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**Key Points:**
- Water production records from 15 Canadian cities show a decline in per-capita demand, with rate of decline greater in semiarid cities with high seasonal variability
- Permanent water use restrictions have only minor impacts on mean or median summer day water demands
- However, stringent restrictions are shown to reduce demand variability at the daily scale, reduce peaks, and suppress demand surges during heat events

**Supporting Information:**
- Supporting Information S1

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# Curbing the Summer Surge: Permanent Outdoor Water Use Restrictions in Humid and Semiarid Cities

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**Abstract** As urban droughts make headlines across the globe, it is increasingly relevant to critically evaluate the long-term sustainability of both water supply and demand in the world's cities. This is the case even in water-rich regions, where upward swings in water demands during periods of hot, dry weather can aggravate already strained water supplies and increase cities' vulnerability to water shortage. Summer spikes in water demand have motivated several cities to impose permanent restrictions on outdoor water uses; however, little is yet known about their effectiveness. This paper examines daily water production data from 15 Canadian cities to (1) quantify how overall and seasonal demands are evolving over time across humid and semiarid settings and (2) determine whether permanent water use restrictions have been effective in curbing summer water demands both seasonally and during specific hot and dry periods. Results show that while per-capita water demand is declining in all cities studied, the seasonal distribution of that demand has remained largely stable in all but a few cases. While average demands in the summer months remain largely unaffected by the imposition of permanent restrictions, cities that enforce stringent limits on outdoor water use have seen a reduction in the variability of daily demands and a decline in peak demands following their implementation. During short-term periods of exceptionally hot and dry weather when vulnerability to water shortage is most acute, cities with strict restrictions also see smaller surges in demand than those with weaker or no restrictions in place.

## 1. Introduction

### 1.1. Urban Drought

Among the myriad threats that are expected to intensify under the effects of climate change is an increased risk of urban water supply shortages, wherein water supplies and/or infrastructure are temporarily incapable of meeting a city's water demand (Buurman et al., 2017; Cromwell et al., 2007; Ginley & Ralston, 2010). In the coming decades, the combination of increased variability in meteorological conditions and a warming Earth is expected to produce an increase in the frequency of severe warm and dry conditions across climate types (Sarhadi et al., 2018). In cities, where water availability is already threatened by growing urban populations and increasingly strained watersheds, these climatic shifts can be expected to further amplify the risk of urban drought events (Douville et al., 2002; Jenerette & Larsen, 2006; Vörösmarty et al., 2000; Wada et al., 2011).

Cities located in temperate and high-rainfall zones are not immune to water supply shortage threats. For example, Canada is a relatively water-rich country when compared to drought-prone nations like Israel and Australia, but despite the country's outsized share of global resources, more than a quarter of Canadian municipalities experienced temporary water supply shortages in the latter half of the 1990s (Environment Canada, 2004). Though no equivalent data are available for later years, this percentage has likely not decreased, considering the high rate at which outdoor water use restrictions have been introduced since that time. Resilience to urban drought is an important concern even in relatively water-secure countries; however, little research evidence yet exists to validate the effectiveness of policy measures enacted to address the water shortage threat in cities located outside of traditionally drought-prone regions.

### 1.2. Water Demand and Urban Drought Vulnerability

Because drought in anthropogenic systems is driven by an imbalance between water use and available supply, urban drought risk is influenced in part by the dynamics of each city's water demand, both over the long term and specifically during periods of water shortage (Bragalli et al., 2007; Padowski & Jawitz, 2012; Van

Loon et al., 2016). In North American cities, the average volume of water consumed per resident has declined significantly in recent decades: both academic studies and city reports point to a steady decline in per-capita water demand since the 1980s in cities across the United States and Canada (Chini & Stillwell, 2018; City of Calgary, 2013; East Bay Municipal Utility District, 2011; Environment Canada, 2011; Rockaway et al., 2011; Sankarasubramanian et al., 2017; Water Inc., 2016). A shortage of disaggregated demand data limits our ability to pinpoint precise causes of declining water use and its distribution among user types, but a downward trend in residential water use is most commonly attributed to a combination of water conservation initiatives, the spread of water- efficient fixtures and appliances, decreasing home and lot sizes, and changing attitudes toward water use (Brelsford & Abbott, 2017; DeOreo et al., 2016; Polebitski & Palmer, 2009; Rockaway et al., 2011).

However, declines in per-capita water demand do not guarantee a concomitant decline in water shortage risk. Downward trends in water demand are necessarily bounded (Dilling et al., 2018; Rockaway et al., 2011) and occur alongside growing city populations that can intensify water withdrawals even amidst declining per-capita demands. Annual demand figures also obscure subannual variations in water use, which are most relevant to the study of water shortage vulnerability in cities. As documented by studies of global watersheds at subannual time steps, periods of low water availability are widespread at the monthly scale even in areas with no history of annual precipitation deficits (Brauman et al., 2016; Wada et al., 2011). When these periods coincide with seasonal or short-term surges in demand, they can create moments of heightened vulnerability for urban water supply systems.

### 1.3. Seasonal and Short-Term Peaks in Water Demand

Urban water demands tend to intensify during the hottest months of each year (herein *summer*) due to a sharp increase in the use of water outdoors. Outdoor water uses include pool filling and car washing, but the category is overwhelmingly dominated by landscape irrigation of lawns, gardens and other urban greenspaces (Cole & Stewart, 2013; Kjelgren et al., 2000). Driven by increased water demand for irrigation, water production rates in the summer months can reach double or even triple the winter average in some cities (Balling & Gober, 2007; Chini & Stillwell, 2018; Kjelgren et al., 2000). Summer increases in water demand tend to be most pronounced in arid and semiarid cities where conventional grass-dominated urban greenspaces require frequent irrigation to stay healthy (Chini & Stillwell, 2018; Groffman et al., 2014; Milesi et al., 2005). This relationship is supported by recent work by Opalinski et al. (2020), who found that seasonal variation in urban water demand was highest in climate zones characterized by aridity and/or cold winters and hot, dry summers; in these climate types, an absolute or relative lack of summer precipitation drives up irrigation water use during that season. Similarly, Chini and Stillwell (2018) found a notable climate gradient in the seasonal variation of water demands across the continental United States, with the ratio of highest: lowest monthly water demand exceeding 300% in some arid western cities while eastern cities with wetter summers see little subannual variation at all.

At finer time scales, short-term peaks in water demand during periods of especially hot, dry weather can strain the urban supply:demand ratio in all climates. Low rainfall and elevated maximum temperatures are known to intensify outdoor water demands and especially irrigation by a significant degree (Balling et al., 2008; Balling & Gober, 2007; Gutzler & Nims, 2005; Jenerette et al., 2011; Polebitski & Palmer, 2009); as such, heatwaves that coincide with precipitation deficits can drive up demand for water at the same time that source water bodies are most strained by competing demands, reduced runoff, and heightened evaporation (Brauman et al., 2016; Hoekstra et al., 2012; Wada, van Beek, Viviroli, et al., 2011). Indeed, surging water demand in response to hotter summers and more frequent and intense heatwaves is identified as among the key threats that water utilities must contend with in an era of climate change (Cromwell et al., 2007). Even in the absence of water shortage threats, *peak demands* (a term commonly used to designate periods of very high demand) are a conventional infrastructure management challenge: Water treatment plants, storage systems, and distribution networks must be sized to meet these temporary surges in demand, resulting in higher design and maintenance costs for systems that are oversized for most of the year (Beal et al., 2016; Burn et al., 2002; Kanakoudis, 2002; Lucas et al., 2010).

Curbing seasonal and short-term peaks in water demand has emerged as a key strategy for promoting adaptation to urban drought risk, and recent work has pointed to the potential of outdoor water conservation generally, and restrictions on irrigation water use specifically, as promising tools for achieving this goal

(AghaKouchak et al., 2015; Breyer et al., 2018; Gober et al., 2015). Outdoor water use is more elastic and discretionary than other water use categories and can theoretically be curtailed rapidly in response to climate signals (Breyer et al., 2018; Espey et al., 1997; Lyman, 1992). Fresh findings also suggest that reducing the use of city water outdoors need not come at a high environmental cost: Research from California suggests that the health of urban greenspaces is largely decoupled from irrigation water use during drought episodes and that the greenness of those landscapes can rebound rapidly once the rains return (Quesnel et al., 2019). Turfgrass species commonly used in urban landscaping are especially adept at surviving summer drought stresses, so reducing irrigation of urban greenspaces during periods of low water availability can potentially be achieved without sacrificing their long-term health (Beard & Green, 1994). What is more, multiple studies have revealed that overirrigation of urban yards is common across climate types, leaving ample room for conservation (Chini & Stillwell, 2018; Endter-Wada et al., 2008; Glenn et al., 2015; Litvak & Pataki, 2016; Romero & Dukes, 2008; Survis & Root, 2012). By stimulating a transition to more efficient and targeted irrigation strategies, policy levers designed to restrict irrigation water use can help to mitigate the impacts of drought events in the immediate term while also promoting long-term adaptation to drought risks by encouraging overall reductions in climate-driven water uses.

### 1.4. Water Use Restrictions

Water use restrictions, which impose limits on the timing and frequency with which city water can be used outdoors and/or specifically for irrigating lawns and gardens, are a key feature of drought mitigation plans implemented by cities across the globe (Buurman et al., 2017; Carrière et al., 2006; Chong & White, 2007; Golembesky et al., 2009; Kenney et al., 2004; Knutson, 2008). Most such restrictions (herein *drought restrictions*) are temporary—imposed as a response to an impending water shortage threat and subsequently lifted—while others (herein *permanent water use restrictions* or *water use bylaws*) are standing restrictions enforced either year-round or during the summer period of each year based on an established calendar. Though temporary drought restrictions have been common practice since the 1970s, the imposition of permanent water use restrictions has become more widespread over the past few decades as aging municipal water systems struggle to keep pace with growing cities and an increasingly variable climate (Hilaire et al., 2008; Milman & Polsky, 2016; Shandas et al., 2015).

This trend is visible in Canada, where the application of seasonal water use restrictions has intensified significantly over the last two decades; today, over 75% of large (population >100 000) Canadian cities impose some sort of permanent water use restriction during the summer months. The increase in the imposition of summer water use restrictions is visible when scanning mentions of "water restriction" keywords within Canadian news media, where upticks in coverage also echo drought-like summer weather conditions in Canada's most populous regions (Figure 1). Though more in-depth research would be needed to explain this trend, given that media coverage has proven useful in tracking public attitudes to environmental events and analyzing transitions in water management policy, the uptick in water restriction coverage over the past 20 years could be indicative of a growing concern over the sufficiency of urban water supplies in Canadian cities conventionally viewed as water secure (Roby et al., 2018; Treuer et al., 2016). Beyond this potential narrative shift, the popularity of summer water use restrictions in Canada is driven by a shared assumption that they effectively reduce peak demands and, as such, help to defer costly expansions of potable water infrastructure in growing cities (Ontario Water Works Association, 2008).

Temporary drought restrictions have generally proven to be effective tools for restraining municipal water demands during periods of drought, reducing overall water production by as much as 56% in some cases (Kenney et al., 2004; Mayer et al., 2015). These restrictions tend to be most effective when they are both stringent and mandatory (Kenney et al., 2004; Shaw et al., 1992). However, permanent restrictions applied irrespective of drought conditions are not ensured to have this same impact. Multiple studies have found that policies enacted to curb excess water use are most effective when users themselves perceive the need for such actions (Bruvold, 1979; Gilbertson et al., 2011; Hannibal et al., 2018; Quesnel & Ajami, 2017); for this reason, permanent water use restrictions that are enforced regardless of climate conditions may not inspire the same degree of water savings as drought restrictions that are accompanied by climate signals and/or evidence of physical water shortage in the environment (Kenney et al., 2004).

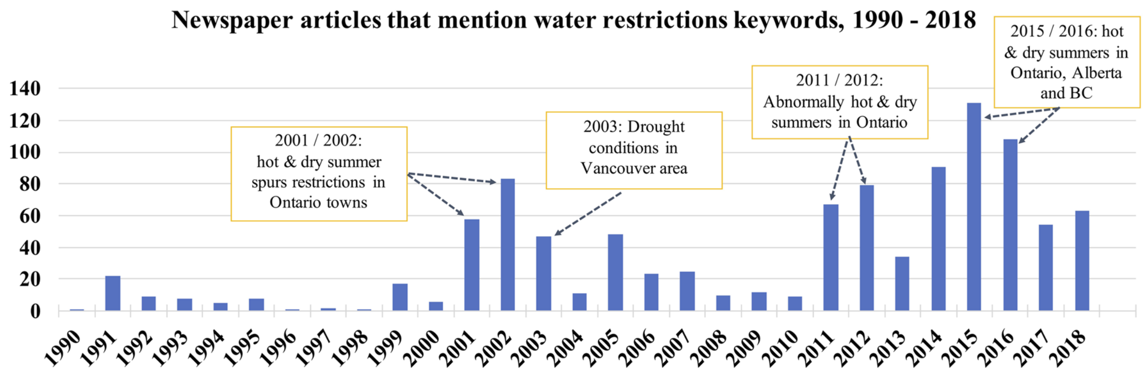


**Figure 1.** Mentions of water restriction keywords in Canadian news media (Factiva™) search of sources by region (Canada) using search terms (water* restriction OR water* ban OR water* bylaw) and excluding sports articles as well as common confounding terms (bottled and farm*). Summer conditions sourced from environment and climate change Canada's weather archives (Environment and Climate Change Canada, 2020).

### 1.5. Objectives of the Research

The utility of permanent water use restrictions is hotly debated within the water efficiency community, where some experts argue that price is a superior mechanism through which excess demands can be curtailed (Mansur & Olmstead, 2012), while others contend that the welfare cost of stringent long-term restrictions on outdoor lawn watering may be unacceptably high for some demographics (Brennan et al., 2007). Some water efficiency professionals have even speculated informally that less-stringent water restrictions such as odd/even day watering limits may in fact lead to increased outdoor water use (Ontario Water Works Association, 2008). Unfortunately, little research yet exists to confirm or quantify the effects of permanent restrictions on outdoor water use (Castledine et al., 2014; Survis & Root, 2012). This research is designed to help fill that gap by examining the seasonal water demand differential in Canadian cities, several of which have imposed some degree of permanent restriction on outdoor water uses during the summer months. In fact, it would seem that Canada is the ideal testing ground for such research because (1) it has a large number of climatically similar cities that impose seasonal water use restrictions of varying severity and (2) the presence of true winter in Canadian cities makes it easy to isolate outdoor water demands from annual water production records (Mayer et al., 1999; Mini et al., 2014; Romero & Dukes, 2014; W. DeOreo & Mayer, 2012).

The objectives of this research are to examine daily water production records from multiple Canadian cities in order to (a) quantify how water demands and their seasonal variation are changing over time in cities across humid to semiarid climate settings and (b) evaluate the effectiveness of permanent (rather than temporary) water use restrictions on the seasonal and short-term variability of demand for city water during the summer months. As the climate warms and the threat of periodic water shortages becomes increasingly prevalent even in water-rich nations, it is critical to better understand seasonal swings in water demand and the ways in which the behavior of urban water users can be influenced by permanent restrictions on certain water uses.

## 2. Data Collection and City Classification

Daily water production data were collected from a total of 12 Canadian municipalities as well as three municipal regions encompassing two or more smaller municipalities, herein grouped as "cities." Midsized cities and exurban agglomerations with a population of less than 1.5 million were favored for the research because of their high prevalence of low-density housing with personal yards; however, only cities with a population greater than 30,000 were invited to participate in an effort to avoid the high variability in water demands characteristic of small systems (Maidment & Miaou, 1986). Each city was asked to provide as many years of daily water production data as possible, along with a suite of contextual information about their water supply system including service populations, water sources (whether surface or groundwater or some combination of both), the size and density of water distribution networks, and their full history of imposing and promoting water use restrictions. Because changes in water price are known to impact water demands

(Campbell et al., 2004; Espey et al., 1997), we also collected information about volumetric water prices and their rates of change over time. Data received were vetted for quality by manually scanning for rapid shifts in demand and/or daily demand variance that could indicate faulty metering. Similarly, lower outliers (defined based on Tukey's Fence method as values lower than the 25th quartile value minus 1.5 times the interquartile range within successive 5-year time windows) were removed from each data set (Tukey, 1977). Unlike upper outliers, which cannot be guaranteed to be erroneous in this context, these extreme low values cannot be reasonably understood to represent the full volume of water distributed to a city's user base and are thus likely to indicate either meter or data recording failures (Helsel & Hirsch, 2015).

Climate data for each city were obtained from Environment Canada's historic weather database, where the closest weather station with consistent data throughout the study period was used (Environment and Climate Change Canada, 2020). Participating cities were categorized into two climatic groups according to aridity index (AI), defined here as the ratio of annual precipitation to potential evapotranspiration (Trabucco & Zomer, 2009). The AI of each city was determined by finding the spatially averaged AI value for the city's geographical limits from within the CGIAR-produced Global AI data set (Trabucco & Zomer, 2009). Subsequent categorization of the cities into climate groups is based on the climate classification system used by the United Nations Environment Programme (UNEP), which designates climate zones characterized by AI of less than 0.5 (but greater than 0.2) as "semiarid," and those with AI > 0.65 as "humid" (Barrow, 1992). Aridity was used as the basis for climate classification because of its strong correlation with environmental water availability and irrigation rates, both of which are highly relevant to the study of seasonal variability in water demands (Hanasaki et al., 2008; Jenerette et al., 2006; Padowski et al., 2016).

Note that because some cities agreed to participate on the condition that they would not be identified, all cities have been kept anonymous in the reporting of results. Instead, a letter name is assigned to each participating city—these are assigned based on AI values so that City A is the most humid and City O is the most arid in the sample.

## 3. Methods

### 3.1. Water Demand and Production

In this text, water *production* designates the total volume of treated, potable water delivered to the water distribution network and is distinct from water *consumption*, which refers to water consumed by individual customers as derived from billing data. Though several studies of water use restrictions rely on water consumption data for a subset of homes within a given city (Boyer et al., 2018; Castledine et al., 2014; Coleman, 2008; Halich & Stephenson, 2009; Jacobs et al., 2007; Mini et al., 2015), we have opted here to follow the example of other large-scale studies (Chini & Stillwell, 2018; Kenney et al., 2004) and base our analysis on water production rates and its per-capita corollary, water *demand*, because of the following:

a) This data set provides greater temporal precision (daily or hourly time steps) than billing data (generally available at time steps of 2 months or more), providing opportunity for analysis of the relationship of climate and water use at fine temporal scales. This temporal precision is especially useful when trying to understand the relationship of water use with heatwaves and/or stochastic rainfall events (Maidment & Miaou, 1986).
b) Not all cities in the sample are metered.
c) Water demands, and especially outdoor water demands, are highly spatially variable within the city, and a small subset of users are largely responsible for most of the excess irrigation water use in cities (Cole & Stewart, 2013; Endter-Wada et al., 2008; House-Peters & Chang, 2011; Mayer et al., 1999), making it very difficult to guarantee the representativeness of a sample of customer billing data.
d) Complete billing data are often prohibitively difficult to obtain (Chini & Stillwell, 2016).

Because water production data encompass the gross water demands of the residential, commercial, industrial, and institutional sectors as well various process water uses and water distribution losses (Cominola et al., 2015; Ruth et al., 2006), per-capita water demand values derived from production data are not directly attributable to consumption by individual water users. For the purposes of this study, the difference between winter and summer water demand is treated not as an approximation of the seasonal water use differential by individual users but rather as a gross seasonal surplus in municipal water production.

### 3.2. Seasonal and Annual Water Demand Metrics

In this text, the term *water demand* is the per-capita expression of daily water production and is presented in liters per capita per day (LCD). While *Annual day demand* ($AD_{i,y}$ for day i, year y; LCD) designates daily water demands throughout the year, *Summer day demand* ($SD_{i,y}$ for day i, year y; LCD) describes daily water demand values specifically in the summer months, where "summer" is defined as June–August of each year. These months were chosen because they represent the period within which outdoor water use is most widespread in Canadian climates and also because the enforcement period for the water use restrictions studied coincide during those months. Annual averages of overall (year-round) and summer season daily demands for year *y* are referred to as $AD_y$ (LCD) and $SD_y$ (LCD), respectively. In contrast, the *base demand* for year *y* ($BD_y$; LCD) refers to the per-person daily volume of water used indoors only and is defined according to the lowest average month method of DeOreo and Mayer (2012). In this method, the mean daily demand value of the 3 months of lowest water demand within each calendar year (which may vary annually) is assumed to represent base water demand—that is, indoor, climate-invariant water flows (and losses) across all user types for that year. The lowest average month method provides a robust estimate of indoor water use in climates where cold winters and plant dormancy preclude outdoor water use for at least 3 months of the year (B. DeOreo, 2011; Maidment & Miaou, 1986; Mayer et al., 1999; Mini et al., 2014; Shaw & Maidment, 1987).

Because segregated indoor/outdoor water metering is rare, the degree to which summer water demands exceed base demands is a commonly used method for approximating outdoor or otherwise climate-dependent water use in the summer months (Endter-Wada et al., 2008). To enable a comparison between cities with widely divergent base demands, we quantify the *summer demand surge* (SDS) for year y ($SDS_y$) as the ratio of mean summer demand to baseline demand in each city and each year:

$$SDS_y = \frac{SD_y}{BD_y} \tag{1}$$

Temporal trends in all metrics are tested for significance using the nonparametric two-sided Mann-Kendall trend test (Helsel & Hirsch, 2015). When the Mann-Kendall test reveals the presence of a monotonic trend that is significantly different from zero at a 95% or 99% confidence level, Sen's slope estimator is used to represent the magnitude of the trend (Sen, 2012). Trends are calculated over the 2000–2017 period (inclusive)—this period was chosen as the most recent and comprehensive timeframe within which all cities have submitted data.

### 3.3. Detecting the Influence of Water Use Restrictions

The effect of permanent water use restrictions was explored by analyzing normalized summer daily water demands before and after restrictions, where normalization is done by dividing daily summer demands ($SD_{i,y}$) by the mean daily water demand ($AD_y$) for that year (Equation 2). This normalization allows us to gauge whether the imposition of the restriction produced a decline in summer demands that exceeds any concomitant decline in average annual demand between those two time periods and facilitates cross-city comparison by compensating for the wide variation in the values of average and seasonal demand among cities. It also provides a rough compensation for the climate differences between the before- and after-bylaw periods by quantifying each summer day's deviation from an average demand value, which itself integrates the naturally higher irrigation demand in hot, dry summers. This metric provides a measure of "peakiness" in demand that can be compared across divergent summer conditions, and which captures the exceptionally high demand days that restrictions aim to curb.

$$nSD_{i,y} = \frac{SD_{i,y}}{AD_y} \tag{2}$$

where $nSD_{i,y}$ represents individual normalized daily per-capita summer demand values. The impact of water restrictions was determined by comparing the distribution of daily $nSD_{i,y}$ values in the years following the imposition of the restriction to that of the years that preceded it. The "before" and "after" periods, respectively, designate the 5 years of data leading up to and following the *implementation year*, defined as the year for which the bylaw was both mandatory and enforced for the entire summer season. Five years was selected as the comparison timeframe in order to favor the inclusion of a range of climate conditions within each time period while limiting the confounding impact of long-term trends in demand—it should be noted however that due to data limitations, the "after" period for city M includes only 3 years and the "before" period for City A spans 4 years instead of 5.

Water restriction impacts are then quantified by calculating the change in mean, median, standard deviation, and the 95th percentile of the $n\mathrm{SD}_{i,y}$ distributions from the "before" to "after" subsets. These metrics provide a range of information about the potential impact of water use restrictions: mean and median values quantify the impact on overall summer demands, while changes to standard deviation measure effects on demand variability at the daily scale and shifts in the 95th percentile value provide a marker for the change in magnitude of peak demands. The distance between the "before" and "after" distributions was further quantified by determining the Kolmogorov-Smirnov (KS) distance ($\mathrm{D}_{\mathrm{KS}}$) and the *P* statistic of the two-sample KS test ($\mathrm{P}_{\mathrm{KS}}$) between the cumulative distribution functions (CDF) of each subset (Wilcox, 2005). The two-sample KS test is a nonparametric statistical test that determines maximum distance between two CDFs:

$$D_{KS} = max\left|F(x)_{before} - F(x)_{after}\right| \tag{3}$$

This methodology is adapted from the direct comparison method used in previous analyses of water restrictions, wherein comparisons are drawn over several years of data to subsume fine-scale variability in the climate conditions that drive outdoor water use (Haque et al., 2014; Jacobs et al., 2007). A 2014 comparison study by Haque et al. found that direct comparison of demand ratios produced a more accurate estimate of water savings than the model-based "expected use" method commonly used to study the effectiveness of temporary drought restrictions, which uses short-term water demand forecasting models to predict a theoretical "expected use" value to which observed water demands under restrictions can be compared. Preliminary explorations into the applicability of the "expected use" method in this study revealed two major issues for our cities: (i) Expected use models were not able to accurately capture the magnitude of short-term peaks in demand, a phenomenon that reflects the complexities of modeling aggregate human behavior on hot summer days (Shaw & Maidment, 1987; Zhou et al., 2000), and (ii) given the low seasonal variability in demand characteristic of humid climates, models of expected use in some cities showed model fit errors that exceeded the difference between "expected use" and observed water demand, making it impossible to use this method to accurately quantify the effect of restrictions in those cases. Based on these findings, we determined that the direct comparison method is both most appropriate and most informative for the purposes of this research. In order to ensure that climate differences between the two time periods do not affect the comparability of demand distributions, we also compared the distributions of daily temperature and rainfall values for the before- and after-bylaw periods in each city. Climate conditions for the two periods were deemed similar when no significant difference was found between these distributions at the 90% confidence level using the two-sample KS test (Equation 3).

### 3.4. Water Demand During Hot and Dry Periods in Bylaw and non-Bylaw Cities

We refined our analysis of bylaw effectiveness by zooming in on time periods of anticipated peak demand—that is, periods of exceptionally hot and dry weather. We use the shorthand *dry heatwaves* to describe these events—namely, periods of three or more days characterized by exceptionally high temperatures combined with lower than normal antecedent precipitation. Such periods are pertinent to the study of water use restriction effectiveness because water demands tend to peak under hot and dry conditions as lawn watering and other climate-driven water uses increase, and a successful water use restriction should reduce this surge in demand in order to minimize the probability of supply shortages. In essence, this test evaluates how well permanent restrictions perform the role of temporary drought restrictions, which seek to reduce excess water use specifically during dry periods when supplies are strained.

To evaluate whether permanent water use bylaws imposed in the sample cities were effective in this regard, we analyzed two groups of geographically clustered cities that experienced simultaneous episodes of exceptionally hot and dry weather to determine if temporary surges in water demand were significantly lower in cities that enforce water use restrictions than in those that do not. Both city groups identified are drawn from within the humid cities category because the study's semiarid cities are too far apart geographically to

**Table 1**
*Study Cities*

| City | Years of data provided | Climate type (AI) | Population class (2016) | Water use bylaw enforced annually? (year imposed) | Hours of watering permitted/week | Relative stringency | City group for hot/dry days analysis (section 3.4) |
|---|---|---|---|---|---|---|---|
| A | 2000–2017 | Humid (2.0) | 50–100 K | Y (2004) | 12 | Medium | — |
| B | 1993–2017 | Humid (1.3) | 100–250 K | Y (2003) | 6 | High | NG |
| C | 2004–2017 | Humid (1.2) | 50–100 K | Y (2010) | 14 | Medium | — |
| D | 2001–2017 | Humid (1.2) | 250–500 K | Y[a] (1971) | 14 | Medium | NG |
| E | 1994–2013 | Humid (1.1) | 500 K to 1 M | Y (2005) | 8.5 | High | SG |
| F | 2000–2017 | Humid (1.1) | 250–500 K | Y[a] (1988) | 42 | Low | SG |
| G | 1997–2016 | Humid (1.1) | 100–250 K | Y (2002) | 9.3 (14/14/0)[b] | High | SG |
| H | 2004–2016 | Humid (1.1) | 250–500 K | Y (2009) | 36 | Low | NG |
| I | 2002–2016 | Humid (1.0) | >1 M | N | n/a | n/a | — |
| J | 2003–2017 | Humid (1.0) | 250–500 K | N | n/a | n/a | SG |
| K | 2003–2017 | Semiarid (0.48) | 100–250 K | N | n/a | n/a | — |
| L | 2003–2017 | Semiarid (0.44) | <50 K | N | n/a | n/a | — |
| M | 2000–2017 | Semiarid (0.39) | 50–100 K | Y (2015) | 13.5 (27/18/9/0)[b] | Medium | — |
| N | 1997–2017 | Semiarid (0.37) | 50–100 K | N | n/a | n/a | — |
| O | 1994–2017 | Semiarid (0.34) | 50–100 K | Y (2000) | 38.5 | Low | — |

*Note*. NG = Northern Group, SG = Southern Group.
[a]Indicates "Fossil" water restrictions that are too old to evaluate. City F does not actively enforce its fossil restriction. [b]Staged bylaw; shown are weekly watering hours permitted under Stage 1/2/3/4 restrictions of increasing severity.

experience overlapping climate conditions, making them ineligible for such a comparison (this analysis was also hindered by the relative recency of semiarid city M's water use bylaw, which limits the number of post-bylaw heatwaves found within the data set). The *Southern group* (SG) includes Cities E, F, G, and J, and the *Northern group* (NG) encompasses Cities B, D, and H (Table 1). All cities in each group are located within 150 km of each other and share general climatic similarities (including AI values, which range from 1.0–1.08 in the SG and 1.15–1.29 in the NG) and, as such, tend to experience similar and simultaneous episodes of exceptionally hot and dry weather. Because there is no universal definition for a *heatwave* (Meehl & Tebaldi, 2004), an iterative process was undertaken to develop a functional definition for a "dry heatwave" based on deviation from climate means. Maximum temperature and days without rainfall were used to define heatwave criteria because of the superior explanatory power of these variables in water demand forecasting models that focus on modeling peak demands at short time scales (Adamowski, 2008; Adamowski & Karapataki, 2010; Bougadis et al., 2005). Under this definition, a dry heatwave is a period of at least 3 days wherein:

a) No significant rainfall (>5 mm) has been recorded for at least Y days, where Y = 50th percentile of consecutive days that pass without significant rainfall, AND
b) the maximum temperature exceeds N, where $N = 90$th percentile of daily maximum temperature values.

This threshold combination, established for individual cities and then averaged to establish a dry heatwave definition for each city group, represents the most extreme hot/dry conditions for which at least 10 post-bylaw dry heatwaves could be identified for both groups. The sensitivity of results to this definition was tested by repeating the analysis for various combinations of 50th, 60th, 70th, 80th, and 90th percentile values for both maximum temperature and antecedent rainfall.

With this definition established, we compared the degree to which water demands increased from the summer baseline within groups of cities simultaneously experiencing dry heatwave conditions. To normalize for differing demand baselines among cities and remove the impact of long-term trends in demand, daily summer demand ($SD_{i,y}$) values during dry heatwave events were expressed as a ratio to that year's median $SD_{i,y}$ value. The median value is used instead of the mean as the normalizing factor in this case in order to minimize the sensitivity of the denominator to the very extreme values that the metric intends to quantify:

$$HSD_{i,y} = \frac{SD_{i,y}}{median\ SD_{i,y}} \tag{4}$$

where the Heatwave Specific Demand ($HSD_{i,y}$) represents the ratio of water demand on a given summer day (i) to the median summer day demand of that same year (y). Individual daily $HSD_{i,y}$ values are then averaged over the duration of each dry heatwave event to present an overall *heatwave demand surge* value for each city and each event.

## 4. Results and Discussion

### 4.1. City Data Analysis

Fifteen participating cities from across five provinces provided a minimum of 13 and a maximum of 25 years of daily water production values for the study. Of these, five were classified as "semiarid," with aridity indices below the UNEP-designated threshold of 0.5, while the other 10 cities were grouped into the "humid" category (AI > 0.65). City populations ranged from a low of 34,000 to a high of over 1.4 million inhabitants (note that some of the "cities" on the high end of the population range are in fact regional water districts that encompass multiple adjacent municipalities). To protect their anonymity, cities are grouped into six classes of population size (<50K, 50–100 K, 100–250 K, 250–500 K, 500 K to 1 million, and >1 million) based on 2016 data. Four of the 15 cities do not have universal water metering of residential customers.

Ten of the study cities enforce permanent water use bylaws that impose mandatory limits on the use of city water for outdoor purposes (irrigation, pool-filling, maintenance, etc.) each summer, while the remaining five either do not impose restrictions on outdoor water use or only reserve the right do so on an emergency basis but have not yet done so in the case of drought. Interestingly, a higher proportion of cities within the "humid" climate category enforce water use bylaws than those in the semiarid category, and most (3/5) semiarid cities studied impose no restrictions on outdoor water use at all (Table 1). Because water use restrictions in Canada are typically municipal bylaws, we refer to cities that impose restrictions as "bylaw cities," while the others are "non-bylaw cities." Note that two of the cities that do nominally impose seasonal restrictions, D and F, are effectively grouped into the non-bylaw category for the purposes of this study because their restrictions (herein dubbed *fossil bylaws*) are over 30 years old, and not enough data are available from before and after their introduction to evaluate their effectiveness.

For the purposes of this study, we use the total number of hours of outdoor lawn and garden watering permitted per week as a determinant of relative bylaw stringency. To arrive at this total, the number of watering days permitted each week is multiplied by the number of watering hours allowed per day. When bylaws make a distinction between watering hours permitted for manually operated and automatic sprinkler systems, the larger of the two numbers is used, and 12 hr is allotted to each watering day in cases where no hourly restrictions are applied. Under this categorization, each week, a bylaw of "high" relative stringency allows fewer than 10 total watering hours, a bylaw of "medium" relative stringency allows 10–20 watering hours, and a bylaw of "low" stringency allows more than 20 watering hours. In the case of the staged bylaws imposed in cities G and M, which increase in severity according to water supply levels, the mean of weekly watering hours permitted under all restriction levels is used to define relative bylaw stringency. All of the eight bylaws evaluated are enforced through the issuance of tickets and/or fines.

### 4.2. Annual Water Demands and Seasonal Variations in Demand

Results show that per-capita water demands, and especially the SDS, vary significantly across the 15 cities studied and tend to be higher in semiarid cities than in humid cities (Figure 2). When looking at average values for the 2010–2015 period (inclusive) for which all cities have sufficient data, we find annual demand ($AD_y$) values ranging from a low of 291 LCD in City E to a high of 645 LCD in City O (Figure 2a). Base demands ($BD_y$) varied considerably less across the board: All but two cities studied show values within the 275–400 LCD range. This provides some confirmation of the assumption that base demands are largely independent of city and climate, while summer demands are sensitive to climate and tend to spike in the driest parts of the country. Indeed, average summer day demands ($SD_y$) varied widely across the sample, ranging from a low of 311 LCD in City E to 1,070 LCD in City O.

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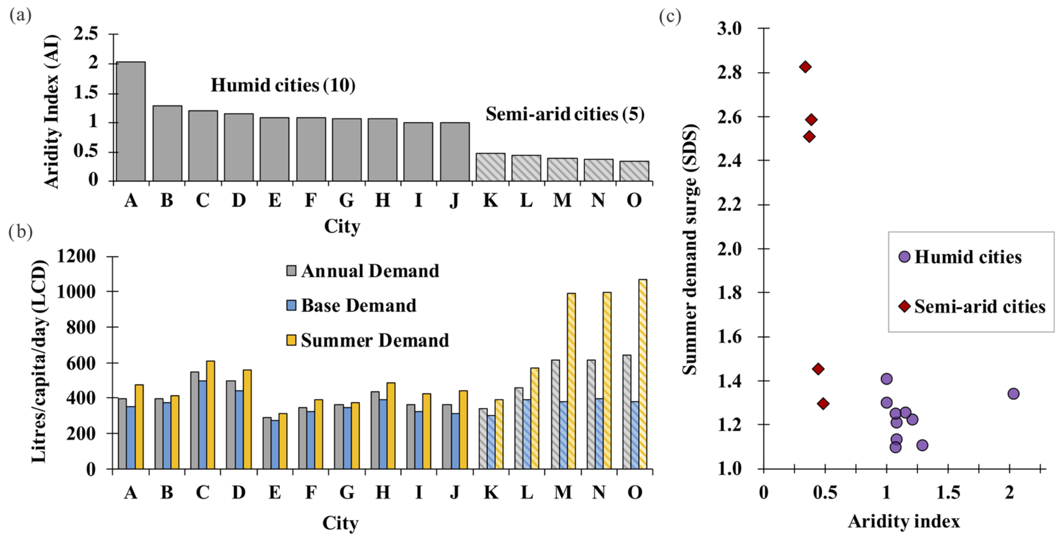


**Figure 2.** (a) Aridity index of all study cities. Semiarid cities are represented by striped bars. (b) The 2010–2015 average annual demand ($AD_y$), base demand ($BD_y$), and summer demand ($SD_y$) for all cities. (c) Scatterplot of cities' aridity index versus 2010–2015 average SDS value.

The range in SDS values across the study cities is notable: whereas in some humid cities summer demands exceed base demand by as little as 10%, summer demand in City O (the most arid in the sample, AI = 0.34) was more than 2.8 times higher than base demand over the 2010–2015 period. The seasonal variation in demand in the three most arid cities (N, M, and O) is indeed striking: When 2012 data from these cities are compared to that presented by Chini and Stillwell (2018), who use the ratios of maximum/minimum monthly demand to gauge the intra-annual disparity in urban water demands across the US, we find that max/min month ratios in study Cities M (301%), O (313%), and N (331%) mirror or even exceed the most extreme values found in cities of the dry southwestern United States like Colorado Springs (335%), Denver (348%), and Bakersfield, California (284%). These three most arid cities are clear outliers within the sample—all other cities have moderate SDSs ranging from 10% to 45% that show little relationship to aridity (Figure 2b). This indicates that seasonal variation in water demand may indeed be driven by aridity in semiarid zones (as suggested by Chini & Stillwell, 2018, and Opalinski et al., 2020), but outside of those climate types may be more contingent on other factors (demographics, socioeconomic characteristics, lot sizes, etc.).

### 4.3. Temporal Trends

All 15 cities studied have witnessed a decline in average per-capita water demand ($AD_y$) over the 2000–2017 period (Figure 3). When analyzed using the nonparametric Mann-Kendall test, these trends were found to be significant at the 95% confidence level with the exception of City A, which did not show a significant trend in

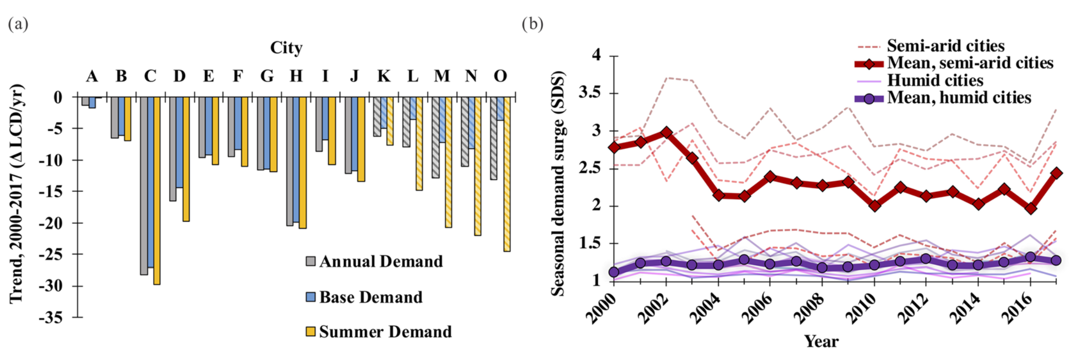


**Figure 3.** (a) Annual trends, 2000–2017. Semiarid cities are represented by striped bars. Note that annual and summer trends in City A are not significant. (b) Seasonal demand surge in semiarid and humid cities, 2000–2017.

overall demand. Rates of decline in demand varied widely from city to city, with the strongest downward trends found in cities with a high starting point—that is, those with the most opportunity for conservation (see Figure S1 in the supporting information). Gross water production is also on the decline in eight of the 15 cities, whereas in six others it is largely stable, suggesting that decreases in per-capita demand are counteracted by increasing populations in those cities. Only one city (City A) saw a statistically significant (though slight) increase in water production between 2000 and 2017 (Table S1).

Annual trends in base demand ($BD_y$) and summer demand ($SD_y$) also show consistent but varying rates of decline across the cities studied (Figure 3a). These trends were all statistically significant at the 95% confidence level except in the case of City A, where no significant trend in summer demand was detected using the Mann-Kendall test. Interestingly, the decline in summer demand is found to largely mirror the trend in base demand in the humid cities studied, while in the four most arid cities, downward trend in summer demands outpaced concomitant reductions in base demand by at least a factor of 2 (Figure 3a). This suggests that most of the decline in per-person water demand in humid cities is likely attributable to climate-invariant water uses (e.g., indoor water conservation and leakage reduction), whereas the lion's share of water savings in semiarid cities is due to reductions in summer-specific demands including irrigation. Again, the phenomenon likely points to the greater water conservation potential in cities with high initial demand—in this case, cities with high rates of climate-driven outdoor water use witnessed a relatively rapid decline in that water use category, while those with low initial rates of outdoor water use have fewer “easy” conservation opportunities and have seen little change in summer-specific demands. However, most of the reduction in summer water demands in semiarid cities occurred over the 2000–2010 period (Figure 3b), and despite these differing rates of decline in seasonal demand, the summer demand surge ($SDS_y$) declined significantly in only two of them (Table S1). In the rest of the semiarid cities and in most humid cities, $SDS_y$ has remained largely stable since 2000.

### 4.4. Bylaw Effects

#### 4.4.1. Changes in Water Demand Distributions Before/After Bylaw Implementation

If bylaws were effective in reducing summer-specific water uses, we would expect to see a shift in a city's summer demands ($SD_{i,y}$) following the imposition of water restrictions so that they more closely resemble the annual average ($AD_y$)—in other words, a decline in $nSD_{i,y}$ values (Equation 2). Anticipated bylaw effects include an overall decrease of normalized demands (smaller mean and/or median $nSD_{i,y}$ values), a reduction in the variability of daily demands as users are coaxed into watering on set days distributed throughout the week (a reduction in the standard deviation of $nSD_{i,y}$ values) and/or a shortening of the upper tail of the distribution indicative of a decline in peak demands (lowered 95$^{th}$ percentile $nSD_{i,y}$ value). Detailed statistical analysis of summer water demands from the prerestriction and postrestriction periods revealed that these anticipated bylaw effects are visible in only some of the eight bylaw cities studied. Cumulative distribution functions for the eight bylaw cities before- and after-bylaw introduction are shown in Figure 4:

The analysis, which included 5 years of normalized summer demand values for each period and each city (with exceptions as noted), revealed that the two-sample KS distance between the pre- and post-bylaw demand distributions was significant at the 90% level in six of the eight bylaw cities studied. However, only two of these (Cities B and G) saw uniform shifts in overall demand distributions in the anticipated (negative) direction (Figure 4; Table 2). In all cases changes in mean and median demand between the two time periods were minor, and some cities even saw net increases in multiple demand metrics following the imposition of bylaws (Table 2). What was striking, however, was that in five of the eight cities studied there was a decrease in the 95th percentile demand, indicating a drop in peak demands even when averages were minimally affected. These same cities also saw a considerable reduction in the standard deviation of daily demand distributions. When these results are examined alongside climate categories and the relative severity of individual bylaws, three distinct patterns emerge:

- Three humid cities that imposed bylaws of high relative stringency (Cities B, G, and E; Figure 4; Table 2) have seen small but significant declines in mean demands alongside more significant reductions in both the standard deviation and 95th percentile values of the normalized summer demand distribution following the imposition of water use restrictions. The cumulative distribution functions of two of these cities (B and G) show a decline in demand across all flows and are found to be significantly different based on the two-sample KS test. In the third case (City E), demands declined most meaningfully in the

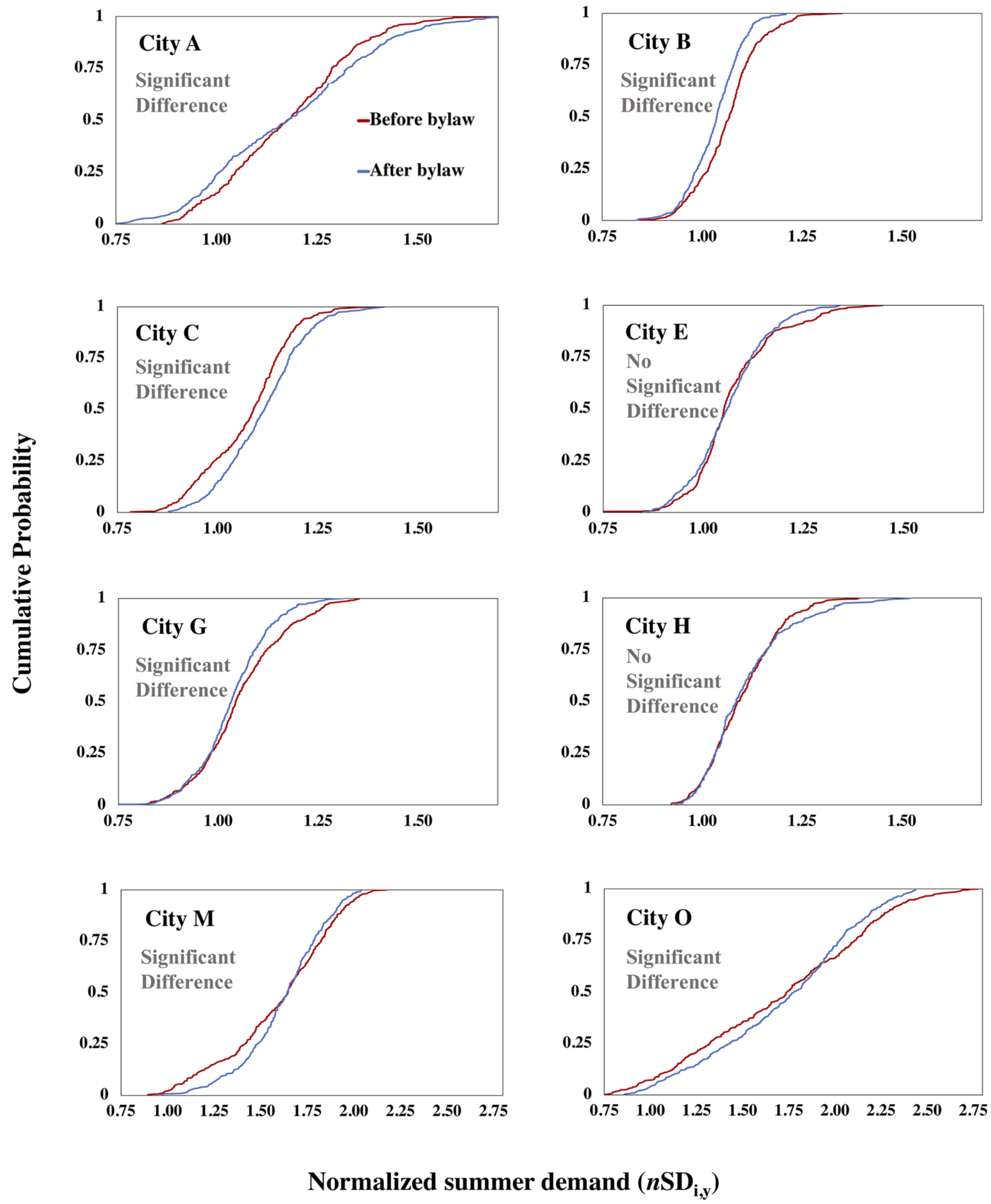


**Figure 4.** Cumulative distribution plots of $SD_{j,y}$ as a function of $AD_y$ ($nSD_{i,y}$) before- and after-bylaw imposition in humid cities (top three rows) and semiarid cities (bottom row—note the difference in *x* axis). Red line represents $nSD_{i,y}$ values before bylaw, blue line after bylaw.

upper tail region, and the standard deviation of the demand distribution declined by 10% following the imposition of restrictions, though $D_{KS}$ was not significant at the 90% confidence level. Although mean water demands decreased only slightly following the imposition of stringent restrictions in these cities, they all witnessed a decline in the variability of summer daily water demands as well as a small decrease in the magnitude of peak demands in the years following the introduction of water use bylaws.

- Three humid cities that impose bylaws of low or moderate relative stringency (Cities C, H, and A; Figure 4; Table 2) saw either minimal decreases or significant net increases in mean normalized summer demands between the two time periods. Unlike the cities with more stringent bylaws, in these cases we see that the standard deviation of the demand distribution has either declined only slightly (City C) or has increased (Cities H and A) following the imposition of bylaws. In all three cases, the 95th percentile value also increased after restrictions were introduced. These cities either did not witness significant

**Table 2**
*Comparison of Bylaw Effects*

| | A | B | C | E[a] | G | H | M[a] | O[a] |
|---|---|---|---|---|---|---|---|---|
| Climate category | Humid | Humid | Humid | Humid | Humid | Humid | Semiarid | Semiarid |
| Bylaw stringency | Medium | High | Medium | High | High | Low | Medium | Low |
| "Before" period | 2000–2003[b] | 1998–2002 | 2005–2009 | 2000–2004 | 1997–2001 | 2004–2008 | 2010–2014 | 1995–1999 |
| "After" period | 2004–2008 | 2003–2007 | 2010–2014 | 2005–2009 | 2002–2006 | 2009–2013 | 2015–2018[b] | 2000–2004 |
| $D_{KS}$ | 0.103 | 0.198 | 0.141 | 0.063 | 0.107 | 0.059 | 0.098 | 0.085 |
| $P_{KS}$ | 2.68E–02[c] | 3.04E–08[c] | 2.05E–04[c] | 3.19E–01 | 1.04E–02[c] | 4.07E–01 | 7.26E–02[c] | 7.33E–02[c] |
| Δ Mean | 0% | −3%[c] | +4%[c] | −1%[c] | −2%[c] | +1%[c] | +2% | +1%[c] |
| Δ Median | 0% | −3% | +2% | +1% | −1% | −1% | 0% | +2% |
| Δ Std. deviation | +25% | −17% | −4% | −10% | −18% | +21% | −23% | −17% |
| Δ 95th percentile | +6% | −6% | +3% | −5% | −6% | +5% | −3% | −5% |

[a]Climate conditions were not equivalent between the before- and after- periods in these cities. See below and Table S2 for detail. [b]These periods include less than 5 years of data, as noted in section 3.3. [c]Significant difference at the 90% confidence level ($P_{KS}$ and Δ mean only).

changes in the distribution of normalized summer water demands as measured by $D_{KS}$ metric (city H) or show a significant difference in an unanticipated direction, pointing to higher summer water use across all flows (City C) or an increase in high-demand days counterbalanced by a concomitant increase in low-demand days (City A) after restrictions were imposed. In these humid cities, not only has summer water use not declined following the introduction of relatively permissive water use restrictions but it has also become more variable at the daily scale with slightly higher peaks in demand.

- The two semiarid bylaw cities studied (Cities M and O; Figure 4; Table 2) have seen little or no net shift in mean or median daily demands but show a marked reduction in the spread of the distribution of daily $nSD_{i,y}$ values after restrictions were imposed. In both cities, the standard deviation of normalized summer demands decreased by approximately 20% in the years following the imposition of restrictions, and both also saw reductions in the 95th percentile daily demand value. Both semiarid cities have experienced a decline in the variability of summer daily water demands as well as a decline in the magnitude of peak demands following the imposition of relatively permissive odd/even day restrictions (City M) or staged restrictions of moderate stringency (City O).

To confirm that the observed changes in normalized summer demand distributions was not due to climate differences between the before- and after-bylaw time periods, we compared the corresponding distributions of daily maximum temperature and daily rainfall for each period using the same two-sample KS test shown above (Equation 3). Results show that based on a 90% confidence interval, Cities E, M, and O showed statistically different climate conditions between the two periods: Cities O and E were slightly hotter in the years following the restriction's introduction than in the years preceding it, while City M was both slightly hotter and drier in the postrestriction period (Table S2). To explore whether the CDF analysis underestimates the impact of bylaws in these cities because of this difference, the model-based "expected use" method described in section 3.3 was also used to quantify bylaw effects in these cases. That analysis largely reinforced the CDF result, while also confirming a minor underestimation of bylaw effects when the post-bylaw period is hotter or drier than the pre-bylaw period (though the difference was only statistically significant in the case of City O). Detailed results of the expected use analysis are provided in the supporting information.

#### 4.4.2. Analysis of Hot and Dry Periods

We refined our analysis by focusing in on time periods of anticipated high demand—that is, periods of exceptionally hot and dry weather. Climate data from the two city groups were used to develop the following threshold conditions for identifying *hot* and *dry days* following the method outlined previously (section 2.6):

- The SG includes four cities (G, E, F, J) for which hot and dry days feature a maximum temperature above 28°C and no significant rainfall over the preceding 5 days
- The NG includes three cities (B, H, D) wherein hot and dry days feature a maximum temperature above 27°C and no significant rainfall in the preceding 4 days.

Based on these definitions and using the years for which bylaws were already in effect and we had access to full daily demand data for all cities, 13 and 10 individual dry heatwave events were identified within the SG

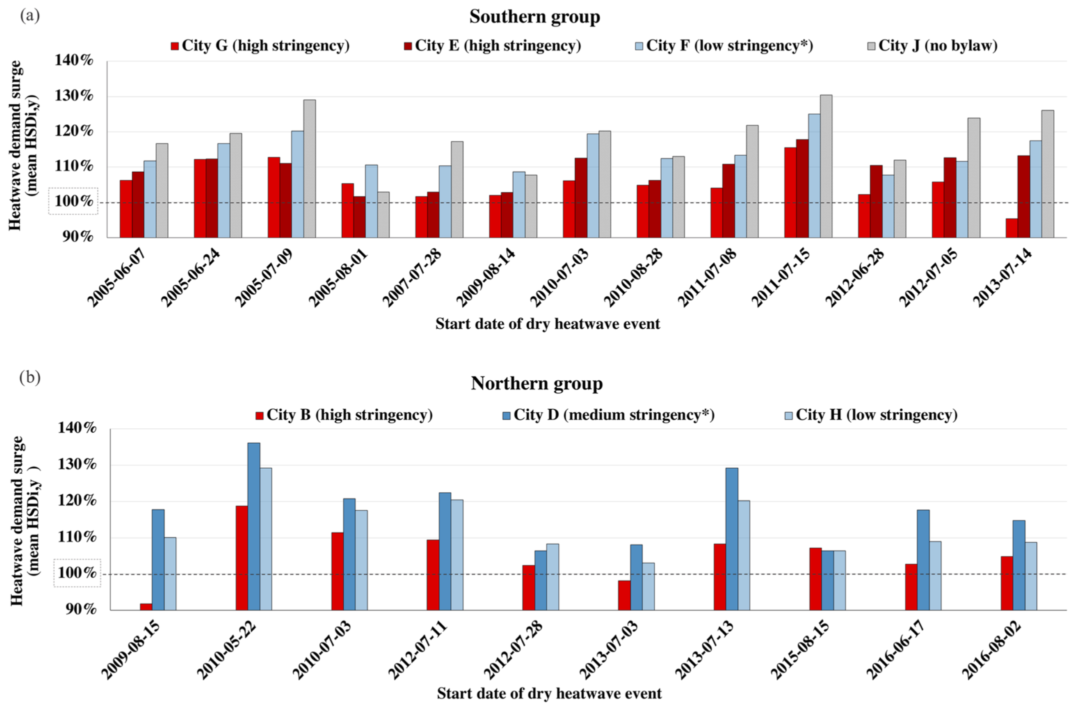


**Figure 5.** Water demand surges during dry heatwaves in (a) the southern group and (b) the northern group. Stringent bylaws are represented in red while blue bars designate less-stringent versions. *Cities F and D have fossil bylaws introduced in 1988 and 1971, respectively (Table 1).

and NG clusters, respectively. These events spanned a minimum of 3 and a maximum of 20 days during which all cities in the group were simultaneously experiencing exceptionally hot and dry conditions.

When water production rates during periods of hot and dry weather are presented as a percentage of the median summer day demand ($HSD_{i,y}$), it becomes evident that the cities that imposed and enforced stringent bylaws are more successful in restraining demand surges during heatwave-like events. During overlapping dry heatwaves, $HSD_{i,y}$ values in cities with stringent water use restrictions remained consistently lower than that in non-bylaw cities or those with less-stringent restrictions: While water demands in strict bylaw cities (G, B and E) rarely exceeded 110% of the summer median value even on the hottest days, non-bylaw cities and those with more permissive bylaws were more likely to exceed 115%, 120%, or even 130% of the $SD_{i,y}$ median during hot and dry periods (Figure 5). With few exceptions, demand surges during dry heatwave events were consistently lower in cities that enforce strict water use restrictions than in those with weaker or no bylaws. Our sensitivity analysis revealed that the criteria used to define dry heatwave events was not influential on this result (see the supporting information).

#### 4.4.3. Study Limitations

It should be noted that though this analysis makes a comparison between metrics measured before and after the application of water use restrictions, it is not possible to establish a causal relationship that would attribute these changes exclusively to the imposition of restrictions. For example, we cannot isolate the behavioral response to water use restrictions from the educational influence of the messaging campaigns used to promote them, which should, depending on their effectiveness, steadily encourage water users to alter their watering habits over time. It is also impossible to attribute the specific impact of regulations without evidence that they are being followed by water users. Not all cities collect data about the enforcement of specific bylaws, so it is difficult to know if the bylaws studied here, stringent or not, are actively policed by city officials. Even with regular enforcement, it remains possible that a share of users does not habitually comply with water use restrictions.

This study also does not specifically address the effects of water price on the consumption of water before and after restrictions are imposed—this is partly of necessity, considering that several of the study cities do not impose a variable price on water, and partly by design, given that while the imposition of water use restrictions in a given year should have a discrete effect that can be analyzed as a changepoint within a time series, water price is expected to exert a persistent background effect on water consumption. Though the elasticity of water demand with regard to price is seasonally variable and more likely to affect outdoor than indoor uses of water, the overall impact of marginal price changes on water consumption remain very low—within the range of 0.4–1% decrease in use per percentage increase in price—and elasticity remains lowest among the cohort of users that typically use the most water outdoors (Coleman, 2008; Espey et al., 1997; Lyman, 1992). Though we did not conduct a detailed price study, a correlation analysis found that trends in water demand in all study cities (presented in section 4.3) were much more strongly correlated with their respective starting values (using 2004 as a benchmark year) than they were with any of the contextual variables studied, including water price, water price structure, and rate of water price increase. For these reasons, we consider that the detection of bylaw effects as performed in this study is only minimally confounded by considerations of water pricing.

## 5. Summary and Conclusion

We used daily water production data from 15 cities across a climate gradient to examine the evolution of water demands over the past two decades and gauge whether permanent water use restrictions implemented to control summer surges in demand have been effective at the city scale. Results show that while base (winter) water demands varied comparatively little across the study's cities and the climate spectrum that they represent, summer demands were much more variable and can exceed the winter value by as much as a factor of three in the driest cities in the sample. All cities studied have witnessed a decline in per-capita water demands over the past two decades, but the degree to which summer demands exceed base demands has remained relatively stable in all but the most-arid cities. In humid cities, where the summer increase in water demand is relatively small, this result may point to the comparatively minor impact of incremental changes in climate-driven water demands (themselves a small portion of total annual demands) within gross water production data sets. In contrast, in our three most arid cities where per-capita water demand more than doubles during the summer months, downward trends in summer water demand are outpacing concomitant declines in winter demand, suggesting that climate-driven water uses make up a smaller and smaller proportion of total water demands each year in those places. Despite this trend, however, water demands remain highly seasonally variable in Canada's driest cities where the ratio of maximum to minimum monthly demand rivals that encountered in parts of the arid southwestern United States.

Permanent water use restrictions had little impact on the mean and median water demand during the summer months in both humid and semiarid cities, irrespective of the stringency of bylaw imposed. This stands in contrast to previous research evaluating the impact of *temporary* drought restrictions, which has largely demonstrated that type of policy to be effective in curtailing overall average water use specifically during drought events (Kenney et al., 2004; Mayer et al., 2015). However, we did find evidence that stringent permanent water use restrictions can reduce surges in demand when it counts the most: During exceptionally hot and dry periods, water demands consistently remained closer to their median value in cities that impose stringent water use restrictions than in neighboring cities that do not. Considering that the need for water conservation is most apparent under such conditions, this finding lends credence to the idea that restrictions are most effective when they are accompanied by physical evidence of drought in urban landscapes and the surrounding environment. As posited by Kenney et al. (2004), this "perception effect" may contribute to the apparent discrepancy in impact between temporary drought restrictions enacted during emergency periods and permanent water use bylaws enforced regardless of climate conditions. As such, permanent water use restrictions may be an effective tool for mitigating short-term imbalances between water supply and demand during hot and dry periods, but their effects in that regard do not necessarily extend beyond those achieved through the imposition of temporary restrictions on an emergency basis. Cities that become vulnerable to water shortages during hot and dry periods may benefit from the enhanced promotion of permanent water use restrictions during those periods in an effort to mimic the perception effect inherent to temporary drought restrictions.

Permanent water use restrictions did impact the distribution of normalized daily summer water demand, with effects being greater for semiarid cities and those with more stringent bylaws. Specifically, we found that in humid cities, stringent water use bylaws have been successful in reducing demand variability, as captured by the standard deviation of the normalized summer daily water demands between the pre- and post-bylaw years. These same cities also saw a marked reduction in peak demands, as captured by the 95th percentile value of daily water demands. In contrast, humid cities with less stringent restrictions showed no decrease in these metrics and sometimes even saw an increase in the variability of daily summer demands after water use restrictions were introduced. This points to the importance of stringency in the imposition of permanent water use restrictions, though more work is necessary to determine what aspect of stringency (watering hours, choice of days, promotional effort, enforcement, etc.) may be most influential on bylaw effects. Because even relatively low-stringency bylaws have contributed to a significant decrease in demand variability in arid cities, the effects of stringency are likely at least somewhat context dependent.

It becomes evident from these observations that focusing on metrics that describe central tendencies (such as median and mean) would be insufficient to describe the changes in summer-season water demand produced by outdoor water use restrictions in cities. The most significant bylaw effects identified—a reduction in the standard deviation of summer daily demand distributions (more constant/predictable daily demands) and a downward shift in the 95th percentile value (lower peak demands and fewer very high demand days)—are not identifiable through a simple comparison of mean or median summer demands before and after restrictions are introduced. A statistical approach to evaluating bylaw effects also provides key information for municipal water managers, for whom short-term surges in water demand in a warming climate are a primary reliability concern. From a short-term operations perspective, the findings listed above may be sufficient to support the tightening of water use bylaws because they suggest that stringent permanent restrictions on climate-driven water uses can help to reduce peak demands and restrain surges in water use during hot and dry periods when the need for conservation is greatest. Conversely, those convinced that overall summer demands can be drastically reduced by the introduction of day-of-week watering restrictions may find the result discouraging. As with any policy tool, the effects of water use bylaws should be evaluated in relation to their specific objectives.

## Statement on Conflict of Interest

The authors have declared no conflicts of interest for this article.

## Data Availability Statement

Data supporting this research are provided by municipal and regional governments and are protected by data-sharing agreements that prohibit its publication. Though these data are not freely accessible to the public or research community, access may be granted by some cities if requests are communicated via the corresponding author so that anonymity may be protected.

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