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Focus Article

Fighting drought with innovation: Melbourne's response to the Millennium Drought in Southeast Australia

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The Millennium Drought in Southeast Australia forced greater Melbourne, a city of 4.3 million people, to find innovative ways of increasing water supply and decreasing water demand. This article explores how water managers in Melbourne reacted to the crisis and evaluates the short- and long-term impacts of their decisions. Reduced water demand occurred primarily through residential and industrial water conservation programs, restrictions, together with emergency reductions in the environmental release of water to streams. The city also experimented with using recycled water, in place of surface water, to support agriculture in the Werribee Irrigation District. Water pricing was not strengthened during the drought, and thus not regarded as a drought demand management tool, primarily because Melbourne water companies lacked independent price-setting powers. Today, five years after the end of the Millennium Drought, gains in water conservation appear to be holding steady, but recycled water for irrigation has declined for various reasons. We contend that the Millennium Drought provided Melbourne with the opportunity to develop and implement a more integrated approach to water management. Many of the innovations it forged (e.g., distributed harvesting and use of stormwater) will continue to enhance the city's resilience to drought and reduce its vulnerability to climate variability for years to come. Nevertheless, a challenge going forward is how to sustain these achievements in light of anticipated population growth and continued climatic change. This challenge—coupled with Melbourne's successes—hold important lessons for water-stressed cities around the world.

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INTRODUCTION

There is broad consensus on the need for more resilient systems for water management in the face of climate perturbations including drought. A

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major quandary scholars face is explaining why it is that some cities are able to break out of path dependent reliance upon traditional approaches to management and boldly adopt innovations—and to do so more effectively than their peers.[1–4] The goal of resilient systems calls for more integrated approaches in land-use and urban planning, including innovations to integrate centralized and decentralized systems and diversify supply for whole watershed management.[1–5] These approaches and frameworks have been called Low Impact Design (LID), Integrated Urban Water Management (IUWM), Water Sensitive City (WSC), and Water Sensitive Urban Design (WSUD) in Australia.[6–9] However, there are many barriers to transitioning to a more adaptive system.[10–16] and few cities have experience with adaptive transitions.[5,10,17] An exception is Melbourne, Australia, where the Millennium Drought afforded an opportunity for implementing policy and infrastructure innovations. This article explores why Melbourne was able to adopt such innovations. We contend that the Millennium Drought provided a window of opportunity for policy change that Melbourne's institutional approaches to water management, and decision-making experiences in outreach and engagement, were able to exploit.[17,18]

The Millennium Drought was a decade-long period (1997–2009) of below-average precipitation in Southeast Australia.[19,20] Just before the Millennium Drought broke in 2009, storage volumes fell to a historic low of 25.6% of capacity in June 2009 (Figure 1). It was the worst reported drought and its impacts were felt across ecosystems, agriculture, the economy, and society.[22] In this article, we focus on policy and infrastructure innovations developed during the Millennium Drought that allowed greater Melbourne, a city of nearly 4.3 million people, to reduce its per capita water demand by almost 50%.[22] Specifically, we set out to answer the following two questions: (1) What were the key water management decisions Melbourne implemented leading up to, and during, the Millennium Drought? (2) What positive outcomes and unintended consequences, if any, emerged from these decisions? The policy decisions are evaluated based on estimated water volumes saved (via demand reduction) or added (via supply augmentation), and whether or not implemented changes have been sustained over time. Our focus on actions and outcomes complements other studies that examined the normative and institutional context underlying Melbourne's response to the Millennium Drought.[17] For the rest of this article, we use the term 'rainwater harvesting' to refer to capture and use of rainwater collected from roofs; 'stormwater harvesting' to refer to capture of runoff from urban land surfaces including parking lots and roads; 'greywater' as water that has been used for washing and showering but does not contain human waste; and 'recycled water' as sewage that has been treated to a degree suitable for nonpotable uses such as irrigation and toilet flushing.

BACKGROUND

Melbourne's Water Supply

Melbourne's water supply is a complex interconnected system of 10 storage reservoirs with a total capacity of 1812 GL, over 40 service reservoirs, 160,000 hectares of catchments, and a transfer system comprising hundreds of kilometers of pipelines, tunnels, and aqueducts.[23] Most of the water catchments are forested and closed to the public, including the two largest catchments, the Yarra and the Thomson. The largest reservoir, the Thomson Reservoir, was completed in 1984 after the 1982–1983 'Short but Sharp' Drought.[17] (See Table 1 for a timeline of events). Catchment water is traditionally an inexpensive source of water for the city due to the minimal need for transfer pumping or treatment but, being climate dependent, can be highly variable in quantity. Relatively little groundwater is used in Melbourne. Groundwater licenses are capped at approximately 30 GL per year,[24] and most groundwater is used for irrigating market gardens and golf courses. In 2010, Melbourne's annual water use is around 356 GL of potable water, 21 GL of recycled water, and an estimated 10 GL of stormwater and rainwater harvesting.[25] Melbourne's supply system consists of over 24,000 km of water mains with a level of leakage (nonrevenue water) that is low by international standards (9% in a typical year).[26] Melbourne has one bulk wholesaler, Melbourne Water, and three water retailers, Yarra Valley Water, South East Water, and City West Water.

National and State Institutional Frameworks for Drought Response

Melbourne's adoption of technical innovations was directly facilitated by institutional arrangements that permitted an integrated government response to drought. Melbourne's water companies are constituted under the Victorian Water Act of 1989. State Ministers of Water, Environment, and Health, and Treasury collectively oversee the water sector. The Department of Environment and Primary Industries (DEPI, also known as the Department of Sustainability and Environment prior to November 2010, and Department of Environment, Land, Water and

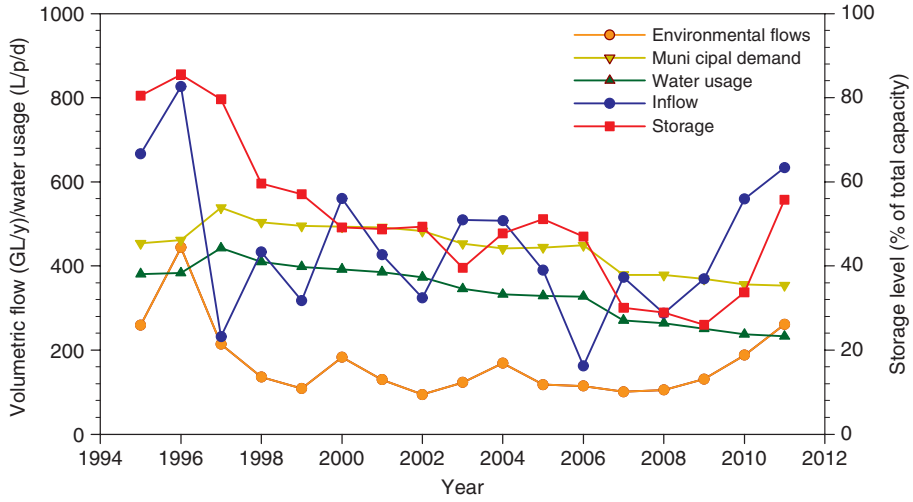

FIGURE 1 | A water budget for Melbourne. Changes to water associated with environmental flows (GL/y), municipal demand (GL/y), water usage (L/p/d), inflow (GL/y), and storage (percentage of total capacity as of June 30). Data sources: Volumetric flow data provided by Melbourne Water and population data from Australian Bureau of Statistics.[21]

Planning after November 2014) supports the Minister for Water and the Minister for the Environment, while an Essential Services Commission regulates the water sector. Retailers must submit plans to the Commission to justify rate increases, while dividends are paid annually to the State Treasury. A clause in the Water Act allows the Minister for Water to issue a Statement of Obligations (SoO) in relation to water companies' performance[27] and requires them to adopt a joint Drought Response Plan (DRP). While the DRP specifies various levels of water restriction based on water storage levels, the water retailers declare and enforce water restrictions[72] (as well as manage any water-saving programs). The latter, as well as DEPI, also influence other drought responses, while the Council of Australian Governments' National Water Reform Framework of 1994 promotes a nationally integrated approach to water management. In short, this framework helped assure that when the Millennium Drought began in 1997, Melbourne could quickly introduce supply and demand-side measures.

SUPPLY-SIDE MEASURES

Augmentation of Centralized Water Supply Systems

Centralized schemes to augment water supply included: (1) constructing the North–South Pipeline with a capacity to deliver 75 GL of water a year from the Goulburn River (located 70 km to the north of Melbourne and over the Great Dividing Range) at a capital cost of AU $700 million plus a $300 million investment (by Melbourne's water companies) in the Northern Victoria Irrigation Renewal Project[28,29]; (2) building the Wonthaggi Desalination Plant, capable of producing up to 150 GL of water per year for Melbourne and the surrounding region at a capital cost of AU $6 billion[22]; and (3) connecting the Tarago Reservoir to a new AU $97 million water treatment plant in June 2009 with an operating capacity of 21 GL/year.[30–32]

The construction of the desalination plant was completed in 2012, just as the drought ended. As of writing this paper, the Wonthaggi Desalination Plant—the largest such facility in the Southern Hemisphere—has not produced a drop of freshwater for the City of Melbourne for a variety of economic, environmental, and political reasons; in particular, because the drought ended around the time the desalination plant was brought online. Likewise, the use of the North–South Pipeline was suspended following the end of the drought, in part due to regional politics associated with transferring water from drought-prone rural areas to drought-prone urban areas, although the North–South Pipeline did provide a small amount of water after the drought. Water retailers also improved their water-leak detection and repair programs.[26] As a result, nonrevenue water decreased by approximately 40% between 2000/2001 and 2010/2011.[33]

Greywater Systems

Permanent greywater systems were installed in some residential units such as Inkerman Oasis (2.5 ML/year in 2009/2010)[34–36] and rebate programs were implemented for permanent residential greywater systems

TABLE 1 | Timeline of Events

	Year	Event
	1984	Thomson Reservoir completed
	1989	Victorian Water Act 1989
	1991	EPA Victoria *Guidelines for Wastewater Irrigation*
	1994	National Water Reform Framework introduced to encourage more integrated and efficient water management
	1994	Reorganization of Melbourne's water utility to Melbourne Water and three water retailers
	1997	Inflow to reservoirs dropped a third of 1996 levels (Melbourne Water)
	1996	CSIRO study *Port Phillip Bay Environmental Study* recommended reduction of nitrogen loads by 500 tonnes/year from Western Treatment Plant and stormwater discharge each
	1997	**Approximately when the Millennium Drought started**
	2001	Victorian Government introduced target of 20% recycling of wastewater inflow by 2010
November	2002	First time water Restrictions imposed in 20 years (Stage 1)
	2002	*Guidelines for Environmental Management: Disinfection of Treated Wastewater*
August	2003	Stage 2 Water Restrictions imposed
November	2003	Victorian Government banned the use of groundwater in the Werribee Irrigation District
	2003	*Guidelines for Environmental Management: Use of Reclaimed Water*
	2004	Victorian Government provided plan for water conservation over the next 50 years with *Our Water Our Future*
	2004	Rising block tariffs introduced for water supply
March	2005	Permanent water-saving rules (PWSR) replaced Stage 2 restrictions (introduced in 2004)
July	2005	5 Star Building Standard required for all new homes to install a rainwater tank (at least 2000 L) or solar hot water system
September	2005	*Victoria Uniform Drought Water Restrictions Guidelines* introduced restrictions for new Stages (1–4)
	2005	*Guidelines for Environmental Management: Dual Pipe Water Recycling Schemes-Health and Environmental Risk Management*
	2005	Class A Recycled Water to Werribee Irrigation District and Eastern Irrigation Schemes launched
	2006	Lowest annual inflow on record, storage levels drop from 58.4 to 38.9% from January to December
September	2006	New Stage 1 Water Restrictions imposed
November	2006	New Stage 2 Water Restrictions imposed
	2006	First dual pipe scheme for recycled water became operational to residential customers
	2006	School Water Efficiency Program (SWEP) established
Late 2006-early 2007		Feasibility study for desalination conducted
	2006	National Guidelines for water recycling
January	2007	New Stage 3 Water Restrictions imposed
April	2007	New Stage 3a Water Restrictions imposed
June	2007	Victorian Government decided to build Wonthaggi Desalination Plant, planned completion in 2012
June	2007	Victorian Government announces North–South pipeline to be constructed by 2010
	2007	Commonwealth Water Act
May	2008	5 Star Building Standard requirement extended to renovated and extended homes
	2008	Melbourne achieved 20% recycling water target ahead of schedule
November	2008	Introduction of 'Target 155' voluntary conservation campaign, effective in December 2008
January	2009	*Joint Water Conservation Plan*
February	2009	Black Saturday Bushfires damaged about 30% of water supply catchments
	2009	**Approximately when the drought ended**, intense rains for the next 2 years
Late	2009	Construction for Wongthaggi Desalination Plant began
November	2010	Election for new Government and change in policy platforms for integrated water management

TABLE 1 | Continued

	Year	Event
Early	2010	North–South pipeline completed
November	2010	Water Restrictions start to relax to Stage 3
April	2010	Water Restrictions relax to Stage 2
September	2011	End of 'T155' Campaign
February	2011	Water Restrictions relax to Stage 1
December	2012	Wonthaggi Desalination Plant completed
December	2012	Office of Living Victoria (OLV) established
May	2012	Victorian Coalition Government committed $50 million to Living Victoria fund for Integrated Water Cycle Management projects
December	2012	Water Restrictions relax to Permanent Water Use Rules (PWUR)
July	2014	OLV reorganized under the Department of Environment and Primary Industries
December	2014	Labor Government abolished OLV

(478 in 2008/2009, 378 in 2009/2010, and 95 in 2010/2011)[33,37,38] However, greywater use at the household level is typically untreated and used for watering gardens.[39,40]

Agricultural and Urban Use of Recycled Water

Water recycling proved to be effective both for reducing nutrient loading to the bay and for augmenting the water supply. In 1997, the Victoria EPA commissioned the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to conduct a large study on the health of Port Phillip Bay. This CSIRO study recommended reducing nitrogen loading to the Bay by 1000 tonnes/year.[41] The CSIRO report had a systemic effect on the Melbourne water industry; in particular, it focused attention on a number of win–win solutions for both reducing nitrogen loading to the Bay and increasing human water security. One example was recycled water. In 2002, the Victorian Government announced a recycled water target of 20% of sewage inflows by 2010, an additional 6.2 GL by 2015, and an additional 10 GL by 2030.[42,43] Most (~93%) of Melbourne's sewage is treated at one of two treatment plants—the Western Treatment Plant and Eastern Treatment Plant—both of which are managed by Melbourne Water.

A rapid increase in the use of recycled water occurred between 2005 and 2009 (Figure 2). In 2005, the government launched two major Class A (suitable for home and agriculture irrigation) recycled water schemes, the Werribee Irrigation District (WID) Scheme and the Eastern Irrigation Scheme.[43] Initial plans called for using Werribee River water, the farmers' traditional source of freshwater, to dilute recycled water from the Western Treatment Plant below a salinity threshold to protect crop yield. However, the Millennium Drought reduced flows and increased the salinity of the river water, resulting in low river-water allocations. In response, farmers in the WID turned to groundwater until that source was banned by the Victorian government over concerns that rapid drawdown of the groundwater table could lead to seawater intrusion.[18,44,45] With limited options, Melbourne Water and distributor Southern Rural Water sold higher-than-expected volumes of recycled water from the Western Treatment Plant to farmers at WID.[18] The low river flows and consequent low river-water allocations during the drought resulted in an increased, and sometimes total, reliance on the high-salinity recycled water from 2006/2007 to the end of the drought (10.9 GL in 2007/2006, up from 1.3 GL the previous year, see Figure 2). The reliance on recycled water was exacerbated by the frequently higher salinity of river water compared with recycled water during periods of low flow. The Eastern Irrigation Scheme came online in 2005. It receives Class A recycled water treated from the Eastern Treatment Plant, produced by a private firm contracted by Melbourne Water, TopAq Pty Limited.[42] With both schemes online, Melbourne was reusing 23% of sewage inflows by 2008, exceeding the Victorian government's goal of 20% reuse by 2010. However, when rain returned in late 2009, total recycled water use quickly declined (Figure 2), due to the decrease in water demand for crops in these two districts. Water managers at WID were now able to follow the original mixing rules,[44] using Werribee River water to dilute recycled water. There was also concern that recycled water may have been responsible for major crop stunting episodes in 2006 and 2008, although scientific

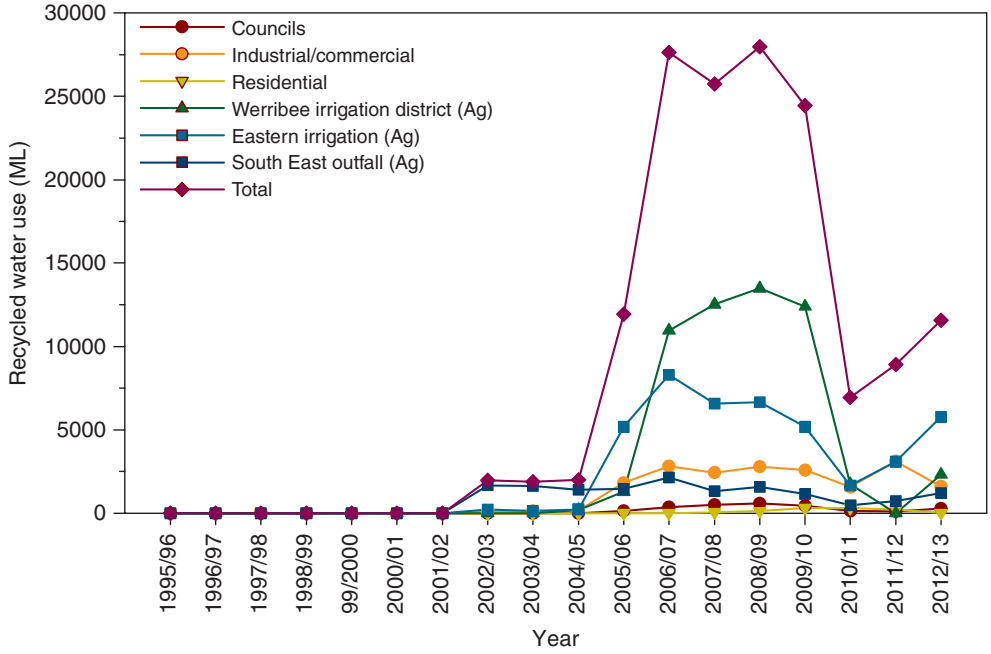

FIGURE 2 | Volume of recycled water used by sector (councils, industrial/commercial, residential, and agriculture) and selected agricultural schemes (Werribee Irrigation District, Eastern Irrigation Scheme, South East Outfall). Industrial/commercial includes golf courses, sports fields, and gardens. Urban recycled water use includes councils, industrial/commercial, and residential uses. Data Sources: Recycled water data provided by South East Water, City West Water, and Yarra Valley Water.

studies were inconclusive about this link.[18] Return to a greater proportion of river water after 2009 assuaged lingering concerns that undiluted recycled water was bad for crops.

The late 2000s also witnessed growth in the use of recycled water for urban use, including residential use (e.g., flushing toilets and outdoor use). While the urban recycled water volumes are modest by comparison to the initial uptake of recycled water by WID farmers, urban recycled water reuse appears to be more sustainable; i.e., the volumes continued to increase following the end of the Millennium Drought (Figure 2). Starting in 2005, urban recycled water schemes included the Wallan supply (365 ML/year capacity) to Mandalay Estate,[46] Whittlesea (548 ML/year capacity) to the Growling Frog Golf Course,[47] and Altona Class A Recycled Water Project for industry and commercial customers (2.5 GL/year).[48] The first residential recycled water dual pipe system was operational in 2006,[17] and Aurora Sewage Treatment Plant began supplying to Epping North Suburb in 2009.[18,49]

Urban Stormwater Use

Stormwater harvesting projects gained more attention after the drought. In a typical year, approximately 440 GL of stormwater flows off from Melbourne's urban landscape into the city's rivers and coastal ocean.[24] Because Melbourne's 4.3 million people consume approximately 356 GL (2010)[25] of potable water annually, even modest efforts to substitute stormwater runoff for potable supply (e.g., by using treated runoff to flush toilets and irrigate ornamental landscapes) has the potential to substantially reduce potable water demand. Biofilters (also known as rain gardens and bioinfiltration systems) are one technology well suited for stormwater use in Melbourne; in addition to reducing potable demand, such systems have many co-benefits for human and ecosystem health[50] (see other articles in this special issue devoted to the design and use of biofilters for stormwater management[51,52]). While biofilters are commonly used for onsite retention and infiltration of stormwater,[53,54] their product water was not typically used for potable substitution before 2009. However, after the drought, about a dozen stormwater harvesting projects have been completed mostly to irrigate gardens, sports fields, and golf courses.[55] An example is the Darling Street scheme in East Melbourne, which was launched in June 2012 at a total cost of AU $1,737,000.[56,57] The Darling Street project provides the local community with 21 ML per year for landscape irrigation—water that would otherwise drain potable supplies.[56] Another example is the Eastern Melbourne Parks and Gardens Stormwater Harvesting Scheme completed

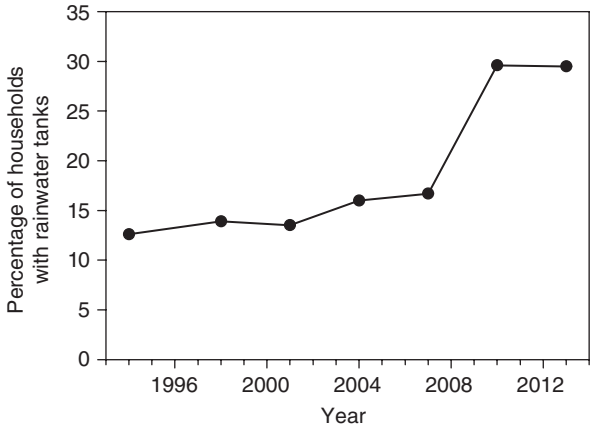

FIGURE 3 | Portion of households with rainwater tanks surveyed by the Australian Bureau of Statistics. Data source: Australian Bureau of Statistics.[61,62]

in August 2013, which can provide 119 ML/year to irrigate public parks.[58] By fiscal year 2012/2013, Melbourne Water, which is responsible for surface water licensing, issued 32 active stormwater harvesting licenses (1.5 GL) mostly to sports clubs and councils.[59] In 2013/2014, the Office of Living Victoria allocated AU $50 million to alternative water projects, mostly to building systems to capture, treat, and use stormwater runoff for potable substitution.[60]

Rainwater Tanks

Rainwater tanks, which capture and store rainwater flowing off of roofs, are another supply-side innovation accelerated during the Millennium Drought. Because rainfall is harvested directly from roofs, it does not require the same degree of treatment as stormwater collected from streets or parking lots. Estimating the volume of potable substitution achieved by the purchase and installation of rainwater tanks is complicated by their decentralized nature and the variability of demand across users. The percentage of households in the State of Victoria with rainwater tanks increased from 16.7% in 2007[61] to 29.6% in 2010[62] (Figure 3). Rainwater tanks were popular because they allowed residents to maintain their ornamental plants and gardens in spite of water restrictions that curtailed the use of municipal water for irrigation. The adoption of rainwater tanks was also accelerated by the 5 Star Building Standard enacted in July 2005, which required all new homes in Victoria to have a rainwater tank for toilet flushing or a solar hot water heating system (reflecting the program's broad interest in sustainability).[63,64] Melbourne's Living Victoria Water Rebate Program also provided rebates for rainwater tanks ranging from $850 to $1500, depending on their size and end uses.[65] A 2013 survey found that rainwater tank use in Melbourne is divided primarily between residential users (68%) and industry, schools, and councils (32%).[66] The same study estimated that 9.06 GL of rainwater were harvested in 2012/2013.[66] Assuming that Melbourne and Victoria had similar uptakes of rainwater tanks, that water savings were 15.8% per household,[67] and adjusting for population growth, residential rainwater use increased from 4 to 8 GL from 2000 to 2009 (Figure 4). The 2009 volume (8 GL) is roughly 2% of Melbourne's total potable water use in 2009. Not surprisingly, after the drought broke the uptake of residential rainwater tanks slowed (after 2010 in Figure 3).[62]

DEMAND-SIDE MEASURES

During the Millennium Drought, per capita water use for Melbourne dropped approximately 50% between 1997 (at the start of the drought) and 2012 (after the drought) (Figure 1). The demand reduction works out to an average of 107 GL of potable water saved per year, roughly equal to 70% of the maximum annual output of the Wonthaggi Desalination Plant. Efforts to reduce demand included: (1) imposing water use restrictions; (2) implementing water conservation measures including a rebate program for water-efficient appliances; (3) providing funding to increase rainwater and stormwater harvesting; (4) reducing environmental flows to rivers; and (5) conducting television, radio, billboards, and print media advertising campaigns to promote water conservation. Without these water saving and environmental flow reductions, studies show that Melbourne's reservoirs would have emptied by the end of 2009.[24] Interestingly, price incentives were in place before the worst of the drought hit, but they were not used as a demand management tool during the drought. For example, Yarra Valley Water (one of the water retailers in Melbourne) uses an inclined block tariff consisting of three tiers with escalating unit price; households with higher unit water consumption pay higher unit prices for water.[69] Tariffs were not adjusted during the drought for the purpose of demand management because water companies in Melbourne have no independent price-setting powers. Instead, prices are set based on an adequate financial return for the water retailers after accounting for all costs and revenues.

Water Restrictions

The *Victoria Uniform Drought Water Restrictions Guidelines*,[70] which were finalized in September 2005, outlined a four-stage water restriction protocol. As

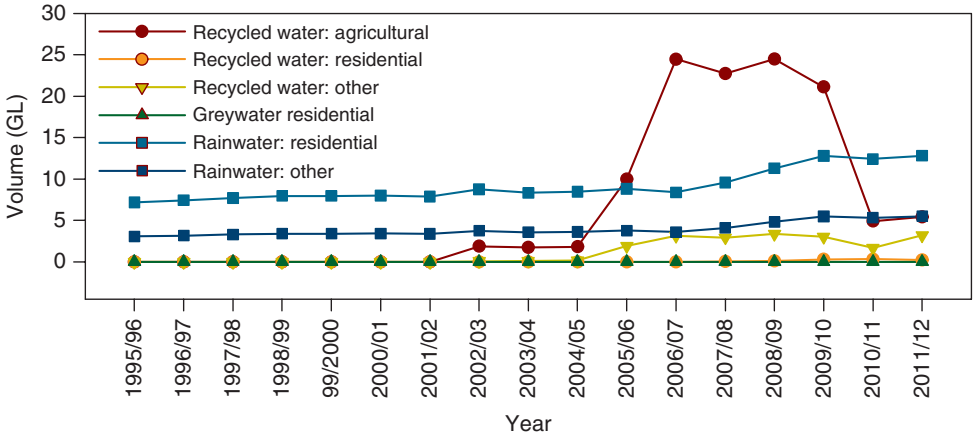

FIGURE 4 | Volume of supply augmentation by sector and source. Total rainwater use was estimated by assuming that the total residential water use was 68% of the estimated total rainwater use[66] over the period of interest. Total residential rainwater use was estimated by multiplying the number of households in Melbourne[21] by the portion of households with residential rainwater tanks in Victoria[61,62] and rainwater use per raintank. Rainwater use per raintank was assumed to be 15.8%[67] of household residential water use.[68] 'Recycled water: other' includes industrial/commercial (including golf courses, sports fields, and gardens), and institutional (councils). 'Rainwater: other' includes schools, commercial, industrial, institutional (councils). Greywater residential only includes Inkerman Oasis. Data Sources: Recycled water data provided by South East Water, City West Water, Yarra Valley Water. Data for Inkerman Oasis provided by South East Water. Population and census data is from the Australian Bureau of Statistics (ABS).[21] Data for portion of households with residential rainwater tanks is from ABS.[61,62] Data for residential water use is from Melbourne Water and water retailers.[68]

specified in the *Guidelines*, the stages range from minor restrictions on outdoor water use (Stage 1) to a complete ban on outdoor water use (Stage 4). A less stringent set of water use rules, the so-called Permanent Water Use Rules, apply when reservoir storage volumes are within safe levels. Stage 1 restrictions were imposed in November 2002.[17] Restrictions were increased to Stage 2 in August 2003, and Permanent Water Use Rules replaced Stage 2 restrictions in March 2005 (Table 1)[17] when the drought appeared to ease. However, in response to extremely low inflows the following year, Stage 1 restrictions were reintroduced in September 2006. As the water crisis worsened restrictions increased to Stage 3 in January 2007 and Stage 3a in April 2007; Stage 3a restrictions remained in effect for the next 36 months.[71] Stage 3a restrictions allowed for minimal outdoor water use and, combined with the Target 155 campaign (described below), saved the city from Stage 4 restrictions that would have banned all outdoor water use. The large reduction in outdoor watering mandated by Stage 3a caused vegetation at many public gardens and sports facilities to wither and die.[17] After the drought broke in late 2009, restrictions were progressively relaxed after April 2010 (Table 1). Not surprisingly, there is a close correspondence between the imposition of restrictions and the reduction in per capita water use (Figure 1). Five years after the drought ended, per capita water use is still at an historic low, although there are indications that summertime per capita water use may be rising.[73]

Voluntary Conservation and Target 155 Campaign

Starting in December 2008, Victorians were also encouraged to respect a voluntary target of 155 L water per person per day (the 'T155 campaign'), for example by taking shorter showers, capturing rainwater from roofs for toilet flushing and gardening, and using greywater for gardening.[74] The campaign was advertised through television, newspapers, and billboards.[75] According to a study commissioned by Melbourne's water retailers, the T155 Campaign netted 53 GL in water savings from December 2008 to August 2010, based on comparing observed water use to a model-predicted water use without this campaign, after correcting for climate variability.[74] Melbournians used less than 155 l/p/d for 49 out of 52 weeks in the 2010/2011 financial year.[33] The Victorian Coalition Government ended the campaign in February 2011.

Water Saving Programs

The Victorian government also funded water rebate and exchange programs for small business and residential water users. For residential users, water retailers replaced showerheads (462,466 from start of program in 2006/2007 to 2010/2011), toilets

and washing machines (365,000 4 star machines installed from 2006/2007 to 2010/2011) with more water-efficient models.[33] These exchange programs reduced potable demand by 5.5, 0.44, and 8.67 GL/year, respectively.[33] The Victorian Government Water Smart Rebate Scheme, which started in January 2003, provided rebates for rainwater tanks, dual flush toilets, permanent greywater systems, hot water recirculators, and efficient showerheads,[33] at some point during the course of the program. A total of 19,008 rebates were granted in 2010/2011, reducing potable demand by 0.35 GL/year.[33] The Evaporative Air Conditioners Program required only water-efficient evaporative coolers be sold on the market (with expected potable demand reductions of 0.8 GL/year by 2015), and a gardening program provided public education on water-efficient gardening.[33]

Businesses that used more than 10 ML/year were required to complete a Water Management Action Plan (Water MAP) that sets water conservation targets and reports progress annually.[76] The goal of the WaterMAP program is to reduce potable demand by 8 GL/year by 2015.[37] Other nonresidential programs include the Cooling Towers Program (1.7 GL of potential savings),[37] the Waterless Wok Program (estimated 4600 L/d day savings for a two-ring stove),[37] and the Water Saver Garden Centres Program to encourage reductions in landscape irrigation.[37] Small businesses were also eligible for rebates up to $2000 for installing water-saving technologies.[77] The national Water Efficiency Labelling and Standards Act 2005 mandated registering and labeling the efficiency of shower heads, tap equipment, flow controllers, toilet equipment, urinal equipment, clothes washing machines, and dishwashers.[78]

Environmental Flows

Environmental flows in the Thomson and Yarra Rivers were curtailed during the worst period of the drought. Actions included: (1) Deferring planned increases of 17 GL per annum and 10 GL per annum in environmental water reserved for the Yarra and the Thomson respectively; (2) Reducing minimum passing flows requirements at sites along the Yarra and Thomson; (3) Permitting greater volumes to be pumped from the Yarra at Yering Gorge by reducing the passing flow volume at which such pumping must cease; and (4) Qualifying operational tolerances for minimum environmental flow releases for the Thomson (e.g., relaxing rules on proportion of time flows are to apply). Altogether, approximately 106 GL were saved in the Yarra Basin and 42 GL in the Thomson Basin. Environmental flows were progressively restored from 2010 onward.[79]

Education Programs Targeting Schools and Homes

In 2006, the Victoria Government launched the School Water Efficiency Program (SWEP) to identify leaks and evaluate water use in public schools, and to promote water education.[80] By 2009, 1737 schools joined the program.[37] An estimated 269.1 ML/year where saved from 2006 to 2009.[37] The *Learn It! Live It!* program was also established to promote water education and awareness in primary and secondary schools, which had 324 committed schools by 2011.[33] The Water Smart Behaviour Change Program developed in 2007, and by 2009, Melbourne water retailers worked directly with 140,000 households to demonstrate water saving habits in the home.[37] Assessing the impact on water savings has been a challenge.[37]

DISCUSSION

In its efforts to alleviate the impacts of the Millennium Drought, Melbourne avoided immediate dangers and also increased its resilience to future climate variability. By the end of the Millennium Drought, Melbourne had undertaken or completed large centralized infrastructure projects as well as decentralized, locally based demand-attenuation, and supply-augmentation projects. It had also conducted a number of information and public education campaigns. These projects and campaigns had various impacts on municipal water supply, cost, and reliability, as well as effects on ecosystem health and function. In addition, they were embraced by the public to varying degrees, and were subject to changes in local, state, and national politics. Investments in the Wonthaggi Desalination Plant and in the North–South pipeline were motivated by a desire to provide Melbourne with a more reliable supply of potable water. While these projects did not contribute to Melbourne's water supply during the Millennium Drought, they are available at the present time and may be needed in the future.[81–83] Melbourne's experience with recycled water is more nuanced. The use of recycled water for local agriculture increased dramatically during the Millennium Drought, but for a variety of reasons the initial uptake did not last. By contrast, urban and residential use of recycled water appears to be on a long-term increasing trend. Rainwater harvesting was embraced by the public, with positive impacts on both Melbourne's potable supply and possibly ecosystem health. The Millennium Drought also spurred interest in stormwater harvesting, in part because of its potential to slack a large fraction of the city's long-term water needs. Government programs to restrict water use, improve water efficiency, and educate the public were both highly

effective and relatively low cost. Indeed, the success of Melbourne's water conservation programs kept the city from running out of potable water during the Millennium Drought.

Water conservation programs are not typically adopted as the primary response to droughts out of concern for the unpredictability of public acceptance and behaviour, and also because of the widespread preference for traditional, centralized, engineered solutions (referred to as 'cognitive lock-in' in the social science literature).[84,85] It has been argued that Melbourne's pursuit of nontraditional 'soft-path' solutions was enabled by the security provided by the North–South pipeline, the desalination plant, and recycled water schemes.[17,85] However, this confidence came at a high economic cost. The desalination plant has a sunk cost of an annual insurance premium of AU $654 million (increasing over time) to be paid to the construction consortium for the first 27 years of operation, even if no water is produced.[29] By contrast, the soft-path solutions performed very well and were comparatively cheap. As per the *Melbourne Joint Water Conservation Plan*,[37] during the drought, water retailers were committed to reducing per capita water use by 30% of total (to 296 l/p/d) and 30% of residential (to 174 l/p/d) using 1990 consumption as a benchmark; these targets were to be achieved by 2015. Innovations in conservation spurred by the Millennium Drought resulted in these targets being exceeded, and ahead of schedule. However, sustaining these targets and innovation schemes over the long term is likely to have varying degrees of success. Since the drought ended, Water Conservation Plans are no longer reported by the water companies and, as noted earlier, summertime water consumption may be increasing.[73,86]

Among supply-augmentation approaches, recycled water use in agricultural irrigation achieved the greatest gains by volume, largely from use in the WID, as a result of historic low river flows and the ban on groundwater use. Because the intended use of recycled water was only to supplement river water, and the use of recycled water was driven by the lack of alternatives, recycled water use dropped after the drought broke. Moreover, sustaining high levels of water reuse would have been politically and economically difficult, partly because of increasing soil salinity that would have decreased agricultural productivity over the long-run. Because of its high cost, there are currently no plans to build a salt-reduction plant for agricultural uses, although a salt-reduction plant is being built for urban uses.[44]

Administrative and governance changes also threaten the sustainability of integrated water management. Shortly after the drought broke, new State and Federal elections were held in 2010, and the new administration introduced a different policy platform. The new Government decided that the North–South Pipeline was to be used only for critical human needs, defined as storage volumes in Melbourne's reservoirs below 30% on November 30. Likewise, since taking office, the new administration has not ordered water from the desalination plant, arguing instead that the desalination plant is an example of the previous Government's mismanagement and waste. Other policy changes included the appointing of an independent Ministerial Advisory Council for developing integrated alternative water sources.[17,87] The Council established the Office of Living Victoria in May 2012 and provided it with substantial financial resources (AU $82.5 million from its inception to 2013/2014).[88,89] These reforms were intended to encourage the harvesting and use of rainwater, stormwater, and treated sewage as new water sources for Melbourne.[60] In July 2014, the Office of Living Victoria was reorganized into the DEPI, and then eliminated in December 2014.[90] Because these investments and decisions are largely political, it is unclear if Victoria will continue to prioritize, for example, the development of stormwater harvesting. While there are estimates for cost-benefits of different water supply and demand approaches,[23,82] it remains a challenge to properly account for economic factors, environmental health, public acceptance, and liveability.[17] To the best of our knowledge, there is no comprehensive study on the costs (including external costs) of distributed and centralized water management approaches compared with the water volumes gained or saved.

CONCLUSIONS

Melbourne's experience with the Millennium Drought offers many lessons, both positive and negative, to other cities of comparable size and drought susceptibility. For one, the severity of the Millennium Drought afforded Melbourne a window of opportunity for supply-side and demand-side measures that in normal times may have proven very difficult, if not impossible, to adopt. One lesson for other cities is that major droughts, if serious enough and long-lasting enough, create opportunities for policymakers, as well as pose challenges. The ability to take advantage of this window of opportunity depends, however, on the willingness of decision makers to engage the public, institutional conditions which encourage adopting innovations, and—ironically—the security provided by investment in some 'hard path' alternatives which

reinforce the public's confidence that diverse and multi-faceted programs and options are being pursued by public officials. These lessons regarding public engagement and institutional reform are especially salient for cities such as, e.g., Los Angeles, struggling with protracted drought and facing challenges in convincing the public of the severity of its causes and consequences.

Finally, in light of the fact that Melbourne considered, and adopted a number of options for water supply (some of which, as we have seen, were implemented but never used such as desalination), its experience raises the following question: can cities develop an evaluation framework to optimize and prioritize their different water management options? For example, a wide range of water conservation initiatives were implemented that varied greatly in cost-effectiveness and amount of water saved, but a smaller number of well-chosen initiatives might have been more effective, less costly, and easier to implement. Melbourne's investment in alternative water supply means that the city will be more resilient in the face of future droughts. However, pressures brought on by government administrative reorganization, public 'fatigue' with continued sacrifice, and the practicality of financing these initiatives constitute a continuing challenge. Clearly, the Millennium Drought forced Melbourne to adopt a more integrated approach to water management, and in the process, the city has become more resilient to drought and less vulnerable to climate variability. The challenge going forward will be to vigilantly sustain the city's many successes while planning for future challenges posed by continued urbanization, population growth, and a changing climate.

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