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# Deconstructing Demand: The Anthropogenic and Climatic Drivers of Urban Water Consumption

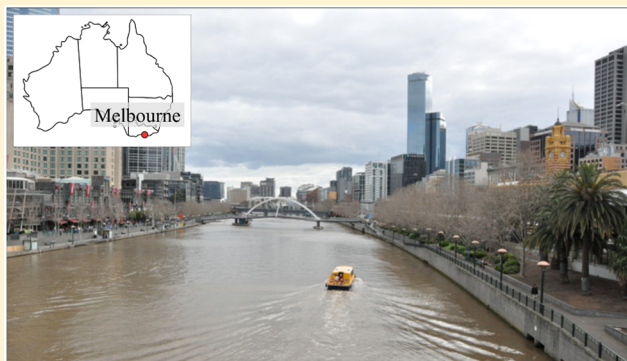
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## S Supporting Information

**ABSTRACT:** Cities in drought prone regions of the world such as South East Australia are faced with escalating water scarcity and security challenges. Here we use 72 years of urban water consumption data from Melbourne, Australia, a city that recently overcame a 12 year “Millennium Drought”, to evaluate (1) the relative importance of climatic and anthropogenic drivers of urban water demand (using wavelet-based approaches) and (2) the relative contribution of various water saving strategies to demand reduction during the Millennium Drought. Our analysis points to conservation as a dominant driver of urban water savings (69%), followed by nonrevenue water reduction (e.g., reduced meter error and leaks in the potable distribution system; 29%), and potable substitution with alternative sources like rain or recycled water (3%). Per-capita consumption exhibited both climatic and anthropogenic signatures, with rainfall and temperature explaining approximately 55% of the variance. Anthropogenic controls were also strong (up to 45% variance explained). These controls were nonstationary and frequency-specific, with conservation measures like outdoor water restrictions impacting seasonal water use and technological innovation/changing social norms impacting lower frequency (baseline) use. The above-noted nonstationarity implies that wavelets, which do not assume stationarity, show promise for use in future predictive models of demand.



## INTRODUCTION

As of 2016, it is estimated that 0.5 billion people live in areas subject to severe year-round water scarcity, with 4 billion experiencing scarcity at least one month per year. Moreover, by 2075, nearly 9 billion are expected to experience scarcity.<sup>1,2</sup> While all continents are affected, Africa, Central and South America, and the Middle East exhibit the highest water vulnerability (reflecting a combination of physical and economic scarcity, as well as demand pressures, infrastructural weaknesses, and institutional capacity).<sup>3</sup> However, severe physical scarcity is also apparent in China, India, Australia, and the western United States.<sup>2</sup> Indeed, despite the promise of a record-breaking El Niño in 2015/2016, the state of California (U.S.) is experiencing its worst drought in over a century, with 51 (of 57) counties presently listed as natural disaster areas.<sup>4</sup> A similar story is playing out in Perth, Western Australia, which remains in a water vulnerable state (running two desalination plants at full capacity to meet public water demand), despite the official cessation of drought in 2009.<sup>5</sup> This water scarcity is unlikely to abate in the near future, as climate models project a warmer, drier, climate for both Southwest and Eastern Australia.<sup>6,7</sup> This will place cities in these regions under increased water stress, and has the potential to shift water

supply systems from generally robust to predominantly insecure.<sup>8,9</sup>

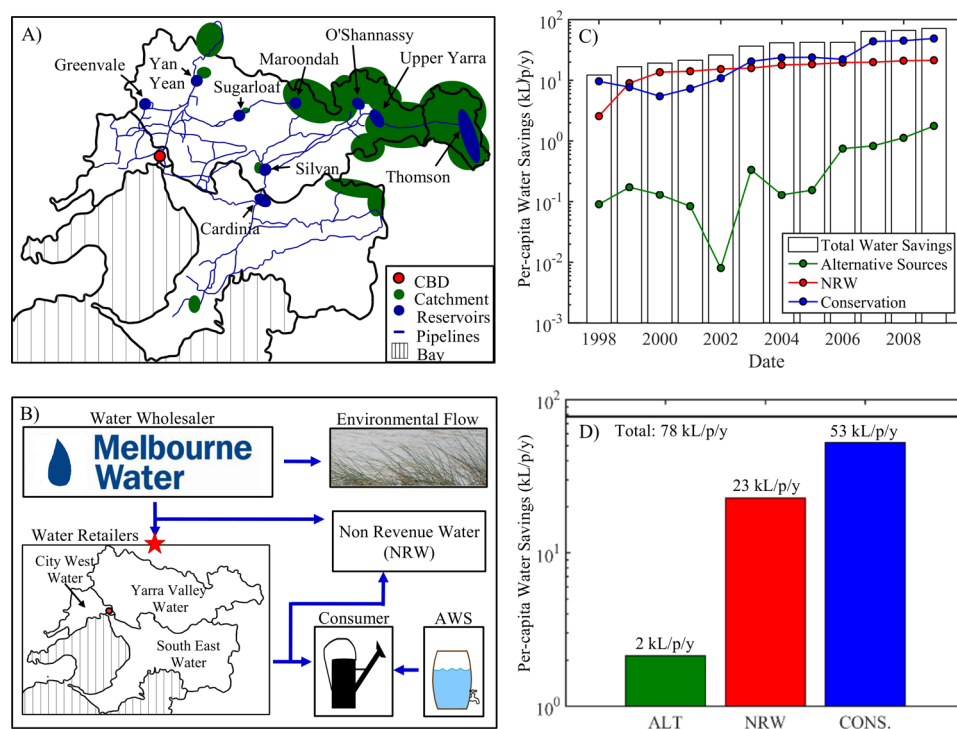
As we prepare to enter an era of increased water scarcity, a premium must be placed on understanding the factors controlling consumption (both climatic and anthropogenic) to promote efficient water use.<sup>9</sup> In this vein, a variety of studies have explored drivers of water demand, including meteorological variables such as rainfall, temperature, and evaporation,<sup>10–16</sup> socioeconomic variables, such as population demographics, household income, and water price,<sup>10,13,16–21</sup> and other anthropogenic variables related to water policy, and water use behavior.<sup>13,16,20–26</sup> Much of this work has utilized traditional multivariate regression models,<sup>20,27</sup> autoregressive moving average models,<sup>10,28</sup> Fourier analysis,<sup>29</sup> or artificial neural networks<sup>30,31</sup> for evaluating relationships between demand and its drivers. However, more recently, wavelet analysis has been promoted as a means for assessing these relationships. The key advantage of wavelets is that they allow

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**Figure 1.** (A) Map of Melbourne's water supply catchments. The map details catchment bounds (green), reservoirs (blue), and Melbourne's city center, the Central Business District (CBD; red). (B) Water management flow diagram (from wholesaler to consumer). The red star denotes where in the water supply system our timeseries of water consumption was obtained; i.e., consumption represents water sold to retailers by Melbourne Water, which includes both nonrevenue and billable water. Timeseries of per-capita urban water savings during (C) and at the end (D) of the Millennium Drought (1997–2009), including total savings (black), savings from alternative water sources (green), savings from nonrevenue water reduction (red), and savings from conservation (blue). Note that 1 kL/p y equals approximately 2.7 L/p d (The map in panels (A) and (B) is adapted from ref 38. Copyright 2013 American Chemical Society).

for synchronous identification of nonstationary relationships between variables at multiple frequencies and times, whereas most other methods assume stationarity.<sup>12,30,32</sup> Given that the anticipated drivers of demand can be nonstationary (e.g., droughts, floods, and water restrictions, among others) we anticipate that wavelet-based approaches will prove well suited for modeling demand.

To date, only a handful of studies have used wavelets to identify coherent patterns in water demand, most notably Adamowski et al., 2013,<sup>12</sup> who revealed high annual coherence between rainfall, temperature, and water consumption in Calgary, Canada (suggestive of strong seasonality in outdoor water use). However, wavelet analysis is more commonly used in the hydrological, geophysical, and climate sciences, where it is paired with multiple linear regression models to facilitate identification of frequency and time-specific drivers of environmental pattern.<sup>33,34</sup> Our study employs this combined approach for the first time to deconstruct the climatic and anthropogenic drivers of urban water consumption in a city with a long history of urban water scarcity, Melbourne, South East Australia.

This paper is organized in two parts. The first focuses on Melbourne's recent Millennium Drought and identifying those urban water practices that saved the most water. Subsequently, we look broadly over Melbourne's urban water history (1940–2012), which spans multiple droughts and use wavelet analysis and multiple linear regression to identify prevailing climatic and anthropogenic drivers at different times and frequencies. In this latter section we (1) characterize coherent patterns between climate variables and consumption, and the evolution of their phasing over time and (2) map transient events in

residual consumption (e.g., following removal of climate-driven patterns) back to anthropogenic drivers with characteristic frequencies and/or temporal signatures.

#### Study Area: Melbourne Australia. Urban Water Supply.

The Melbourne metropolitan area, Victoria, Australia, has a population of 4.3 million people and sources its drinking water from protected catchments located to the northeast of the city (green symbols in Figure 1a). Melbourne's catchments cover a total area of approximately 156 700 ha.<sup>35</sup> Water from these catchments is stored in 10 major reservoirs with a total capacity of 1812 GL. The largest of these reservoirs, the Thomson, was constructed in 1984 and holds around 60% of Melbourne's total water supply (Figure 1a).<sup>36,37</sup>

Melbourne's stored reservoir volume is managed by a water wholesaler, Melbourne Water, that is responsible for ensuring its quality and partitioning it between environmental flows and urban consumption. The volume allocated for environmental flows is 30–70% of the allocation for urban consumption, and was smallest (10 GL/month) during the Millennium Drought.<sup>38</sup> Water for urban consumption is transferred to three retail authorities (City West Water, Yarra Valley Water, and South East Water), who are responsible for delivering it to consumers (e.g., homes and businesses within the greater metropolitan area) (Figure 1b).<sup>36,37,39,40</sup> As water is transferred from wholesaler to retailer and retailer to consumer, a fraction is lost as nonrevenue water (NRW) due to physical leaks in pipes, theft, or inaccurate water metering. NRW and delivered, billable water are tracked separately by retailers, but are both part of the total urban consumption reported by Melbourne Water (red star in Figure 1b).

**Drought in SE Australia.** Since 1930, Melbourne has experienced three long-term droughts lasting more than five years each (the Second World War Drought 1937–1945, the 1960s Drought 1962–1968 (most intense in 1967/1968), and the Millennium Drought 1997–2009), as well as two shorter-term droughts approximately one year in duration (the Dust Cloud Drought 1982–1983 and the 1990s Drought 1994–1995).<sup>41</sup> This means that about 38% of the past 82 years in SE Australia have been dry, suggesting that drought, particularly prolonged drought, is a persistent feature of SE Australia's climate. While the Millennium Drought has been called one of the most severe droughts in recent memory,<sup>42</sup> it is notable that its spatial extent was smaller and its maximum precipitation deficit lower than both the Federation Drought (early 1900s) and the Second World War Drought, perhaps reflecting different climate drivers.<sup>43</sup> Nonetheless, the Millennium Drought is both the hottest on record and associated with the lowest inflows in the Murray-Darling Basin (the breadbasket of Australia) ever recorded.<sup>44,45</sup> Furthermore, in Melbourne itself, the annual rainfall deficit during the Millennium Drought was actually larger than other droughts, making its impact on the urban water supply keenly felt.<sup>43</sup>

## METHODS

**The Millennium Drought: A Water Savings Budget for Melbourne.** During the Millennium Drought, Melbourne trialed a variety of approaches for reducing pressure on its primary storage reservoirs. These approaches targeted alternative water sources, NRW, and conservation. To determine the relative utility of each approach we performed a water savings budget from 1997, when the drought began, to 2009, when the drought officially ended. Total annual per-capita water savings ( $S_{TOT}$ ) were calculated as

$$S_{TOT}(t) = \frac{V_R(1997)}{P(1997)} - \frac{V_R(t)}{P(t)} \quad (1)$$

where  $V_R$  (GL/y) is the total volume of reservoir water purchased from Melbourne Water by all three retailers each year (red star in Figure 1b) and  $P$  is the population of consumers (residential, industrial, and commercial) in the retailers' service area.

In order to estimate the fraction of  $S_{TOT}$  associated with increased use of alternative water sources, information concerning their annual uptake and volumetric storage capacity was compiled from the work of Low et al.<sup>22</sup> Although centralized (and potable) supply alternatives were pursued during the drought (e.g., the Wonthaggi Desalination plant and the Sugarloaf pipeline), both projects were completed after the drought ended, and have since contributed minimally (or not at all) to Melbourne's potable supply.<sup>5,38,46</sup> A variety of nonpotable projects were also pursued, intended to save potable water for required uses such as drinking. These include recycled water schemes (e.g., dual pipe systems for in-home uses such as toilet flushing), permanent greywater and stormwater harvesting systems, and rainwater catchment measures (e.g., rainwater tanks).<sup>22,38</sup> Of these different measures, rainwater tanks and recycled water schemes were the most prevalent (and well-documented) during the drought.<sup>22</sup> As such, we define alternative water sources as the sum total of these two technologies in this paper. We also assume that potable substitution causes a corresponding decrease in potable water use, a reasonable assumption in

light of the strict potable water restrictions during the Millennium Drought. Given these assumptions, the annual per-capita water savings attributable to alternative source adoption ( $S_{ALT}$ ) was calculated as follows:

$$S_{ALT}(t) = -\frac{V_{RW}(1997) + V_{RT}(1997)}{P(1997)} + \frac{V_{RW}(t) + V_{RT}(t)}{P(t)} \quad (2)$$

where  $V_{RT}$  and  $V_{RW}$  (GL/year) are estimates of the stored water volume in rainwater tanks or recycled water schemes, respectively (see the work of Low et al. for procedural details regarding estimation of  $V_{RT}$  and  $V_{RW}$ ; Figure S1b).<sup>22</sup> Importantly, because eq 2 equates increased nonpotable volume with potable water savings,  $S_{ALT}$  is best understood as the maximum annual per-capita savings that alternative water sources could have provided during the Millennium Drought; savings would be smaller if incomplete potable substitution were assumed.

In addition to the above-noted supply augmentation measures, Melbourne also explored a variety of NRW reduction strategies targeting both real (leaks and bursts) and apparent (theft and meter error) water loss. These strategies were intended to reduce loss through improved distribution efficiency and included (1) zone metering programs, where flow meters installed across the water supply network were used to quantify zone-specific NRW and prioritize leak repair, (2) burst repair programs, where saving water during bursts was prioritized over continuity of customer service, and (3) water meter replacement programs targeting aging and incorrectly sized meters, among others.<sup>47,48</sup> The annual per-capita water savings due to these NRW reduction measures ( $S_{NRW}$ ) was calculated as follows:

$$S_{NRW}(t) = \frac{V_{NRW}(1997)}{P(1997)} - \frac{V_{NRW}(t)}{P(t)} \quad (3)$$

where  $V_{NRW}$  (GL/y) is the total reported NRW volume summed across Melbourne's water retailers (data sourced from the following reports: 47, 49–56). In instances where NRW data were incomplete (e.g. in 2009 for South East Water, and 1997 for Central West and South East Water),  $V_{NRW}$  was estimated from Yarra Valley reports<sup>47</sup> using the average ratio (1996–2012) of  $V_{NRW}$ : Yarra Valley NRW, which was relatively stable at 2.4 GL/y (Figure S1c).

The third major approach for saving water during the Millennium Drought, conservation, is difficult to quantify directly given (1) the myriad of individual programs involved (e.g., mandatory and voluntary water restrictions, rebates for water efficient appliances, school and homeowner water education programs, and waterwise advertisements)<sup>22</sup> as well as (2) the challenges associated with linking programs to volumetric estimates of potable water saved. For instance, while the water savings associated with certain appliance exchange programs have been tabulated directly (e.g., 8.67 GL/y from washing machine replacement alone),<sup>22,49</sup> the effects of other programs, particularly educational ones like "Water Smart Behavior Change", remain unknown.<sup>22</sup> Given these challenges we have chosen to define the annual per-capita water savings due to conservation ( $S_C$ ) by difference (e.g.,  $S_C = S_{TOT} - (S_{ALT} + S_{NRW})$ ), and have not attempted to compare the relative merits of specific conservation programs. While this definition



of  $S_C$  is admittedly simplistic (e.g., savings from alternative water sources built in response to a rebate program are part of  $S_{ALT}$ , not  $S_C$ ) we feel that it makes the best use of the data available.

**The Historical Water Record: Anthropogenic vs Climatic Drivers of Consumption.** We use wavelet analysis and multiple linear regression to evaluate the combined influence of climatic and anthropogenic factors on Melbourne's long-term urban water consumption. This analysis considers 72 years of Melbourne's recorded water history (1940–2012) and involves two monthly averaged meteorological data sets (temperature,  $T$ , and rainfall,  $R$ ), one monthly averaged hydrological data set (reservoir inflow,  $I$ ), and one monthly averaged per-capita urban water consumption data set ( $C_{pc}$ ). Per-capita consumption was calculated using population census ( $P$ ) and consumption data ( $C$ ) provided by Melbourne Water (e.g.,  $C_{pc} = C/P$ ). Temperature and rainfall timeseries are from the Australian Water Availability Project; rainfall data were generated via a gridded ( $5\text{ km} \times 5\text{ km}$ ), anomaly based analysis of rainfall from meteorological stations in and around Melbourne's major water supply catchments (e.g., the Thomson, Upper Yarra, O'Shannassy, and Maroondah reservoirs, Figure 1a; details in the work of Jones et al.<sup>57</sup>). In contrast, reservoir inflows were calculated by difference across all reservoirs (e.g.,  $I = dV_{res}/dt + C$ , where  $t$  is time,  $V_{res}$  is reservoir storage (measured by Melbourne Water, details in the SI),  $C$  is urban water consumption, and  $I$  is reservoir inflow). Because our calculations do not account for additional water sinks such as evaporation and/or spills, actual inflows will exceed our estimates.

Analysis was performed in three parts (detailed separately below) using the wavelet coherence toolbox,<sup>32</sup> the wavelet toolbox, and the statistics and machine learning toolbox from Matlab, Mathworks (2015b). All timeseries were demeaned and detrended prior to analysis.

**Continuous Wavelet Transformation.** Continuous wavelet transformation (CWT) was used to characterize frequency and time specific patterns for rainfall, temperature, inflow, and per-capita consumption. CWT, unlike traditional spectral techniques, does not assume that dominant modes of timeseries variability are stationary, allowing it to be used to resolve events that are episodic or intermittent such as droughts, floods, and disease epidemics.<sup>30,58</sup> CWT resolves the contribution of different frequencies to overall variance using packets of wave-like oscillations (or wavelets) with an amplitude that begins and ends at zero. The wavelet, in our case a Morlet Wavelet (a sine wave multiplied by a Gaussian packet; Figure S2), is stretched or compressed to reveal the information content at different frequencies.<sup>32,59,60</sup> This content is often depicted using wavelet power, where power is simply the amount of a signal present at any given time-frequency region (e.g., the squared absolute value of the wavelet transform).<sup>32,60</sup>

One disadvantage of CWT is that it requires long, finely resolved and evenly spaced timeseries data (fortunately not a problem for this study).<sup>59</sup> Furthermore, all wavelet-based analyses have edge effects,<sup>60</sup> and care must be taken to evaluate only the time-frequency region that is "free" of these effects (i.e., beyond the so-called cone-of-influence, see the work of Grinsted et al.<sup>32</sup>). In this analysis we identify regions of significant wavelet power beyond the cone-of-influence as those where power is consistently in excess (e.g., 95% of the time) of the power expected in a red noise signal (details in the SI). All patterns in wavelet power were assessed relative to known

climatological or anthropogenic events in Melbourne's water history to identify those patterns characteristic of specific events.

**Wavelet Coherence Analysis.** Wavelet coherence was used to identify shared patterns (i.e., correlated regions) between rainfall, temperature, inflow, and per-capita consumption, and to explore their phase relationships. Coherence measures the cross-correlation between two time series as a function of frequency and is therefore analogous to a correlation coefficient in time-frequency space (0 no coherence and 1 perfect coherence between signals).<sup>32,60,61</sup> Wavelet coherence, like CWT, has associated edge effects and can only be interpreted outside the cone-of-influence (defined as above).

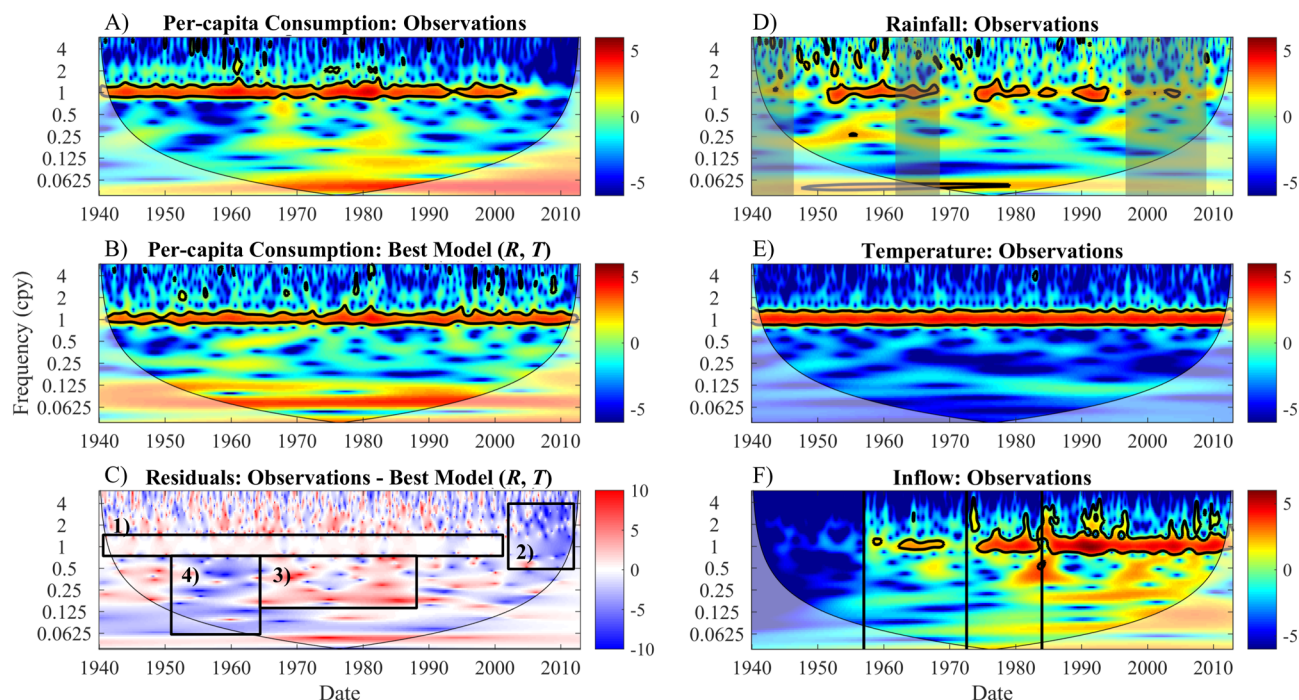
Phase relationships between rainfall, temperature, inflow and per-capita consumption were estimated for all regions of significant coherence (see the SI for details). Phase information was translated into monthly time lags ( $\tau$ ) using the following relationship

$$\tau = \theta_{ft}/2\pi f \quad (4)$$

where  $f$  is frequency in cycles per month and  $\theta_{ft}$  is the frequency and time-specific phase angle. The temporal evolution of phase relationships between climate variables and per-capita consumption was evaluated. Phase relationships were also compared across major drought events.

**Discrete Wavelet Transformation and Multiple Linear Regression.** Discrete wavelet transformation (DWT) was used in combination with multiple linear regression to construct two best-fit "climate" models for per-capita consumption (a rainfall–temperature–inflow and a rainfall–temperature model), allowing information regarding anthropogenic controls to be assessed through evaluation of the residuals (e.g., modeled–observed per-capita consumption). Inflow was omitted from the second climate model because it can reflect anthropogenic factors (e.g., urban catchment modification) in addition to climate. Note that DWT was employed for this analysis in lieu of CWT because it generates unique (nonredundant) wavelet coefficients that are suitable for regression analysis.<sup>34</sup>

Following a six-level (e.g., seven frequency) DWT, multiple linear regression was performed at each frequency band (dependent variable: per-capita consumption; independent variables: rainfall, temperature, inflow (or rainfall and temperature only) and all pairwise interaction terms). Note that visual inspection revealed no evidence of nonlinear relationships between sets of wavelet coefficients that would preclude multiple linear regression. Best-fit, frequency-specific models were selected using Akaike's Information Criterion (corrected for small sample sizes)<sup>62</sup> and then compiled into an overall best-fit model for per-capita consumption. Subsequently, inverse DWT was used to recover our modeled per-capita consumption timeseries. Because CWT provides higher fidelity timeseries decomposition than DWT (facilitating pattern analysis), CWT was performed on both observed and modeled per-capita consumption prior to taking their difference and assessing the residual for time-frequency signatures indicative of anthropogenic controls on urban water consumption. A detailed description and flow diagram of our complete DWT and regression procedure (inspired by Westra et al.<sup>34</sup>) can be found in the SI (Figure S3a).



**Figure 2.** Heat maps of wavelet power for the continuous wavelet transform (CWT) of (A) per-capita consumption, (B) modeled per-capita consumption (using the rainfall-temperature “*R, T*” climate model), (C) residual per-capita consumption (observed minus *R, T* climate model), (D) rainfall, (E) temperature, and (F) inflow. Black boxes in part C indicate regions of good (box 1) and poor (boxes 2–4) fits between observed and modeled per-capita consumption. Shaded gray bars in part D indicate long-term droughts, including (from left to right) the Second World War Drought, the 1960s Drought, and the Millennium Drought. Black vertical lines in (F) mark large reservoir additions (e.g., capacity exceeding 200 GL), including (from left to right) the Upper Yarra, Cardinia, and Thomson reservoirs. Time (years) is on the *x*-axis, and frequency (cpy) is on the *y*-axis for all panels. Thick black contours denote regions of significant power ( $p < 0.05$  level), and white shading (e.g., the cone of influence) indicates regions where estimates of wavelet power are unreliable.

## RESULTS

**The Millennium Drought.** Annual per-capita consumption peaked in 1997 at the start of the Millennium Drought (167 kL/p y) and reached its lowest value in 2011, two years after the drought concluded (86 kL/p y, Figure S1a); for conversion purposes, 1 kL/p y equals approximately 2.7 L/p d. This means that by 2009, when the drought officially ended, total per-capita potable water savings exceeded 70 kL/p y (Figure 1c and d). A small fraction of these savings was due to alternative water sources (approximately 2 kL/p y), reflecting increased adoption of rainwater tanks (post-2007) and recycled water systems (post-2005) (Figure 1d, S1b).<sup>22</sup> NRW savings (all water retailers) totaled 23 kL/p y by the end of the drought (Figure S1c) and were initially higher than those from conservation (Figure 1c). After 2002, however, savings from conservation exceeded those from NRW and alternative water sources combined, totaling 53 kL/p y by the end of the drought.

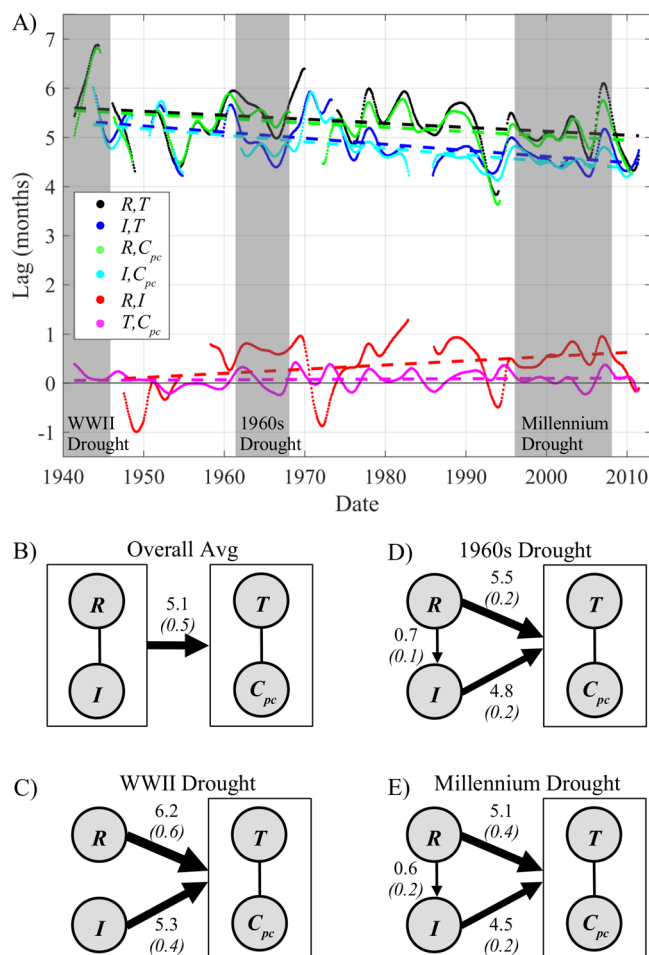
**The Historical Water Record. Frequency and Time-Specific Variability in Climate and Consumption.** Although Melbourne’s annual per-capita consumption was elevated at the start of the Millennium Drought, the summer high (1940–2012) occurred earlier (1982), and the summer low, later (2011) (Figure S3b). Per-capita consumption exhibited the most power at annual frequencies (significant at the  $p < 0.05$  level), diminishing in strength post 2002 (Figure 2a). Power was also elevated between 1960 and 1990, at frequencies below 0.5 cycles per year (cpy).

Climate variables also took on a wide range of values between 1940 and 2012, with rainfall ranging from 5.7 to 399 mm/month (lower in 1991 than during the Millennium

Drought), mean monthly temperature ranging from 3.8 to 20 °C (hottest in 1997 at the start of the drought), and inflow ranging from less than 0–1700 GL/y (highest after the construction of the Thomson reservoir in 1984; Figure S3c–e). All three variables exhibit high power at annual frequencies, particularly temperature (Figure 2e). As expected, rainfall exhibits discontinuities in annual power during the Second World War and Millennium Drought (Figure 2d), whereas inflow exhibits increases in power at all frequencies coincident with reservoir additions (vertical black lines in Figure 2f).

**Wavelet Coherence and Phase Relationships.** Significant coherence was observed at annual frequencies for all possible pairings of rainfall, temperature, inflow, and per-capita consumption, consistent with the high power annual band observed for each timeseries (Figure S4). Annual coherence was persistent (detected more than 70% of the time across all timeseries pairs) and was highest between temperature and per-capita consumption (coherent 99% of the time; Figure S4c) and lowest in pairings with inflow (coherent 74–79% of the time; Figure S4d–f). Significant coherence was also detected at subannual frequencies (e.g., 0.25 and 0.125 cpy), but only transiently (see, for example, Figure S4d).

Given that significant coherence was most consistently detected at annual frequencies, our exploration of phase relationships between rainfall, temperature, inflow, and per-capita consumption was limited to the annual band. On average, temperature and per-capita consumption were in phase (see box in Figure 3b), as were rainfall and inflow ( $0.1 \pm 0.2$  and  $0.4 \pm 0.5$  month lag, respectively), with rainfall and inflow leading temperature and per-capita consumption by approx-



**Figure 3.** (A) Timeseries of significant phase lag (estimated at an annual frequency) between rainfall (*R*), inflow (*I*), temperature (*T*), and per-capita consumption (*C<sub>pc</sub>*) from 1940 to 2012. Time (years) is on the *x*-axis, and phase lag (months) is on the *y*-axis. Observed phase relationships (circles; gaps indicate regions where no significant relationship occurred) and long-term trends (dashed lines) are shown in color: *R* leads *T* (black), *I* leads *T* (blue), *R* leads *C<sub>pc</sub>* (green), *I* leads *C<sub>pc</sub>* (cyan), *R* leads *I* (red), and *T* leads *C<sub>pc</sub>* (pink). Gray bars mark individual drought events as in Figure 2d. (B–E) Maps illustrating average phase relationships between 1940 and 2012 (B) and for individual drought events, including the Second World War Drought (C), the 1960s Drought (D), and the Millennium Drought (E). Arrow widths and associated coefficients indicate the magnitude ( $\pm$  standard deviation) of the lag. Boxes are used to group model components that are in-phase (e.g., exhibit no significant monthly lag).

imately 5 months (see arrow and monthly lag value in Figure 3b, Table S1). However, phase relationships between variables were not constant, and exhibited small, but significant ( $p < 0.01$ ), trends (statistical details in the SI). For instance, the lag between rainfall and inflow increased over time (total change of approximately 1/2 months between 1940 and 2012), whereas decreasing lags of similar magnitude were observed between rainfall and temperature, rainfall and per-capita consumption, inflow and temperature, and inflow and per-capita consumption (1/2–1 months) (see trend lines in Figure 3a, Table S1). Phase relationships for individual droughts generally reflect these trends, with rainfall and inflow leading temperature and per-capita consumption by the greatest margin during the Second World War Drought, followed by the 1960s Drought and the

Millennium Drought (see arrows and reported monthly lags in Figure 3c–e).

**Climatic and Anthropogenic Patterns in Urban Water Consumption.** More than 55% of the observed variance in per-capita consumption reflects climate forcing (i.e., is captured by either our rainfall–temperature–inflow or rainfall–temperature climate model; Tables S2, S3 and Figures S5, S6). Willmott’s index of agreement ( $d$ , 0 poor agreement, 1 perfect agreement) is also high for both climate models (more than 0.8), with  $d$  defined as in Willmott, 1982.<sup>63</sup>

$$d = 1 - \frac{\sum_{i=1}^n (C_{pc}Mod_i - C_{pc}Obs_i)^2}{\sum_{i=1}^n (|C_{pc}Mod_i - \overline{C_{pc}Obs_i}| + |C_{pc}Obs_i - \overline{C_{pc}Obs_i}|)^2} \quad (5)$$

Here  $C_{pc}Mod$  is modeled per-capita consumption,  $C_{pc}Obs$  is observed per-capita consumption, and  $n$  is the number of data points. The high  $d$  values for both models indicate that (1) they have comparable (and low) mean square error relative to potential error and (2) inflow contributes relatively little to overall model fits (see Tables S2 and S3 for additional fit metrics). Indeed, inflow only improved model fits at frequencies greater than 0.3 cpy (e.g., corresponding to less than 3.3 year cycles, Table S2, Figure S5). In contrast, rainfall and temperature were significant predictors of per-capita consumption at all frequencies except 0.09–0.2 cpy (e.g., 5–11 year cycles). In this frequency band no variable explained more variance in per-capita consumption than expected by chance (i.e., the best model was the null model; see Figures S5f and S6f). Importantly, the best-fit frequency-specific models presented here should be interpreted as one possible realization of a family of best-fit models, as their corrected Akaike weights fall between 0.15 and 0.67 (i.e., there is only a 15–67% chance that the models we selected are truly the “best”; Tables S2 and S3).

Given the similarity between the rainfall–temperature–inflow and rainfall–temperature climate models (see above and Figure S7), as well as the above-noted association between inflow and nonclimate factors (e.g., reservoir addition, Figure 2f), the rainfall–temperature model was selected as our final, most parsimonious, “climate-only” model (Figure 2b). The rainfall–temperature model reproduced patterns in per-capita consumption most reliably at annual frequencies (more than 80% variance explained; Table S3), particularly between 1990 and 2002 (box 1 in Figure 2c). This said, it clearly fails to capture the decrease in annual power observed after 2002 during the Millennium Drought (box 2 in Figure 2c). The model also overpredicts power in greater than annual frequencies (during the Millennium Drought) as well as in subannual frequencies between 1950 and 1965 (boxes 2 and 4 in Figure 2c). Finally, the model under-predicts power from 1965 to 1990 at subannual frequencies (box 3 in Figure 2c).

## DISCUSSION

During the Millennium Drought demand-side approaches for reducing urban water consumption (e.g., conservation 69% and NRW reduction 29%) conferred a proportionally greater benefit than supply side approaches (e.g., alternative non-potable sources 3% and desalination plant and Sugarloaf pipeline—completed post drought 0%) (Figure 1d). This disparity seems reasonable given the long timeframes required



for construction of water supply infrastructure (see discussion below). Similar success with demand-side techniques has been reported by Seattle, Washington, where conservation-minded media efforts in combination with more permanent efficiency measures such as low flow appliances saved almost 3 kL/p y in 2001 (a drought year), as well as in Boston, Massachusetts, where consumption declined approximately 25% in the early 90s (and has remained low) primarily due to aggressive leak repair, rebate programs for water saving technologies, and increased efficiency of industrial water use.<sup>64</sup> Indeed, demand-side approaches have also been credited with the more than 2-fold higher per-capita water savings in South East Queensland than Perth Australia since 2002 (with Perth investing more heavily in energy intensive, supply side approaches like desalination).<sup>65</sup>

Although conservation saved more water by the end of the Millennium Drought than NRW reduction, the inverse was true between 1999 and 2002 (Figure 1c), suggesting that early investment in NRW programs can have rapid (if diminishing) returns. Furthermore, because pressure/leak management initiatives can reduce utility maintenance costs through extending the lifetime of infrastructure, NRW programs may prove an attractive (even profitable) means of reducing water consumption in the long term.<sup>66,67</sup> Indeed, a pilot study by Gold Coast Water in Queensland, Australia revealed that pressure and leak management initiatives can save upward of 3.4 million AU dollars per year in maintenance costs and provide more water savings benefits per dollar than supply augmentation or the sum total of existing water rebate programs.<sup>66</sup>

Although savings from alternative water sources during the Millennium Drought were low (Figure 1d), this may, in part, reflect the longer timeframes required for such projects to be planned, funded, and constructed. Indeed, by 2013/2014 (five years postdrought), \$50 million AU dollars had been allocated to building stormwater systems for the purposes of potable substitution, implying that the full effect of these measures is yet to be realized.<sup>22</sup> Furthermore, given that many alternative water systems provide benefits beyond supply (e.g., related to improved water quality, flood mitigation, energy savings, and ecosystem/public health), their utility is expected to exceed their importance for drought mitigation alone.<sup>68–71</sup>

While the centralized supply side projects initiated during the Millennium Drought have been underutilized (e.g., the desalination plant and the Sugarloaf pipeline), they may have afforded the security necessary to innovate, enabling pursuit of less traditional (and possibly riskier) solutions to urban water problems.<sup>22,72</sup> This kind of innovation comes at a cost, however, including (1) the price of infrastructure (AU\$ 6 billion for the desalination plant alone),<sup>38</sup> (2) any public debt obligations amassed in paying for large-scale projects, (3) energy and environmental costs (an example of the former being Perth, where water-related per-capita energy costs more than doubled between 2002 and 2014 due to investment in desalination),<sup>65</sup> and (4) any future costs that accrue if infrastructure is maladaptive (e.g., increases emissions of greenhouse gases, reduces incentives for adaptation, and/or the options available for future generations).<sup>46</sup> These considerations complicate efforts to quantify the net costs and/or benefits of centralized infrastructure to urban water security in the long term.

Looking beyond the Millennium Drought, there are clear patterns in urban water consumption throughout Melbourne's

history (1940–2012), some of which appear driven by meteorological and/or hydrological variables. This is clearly evidenced by the high annual coherence between per-capita consumption and climate variables (Figure S4), previously noted for Melbourne<sup>10</sup> and three cities across Canada.<sup>12</sup> High annual coherence points to significant seasonality, with temperature and per-capita consumption oscillating in phase (more consumption in warmer summer months, see boxes in Figure 3b–e), and rainfall and inflow being nearly out of phase with temperature and per-capita consumption, consistent with the idea that consumption and temperature are highest when rainfall and inflow are lowest (see arrows and reported phase lags in Figure 3b–e). Interestingly, the phase lag between rainfall and inflow in Melbourne appears to have increased slowly but significantly over time, from in-phase around 1950 (peaking in winter/spring) to rainfall leading inflow by approximately 1/2 month in 2012 (Figure 3a, Table S2). This is consistent with the findings of Cai et al. and others, who identified altered rainfall:inflow relationships during the Millennium Drought compared to prior mega-droughts like the Second World War and Federation Droughts: essentially, reduced autumn rainfall fails to prime upper soil layers with moisture, resulting in delayed (and reduced) inflow in response to major rain events in winter/spring.<sup>43,44,73,74</sup>

Given the high shared power between climate and per-capita consumption at annual frequencies, it is not surprising that our optimal climate-based consumption model (the rainfall–temperature model) performed best at those frequencies (Figure 2c, box 1, Table S3). That said, post 2002 the model clearly overestimates the contribution of annual and higher frequency variability to per-capita consumption (Figure 2c, box 2). This mismatch likely reflects the influence of water conservation programs during the Millennium Drought, as these programs: (1) saved more water after 2002 than other approaches (Figure 1c) and (2) targeted outdoor (as well as indoor) water use, which varies seasonally. Indeed, the first wave of mandatory water restrictions targeting outdoor water use (Stage 1 restrictions) were implemented in November 2002, coincident with the onset of our reduced model–data fits (Figure 2c, box 2).<sup>22</sup>

Another notable failure of our climate-only model is evident between 1960 and 1990, where power is underestimated at subannual frequencies (Figure 2c, box 3). This long-term model–data mismatch (also seen in Figure S6f) suggests that rainfall and temperature alone are insufficient predictors of low frequency variability in urban water consumption. However, the 1960s–1990s were a period of technological innovation and changing social norms regarding water use in Melbourne, which together could have driven low-frequency changes in demand. For instance, by the mid-1960s piped hot water became freely available in the home paving the way for hot water appliances (e.g., the dishwasher and washing machine) and new accepted hygiene practices (e.g., daily showers).<sup>75</sup> These changes, alongside shifts in outdoor watering habits (spurred by suburban sprawl and a preference for backyard lawns) ushered in an era of high urban water use (see peak per-capita consumption in Figure S3b).<sup>75</sup> The 1980s, in contrast, mark the start of a water conservative mindset for Melbourne, including mandatory use of dual flush toilets in new toilet installations (1984), public awareness campaigns like “Don’t Be a Water Wally” (1984), and user-pays water pricing (1986).<sup>22,75,76</sup> Superimposed on this long-term (low frequency) pattern are two droughts, first in 1968, the worst year of the 1960s



Drought, and then in 1983, the Dust Cloud Drought (see hotspots at approximately 0.2 cpy in box 3, Figure 2c). The intense model–data mismatch during these periods likely reflects (1) the short, sharp nature of the droughts themselves and (2) their occurrence in an era when Melbourne's per-capita consumption was at an all-time high.

Importantly, unresolved climate drivers could also have impacted low-frequency variability in consumption post 1960s. Indeed, because the mismatch between modeled and observed per-capita consumption was highest at 5–11 year cycles (e.g., between 0.09 and 0.2 cpy, Figure S6), the following climate modes warrant further evaluation: the El Niño Southern Oscillation (ENSO; 3–7 year return period) and the Indian Ocean Dipole (IOD; 6–17 year return period).<sup>77</sup> Interactions among climate modes (e.g., ENSO, IOD, the Interdecadal Pacific Oscillation, and the Southern Annular Mode) should also be evaluated, as the relationship among modes shifted mid-1970s, changing drought dynamics<sup>78</sup> (and potentially, urban water consumption) in the Southern Hemisphere.

Our combined wavelet and multiple linear regression analysis clearly identifies both climatic and anthropogenic factors as important drivers of per-capita consumption in Melbourne, Australia. Given that rainfall and temperature capture more than 55% of the variance, it is expected that consumption will be sensitive to climate change. However, anthropogenic activities also exert strong control over per-capita consumption, explaining up to 45% of observed variance. This suggests that climate-only models will have limited predictive power in practice, and require inclusion of additional, anthropogenic drivers of consumption (e.g., social norms for water use, water-related technological innovations, and/or water demand management programs, particularly those related to conservation; see Figure 1d) in order to be efficacious. Furthermore, it is clear that nonstationarity is a key characteristic of Melbourne's urban consumption, with regions of elevated or diminished power appearing at different frequencies over time (see, for example the diminished annual band post 2002 and the hotspots at 0.2 cpy in the 60s and 80s; Figure 2a). This finding suggests, as advocated by Tiwari et al.,<sup>30</sup> that wavelets have something to offer scientists and practitioners looking to incorporate nonstationarity into predictive models of demand. Finally, both our wavelet analysis and urban water savings budget illustrate that Melbourne has a flexible array of tools to deal with future water challenges. These tools are flexible both in type (e.g., conservation vs technological innovation) and in the frequency they target (e.g., seasonal outdoor use vs low-frequency, baseline use; box 2 and 3, Figure 2c). Such flexibility is often cited as a key determinant of resilient urban water systems and can impact the ability of cities to mitigate and/or adapt to urban water stress.<sup>79,80</sup>

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b02938.

Additional text, seven figures, and three tables (PDF)

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## Notes

The authors declare no competing financial interest.

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