar, A.; Gray, B.; Howitt, R.; Mount, J.; Moyle, P.; Thompson, B. *Managing California's Water: From Conflict to Reconciliation*; Public Policy Institute of California: San Francisco, CA; 2011.
(56) *Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability*; Committee on the Scientific Bases of Colorado River Basin Water Management, National Research Council: Washington, DC, 2007; available online: http://www.nap.edu/catalog/11857.html.
(57) *U.S. Climate Change Science Program Synthesis and Assessment Product 5.3—Decision Support Experiments and Evaluations using Seasonal to Interannual Forecasts and Observational Data: A Focus on Water Resources*; National Oceanic and Atmospheric Administration: Washington, DC, 2008.
(58) *Governor's Commission to Review California Water Rights Law*, Final Report; State of California: Sacramento, CA, 1978.
(59) Phelps, C. E., Moore, N. Y.; Graubard, M. H. *Efficient Water Use in California: Water Rights, Water Districts, and Water Transfers*, R-2386-CSA/RF; RAND Corporation: Santa Monica, CA, 1978.
(60) Phelps, C. E.; Graubard, M. H.; Jaquette, D. A.; Lipson, A. J.; Moore, N. Y.; Shishko, R.; Wetzel, B. *Efficient Water Use in California: Summary*, R-2385-CSA/RF; RAND Corporation: Santa Monica, CA, 1978.
(61) Central Valley Project Improvement Act, Public Law 102-575, 1992.
(62) *Securing Arizona's Water Future*; Arizona Department of Water Resources: Tucson, 2006.
(63) Beller-Sims, N.; Ingram, H.; Feldman, D.; Mantua, N.; Jacobs, K. L. *U.S. Climate Change Science Program Synthesis and Assessment Product 5.3—Decision-Support Experiments and Evaluations Using Seasonal to Interannual Forecasts and Observational Data: A Focus on Water Resources*; National Oceanic and Atmospheric Administration: Silver Spring, MD, Nov. 2008.
(64) Gleick, P. H. Climate change, exponential curves, water resources, and unprecedented threats to humanity. *Climatic Change* **2010**, *100*, 125−129, DOI: 10.1007/s10584-010-9831-8.
(65) *Colorado River Basin Water Supply and Demand Study Executive Summary*, Pre-Production Copy; U.S. Bureau of Reclamation: Washington, DC, 2012.