Lest the Taps Run Dry:
Urban Infrastructure, Water Demands and Drought

by

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This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Statement of Contributions

Sara Finley was the sole author for Chapters 1, 2 and 6 which were written under the supervision of Dr. Stephen Murphy and were not written for publication.

This thesis consists in part of three manuscripts written for publication. Exceptions to sole authorship are as follows:

Research presented in Chapters 3 and 5:

Data collection, analysis, research and writing for these chapters were completed by the author under the supervision of Dr. Stephen Murphy. Dr. Murphy provided advice and recommendations to help the author define the research methodology and scope of each study, and supplied editorial support in the form of comments and corrections to multiple iterations of the text for each paper.

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As lead author of these three chapters, I was responsible for contributing to conceptualizing study design, carrying out data collection and analysis, and drafting and submitting manuscripts. My coauthors provided guidance during various steps of the research and provided feedback on draft manuscripts.

Abstract

Hydrologically-driven urban water shortage situations (urban droughts) are becoming increasingly widespread under the combined forces of urbanization and global climate change. Canadian cities are not exempted from these worries: though most parts of the country receive abundant rainfall on an annual basis, summer droughts driven by sub-annual periods of low relative precipitation or snowmelt anomalies are commonplace in different parts of the country. In cities where climate-sensitive water use is widespread, summer drought conditions can be accompanied by upward swings in municipal water demands in response to hot, dry weather; this combination of reduced supply and surging demand can increase cities' vulnerability to urban drought on a range of timescales.

The research presented in this thesis seeks to evaluate and quantify the role of water demand dynamics in driving urban drought conditions in Canada. It employs a combination of literature and case study review, conceptual exploration, and quantitative analysis of water demand data collected from 15 Canadian cities to assess the degree to which water demand fluctuations can contribute to urban water shortage threats across the country. The research begins with a conceptual review of urban drought and the endogenous drivers that influence its impacts, finding that the experience of drought in the urban context is uniquely dependent on the response actions of water managers and water users who provide the driving force behind short-term changes in demand intended to mitigate drought impacts within the urban system. Next, the analysis shifts to an evaluation of the role of summer water use bylaws imposed in Canadian cities in mitigating short-term increases in urban water demand during the summer months, revealing that these restrictions have little overall impact on seasonal water demand patterns, though the most stringent formats did show some demand dampening effects during short-term periods of exceptionally hot, dry summer weather. The research program concludes with an in-depth analysis of long-term climate and water demand datasets to detect shifts in urban water demand during summer periods of meteorological drought in Canadian cities. This analysis revealed that summer drought periods are indeed strongly correlated with excess summer water demands, though maximum summer temperatures were more influential than drought condition in most cases.

Results from the research presented in this thesis suggest that water demands in Canadian cities tend to surge during summer periods of hot and drought-like conditions, thus aggravating the strained supply:demand relationship that drives urban water shortage threats. While findings confirm that the actions of water managers and water users are highly influential in mitigating urban drought impacts, quantitative data analysis finds no indication that the types of seasonal water restrictions commonly imposed in Canadian cities are effective in reducing climate-driven surges in water demand.

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Dedication

This work is dedicated to my soon-to-be-born daughter. Can’t wait to meet you.

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Chapter 1:

Introduction

1. Introduction

1.1. Motivation and need for research in urban water demands and drought

Evidence collected from around the globe suggests that the world is entering an era of water crisis (Gleick, 2014; Jury & Vaux, 2007; Loucks, 2011). The combined forces of growing demand, declining quality, and amplifying climate extremes already exert a degree of pressure on water supplies that is unprecedented in modern times, resulting in a combination of widespread shortages, intensified conflict over access to water supplies, and a rise in occurrence of water-borne illnesses (Jury & Vaux, 2007; Srinivasan et al., 2012, Ray & Shaw, 2019; Mekonnen & Hoekstra, 2016). In cities, where most of the world's population is concentrated, water demands intensify as urban populations grow, exerting ever more pressure on urbanized watersheds. In most developed nations, the increased demand of growing cities is counteracted by a trend toward lower per-capita water use as technologies and behaviours change over time (Jenerette & Larsen, 2006; Sankarasubramanian et al., 2017). However, climate-sensitive water uses, which can intensify urban water demand on short timescales during periods of warm weather and/or lower-than-normal precipitation, can create short-term water supply issues even in cities where long-term demand trends are flat. This phenomenon is exacerbated by the effects of anthropogenic climate change, which in many regions has contributed to a trend toward hotter, drier, and thirstier cities during the summer months (Jenerette & Larsen, 2006; Polebitski, 2010; Polebitski & Palmer, 2009; Schatz and Kucharik, 2015, Mazdiyanski and AghaKouchak, 2015, Szalinska et al., 2018, Paton et al., 2021, Ludwig, 2009).

In developed nations and especially in Canada and the US, many cities feature low-density housing and commercial developments interspersed with widespread landscaped areas that are dominated by manicured turfgrass (*lawn*) and punctuated by trees and decorative horticultural plant varieties (Groffman et al., 2014, Henderson et al., 1998, Zmyslony & Gagnon, 2000). Because these plant varieties tend to require significant water inputs to stay green, most of the climate-related increase in urban water demand In these city types is driven by an intensification in the use of water outdoors (Cole & Stewart, 2013; Downing et al., 2003; Ontario Water Works Association, 2008, Chini and Stillwell, 2018, Chang et al., 2014; Gober et al., 2015). Outdoor water use during the summer months can account for a startling proportion of total water distribution at the municipal scale; studies from across North America for instance report that outdoor water use represents from 10-75% of the annual total annual in various cities (Kjelgren et al., 2000; Mayer et al., 1999; Vickers, 2006; Litvak et al. 2017; Gober et al. 2013). The outdoor water use category in these cities is almost entirely attributable to irrigation activities by residential, municipal, institutional and commercial water users during the warm summer months (Cole and Stewart, 2013; Kjelgren et al., 2000; Ontario Water Works Association, 2008). Elevated levels of outdoor water use during summer creates temporary *peaks* in urban water demand (peak demands); peak demands in lawn-dominated urban landscapes are often more than double the year-round average (Chini & Stillwell, 2018; Ferguson, 2011). Peak demands are especially consequential in urban water systems because they are used to size new water infrastructure, making this by far the most expensive water for a city to produce (Ferguson, 2011; Ontario Water Works Association, 2008; Burn et al., 2002; Lucas et al., 2010).

The climate-driven intensification of municipal water use during hot summer periods can have an especially drastic impact on urban water supplies when it coincides with drought. While most popular conceptions of drought invoke long-term episodes of low rainfall over a multi-year period, short-term droughts driven by precipitation anomalies at the sub-annual scale are common even in otherwise high-rainfall climates, and these conditions are only expected to increase and intensify under the effects of climate change (Brauman et al., 2016; Hoekstra et al., 2012; Wada et al., 2011). Seasonal drought conditions are common in many parts of Canada, aggravated by a temporal distribution of precipitation that results in a combination of low precipitation and high heat in the late summer months (Trudel et al., 2016). Studies from Quebec have demonstrated that drinking water supply infrastructure is vulnerable to low-flow conditions during the summer period in multiple highly-populated watersheds, and a global analysis of monthly water scarcity has shown that even the water-rich St. Lawrence watershed routinely becomes susceptible to severe water stress annually in August (Carrière et al., 2006; Hoekstra et al., 2012; Trudel et al., 2016). Issues of low water availability in the warmer months have spurred aggressive seasonal water conservation efforts in most of Canada's large urban centres, including cities as diverse as Guelph, St. John's, Calgary and Vancouver (Table 1.1). Because the overuse of water for irrigating lawns and gardens regularly coincides with seasonal periods of low water availability, the control of peak demands during the warm summer months is both an infrastructure planning concern and a climate adaptation measure for cities across climate types (Burn et al., 2002; Gober et al., 2015).

In Canada, perhaps due to a widely-held perception that the country is and will forever be water-rich, little research exists to document, quantify, or identify the drivers of water shortage threats in cities. Despite a 2004 federal government report finding that over 25% of Canadian cities had experienced periods of threatened water shortage between the years of 1994-1999 (Environment Canada, 2004), very few academic studies and government reports have dedicated attention to the potential for municipal water provision to be disrupted due to low water availability in Canada. There are several possible reasons for this lack of attention, including the higher relative cost of flooding events within the water risks facing Canadian cities and a lack of experience with acute, unmitigated water shortage events culminating in disruptions to water service provision. The real risk profile for water shortages in Canadian cities is difficult to quantify, in part because municipal water agencies tend to refrain from publicising information about potential threats to water service reliability to avoid panic among water users and to reduce reputational risk for cities that seek to attract new residents and business development (Medd & Chappells, 2007; Taylor et al., 2009).

Despite this dearth of public attention, indicators of urban water shortage threats in Canada can be detected within media reports and through the actions of municipal water agencies. Since the year 2000, most major Canadian cities, as well as a plethora of small cities and towns, have instituted seasonal or permanent restrictions on the use of water outdoors in an effort to curb the peaks in demand that drive summertime water shortage threats. Today, over 75% of major Canadian cities (>100K population) enforce summer water use restrictions of some kind (Table 1.1). Media analysis shows that the number of articles

Table 1.1: Watering bylaws in Canada's 50 Most Populous Cities

City	Province	Population (2016)	Watering bylaw?	Water use bylaw format	reference
Toronto	Ontario	2,615,060	none		
Montreal	Quebec	1,649,519	Yes	odd/even	link
Calgary	Alberta	1,096,833	Yes	staged	link
Ottawa	Ontario	883,391	none		
Edmonton	Alberta	812,201	none		
Mississauga	Ontario	713,443	none		
Winnipeg	Manitoba	663,617	none		
Vancouver	British Columbia	603,502	Yes	staged	link
Brampton	Ontario	523,911	none		
Hamilton	Ontario	519,949	Yes	staged	link
Quebec City	Quebec	516,622	Yes	odd/even no Saturdays	link
Surrey	British Columbia	468,251	Yes	staged	link
Laval	Quebec	401,553	Yes	odd/even	link
Halifax	Nova Scotia	390,096	none		
London	Ontario	366,151	Yes	odd/even plus weekends/holidays	link
Markham	Ontario	301,709	Yes	odd/even	link
Vaughan	Ontario	288,301	Yes	odd/even	link
Gatineau	Quebec	265,349	Yes	assigned 3 day	link
Longueil	Quebec	231,409	Yes	assigned 2 day	link
Burnaby	British Columbia	223,218	Yes	staged	link
Saskatoon	Saskatchewan	222,189	none		
Kitchener	Ontario	219,153	Yes	assigned one day	link
Windsor	Ontario	210,891	none		
Regina	Saskatchewan	193,100	Yes	assigned 3 day	link
Richmond	British Columbia	190,473	Yes	staged	link
Richmond Hill	Ontario	185,541	Yes	odd/even	link
Oakville	Ontario	182,520	Yes	staged	link
Burlington	Ontario	175,779	Yes	staged	link
Greater Sudbury	Ontario	160,274	Yes	odd/even	link
Sherbrooke	Quebec	154,601	Yes	assigned 2 day	link
Oshawa	Ontario	149,607	Yes	odd/even	link
Saguenay	Quebec	144,746	Yes	every day	link
Lévis	Quebec	138,769	Yes	odd/even no Saturdays	link
Barrie	Ontario	135,711	Yes	staged	link
Abbotsford	British Columbia	133,497	Yes	staged	link
St. Catharines	Ontario	131,400	none		
Trois-Rivières	Quebec	131,338	Yes	odd/even	link
Cambridge	Ontario	126,748	Yes	assigned one day	link
Coquitlam	British Columbia	126,456	Yes	staged	link
Kingston	Ontario	123,363	Yes	odd/even	link
Whitby	Ontario	122,022	Yes	odd/even	link
Guelph	Ontario	121,688	Yes	staged	link

Kelowna	British Columbia	117,312	Yes	staged	link
Saanich	British Columbia	109,752	Yes	assigned 2 day	link
Ajax	Ontario	109,600	Yes	odd/even	link
Thunder Bay	Ontario	108,359	none		
Terrebonne	Quebec	106,322	Yes	assigned 2 day	link
St. John's	Newfoundland and Labrador	106,172	Yes	assigned 2 day	link
Langley	British Columbia	104,177	Yes	staged	link

in Canadian newspapers mentioning water use restrictions, bans, or bylaws has increased over the same period, with the highest article density in periods characterized by especially dry and hot summer conditions (See Chapter 4, Figure 4.1).

Investigating the possible drivers, risks, and implications of seasonal water shortages in the Canadian context is made more difficult by the lack of academic or grey literature to help gauge the scale and severity of the issue. However, humans have a long history of underestimating risks, and the impacts of acute water shortage in cities are potentially severe for both urban resident populations and regional economies (Gonzales & Ajami, 2017). What's more, several studies suggest that cities with the least experience of drought may be most vulnerable to serious impacts when one does occur (Dilling et al., 2019; Gober & Kirkwood, 2010; Gonzales & Ajami, 2017b; Hall & Borgomeo, 2013; Lund et al., 2018; Zscheischler et al., 2018). The work in this thesis was motivated by a desire to better understand the conditions that lead cities across Canada to appeal to water users to reduce their use of water outdoors during dry summer months: what is the scale of the concern, and how do the actions of water users and water management agencies contribute to or mitigate water shortage risks? The first question is difficult to answer absent data about how close Canadian cities have come to running low on supply, but the second is possible to explore through a detailed analysis of water demand data from cities across the country.

1.2. Literature Review

1.2.1. Terminology used to describe urban water threats

Many (sometimes conflicting) definitions exist within academic literature to describe the situation when cities face real or threatened difficulties in providing sufficient water to meet users' demands. However, considering that this problem already affects a significant number of cities across the globe – McDonald et al., 2014 estimated that ~25% of residents in the world's largest cities already experienced water stress at time of writing (McDonald et al., 2014)– and that the conditions that contribute to water shortage threats – high heat, increased precipitation variability and the coincidence of both together – are expected to increase over the coming decades (Ludwig, 2009; Mazdiyasni & AghaKouchak, 2015), it seems justified to seek to refine the lexicon used to describe this set of phenomena. The terminology adopted to describe the type of events that are the focus of this research- that is, episodic, acute urban water shortage threat situations, should be comprehensive enough to reflect the wide contextual variability of urban water systems around the globe, which differ in numerous dimensions including the degree of centralization of water infrastructure, the baseline reliability of water services, population growth rates, type and redundancy of water sources, the coping capacity of the user base, and administrative capacity of water management agencies (Bragalli et al., 2007; Buurman et al., 2017; Gonzales & Ajami, 2017; Srinivasan et al., 2017). Definitions and concepts in this space should also reflect the differences in degree of impact between water shortage situations that result in system failure – that is, an interruption or diminution of piped water supply – and those that only threaten potential failures but wherein users do not directly experience physical scarcity at the taps (Hashimoto et al., 1982). Certainly, a dry summer in Vancouver in which users are subjected to outdoor water use restrictions is experientially different from the 2014/15 drought in Sao Paulo, when some residents' piped water supply was limited to a few hours per week due to supply shortages (Muller, 2018). Both, however, deserve to be clearly described so that they may be effectively addressed: just as early researchers were stymied by the lack of common definitions of drought itself (Wilhite & Glanz, 1985), modern researchers should avoid language roadblocks on the path to fully understanding how cities become vulnerable to, and can effectively mitigate the effects of, urban water shortage situations.

In some texts, urban water shortages are defined within the terminological umbrella of *water security* (Hall & Borgomeo, 2013; Hoekstra et al., 2018; Srinivasan et al., 2017). Through this lens, lack of water is among myriad water security threats, which also include poor quality and inaccessibility of water due to poor infrastructure; however, water security literature is necessarily wide in scope, with little direct attention paid to (hydrologically-driven) episodic and acute shortages as a distinct phenomenon. A similar relationship exists with the notions of *water scarcity* and *water stress*, which are sometimes invoked in discussions of water shortage in cities (Ray & Shaw, 2019; Zhang et al., 2019). While water scarcity and water stress remain relevant to the study of urban water risks, the former term refers to the innate environmental characteristic of regions that do not receive a high volume of annual precipitation, and the latter refers to a long-standing character of regions where water demands are high as compared to water supply even under normal conditions (Buurman et al., 2017; Van Loon et al., 2016). These terms do not accurately describe the episodic events of low relative precipitation (*droughts*) that can afflict cities even outside of water-scarce or water-stressed regions, and which inspire the form of demand response measures studied in the present research. We argue that the use of drought terminology is most useful as a reference to the urban phenomenon that ultimately flows, like other forms of drought, from a relative deficit of precipitation over various timescales. While some authors expand the concept of *drought* within a city system to include wholly pollution- and infrastructure- related threats to urban water security (for example, Zhang et al. 2019, who include ‘pollution-driven water scarcity’ as a type of urban drought), we argue that the term should be reserved for episodic, hydrologically-driven quantitative water threats.

1.2.2. Defining drought and contextualizing urban drought within this frame

Drought itself remains notoriously difficult to define, in part because it is a highly location- and context-specific hazard that lacks clear start and end dates (Bragalli et al., 2007; Buurman et al., 2017). Firm definitions are also complicated because the concept is relative: drought is most universally defined as a deficit of water as compared to 'normal' conditions, leaving the definition captive to the complexity of determining what constitutes a 'normal' state (Breyer et al., 2018; Van Loon et al., 2016; Wilhite, 2011). Standard definitions of drought focus on the way that water shortage manifests itself within the physical environment as the impacts of precipitation deficits cascade through the hydrological system: meteorological droughts refer to raw precipitation deficits, hydrological droughts relate that deficit to lowered blue water levels, agricultural droughts point to soil moisture deficits, and groundwater droughts extend that definition into reduced groundwater levels (Mishra & Singh, 2010). However, there is also widespread recognition that the conception of drought as a purely hydrological phenomenon is insufficient, as the occurrence and impacts of drought are most readily understood through the experience of human water users, which will define in real terms the severity, duration, and spatial extent of a drought event (Wilhite & Glanz, 1985).

The phenomenon of urban water shortages has yet to be firmly positioned within the standard set of drought types in academic literature. Some authors consider urban droughts to be an extension of hydrological drought (or groundwater drought), wherein a water shortage in a city's primary water source echoes into the city's system (Buurman et al., 2017; Rossi & Cancelliere, 2013; Szalińska et al., 2018; Zhang et al., 2019; Zipper et al., 2017). Others classify urban water shortages as a type of 'socio-economic drought', a catch-all term that is generally used to refer to drought situations which are significantly influenced by the (usually anthropogenic) demand for water (Mishra & Singh, 2010; Wilhite & Glanz, 1985). However, the latter distinction is difficult to draw since several drought types, including hydrological and agricultural varieties, involve the interplay of supply and demand, and the term *socio-economic drought* has been used to describe a wide range of conditions that do not reference cities nor consider the important role of urban water infrastructure systems in mitigating the experience of drought in urban areas (Mishra & Singh, 2010; Padowski & Jawitz, 2012; Van Loon et al., 2016). The role of demand in driving drought is expected to be especially significant in the urban case because city water systems are optimized to provide sufficient supply to meet expected demands under normal hydrological conditions, creating a taut supply:demand relationship that is readily affected by variability in either side of the ratio (Kurek & Ostfeld, 2013; Zhao et al., 2016). In light of a recently renewed emphasis on the anthropogenic influence over modern hydrological systems, and given that the broadest definition of drought remains 'less water than normal', it seems pertinent to conceptually delineate the notion of "urban drought" to reflect the complex ways that water scarcity is experienced by urban systems across contexts (Breyer et al., 2018; Van Loon et al., 2016).

1.2.3. Socio-hydrology and urban drought

Recent advances in the concepts of socio-hydrology and anthropogenic drought further refine classical drought definitions to highlight the impacts of human activity on both the occurrence and impact of droughts at all scales (Breyer et al., 2018; Srinivasan et al., 2017; Van Loon et al., 2016; Zipper et al., 2017). Socio-hydrology is a relatively new discipline that highlights the coupled nature of human-water relationships, with the goal of "uncovering the dynamic cross-scale interactions and feedbacks between the natural and human processes that may give rise to water sustainability challenges [in] the Anthropocene" (Sivapalan et al., 2014). In a similar vein, drought literature emerging over the last decade has refined the concept to highlight the anthropogenic influences that shape the experience, severity and occurrence of drought at all scales (Van Loon et al., 2016, Breyer et al., 2018). Both concepts add significant depth to the study of urban water systems, where water supply and demand are both highly human-mitigated processes:

urban water demand is largely determined by the actions of individual water users, and water supply systems are designed by engineers to extract water from the source(s) that they select, at the rate that water managers deem necessary to fulfill current and projected demands (Kurek & Ostfeld, 2013). The highly managed nature of city water systems also plays a role in the perception and response mechanisms that define how the city-as-system can respond, learn, and adapt to drought threats (Marlow et al., 2013). Urban droughts can be best understood through a study of feedbacks between social and natural systems in urban areas, where water users are largely disconnected from the wider hydrological environment by the highly-engineered and managed nature of urban water infrastructure systems, and where water storage structures and actions taken behind the scenes by water management agents (utility managers and/or city water department officials) work to ensure that tap water supply can continue uninterrupted under a wide range of hydrological conditions (Buurman et al., 2017; Kallis, 2008).

Socio-hydrological relationships also shape the ways that urban water systems are built and managed, factors which ultimately influence how they may be impacted by water shortage situations (Srinivasan, 2015). Little research yet exists to assess the dynamics of urban drought in Canadian cities, yet findings from research conducted elsewhere contain hints that they may be uniquely vulnerable to drought impacts during extreme events because they were constructed and are managed under an assumption of hydrological stability. For instance, multiple studies have posited that prior experience of drought is key to building resilience to water shortages during periods of precipitation deficit (Dilling et al., 2019; Gonzales & Ajami, 2017; Hall & Borgomeo, 2013; Lund et al., 2018) and a US-wide assessment of urban water availability that included infrastructure systems showed that cities in conventionally water-rich regions tend to have less water storage capacity and thus more sensitivity to reduced water availability during drought (Padowski & Jawitz, 2012). Water users add another dimension to this relationship; because urban water demand is a function of water-use behaviours, and much of the excess demand that contributes to water shortage risk during drought periods is non-essential (irrigation and pool-filling, for example), social experience with or awareness of water shortage risk will ultimately affect how users choose to respond to appeals to reduce demand during urban droughts (Dilling et al., 2019; Gonzales & Ajami, 2017; Hall & Borgomeo, 2013; Lund et al., 2018).

1.2.4. Distinguishing the timescales of urban drought

Because urban drought, like hydrological and agricultural (and indeed socio-economic) forms of drought, is driven by the interplay of environmental water availability and the demand for water, it is best understood as an expression of a lack of water *compared to* demand at a range of timescales (Wilhite & Glanz, 1985). Drought is understood as a creeping phenomenon, the start and end dates of which are defined primarily in terms of the impacts experienced by (human or natural) water users (Wilhite & Glanz, 1985). Because the impacts of (meteorological, hydrological, and agricultural) drought are most commonly measured in terms of economic or agricultural impact at the regional or national scale, popular and scholarly conceptions of drought tend to focus on multi-year events (González Tánago et al., 2016). However, drought remains a contextually-defined, relative phenomenon which can be best understood as a situation wherein precipitation deficits lead a system to experience “less water than normal” over any temporal horizon (Van Loon et al., 2016).

The impacts of drought on sub-annual timescales are particularly relevant when studying cities because some urban water systems can be sensitive to drought conditions on comparatively short time horizons- weeks or months- as their design is optimized to provide acceptable water supply reliability while minimizing cost and complexity (Buurman et al., 2017; Kallis, 2008). This sensitivity is aggravated by a potential concomitant increase in climate-sensitive water demand, itself highly variable on short timescales

(Finley et al., 2020, Cole and Stewart, 2013, Adamowski, 2008). Excess urban water demand during the summer season is an aggregate representation of the outdoor water use behaviours of thousands or millions of water users, and given that most outdoor water use is for irrigation purposes, these behaviours are most likely to be responsive to individual perceptions of meteorological drought and soil moisture conditions, which respond to precipitation anomalies on short timescales of 1-2 months or less (World Meteorological Organization, 2012; Zhou et al., 2000). In fact, water demand modelling has shown that the variability of climate-sensitive water demand (primarily outdoor water uses and especially lawn and garden irrigation, which tend to intensify with higher temperatures and decrease in response to precipitation events), is most clearly visible at the daily or weekly scale, as it reflects the immediate-term decisions of urban water users and their (often inaccurate) perceptions of landscape water need (Balling & Gober, 2007; Bougadis et al., 2005; House-Peters & Chang, 2011; Maidment and Miaou, 1986). If both water supply and water demand vary on these short timescales within city water systems, urban drought conditions may be generated by shorter-term periods of relative climate variability than other drought types, a notion that could itself explain the occurrence of urban drought threats even in ‘normally’ (as viewed at annual or longer timescales) high-precipitation climate zones. Shorter sub-annual timescales of activity both create the possibility for ‘drought’ conditions based on short-term hydrological anomalies (for example, unevenly distributed annual rainfall or early snowmelt) and potentially amplify the impacts of drought-aggravating factors like high heat and intensified evapotranspiration that reach their zenith during the summer months when climate-sensitive urban water uses are also at their peak (Carrière et al, 2007; Paton et al., 2021). Within this perspective, we can conceptualize the urban drought category to span water shortage threats driven by short- or long-term drought in areas with year-round climate-sensitive water demand and those driven by summer droughts in areas with summer-only outdoor water use patterns.

1.2.5. The influence of demand shifts in driving urban drought

Independent of debates over its precise drought definitions and typologies, there is general agreement that drought conditions that affect human societies are formed through the interplay of water supply and water demand, and drought impacts are felt when the latter outstrips or threatens to outstrip the former (Bragalli et al., 2007; Gonzales & Ajami, 2017; Kallis, 2008; Van Loon, 2015; Wilhite, 2011; Wilhite & Glanz, 1985). In cities, the supply portion of this relationship is mediated by complex factors spanning local meteorological patterns, blue water flows, groundwater storage and watershed-scale competition for water resources. The demand side, however, is rather straightforward: within the scale of a centralized urban water infrastructure network, the main driver of water demand is water use (and associated water loss) by residents, businesses, institutions, and industries that are supplied by the municipal drinking water system. Water demand in cities is not stable over time: over the long term, demand will vary with changes in the size and characteristics of the serviced population, with the types of water-using technologies that are dominant within the local building stock, and with trends in commercial and industrial development, among other factors (Coomes et al., 2009; Mayer et al., 1999). In the shorter term (usually expressed as seasonal, monthly or daily timescales), water demand will vary according to changes in the behaviours of urban water users at the aggregate scale (Zhou et al., 2000). Both long-term trends and short-term variability in demand are relevant to the study of urban drought situations; however, once drought hits, short-term behaviour changes take on an outsized importance in mitigating the impacts of drought on the city water system and its users (Breyer et al., 2018; Dilling et al., 2019; Gober et al., 2015; Rossi & Cancelliere, 2013). Short-term demand shifts - and the management actions taken during drought to inspire them - underpin drought mitigation and adaptive capacity in the urban case; as such, these shifts are the principal focus of the current research (Dilling et al., 2019).

1.2.6. Drought/demand relationships in Canada and elsewhere

In climates like Canada's where climate-sensitive water use is highly seasonal, the influence of water demand on a city's water supply reliability is most visible in the summer months, when the coincidence of peak demands and seasonal periods of low water availability create the tightest relative ratio of supply:demand within the urban water system. Inconveniently, the same conditions that drive increases in urban water demand – that is, hot, dry weather during the peak period for outdoor water use – are also those that characterize seasonal drought conditions that result in reduced water availability in the surrounding watershed (Gober et al., 2015). Though ample water demand modelling research exists to demonstrate that urban water demand increases in response to hot and dry weather in the immediate term (Adamowski et al., 2012; Balling & Gober, 2007; Polebitski & Palmer, 2009), the distinct influence of persistent, drought-like summer conditions on aggregate urban water demand is not yet well established in research. The research that does exist to explore the association between drought conditions and water demand in cities has largely been carried out in arid regions of the southwestern US and Australia, where both outdoor water use and droughts can persist throughout the year and over multi-year periods (Bolorinos et al., 2020; Gonzales & Ajami, 2017a; B. A. Taylor et al., 2012). These studies have found that the demand impact of sustained or seasonal drought conditions is distinct from that of raw (daily/weekly/monthly) precipitation values most often incorporated into water demand models (Gonzales & Ajami, 2017; Hannibal et al., 2018).

In Canada, where climate-driven water use is limited to the summer months, the relationship between drought and demand is largely temporally bounded within an annual cycle influenced by both rainfall variability and snowmelt, creating a unique dynamic that is likely to exert a particular influence on the demand response to drought. Studies from arid regions suggest that the relationship between drought and urban water demand is timescale-dependent: while short-term periods of drought-like conditions (measured at the sub-annual scale) are associated with increases in water demand at the city and parcel scale (Bolorinos et al., 2020; Gonzales & Ajami, 2017a), long-term droughts that persist over many years may produce overall decreases in water demand as urban water users gradually adjust to reduced water availability (Bernardo et al., 2015; Hannibal et al., 2018). The former relationship is expected to dominate in Canadian cities, where multi-year periods of drought are rare and climate-sensitive water is limited to a few months of the year (Kreutzwiser et al., 2003; Ontario Water Works Association, 2008, Adamowski et al., 2013, Eslamian et al., 2016). Water demand modelling conducted in Canadian cities shows a sharp increase in water demand associated with elevated temperature and multi-day periods without rain (Adamowski et al., 2012; Adamowski, 2008; Eslamian et al., 2016), and this relationship can be expected to persist or even intensify during extended periods of hot, dry conditions. Summer droughts are becoming more common in many regions of the world, including North America (Ludwig, 2009; Mazdiyasni & AghaKouchak, 2015; Zscheischler et al., 2018), and it seems pertinent to explore the degree of pressure that these short-term drought conditions may exert on urban water supplies in Canada’s otherwise water-secure cities.

1.2.7. Drought risk management and drought response

The degree of impact experienced by city-dwellers during periods of urban drought is strongly influenced by both physical infrastructure systems and the actions taken by operational actors (utility managers and governance bodies at various scales) to mitigate the threat of water supply shortages. Within such actions, *drought risk management* refers to a set of strategic actions taken between drought events to reduce the probability of water supply disruptions during future periods of urban water shortage, while *drought response* encompasses strategies undertaken during an urban event to reduce the impact of water shortages on a city's residents and businesses in the immediate term (Rossi and Cancelliere, 2013; Werick and Whipple, 1994; Dziegielewski, 2003; Hayes et al., 2004; Wilhite et al., 2000). While both types of action are relevant to the assessment of urban drought management, it should be noted that they occur on different time scales and also differ in their locus of activity: while drought risk management occurs over medium- to long-term time scales and is centered on changes to the systems and structures that influence both water demand and water supply, drought response measures occur on shorter time scales (the duration of the drought) and tend to focus on reducing demand over short timescales via infrastructure decisions and efforts to influence the behaviour of water users (Buurman et al., 2017; Mortazavi et al., 2012). In many parts of the world, drought risk management remains mostly reactive in nature: a review of drought plans from 10 global cities revealed that most drought mitigation actions enacted by cities were of the response variety, enacted during the drought itself (Buurman et al., 2017). It should be noted however that such measures are not strictly ad-hoc: many drought response actions are planned in advance for rapid deployment once drought hits.

When markers that indicate a looming urban drought threat become visible (typically, surface water or reservoir storage level thresholds coupled with forecasts that indicate low relative precipitation), water management agents are likely to enact drought response measures to minimize the risk of water shortage at the taps (Buurman et al., 2017). Because physical water infrastructure and the ongoing availability of water in homes and businesses isolates water users from the impacts of hydrological variability in the surrounding watershed, these drought response measures often constitute the main signifier of drought for city residents who would not otherwise become aware that urban water supplies were strained. One study from the UK indicated that water users in London remained wholly unaware of hydrological drought in the local environment until water management agencies alerted them via conservation messaging (Medd & Chappells, 2007). Ultimately, drought response measures are enacted to mitigate the drought impacts felt by water users, but are also sources of drought impact themselves, in that they most often involve imposing limits on the water-using behaviours of city-dwellers.

1.2.8. Water use restrictions

The predominant form of urban drought response measures are regulations and messages designed to convince or compel water users of all types to reduce their consumption. These actions take a number of forms, including water conservation messaging (appeals to voluntarily reduce water use typically broadcast on city websites, radio, and TV ads), water rate increases (drought pricing), and regulatory mechanisms that impose restrictions on water use. Water use restrictions are by far the most widespread of these measures, likely because they have been shown to be effective at reducing water demand over short timescales (Kenney et al., 2004; Mayer et al., 2015). This strategy is so ubiquitous that some authors consider the application of restrictions to be an indicator of drought severity and impact in city systems (Dilling et al., 2019). One study of drought response plans from 10 cities across the globe found that all included drought restrictions as a leading strategy (Buurman et al., 2017).

Water use restrictions take various forms, though most target the use of water outdoors, as this is 1) a significant source of non-essential water consumption, 2) the primary water use category that is influenced by climate conditions, and 3) the easiest form of water use to police. Water use restrictions can be classified as temporary (imposed only during drought and lifted when drought conditions ease) or permanent (imposed either at all times or seasonally during each summer season) (see Chapter 4). Because temporary restrictions (*drought restrictions*) have proven to be effective tools for reducing municipal water demands during emergencies (Kenney et al., 2004; Mayer et al., 2015), some cities and districts have opted to institute water use restrictions on a permanent basis, imposing limits on outdoor water use even when water scarcity is not acute (Hill & Polsky, 2007).

Several studies have confirmed the effectiveness of temporary *drought restrictions* in curtailing water use during times of water stress (Anderson et al., 1980; Halich & Stephenson, 2009; Haque et al., 2014; Kenney et al., 2004; Lee & Warren, 1981; Mayer et al., 2015; Spaninks, 2010). In Colorado, drought restrictions enacted by eight municipalities during a 2002 summer drought reduced water consumption by between 18% and 56% (Kenney et al., 2004), and in Australia, where drought restrictions were widely applied during the decade-long millennium drought, temporary restrictions were estimated to reduce Sydney's water use by between 12% and 17% (Spaninks, 2010). In most cases studied, stringent restrictions led to the biggest water savings, and mandatory water use restrictions were found to be significantly more effective than their voluntary counterparts (Halich & Stephenson, 2009; Kenney et al., 2004; Mayer et al., 2015; Polebitski & Palmer, 2009).

1.2.9. Factors that drive the effectiveness of outdoor water restrictions

Because outdoor water use is largely a function of the landscape watering decisions of individual water users, the effectiveness of water use restrictions is directly influenced by human perceptions and psychology (Shaw & Maidment, 1987; Zhou et al., 2000). Water conservation behaviours exhibit a strong dependence on perceptions of need, and the efficacy of temporary water use restrictions has been found to increase in response to signals of impending water scarcity, such as warnings from local officials or drought emergencies in neighboring communities (Lee & Warren, 1981; Russell & Fielding, 2010). The success of restrictions is also influenced by the degree to which they are communicated and enforced, and the trust that residents place in water authorities' conservation messaging (Halich & Stephenson, 2009; Jorgensen et al., 2009). For example, in Los Angeles and San Diego, emergency drought restrictions produced only an 8-9% reduction in water use in the summer of 1990, but this number grew to 27-36% in the summer of 1991 when the drought was at its peak and public officials' calls for conservation were most persistent (Shaw et al., 1992).

If water restriction success is indeed tied to perceptions of need and the credibility of water shortage information, there is reason to believe that the effectiveness of permanent watering bylaws (which are applied in both wet and dry conditions) could be significantly different from that of temporary drought restrictions (which are generally accompanied by hot, dry weather and public conservation campaigns) (Kenney et al., 2004). Unlike drought restrictions, little research attention has yet been paid to the effectiveness of permanent water use bylaws and ordinances. The few studies on this topic suggest that unlike the findings for drought restrictions mentioned above, more restrictive models of permanent water use bylaws may not lead to more savings, and some bylaws may not have the desired effect at all (Castledine et al., 2014; Ozan & Alsharif, 2013; Survis & Root, 2012). In Canada, where perceptions of drought urgency may be dampened by a widespread belief in the perennial abundance of the resource, and where water restrictions are imposed on a seasonal or permanent basis, the effectiveness of these drought response tools may be starkly different from that of drought restrictions imposed in more arid climates where awareness of water shortage threats is more entrenched through past experiences (Bolorinos et al., 2020; Dilling et al., 2019; Kenney et al., 2004).

1.3. Research objectives

The overall objective of the work presented in this thesis is to narrow the apparent knowledge gap between the experience of Canadian cities that (as visible in management actions and media reports) face quantitative water supply threats during dry summer periods and the near-complete lack of scientific research examining the potential scale and drivers of this problem. As they constitute among the first works to approach a relatively untouched subject, the research articles included in this thesis represent an early foray into the analysis of what is expected to be a complex interplay of water demand and water supply dynamics that conspire to create moments of quantitative water vulnerability for urban water systems in Canada. The thesis begins with a conceptual review (Chapter 3) that seeks to situate the experience of Canadian cities within the larger category of water shortage threats and drought nomenclature, then continues with two data-driven studies that leverage a rich dataset of fine-scale water demand values collected from cities across the country to evaluate how effective water use restrictions are in mitigating summer surges in demand in Canadian cities (Chapter 4) and to investigate the degree to which variability in outdoor water use is influenced by short-term summer drought conditions within the Canadian climate context (Chapter 5).

1.3.1. Research Questions

The specific research questions pursued in the articles included in this thesis are:

1.3.1.1. Considering that urban water shortage threats of varying severity are experienced in a wide variety of city types and climate zones, what conceptual frame can be used to characterise "urban droughts", how are they defined in relation to other forms of drought, and what endogenous factors contribute to drought impacts within city systems?

It seems possible that part of the reason that Canadian cities' water shortage risks are so far understudied is related to a lack of common terminology and conceptual frameworks to link them to more well-researched urban droughts affecting cities in more arid regions. However, water shortage threats in Canadian cities are likely to exist on the same continuum as those affecting cities in widely varying hydrological contexts worldwide, including the urban water scarcity emergencies that have recently affected cities such as London, Cape Town, Los Angeles and Melbourne. In order to better situate urban water shortage threats within a common framework, it will be important to:

1) Consolidate a coherent definition for ‘urban drought’ that situates the drought phenomenon within the particular context of the city and that includes in-depth consideration of the water infrastructure systems that provide urban water services.
2) Develop a comprehensive conceptual framework of urban drought that focuses on the urban context as independent from the hydrological setting.
3) Identify the endogenous (city system-specific) drivers of drought impact that have been identified in previous urban drought literature and case studies.

The first paper presented in this thesis (Chapter 3) seeks to respond to this question by proposing a definition of *urban drought* that is supported by a conceptual review of drought and urban water supply/demand dynamics from within a wide range of literature. The review is complemented by an exploration of the endogenous drivers of urban drought impacts identified within existing literature and case study reports.

1.3.1.2. How effective are permanent or seasonal water use restrictions such as those applied in most major Canadian cities? Have the water use restrictions imposed in Canadian cities led to a reduction in outdoor water use overall, and have they been effective in curbing surges in demand that may accompany summer periods of exceptionally hot and dry conditions?

Drought management literature identifies the application of water use restrictions, and particularly outdoor water use restrictions, as the primary drought response measure applied to mitigate drought impacts in the city context (Dilling et al., 2019, Buurman et al., 2017). Multiple studies have shown that emergency-based drought restrictions are effective in reducing water demands during drought events; however, permanent and seasonal restrictions are the dominant form imposed in Canadian cities (Table 1.1). Some researchers suggest that permanent water use restrictions may not inspire the same degree of water savings as temporary, drought-induced measures (Kenney et al., 2004), but little research yet exists to confirm or quantify the effectiveness of permanent restrictions (Castledine et al., 2014; Survis & Root, 2012).

The second paper presented in this thesis (Chapter 4) makes use of extensive daily-scale water demand data from across the country to evaluate the effectiveness of the permanent water use bylaw models currently enforced in many Canadian cities.

1.3.1.3. Given that urban drought involves an interplay between water supply and demand within the urban water system, to what degree do changes in water demand contribute to water shortage risk in the Canadian context? How much do water demands change during summer drought-like periods in Canadian cities?

In previous studies, urban water demands have been shown to increase during short-lived drought conditions (and the initial phases of long-term drought) as the use of water outdoors intensifies in response to hot, dry conditions (Bolorinos et al., 2020; Gonzales & Ajami, 2017a), though demand may eventually stabilize and fall if drought persists over several years (Bernardo et al., 2015; Hannibal et al., 2018). In Canadian cities, drought conditions are expected to affect water demands during the summer months due to an increase in climate-sensitive water use; however, the degree to which demands may react to summer drought conditions is not yet well understood. Although much remains to be studied to better understand the risk of water shortage in Canadian cities during periods of short- or long-term drought, detailed analysis of water production data from multiple cities can provide some insight into the degree to which water demands are impacted by drought-like conditions that strike during the summer watering period in Canadian cities.

The third paper presented in this thesis (Chapter 5) seeks to answer this research question by analysing the water demand data along with historic climate records to investigate the relationship between drought conditions and water demand in Canadian cities.

1.4. Thesis overview (manuscript format)

Chapter 1 – Introduction

Chapter 2 – Methods

Chapter 3 – Paper 1: *Drought in Urban Water Systems: A Conceptual Review*

Chapter 4 – Paper 2: *Curbing the Summer Surge: Permanent Outdoor Water Use Restrictions in Humid and Semiarid Cities*

Chapter 5 – Paper 3: *Drought Demand Dynamics: Analysis of Changes in Water Demand During Short-term and Seasonal Droughts in Canadian Cities*

Chapter 6 – Conclusions

Chapter 2:

Methods

2. Methods

The detailed methods employed to answer the research questions guiding the research presented in this thesis are more extensively described within each chapter; however, by word of introduction, the overall methodology employed to conduct the three studies included:

2.1. Extensive literature review, including the compilation of urban drought case studies from literature

To date, the field of research pertaining specifically to the occurrence and impacts of water shortages within an urban system remains relatively limited. Of the studies that do touch directly on this topic, only a few are polemic or definitional in focus; these (mostly recent) works generally seek to situate the experience of urban water shortage threats within the wider context quantitative or qualitative water insecurity and meteorological or hydrological drought (Szalińska et al., 2018, Zhang et al., 2019, Paton et al., 2021). Further information can be gleaned from the larger field of water resource management research where many works focus on the assessment and mitigation of drought risks by water utility managers: these studies expose the experience of urban drought through the lens of management actions taken to prevent or moderate its impacts (Wang et al., 2020; Buurman et al., 2017; Shandas et al., 2015; Steiner et al., 1994; Chong and White, 2007; Rossi and Cancelliere, 2013). Often, the most specific and concrete information about urban drought events can be gathered from papers that focus on detailed case study reports; these articles provide narrative assessments of the experience of urban drought, and in so doing provide useful information about how drought impacts are experienced by urban water users and managed by utility actors responding to the ongoing event (Chuah et al., 2018; Changnon, 2000; Hill and Polsky, 2007; Ray and Shaw, 2019; Shaw et al., 1992; Saurii, 2010; Parks et al., 2019).

Because of the highly interrelated nature of outdoor water demands, water use restrictions, and urban drought threats, much of the information gathered to write this thesis was drawn from quantitative research papers examining the drivers and dynamics of climate-driven outdoor water use patterns in cities. Such studies span water demand modelling experiments that seek to precisely quantify water demand-climate relationships for the purposes of future demand projection (Adamowski, 2008; Adamowski et al., 2012; Bougadis et al., 2005; House-Peters & Chang, 2011; Maidment & Miaou, 1986; Balling & Gober, 2007; Gober & Kirkwood, 2010; Eslamian et al., 2016, Jorgensen et al., 2009; Lee & Warren, 1981), and analyses that seek to evaluate the impact of the imposition of varying forms of restrictions on the use of water outdoors (Haque et al., 2014; Castledine et al., 2014; Anderson et al., 1980; Halich & Stephenson, 2009; Kenney et al., 2004; Shaw & Maidment, 1987; Spaninks, 2010; Survis & Root, 2012; Jacobs, 2007).

The study of urban water systems, which necessarily combines consideration of physical infrastructure elements, resource management practice, and interrelationships with wider hydrological conditions, is an inherently cross-disciplinary endeavor. As such, the literature reviewed to build the studies presented in this thesis spanned multiple academic domains, including civil engineering, municipal utility management, water resource management, water demand management, drought risk management, drought vulnerability analysis, the psychology of water use behaviour, water demand modelling, econometrics, climate change adaptation and resilience, hydrological modelling, and more. The research also included review of multiple non-academic ‘grey literature’ sources such as municipal reports, policy documents emerging from various levels of government, and publications produced by non-governmental organizations.

2.2 Collection and detailed analysis of an extensive water demand dataset

2.1.1. City selection and data collection

Water production data and a range of contextual and demographic information about the water system and service area was collected from municipal water utility managers in a total of 15 Canadian cities. Criteria for inclusion in the city sample for this research included:

a) availability of good quality water production data (daily metering data spanning a minimum of ten years including at least one ‘dry’ year when rainfall is significantly below average),
b) availability of good quality climate data (daily temperature and rainfall sourced from a weather station located within the water service area), and
c) population over 30,000

Participants were contacted by email and provided the requested information by means of a fillable PDF questionnaire (see Annex B) accompanied by Excel files containing multi-year datasets of water production data. The sample city set includes 12 municipal water utilities and three regional utilities (represented in this research as ‘cities’, see Chapter 4) that supply more than one municipality; in two of these cases, water production data was provided as a single system-wide water production dataset, while in the third, data from multiple metered municipal water connections were added together (and exported volumes removed) to derive a system-wide total. A total of 17 cities agreed to provide data for the study, but two respondents did not have sufficient continuous daily-scale data to provide a basis for the analyses proposed. As water system performance information can be sensitive and the publication of study results could pose potential reputational risks for municipal governments, city respondents were offered the option of maintaining their anonymity in published results. Because several respondents chose this option, we opted to maintain the anonymity of all cities throughout the research and resultant publications. In exchange for their cooperation in the study, all cities were provided individualized (non-anonymized) result summaries by email.

Canadian cities provide an ideal testing ground for the study of outdoor water use patterns because their stark seasonality and snowy winters ensure that the near entirety of outdoor water use is confined to the summer months, making it easier to distinguish between base and outdoor water uses (Mini et al., 2014). Because the research presented in this thesis depends on isolating and quantifying outdoor water use, data collection targeted mid-size Canadian cities with a significant proportion of single-family homes with lawns. Medium-sized agglomerations of at least 30,000 people were favored because the daily water demand patterns of small communities have been found to contain a high degree of inherent randomness in previous cross-city comparisons (Maidment and Miaou, 1986). We also sought out cities within Canada's semi-arid climate regions so that the research would be able to represent 2 divergent Canadian climate types; of the cities included, ten represent temperate high-rainfall humid climate types where annual precipitation normally exceeds reference evapotranspiration ($P/ET_o > 1$), and five represent the drier continental semiarid climate type found in the southern reaches of the Canadian Prairie region, where annual precipitation is less than 65% of reference evapotranspiration ($P/ET_o < 0.65$) on average.

Climate data for each sample city was sourced from local weather stations maintained by municipal, federal or university institutions and reported in Environment Canada's historical climate data portal (Environment and Climate Change Canada, n.d.). When multiple weather stations were available in one city, the station located nearest to distinctly urban land features (paved areas, buildings) was be selected to best represent the various micro-climatic conditions that can influence temperature and evapotranspiration in an urban environment (Grimmond & Oke 1999; Grimmond & Oke 1991; Kjelgren et al. 2000; Litvak & Pataki 2016).

Because the vast dataset compiled for the studies presented in this thesis was collected from a range of sources with a variety of data quality standards, all water demand and climate data was thoroughly vetted and cleaned. Missing values within water production datasets were excluded from the analysis, and outliers removed based on the range of expected variation observed within the data (double extreme upper and normal lower outliers removed based on a detrended range of (Q1-1.5*IQR > data < Q3+6*IQR)). Per-capita demands were obtained by dividing total water production values by the service area population statistics provided by city respondents. More detail about the collected dataset, data preparation, and the selection of water demand metrics is presented in Chapter 4.

2.1.2.Data analysis

Detailed data analysis steps are outlined within the methods sections of the thesis' two data-driven studies, presented in Chapters 4 (see section 4.3) and 5 (see section 5.3). Analyses performed within the first of these studies (Chapter 4) include seasonal water demand trend testing using ordinary least squares regression, testing for water restriction-driven changes in the statistical distribution of normalized summer water demand metrics using the non-parametric Kolmogorov-Smirnov distance, and the direct comparison of temporary increases in water demand during hot and dry periods based on daily deviations from a seasonal median in climatically similar and geographically grouped city clusters. The second data-driven paper (Chapter 5) uses univariate, bivariate and pooled multiple linear regression analyses to quantify the relationship between standardized summer water demands and meteorological drought condition at monthly timesteps; both correlation analysis and non-parametric slope detection using the Mann-Kendall test and Senn's slope estimates are also employed to validate and isolate the direct relationships between drought status, maximum temperature, and water demand.

Chapter 3:

Drought in Urban Water Systems: A Conceptual Review

Finalized paper to be submitted to *Environment and Behavior* (Sage)

3. Drought in Urban Water Systems: A Conceptual Review

3.1. Overview

Hydrologically driven urban water shortage situations (*urban droughts*) are becoming increasingly widespread under the combined forces of urbanization and global climate change. However, these events remain difficult to predict, in part because the complex interplay of water demand and supply in highly managed urban water systems creates a drought dynamic that is unique to the urban context. This paper uses the experience of water shortage threats in cities with otherwise reliable water services to develop a conceptual review of urban drought dynamics, with a special focus on the role of water system characteristics (including physical and operational infrastructure arrangements) in mitigating the experience of drought for urban water users. Through extensive review of case studies and relevant literature, we outline the different ways that drought interacts with urban water systems and identify key endogenous drivers of water insecurity during these events. We find that the influence of physical and operational infrastructure systems in determining both water supply and demand within the urban system leads to a partial decoupling from hydrological drought conditions as conventionally defined, and the tightly-planned nature of city systems leave them sensitive to deviations from ‘normal’ precipitation on comparatively shorter timescales, generating water shortage risks for cities even outside of drought-prone climate zones. Unlike in the case of hydrological or agricultural drought, the impacts of drought in the urban context are uniquely contingent on the response actions of both water managers and water users. Although urban water users provide the driving force behind actions taken to mitigate drought impacts in cities, their response to drought is indirect, impeded by their physical and psychological disconnect from the wider hydrological environment. This study is the first to develop the concept of *urban drought* using an infrastructure rather than a hydrological lens, with the effect of sharpening the term so that it may be coherently applied to better understand water shortage threats across city and climate types.

3.2. Water shortage and cities

Cities that experience difficulties in providing uninterrupted water service to all users can be considered to suffer from *urban water insecurity* (Ray & Shaw, 2018). While water insecurity is generally less acute in cities that provide centralized water service delivery, even highly managed urban water systems that normally provide reliable water services can occasionally experience issues in supplying adequate water to meet demands of their user base of individual residents, businesses and industries (henceforth, *water users*) when faced with averse hydrological conditions, infrastructure failures, or some combination of both (Zhang et al., 2019, Buurman et al., 2017). Each city relies on one or a combination of surface water bodies, groundwater aquifers, and/or man-made water transfer systems (*water sources*) from which water is extracted and subsequently delivered to meet the requirements of its water users (*water demands).* This is accomplished via an urban water system (UWS) composed of a network of interconnected water infrastructure assets designed to pump, treat, store, and distribute water throughout the city. When water sources decline in quality or quantity, water demands increase beyond provision capacity, or infrastructure systems become unable to efficiently transport water from source to user, it can become difficult for an UWS to fully meet water demands without interruption. This creates a *water shortage* situation – a period of real or threatened quantitative water insecurity.

In this research we explore the phenomenon of *urban drought*: that is, hydrologically-driven, episodic periods of quantitative water insecurity within the urban system. While contextual factors like baseline water stress, aridity, and poor source water quality can aggravate urban droughts, their principal cause is considered here to be a lack of precipitation (or related hydrological anomalies) ultimately leading to an ‘uncomfortable’ imbalance between water supply and water demand within the city boundary. Urban droughts can affect cities across all climate types, and these events are expected to become increasingly prevalent in the coming decades under the combined forces of bourgeoning city populations, degraded ecosystems, declining source water quality, and global climate change (Krueger et al., 2019; McDonald et al., 2011). Several studies have found that urban water shortage crises are increasing in both frequency and intensity, driven in part by heightened precipitation variability linked to climate change, and also by a combination of increasing populations and a rise in amenity water use as urban water users become more affluent (Savelli et al., 2023; Ray & Shaw, 2019). However, the prediction of such events remains elusive, impeded at least in part by a dearth of cross-city research and a generally poor grasp of the specific drivers of drought-driven water insecurity within urban water systems (Kallis, 2008; McDonald et al., 2011).

3.2.1. Defining urban drought

Drought is commonly described as a ‘phenomenon’ or a ‘disaster’ that stems from a lack of precipitation (meteorological drought) and cascades through the hydrological system contributing to a critical deficiency of soil water (agricultural drought) and a significant reduction of runoff and groundwater levels throughout regional hydrological systems (hydrological drought, groundwater drought) (Wilhite & Glanz, 1985, Mishra & Singh, 2010). Note that although these definitions are precipitation-focused, most texts recognize that drought conditions can also be caused by related hydrological anomalies like poor rainfall distribution or rapid early snowmelt, and they can also be aggravated by multiple other climate factors, including most notably elevated air and land temperatures (and especially heat waves) which contribute to increased evapotranspiration rates (Mishra & Singh, 2010, Hanel et al., 2018). Much has been written about the difficulty of establishing a universal definition of drought, considering the importance of regional context and the experience of drought on the meaning of the term (Van Loon et al., 2016; Wilhite & Glanz, 1985). These efforts have largely concluded that drought is, in essence, defined as a period characterized by “less water than normal” for a given system, and that drought is ultimately an intertwined social and hydrological (*socio-hydrological*) phenomenon, for which anthropogenic influences affect both how much “less” water is available as well as what is considered “normal” in that statement (Van Loon et al., 2016). While the origins of drought conditions are largely straightforward - a deficit of precipitation possibly aggravated by other climate conditions that cascades through the hydrological system - the experience of drought for human water users is more complex, as it involves the interplay between expectations and reality of water availability as revealed through the ability to perform various water-using functions. When the expectation is one of unlimited and uninterrupted supply, a drought can be socially perceived even when biophysical conditions do not represent a life-threatening absence of water (Booysen et al., 2019; Marlow et al., 2013, Gonzales & Ajami, 2017).

Table 3.1: Standard drought categories (Wilhite & Glanz, 1985, Mishra & Singh, 2010, Van Loon et al., 2016)

Drought type	***Identified by***	***as relative to***
Meteorological	Precipitation deficiency, possibly combined with increased potential evapotranspiration	Average precipitation / normal conditions
Hydrological / groundwater	Precipitation deficiency / hydrological anomalies resulting in a shortage of surface and subsurface water	Average water availability from surface and subsurface sources
Agricultural / soil water	Lack of precipitation / hydrological anomalies (possibly compounded by increased potential evapotranspiration) resulting in a shortage of soil water or agricultural productivity	Crop water demand and/or normal agricultural productivity
Socioeconomic	Lack of precipitation / negative anomalies in water availability resulting in a shortage of water supply	Economic/anthropogenic water demand
		(for each region and timeframe)

While the meteorological definition of drought focuses exclusively on water supply (precipitation, with the possible contribution of increases in evapotranspiration), both the hydrological and agricultural definitions invoke the interplay of supply and demand for water: in these cases, drought is a relative phenomenon, the severity and impacts of which are most easily understood through the experience of different types of water users in a given context (Wilhite, 2005; Wilhite et al., 2007, Van Loon et al., 2016). The same is true of 'socioeconomic drought', which is alternately defined as the socioeconomic *impact* of drought stemming from a lack of easily accessible clean water (Van Loon et al., 2016), as a temporary 'uncomfortable imbalance' between human and natural demand for water and available freshwater supply (Zhang et al., 2019), or as a situation where water demands threaten to outstrip the water provision capacity of a particular UWS (Hill & Polsky, 2007).

Though drought affecting cities and city residents is commonly grouped into the broad category of socioeconomic drought, we argue that *urban drought* should be more explicitly defined and fitted within the drought pantheon. Urban water shortage situations ultimately stemming from precipitation deficits and related hydrological anomalies merit classification as a type of drought because:

a) like their meteorological, agricultural and hydrological counterparts, they are episodic and/or temporary situations stemming from a relative shortage of available water as compared to 'normal' conditions within the urban system,

b) like hydrological and agricultural varieties, urban drought designates a relationship between demand and supply wherein the former outstrips or threatens to outstrip the latter (Van Loon et al., 2016), and

c) like hydrological and agricultural drought, the impact and severity of the phenomenon can be most effectively gauged through the experience of water users (Wilhite et al., 2007).

Although urban drought events share these definitional characteristics with other drought types, they are distinct and at least somewhat decoupled from the larger definitions of meteorological, hydrological, and agricultural drought because:

a) UWS are largely bottlenecked (i.e., connected only via inflexible structures) from the surrounding watershed by physical infrastructure elements that determine how blue water sources will flow in to and away from urban water networks. Because of these control structures, urban water supplies do not ebb and flow directly in phase with environmental water resources (Hoekstra et al., 2018; Padowski & Jawitz, 2012)

b) Infrastructure systems that mitigate the relationship between urban water users and the surrounding hydrological system can themselves influence the balance of water supply and demand in cities (Kallis, 2008; McDonald et al, 2014)

c) Because UWS are constructed systems optimized to provide adequate storage reliability (based on projected demand) while minimizing tank size and energy costs, fluctuations in demand have a higher relative significance in urban drought situations than they do at the watershed scale (Kurek & Ostfeld, 2013; Zhao et al., 2016).

d) Because of this tight supply/demand ratio and the relative volatility of urban demands, urban drought can operate on shorter timescales than regional or watershed-scale drought (Hill & Polsky, 2007; Kallis, 2008).

Cities that rely on water sources that have diminished in quantity due to hydrological/groundwater drought conditions experience an *exogenous* water shortage threat (lack of environmental water) which will then be filtered through *endogenous* factors related to the UWS system itself to generate drought impacts for urban water users (Hoekstra 2018). This dynamic confluence of exogenous and endogenous drivers make urban drought events difficult to predict and produces at least a partial decoupling from wider-scale drought events.

Given that cities are centres of concentrated population and political power which house more than half of the world’s population (United Nations Publications, 2019), we posit that it would benefit urban water security research to move beyond a casual grouping in the cross-cutting category of socioeconomic drought and carve out specific terminology for the experience of drought in urban centres, so that the specific risks and drivers of these events can be addressed. Derived from Medd and Chappells (2007), we propose a definition for urban drought as a condition wherein urban water sources are threatened by precipitation deficits or related hydrological anomalies to an extent that the normal day-to-day practices of urban water users is affected. In turn, the impacts of urban drought are determined by the *degree* to which those practices are affected (per Van Loon et al., 2016). In essence, the definition of urban drought that we propose applies the wider definition of drought- that is, an uncomfortable imbalance between demand and supply- to the UWS itself, where the system boundary is defined as the spatial extent of the potable water infrastructure system. Though no hard division can be drawn between an infrastructure system and the water supply portfolio that it is designed to operationalize, drawing a system boundary around the infrastructure system allows us to identify drivers of drought risk inherent to an urban water system itself, as isolated from the highly geographically- (and climatically-) specific sources of water source vulnerability within the wider hydrological system.

For the purposes of this definition, we consider the intake pipe(s) that draws(s) raw water from a lake, river, reservoir, aquifer or other water storage structure to form the boundary between a UWS and the surrounding hydrological system. In cases where multiple UWS exist within the same city, or where one

UWS services several municipalities, the system boundary of a UWS does not necessarily coincide with the geographical boundary of a *city* in the administrative sense. The shorthand “cities” is nonetheless used in this text to denote the administrative and demographic unit that manages and houses an UWS.

3.3. Urban drought : advancing a conceptual framework

Advances in the subfields of socio-hydrology and anthropogenic drought highlight how humans and water act as interdependent components within a coupled system dynamic (Breyer et al., 2018; Sivapalan et al., 2014; Pahl-Wostl et al., 2007; Srinivasan, 2015; Srinivasan et al., 2016). This is especially germane to cities, where water supply and demand are both highly human-mitigated processes. Though intimately linked to hydrological conditions affecting a city’s main water sources, the physical parameters of urban drought are distinct from that of wider drought events because cities are highly managed systems where environmental pressures are mediated by human-manufactured infrastructure and the decisions of city water managers, and where the supply:demand ratio can fluctuate on short timescales (Bragalli et al., 2007; Kallis, 2008).

3.3.1. Urban drought impacts

The impact and severity of urban droughts are most often measured at the level of individual agents: that is, residential water users, businesses or industries operating with water sourced from a UWS (Kallis, 2008, Wilhite et al., 2007). This differs somewhat from the analysis of wider hydrological and agricultural drought events, wherein the impacts of drought are most commonly measured at the regional, sub-national or national scale by assessing aggregate impacts on agricultural/economic sectors, ecological systems, geographic sub-groups, or populations as a whole (González Tánago et al., 2016; Hagenlocher et al., 2019). It should be noted that centering the experience of water users to measure drought impacts in cities necessarily downplays corollary effects on urban ecosystems; while this perspective is used here to highlight the influence of anthropogenic factors that contribute to the experience of drought, it is important to acknowledge that other species inhabiting the urban form are also impacted by a lack of available water during these events, and that urban drought dynamics can affect non-urban water users as well (Breyer et al., 2018; Zipper et al., 2017).

Because most water users in an UWS depend exclusively on piped water supply delivered through an infrastructure system, their experience of urban drought is predominantly indirect: though direct impacts may be experienced in the form of parched gardens and dry city streams, most of the impacts they experience are a product of the *response measures* enacted by water managers to preserve available water supply (Medd & Chappells, 2007). Such measures range in severity from the imposition of voluntary water use restrictions to the full interruption of piped water supply (see fig. 3.1). In some cities, water management agents can temporarily fine-tune physical infrastructure controls to reduce the pressure or flow of water to maintain uninterrupted water service, while in others drought surcharges are applied during emergencies as a tool to encourage water conservation (Sinisi and Aertgeerts, 2011, Dilling et al., 2019; Kenney et al., 2004). As such, drought response measures enacted at the scale of infrastructure systems are experienced as drought impacts at the user scale through some combination of limitations on permitted uses of water, reductions in the quantity or pressure of water delivered, added costs to access water services, or in extreme cases, interruptions in water service delivery (Dilling et al., 2019, Buurman et al., 2017). In this way, drought response measures seek to impose *mild* drought impacts for water users (for example, by limiting their permitted uses of piped water) as part of an effort to reduce the potential for *severe* drought impacts (for example, water service interruptions) if the event wears on.

Figure 3.1: Common drought response measures and impacts (adapted from Sinisi & Aertgeerts, 2011)

In this paper, drought impacts are limited to those experienced during the event itself and exclude any potential drought-related effects on water users outside of that period, including those generated by longer-term risk management actions that may take place between events. This distinction mirrors the categorization of management actions within the larger field of drought risk management, where there is a distinction drawn between drought *response* actions deployed during a drought to reduce impacts in the immediate term and *strategic* actions taken to improve adaptive capacity and prepare for future droughts over the longer term (Buurman et al., 2017; Dziegielewski, 2003). Drought response measures are not strictly ad-hoc: many such actions are included in municipal drought preparedness plans and are designed to be rapidly deployed once drought hits. Because of the time horizons involved, response actions focus primarily on reducing water demand on short timescales (Buurman et al., 2017; Dilling et al., 2019).

Water restrictions are the primary regulatory tool deployed during drought to reduce impacts in urban contexts; these measures are so universal that the presence or absence of restrictions is sometimes used as a barometer of urban drought severity and impact (Dilling et al., 2019). Most commonly, restrictions are enforced only on outdoor uses of water, where they introduce limits on the times within which water users in various parts of the city can run the hose, wash cars, fill pools, or (most significantly) irrigate the garden (Cole & Stewart, 2013; Gober et al., 2016). While some cities impose limits on the use of water outdoors on a permanent or seasonal basis, drought restrictions are applied only during drought as an emergency effort to bring down demand while water supplies are limited (Finley et al., 2020; Kenney et al., 2004). Drought restrictions can be very effective at reducing water demands during an emergency: studies have found water use reductions of over 50% when strict, mandatory restrictions are applied (Kenney et al., 2004; Mayer et al., 2015). The effectiveness of drought restrictions is influenced by water users' perceptions of drought severity: these measures are more likely to reduce water demands if users perceive that there is an urgent need to reduce consumption (Bolorinos et al., 2020; Hannibal et al., 2018; Quesnel & Ajami, 2017). Mandatory drought restrictions are most effective, but voluntary restrictions and public appeals to conserve water (or to observe existing permanent restrictions) can also produce water use reductions when drought hits (Bolorinos et al., 2020; Quesnel & Ajami, 2017).

Although action taken by water users provides the main mechanism for reducing the severity of drought impacts, these users are largely disconnected from the hydrological event itself, as water infrastructure systems continue to deliver an uninterrupted supply of clean water at the tap in all but the most severe drought emergencies. Drought response measures undertaken by water managers are often the primary means by which urban water users learn of hydrological drought conditions in the surrounding environment: water conservation messages and the introduction of restrictions provide cues about the water security threats that might otherwise go unnoticed by city-dwelling water users that are otherwise relatively unaffected by hydrological variability (Zhang et al., 2019). One survey conducted in London, UK following a period of recurrent urban drought events found that city residents only became aware that the city was in drought once it was announced by water management agencies and/or restrictions were imposed (Medd & Chappells, 2007). The character of the messaging and its purveyors is important: the urgency conveyed in communications, the stringency of imposed restrictions, and the credibility and trustworthiness of water management agencies enacting drought response measures all influence users' willingness to conserve water (Jorgensen et al., 2009; Lee & Warren, 1981). Water users also learn about drought through the media they consume: water use patterns have been found to be highly correlated with mentions of drought in print and online sources, and spikes in drought-related media coverage can drive users to conserve water even before restrictions have been imposed (Quesnel & Ajami, 2017, Bolorinos et al., 2020). In this way, the critical work of reducing the impact of urban droughts is contingent on the actions of water users who are not responding directly to drought signals directly, but to the messages they receive *about* the drought via media sources and the response measures enacted by water management agencies.

3.3.2. Considerations of scale

Key to our understanding of urban drought is the scale of analysis. Because water service provision is contingent on infrastructure, a UWS boundary can be understood as the physical extent of its potable water network, including all storage structures, distribution piping, pump stations, and associated assets. *Pace* Ostrom (1990), we use *infrastructure system* to describe the combination of *physical* infrastructure that makes up an UWS (including drinking water treatment, storage and distribution structures) and the *operational* infrastructure that determines how that physical infrastructure is designed and managed (including municipal water agencies and related governance actors) (Ostrom, 1990). Our infrastructure definition combines these two elements because a) the act of water management in cities cannot be separated from the operation of physical infrastructure systems that deliver water to users and b) physical water infrastructure would not be effective absent the actions of water managers (Mostert, 2008). The scope of operational infrastructure includes all management actions undertaken to influence the functioning of water infrastructure and the delivery of drinking water service within the geographic extent of the UWS.

Urban droughts also operate on distinct temporal scales from wider meteorological, agricultural, or hydrological drought categories. Though there is no universal definition of drought and thus no agreed-upon timescale, it is conventionally described as a ‘creeping phenomenon’ whose effects accumulate over a period of months or years, the onset and end dates of which are highly contingent on the perceptions and experience of water users (Wilhite & Glanz, 1985 and Wilhite et al., 2007). At the much smaller scale of urban water systems operating within a relatively narrow supply/demand relationship highly mediated by infrastructure, urban drought- as characterized by the experience of water users- can occur on shorter timescales because:

a) *Users may perceive water availability to be 'suddenly' changed:*

   The water intake structures that supply urban water systems are generally fixed in place and cannot be adjusted to reflect changes in source water availability. As such, as source levels (in rivers, lakes, aquifers or storage structures) approach the critical supply thresholds established to signal a water shortage threat, the impact of drought on urban users -in the form of water restrictions and/or disrupted service- can accelerate rapidly as water managers intensify efforts to avoid more severe consequences (Buurman et al., 2017; Watts et al., 2012). Because urban dwellers are otherwise largely insulated from hydrological fluctuations, this creates the experience of 'sudden onset' drought for urban water users.

b) *Water storage and redundancy provide a temporary buffer against drought:*

   The experience of urban drought can be offset from that of other users within the wider watershed because water storage and/or supply redundancy provide a buffer against declining water availability in natural water sources and serve to delay or avert the impacts of low water availability on urban populations during drought events (Padowski & Jawitz, 2012; McDonald et al., 2014). However, if drought persists to the point where the buffering capacity of an UWS is exhausted, or where water management agencies foresee its upcoming exhaustion, drought effects can seem to come on suddenly. For example, while the watershed surrounding Cape Town, South Africa had been in a state of hydrological drought since 2015, the impacts of drought for city residents accelerated suddenly in January 2017 when city officials announced the introduction of aggressive demand management actions to avert a ‘day zero’ event (Muller, 2018). Storage and redundancy structures are most common in cities with previous experience with drought and those located in arid or otherwise drought-prone climate zones (Padowski & Jawitz, 2012).

c) *During drought-like conditions, water demand can surge rapidly:*

Water demand in some cities can be highly climate-sensitive: this is especially true in urban forms that feature a large area of grass lawns and other irrigation-dependent landscaping (Chini & Stillwell, 2018; Groffman et al., 2014; Milesi et al., 2005). Drought conditions that arise during the watering season and coincide with hot temperatures can significantly increase demand for water at short time scales (Balling & Gober, 2007; Finley et al., 2020; Gutzler & Nims, 2005; Jenerette et al., 2011; Polebitski & Palmer, 2013). In the context of an UWS’ already tight supply/demand ratio, these surges in water demand can worsen the city’s drought status within a matter of days or weeks (Kallis, 2008).

d) *Urban systems can also be vulnerable to short, “flash” droughts:*

Flash droughts are defined as rapid-onset and/or short duration droughts driven by a combination of heat and precipitation deficit (Lisonbee et al., 2021). Because they tend to coincide with heat events, flash droughts mirror the conditions that drive increased water demand in cities and as such can generate rapid shifts in a city’s supply:demand ratio and create water shortage threats over short timescales (Carrão et al., 2016; Obringer et al., 2016).

The distinct timescales of urban drought as compared to the meteorological, agricultural and hydrological categories is reflected in the fact that most drought indices used to quantify the latter group (including the commonly-used Standard Precipitation Index and Palmer Drought Severity Index) function at monthly to annual timesteps, whereas indicators used to detect low water levels in urban systems conventionally measure water reserves in terms of *days of remaining supply* (Kallis, 2008).

3.3.3. The significance of infrastructure systems in driving urban drought impacts

The highly managed nature of city water systems plays a key role in the perception and response mechanisms that define how the city-as-system can react, learn, and adapt to drought threats (Marlow et al., 2013). Unlike in farming, where individual water users make management and ultimately adaptation decisions based on their direct experience of drought impacts (Rockström, 2003; Urquijo & De Stefano, 2015), the relationship between urban water users and their local hydrological system is indirect, mediated through the infrastructure system. This intervening system influences water users' perception of the drought threat and their experience of drought impacts, ultimately shaping the effectiveness of the city's drought response. The disconnect between water users and water sources in the urban system is reinforced by both physical and operational infrastructure systems:

a) Physical water infrastructure (pipes, pumps and reservoirs) creates a layer of complexity that determines the degree to which water users will be impacted by low source water availability. This intervention works in both directions – the incorporation of water storage and redundancy in a UWS protects water users from the impacts of drought, but poorly performing, leaky or under-designed infrastructure can also aggravate shortages during times of water stress (Padowski & Jawitz, 2012; Srinivasan, 2015). If we consider that water users are the locus of drought impacts in the city, it is significant that these impacts can be either mitigated or emphasized by the condition or capacity of urban water infrastructure.

b) Operational infrastructure systems create a further buffer between water users and the surrounding environment by working behind the scenes to ensure continuous water service delivery even during times of water scarcity. Most drought response measures focus on reducing demand- as such, their success depends on the actions of thousands or millions of residential and commercial water users (Buurman, 2017). The effectiveness of drought response measures will ultimately shape the degree of drought impact experienced within the urban system, and is strongly dependent on a variety of social and psychological factors relating to the urgency of the message, the credibility of the messenger, and the stringency of water use restrictions imposed (Anand, 2001; Medd & Chappells, 2007; Halich & Stephenson, 2009).

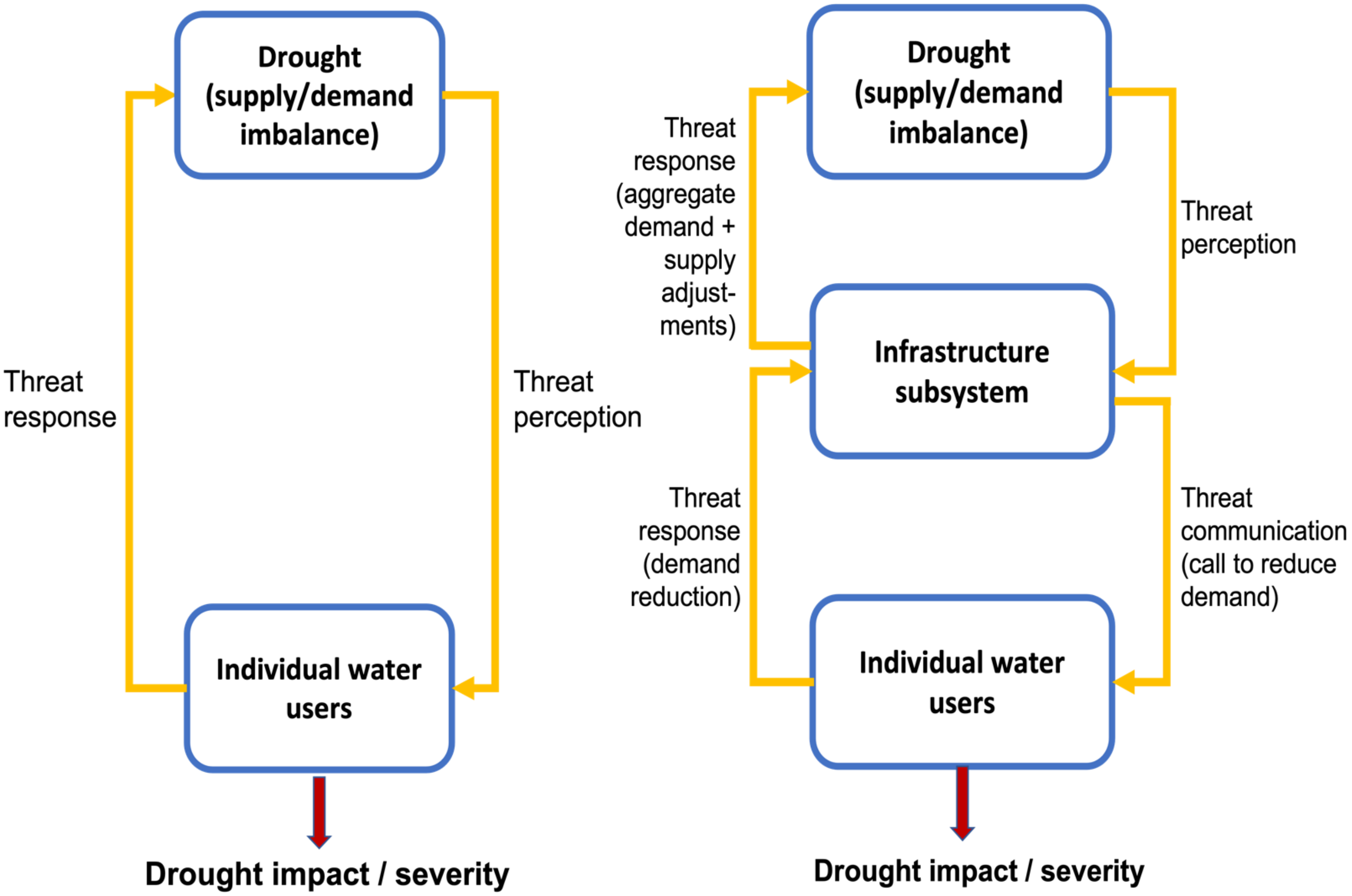

Figure 3.2: Threat perception and response in hydrological/agricultural drought (left) and urban drought (right). The severity and impact of drought are determined by the experience of water users.

Water systems have been theorized to function as complex social-technological-environmental systems that undergo adaptive processes and social learning in the wake of disruptions or hazard events - through this lens, urban droughts should function as windows of opportunity for driving adaptation at the individual and system level (Heino & Anttiroiko, 2014; Pahl-Wostl et al., 2007). However, in a centralized urban water infrastructure context, the infrastructure system mitigates water users' experience of urban drought by influencing their perception of drought severity and by generating drought impacts through the introduction of response actions intended to reduce the risk of water supply shortage. Though water users provide the primary effort behind drought response actions, their experience of drought impacts is largely indirect, filtered through the performance of hard infrastructure assets and the actions of the operational infrastructure systems that manage them. As such, the presence of the urban infrastructure system intervenes in the response and adaptation decisions made by individual water users in a city system and exerts influence over the processes of adaptive learning and resilience-building that may occur at the individual and city scale (Marlow et al., 2013).

3.3.4. Significance of water demands in driving urban drought impacts

Water demands at the city scale can be highly variable at sub-annual timesteps and even from day to day (Adamowski, 2008; Finley et al., 2020). Analysis of monthly water use records from Canada and the US show that summer-monthly demands can be over 3 times higher than that of the lowest-demand winter months in some cities (Chini & Stillwell, 2018; Finley et al., 2020). Within the peak summer months, daily water use rates during periods of hot and dry weather can exceed the summer median daily demand by 30 to 40% even in humid Canadian cities, and by as much as 60 to 70% in semi-arid ones (Finley et al., 2020, unpublished data). While it is clear that water demands are significantly and positively correlated with drought conditions (Balling and Gober, 2007; Taylor et al., 2012; Gutzler & Nims, 2005; Chang et al., 2014;

Finley et al., 2020), the relationship can change over time if drought wears on. Existing research suggests that in the initial stages of drought, a lack of precipitation can lead to increased demand for outdoor water uses, especially lawn and garden watering (Balling & Gober, 2007; Szalińska et al., 2018), and one study found that the co-incidence of heat and low-precipitation conditions can also generate supplemental increases in water use for cooling and intensify indoor domestic use (Downing et al., 2003). However, longer-term studies of multi-year drought events suggest that aggregate water demand can decline in the later stages of drought as users respond to conservation messages from water agencies and adopt new behaviours in reaction to drought signals in the environment and the media (Breyer et al., 2018; Gonzales and Ajami, 2017; Bolorinos et al., 2020, Quesnel & Ajami, 2017; Hannibal et al., 2018). Of course, not all water users are alike- some will increase water use even while others are actively conserving (Bolorinos et al., 2020).

Most drought response measures focus on reducing demand, and as such, the success of municipal agencies in reducing the impact of drought is highly contingent on their capacity to inspire and enforce reductions in water use on short timescales (Buurman et al., 2017, Dilling et al., 2018). In theory, water demands can be highly flexible and quickly reduced when the need hits; this is most true in cities where water demands include a high proportion of discretionary water use- that is, not necessary to the maintenance of basic quality of life (Breyer et al., 2018, Zipper et al., 2017, Gober et al, 2016). However, there are limits to the degree to which users can and will conserve water, and water use is highly correlated with psychological, behavioural, and cultural conditions in the populace that cannot be quickly altered (Gober et al., 2016). What's more, research has shown that demand can harden (become less flexible) as water users integrate more water conserving practices into their daily routines and adopt more water-efficient fixtures, leaving less room to reduce when drought hits (Dilling et al., 2019). As urban drought impacts are contingent on the aggregate demand response of a highly heterogeneous set of individual water users, the character of each city's water demand profiles and water user base are themselves highly influent on the experience of drought.

3.4. Endogenous drivers of urban drought impacts

Drought risk and vulnerability assessments have flourished in the past two decades along with a growing awareness of the need to move to a more proactive approach to disaster risk management (Hagenlocher et al., 2019, Rossi and Cancelliere, 2013; González Tánago et al., 2016). However, these assessments tend to focus on the impacts of hydrological or agricultural drought at the scale of catchments, regions, countries or continents (Carrão et al., 2016; González Tánago et al., 2016; Hagenlocher et al., 2019; Wang et al., 2020). While such assessments are critical, droughts act differently on rural and urban systems, and regional-scale assessments fail to account for the extensive role that urban infrastructure and water demands play in determining the scale and scope of drought impacts experienced at the city scale (Zipper et al., 2017). The specific drivers of drought-related water insecurity within urban water systems merit more specific attention, especially when we consider the high concentration of both water users and economic activity in urban areas worldwide (Buurman et al., 2017; Kallis, 2008).

Wide-scale assessments tools provide insights about the status of drought risk in major urban centres even in the absence of city-scale contextual detail. Acknowledging the growing social and economic threat that droughts pose to urban residents and economic activities, some global organizations have worked toward refining drought preparedness tools to better address the threat of drought at the national and regional scale: such tools include the World Bank's Water Risk Filter, the Asian Development Bank's urban water security index, and the World Resource Institute's Aqueduct Water Risk Atlas (Laporte-Bisquit, 2019; Hofste et al., 2019; Asian Development Bank, 2020). These tools provide invaluable information about baseline water stress at national and regional scales and provide an assessment of local administrative capacity to deal with drought, but stop short of examining the potential influence of urban water infrastructure configurations and/or water demand dynamics on drought risk profiles.

The world's largest cities have received considerable research attention in the study of urban drought risk. McDonald et al. (2014) concluded that when we take into account the reach of urban water infrastructure in major cities across the globe, significantly fewer urban dwellers worldwide are affected by water stress than would be predicted through hydrological modelling. Some of the same authors conducted similar research in over 225 large cities across the US and 70 more worldwide, finding that urban water infrastructure systems increased water supply security as compared to that assessed using runoff-based hydrological models that do not account for infrastructure, and that cities that rely on more variable (usually river-based) water sources were more likely to have constructed storage structures to reinforce natural supplies (Padowski & Jawitz, 2012; Padowski et al., 2016). In their 2019 book Urban Drought: Emerging Water Challenges in Asia, editors Ray and Shaw compile a series of essays focusing on the urban drought risk, vulnerability, and adaptive capacity of major cities across the Asian continent and highlighting the unique impacts of urban drought on cities characterized by a varying degree of baseline water insecurity and user vulnerability. Buurman et al (2017) examined drought risk management strategies developed by 10 large global cities that had recently experienced a drought; they found that most of these plans included a relatively limited number and variety of measures, but in most cases featured a good mix of strategic, long-term risk reduction initiatives and tactical response measures ready for deployment during drought events. These surveys provide a useful glimpse into the assessment and management of drought risk in some of the world's largest cities, but do not examine in detail the influence of infrastructure configurations or shifts in water demand on the experience of urban drought.

The individual or socio-economic vulnerability of urban water users during drought (that is, their relative ability to respond to, cope with, or recover from the adverse effects of drought) has also received some attention in academic literature; in such studies, water management actors and agencies are often framed as the dominant intermediary between the (varyingly vulnerable) user and the larger hydrological system (Gober & Kirkwood, 2010; Gonzales & Ajami, 2017, Zscheischler et al., 2019). Although the vulnerability of water users is indeed significant in measuring drought impact, this approach elides the critical role of physical water infrastructure in driving drought impacts in cities. Here we provide an examination of higher-order factors that influence the scale of impact at the level of the city system to complement analyses of individual or household-level drought vulnerability in city systems (Srinivasan et al., 2012, Gober & Kirkwood, 2010).

3.4.1. Key drivers of drought impact identified within relevant literature

Table 3.2 presents a range of infrastructure and demand- specific drivers of drought impacts in cities identified in relevant literature. Congruent with the conceptual framework used in this review, drivers were identified within the specific scope of a) urban water systems undergoing periods of low water availability (urban droughts), where b) the city(ies) in question is(are) characterized by centralized drinking water delivery infrastructure that is generally capable of providing sufficient and continuous water services to the majority of water users outside of urban drought events. Studies and reports that focused on case studies of recent (post-2000) drought events were prioritized in an effort to consolidate the most salient, up-to-date information possible.

Identified drivers are categorized into three general categories, selected to cross-cut the varying terminology favored by various disciplines of study (notably water governance, engineering and case study reports). The categories are:

a) Operational infrastructure

The capacity of water management actors (municipal water managers, engineers and/or private water agencies) to anticipate, prepare for, and respond to droughts is of utmost importance in the degree to which water users will be impacted by precipitation deficiencies.

b) Physical infrastructure

Physical water infrastructure systems can strongly influence the impacts of hydrological drought on urban residents, in both directions: storage and redundancy can protect water users by creating a buffer against low-water conditions, but poorly performing and leaky infrastructure can also aggravate water shortage situations even when wider drought conditions are not severe.

c) Flexibility and control of water demand

The ability to curb demand, and avoid demand surges when drought hits, is a function that cross-cuts water management agents and water users. Because demand has a uniquely high relative importance within urban water systems, the (in)flexibility of demand during drought conditions is a key determinant of the event’s impact on water users.

Table 2.2: Endogenous drivers of drought impact identified in literature

Category	Driver of drought impacts	References
Operational infrastructure	No or poor drought preparedness planning	Bragalli et al., 2007; Buurman et al., 2017; Gober & Kirkwood, 2010; González Tánago et al., 2016; Iglesias et al., 2009; Kallis, 2008; Mortazavi et al., 2012
	No or poor drought monitoring and demand modelling capacity	Muller, 2018; Van Belle & Hlabano, 2019; Wilhite, 2011
	Little experience with drought (within management actors)	Dilling et al., 2019; Gober & Kirkwood, 2010; Gonzales & Ajami, 2017; Hall & Borgomeo, 2013; Lund et al., 2018; Padowski & Jawitz, 2012
	Lack of dedicated funding for drought response	Dilling et al., 2019
	Poorly established rural-urban transfer mechanisms	Gober & Wheater, 2014; Zipper et al., 2017
	Poor integration across scales of government	Dilling et al., 2019; Gonzales & Ajami, 2017; Karavitis, 1998
	Private or fragmented administration of drinking water systems	Medd & Chappells, 2007
	Poor communication with water users	Enqvist & Ziervogel, 2019, Medd & Chappells, 2007
	Limited ability or reluctance to impose drought response actions when needed	Jorgensen et al., 2009; Karavitis, 1998; Kreutzwiser et al., 2003
	Lack of credibility/trust in the eyes of water users	Anand, 2001; Halich & Stephenson, 2009; Medd & Chappells, 2007
Physical infrastructure	Lack of redundancy in supply (system intake from only one water source)	Anand, 2001; Bragalli et al., 2007; Chuah et al., 2018; Gonzales & Ajami, 2017; Kreutzwiser et al., 2003; Parks et al., 2019
	Reliance on water transfers from far off sources or other basins	Bragalli et al., 2007; Padowski & Jawitz, 2012
	Limited storage capacity relative to demand	Kreutzwiser et al., 2003; Padowski & Jawitz, 2012, Padowski et al., 2016
	Limited pumping and/or treatment capacity relative to demand	Kreutzwiser et al., 2003
	Lack of interconnectedness between pumping, storage and treatment facilities	Kreutzwiser et al., 2003; Padowski & Jawitz, 2012
	Aging infrastructure / leaky conveyance network	Bragalli et al., 2007; Kreutzwiser et al., 2003;
	No or only partial metering of water use	Karavitis, 1999; Kreutzwiser et al., 2003; Parks et al., 2019
Water demand	High average (pre-drought) water demand	Bragalli et al., 2007; Fu et al., 2013; Kallis, 2008; Dilling et al., 2019
	Inflexible/hardened demand	Bragalli et al., 2007; Breyer et al., 2018; Dilling et al., 2019; Fu et al., 2013; Zscheischler et al., 2019; Taylor et al., 2009
	Surges in demand during drought conditions	Breyer et al., 2018; Kreutzwiser et al., 2003; Shandas et al., 2015
	Agricultural demands supplied by urban water system	Kreutzwiser et al., 2003, Padowski & Gorelick, 2014
	No access to open/public water use data	Van Belle & Hlabano, 2019
	Larger proportion of climate-sensitive water demands (lawns, golf courses, seasonal industries)	Gober et al., 2016; Hill & Polsky, 2007; Shandas et al., 2015; Zscheischler et al., 2019
	Rapid population growth and/or rapid industrial growth	Bragalli et al., 2007; Gober et al., 2016; Gonzales & Ajami, 2017; Kreutzwiser et al., 2003; Parks et al., 2019; Shandas et al., 2015
	Season population surges (influx of tourists and/or seasonal inhabitants during the hot season)	Hill & Polsky, 2007; Karavitis, 1998
	Poor demand response to restrictions/water conservation messages	Buurman et al., 2017; Dilling et al., 2019; Gonzales & Ajami, 2017; Zipper et al., 2017
	Widespread use of automated irrigation systems for lawn watering	Hill & Polsky, 2007
	Low awareness of drought	Bolorinos et al., 2020; Kenney et al., 2004; Kreutzwiser et al., 2003
	Little experience with drought (within water users)	Dilling et al., 2019; Gonzales & Ajami, 2017; Hall & Borgomeo, 2013; Lund et al., 2018

3.5. Discussion

Among the drivers identified in Table 3.2, we find some common themes that highlight the deep interconnectedness of infrastructure, user behaviour and the effectiveness of drought response. One such theme is a lack of prior experience with drought; we find mention in multiple studies and case study reports of increased drought impact in cities where drought is a relatively new phenomenon, leaving both water management agencies and water users ill-equipped to cope with the threat of water shortage. This theme is also reflected in the characteristics of physical and operational infrastructure systems: in fact, one study of over 100 urban water systems found that cities with a baseline of 'natural abundance' of water resources, and thus little drought experience, were least likely to have the institutional arrangements and physical infrastructure elements (including water storage structures) in place to ensure continued water availability during drought events (Padowski et al., 2016). This is an interesting finding in that it suggests that all else being equal, cities located in regions that are normally water secure and/or at low drought risk may be more vulnerable to drought impacts than those located in drought-prone areas, which have had more time and experience to prepare for these events.

Another theme that emerges is the increased impact of droughts in systems that have not invested in drought preparedness. This theme, which can be identified in drivers relating to a lack of drought planning, poor drought monitoring and modelling, a lack of redundancy in source supply, poor communication with water users, is less surprising - the importance of drought preparedness planning is well-established in research and its influence on the experience of drought impacts is intuitive (Gober et al., 2016; Buurman et al., 2017; Padowski et al., 2016). We may infer some relationship between this theme and the first: it is expected that cities with little experience with drought would be less likely to have invested the time and resources to prepare the infrastructure, institutional arrangements, and user communication tools needed to lessen the impact of drought when it arises.

A review of Table 3.2 also reveals the clear importance of baseline physical infrastructure efficiency in lessening the impact of drought; when water availability is low, leaky pipes, aging water storage and conveyance assets, and unmetered networks will tend to worsen the impacts of drought by decreasing the amount of scarce water that can be successfully delivered to water users. Similarly, a lack of interconnectedness among water treatment plants, storage reservoirs and pumping stations means that cities are unable to move water to where it is most needed during drought events.

Finally, the primacy of aggregate water user behaviour is made clear in the multiple drivers of drought impact that relate to water demand. Water conservation is the primary mechanism for reducing impacts during urban drought; however, water conservation is borne out of a complex interplay between water managers and water users themselves. Water managers must be able to provide timely and credible messaging to water users about the need to reduce water use, and in turn, those users must clearly perceive the need and benefit of reducing water use to effectively enact behaviour changes. In effect, water users must agree to some degree of impact on their own lifestyle (for example, browning lawns and/or restrictions on certain water uses) as part of a collective effort to reduce the risk of more severe drought impacts (such as water shutoffs or pressure reductions) as the drought continues. Because users primarily experience drought indirectly via the infrastructure subsystem while their taps continue to flow, their perceptions of scarcity and the credibility of water managers' conservation messaging emerge as essential elements in a complex process that ultimately seeks to limit drought impacts for the city as a whole.

3.6. Conclusion

Like hydrological and agricultural droughts, urban droughts are relational phenomena where impact and severity are most easily understood through the experience of users. However, unlike in those drought types, the feedback loops that mitigate the impact of urban drought via altered water-use behaviour are not direct, but instead filtered through a complex web of physical and institutional infrastructure arrangements. As a result, the conceptual framework that best describes urban drought events is one that focuses on the specific temporal scales of activity within a city water network, and that foregrounds the iterative relationships between drought impacts, operational and physical infrastructure systems, and user-driven water demands during drought periods. Within this framework, we find within literature and case study reports a suite of endogenous (infrastructural and demand-related) drivers that influence the degree to which water users are impacted by drought. These drivers support the conceptual framework identified, as they relate to the character of both physical and operational infrastructure elements, and ultimately hinge on how these elements influence the experience and perceptions of water users themselves, who through their actions will determine the degree of drought impacts that will ripple through the city system.

The framework advanced in this review establishes a conceptual structure for understanding the experience of urban drought within an urban water system itself, as independent from its hydroclimatic setting. This work provides a context-independent perspective on urban drought that should facilitate the analysis of water shortage situations affecting cities that share structural similarities- that is, normally reliable centralized water service provision – but that exist under divergent hydrological regimes.

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Bridging section

Having constructed a more comprehensive, cross-contextual understanding of the experience of urban drought, it is now possible to turn our attention to the analysis of water shortage threats in Canadian cities. Under what conditions do Canadian cities become most vulnerable to urban drought situations, and how effective are the response actions enacted by water managers to mitigate water shortage risks?

Water use restrictions are the most widely applied drought response tool used to reduce the impact of urban drought events in cities studied worldwide, and they are also a key climate adaptation measure for cities looking to adapt to increasing hydrological variability under the effects of climate change (Dilling et al., 2019, Buurman et al., 2017, Gober et al., 2016). In Canada, over 75% of major cities impose some kind of water use restriction, though these *water use bylaws* are typically applied on a seasonal or permanent basis rather than directly in response to drought threats.

To better understand how Canadian cities experience, react and adapt to water shortage threats, an important first step is to assess the degree of seasonal variability in water demand experienced by various cities across the country. If indeed climate-sensitive water uses like lawn and garden irrigation drive a sharp increase in urban water demand during the warm summer months, it is then relevant to quantify the effectiveness of the seasonal water use restrictions imposed in so many Canadian cities as a means to reduce water shortage concerns during the summer period. The next study provides a detailed analysis of seasonal water use profiles in 15 Canadian cities and evaluates the impact of water use restrictions in reducing climate-sensitive water demands at seasonal and summer-daily timescales.

Chapter 4:

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

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

4.1. Overview

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 Canada, where upward swings in municipal 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 Canadian cities to implement permanent restrictions on outdoor water uses; however, little is yet known about the about their effectiveness. This paper examines daily water production data from 15 Canadian cities to gauge 1) how overall and seasonal water demands are evolving over time, and 2) whether permanent water use restrictions have been effective in curbing summer water demands at the city scale. Results show that while per-capita water demand is declining in most Canadian cities, the seasonal distribution of that demand has remained largely stable in all but a few very dry cities. 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. When we zoom in on 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.

4.2. Introduction

4.2.1. Urban droughts

Among the myriad threats that are expected to intensify under the effects of climate change is an increased risk of urban water 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). A combination of longer and more frequent heatwaves, burgeoning city populations, and an increased variability in meteorological conditions is expected to amplify the risk of periodic drought in many regions (Douville et al., 2002; Jenerette & Larsen, 2006; Sarhadi et al., 2018; Vörösmarty et al., 2000; Wada, van Beek, L. P. H., & Bierkens, 2011). Because urban water systems are socio-hydrological in nature, drought resilience in cities is rooted in the capacity of urban water users, water managers, and infrastructure systems to minimize the impact of water shortage instances (temporary imbalances between supply and demand) and to avert system failure during periods of prolonged precipitation deficiency (Buurman et al., 2017; Hashimoto et al., 1982; Yung et al., 2011). However, more research is needed to evaluate how resilience to water shortages can be improved and promoted in vulnerable cities; this attention seems especially warranted in an era where numerous cities worldwide are beginning to run dry and looming shortages in cities across climate zones alerts us to the complex nature of urban drought (African News Agency, 2017; BBC News, 2018).

Canada is a relatively water rich country when compared to drought-prone nations like Israel and Australia. However, 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 is 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 thus an important concern even in relatively water-secure countries like Canada; however, few studies to date have explored seasonal trends in water use across multiple Canadian cities, and no research evidence yet exists to validate the effectiveness of policy measures enacted to address the water shortage threat.

4.2.2. Urban water demands

Because drought in anthropogenic systems is driven by an imbalance between water use and available supply, baseline and seasonal demands for water are key components to consider in the evaluation of urban drought risk (Bragalli et al., 2007; Padowski & Jawitz, 2012; Van Loon et al., 2016). Water demands have changed significantly in recent decades: though a lack of publicly-available municipal water data hinders the comparative study of water use rates across multiple cities (Chini & Stillwell, 2016), a handful of US-focussed studies and reports point to a steady decline in per-capita water use in North American cities since the 1980s (C3 Water Inc., 2016; Chini & Stillwell, 2018; City of Calgary, 2013; East Bay Municipal Utility District, 2011; Environment Canada, 2011; Rockaway et al., 2011; Sankarasubramanian et al., 2017). In a 2017 survey of county-level data across the mainland US, Sankarasubramanian et al. discovered that per-capita water demand has declined in most US counties since 1985, a result that echoes work by Rockaway et al. (2011) that found declining water use rates within city data from across the US and Canada. Interestingly, some of the sharpest reductions in per-person water demands occurred in the more traditionally water-secure parts of the country, including New England and the Northwestern states (Rockaway et al., 2011; Sankarasubramanian et al., 2017). 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; Polebitski & Palmer, 2009; Rockaway et al., 2011). However, declines in per-capita rates of municipal water use are necessarily bounded (Dilling et al., 2018; Rockaway et al., 2011) and occur alongside an accelerating background threat of periodic urban water shortage (Ginley & Ralston, 2010; McDonald et al., 2011; Padowski & Jawitz, 2012) and growing city populations that can intensify water withdrawals even amidst declining per-capita demands. Annual demand figures also obscure intra-annual variations in water use, which are highly relevant to water shortage vulnerability in cities. As documented by recent studies of global watersheds at sub-annual time steps, water shortage vulnerability is widespread at the monthly scale even in areas with no history of annual precipitation deficits (Brauman et al., 2016; Wada, van Beek, L. P. H., Viviroli, et al., 2011).

4.2.3. Summer peaks in water demand

In North American cities, water demand tends to surge during the hottest and driest months (herein *summer*) of each year (Balling & Gober, 2007; Gober et al., 2015; Gutzler & Nims, 2005). This surge is largely attributable to an increase in climate-driven water uses in the summer months: this use category, commonly grouped under the moniker of 'outdoor water use', includes water used for outdoor maintenance tasks and pool-filling, but is overwhelmingly dominated by landscape irrigation (Kjelgren et al., 2000). Outdoor water use, especially in the residential sector, can account for over half of total water use in some arid cities (Balling & Gober, 2007; Gutzler & Nims, 2005). Driven by increased water demand for irrigation, urban water production rates in summer months can reach double or even triple the winter average (Balling & Gober, 2007; Chini & Stillwell, 2018; Kjelgren et al., 2000).   Summer peaks in water demand tend to be most pronounced in arid and semi-arid cities where conventional grass-dominated landscapes 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 Chini et al. (2018) that points to a notable climate gradient in the seasonal variation of water demands across the continental US, with the ratio of highest:lowest monthly water demand exceeding 300% in some arid western cities while wetter eastern cities see little sub-annual variation at all (Chini & Stillwell, 2018).

Surging water demand in response to hotter summers and more frequent and intense heatwaves are identified as among the key threats that water utilities must contend with in an era of climate change (Cromwell et al., 2007). Heatwave events that coincide with precipitation deficits are especially problematic for water systems because they drive increases in irrigation and associated spikes in municipal water use at the same time that source water bodies are most strained by competing demands, reduced runoff, and increased evaporation (Brauman et al., 2016; Hoekstra et al., 2012; Wada, van Beek, L. P. H., Viviroli, et al., 2011). While little is yet known about municipal water demand dynamics specifically during summer heatwaves, low rainfall and elevated maximum temperatures are known to intensify outdoor water demands and especially irrigation by a significant degree (Balling & Gober, 2007; Jenerette et al., 2011; Polebitski & Palmer, 2009). Short-term bursts of hot and dry weather can cause *peaks* in water demand, defined as the highest day/hour/week of water demand as compared to the annual average (Beal & Stewart, 2013). Even in the absence of water shortage risks, peak demands (a term commonly used to designate individual peak events as well as periods of very high demand that approach the peak value) 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 (Burn et al., 2002; Kanakoudis, 2002; Lucas et al., 2010). As such, the timing and magnitude of peak demands are a key source of vulnerability in urban water systems, and levelling peaks and reducing the short-term variability in summer water demand are among the primary goals of outdoor water demand management programs implemented worldwide (Burn et al., 2002).

4.2.4. Water use restrictions

If peaks in water demand in response to climate signals constitute a source of drought vulnerability in cities, then the behaviour of water users during times of water stress becomes pivotal in promoting the robustness and resilience of urban water systems. Indeed, 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 only become 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, a shift that is echoed by an increase in mentions of such restrictions within the Canadian news media over that period (see Fig. 4.1). Today, over 75% of large (population >100K) Canadian cities impose some sort of permanent water use restriction during the summer months, and the majority of these bylaws have entered into force within the past 20 years.

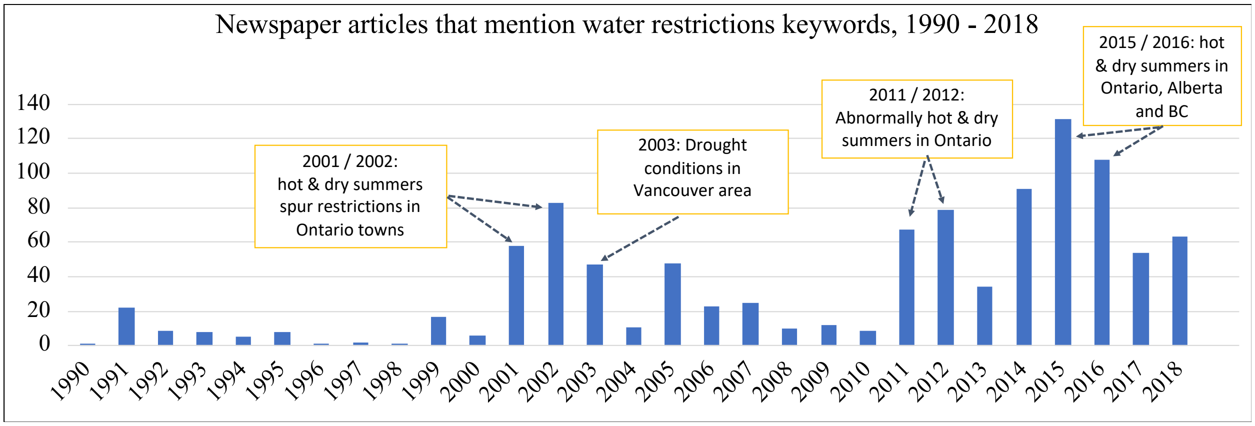

Figure 4.1: Mentions of water restriction keywords in Canadian news media (source: Factiva search of Canadian newspaper articles containing water restriction keywords (water restriction OR water* ban OR water* bylaw) and exclude common confounding terms (bottled* and farm*)*

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). Multiple studies have also 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, it is possible that 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). 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 restrictions may lead to increased outdoor water use (Ontario Water Works Association, 2008). Unfortunately, little research yet exists to confirm or quantify the effectiveness 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 trajectories of 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 (W. DeOreo & Mayer, 2012; Mayer et al., 1999; Mini et al., 2014; Romero & Dukes, 2014).

Recent research has highlighted the extent to which urban water systems function as complex adaptive systems within which water demand and supply interventions, and water users and water sources, are inherently linked (Breyer et al., 2018; Gonzales & Ajami, 2017; Kanta & Zechman, 2013). Within this framework, the behavioural response of water users in times of water shortage emerges as a critical factor in determining system robustness and resilience to drought (Buurman et al., 2017). However, it is not yet clear how water demand patterns at sub-annual timescales might contribute to water supply vulnerability, nor how permanent restrictions on climate-driven water uses may affect demand outside of drought emergencies. The objectives of this research are to examine daily water production records from multiple Canadian cities in order to quantify a) how water demands and their seasonal variation is changing over time and b) the impact of permanent water use restrictions on the volume and 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 long-term trends in seasonal water demands and the ways in which the behaviour of urban water users can be influenced by permanent restrictions on certain water uses.

4.3. Methods

4.3.1. 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:

a) This dataset provides greater temporal precision (daily or hourly timesteps) than billing data (generally available at timesteps 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 understanding 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 few users are largely responsible for most of excess irrigation water use in cities (Cole & Stewart, 2013; House-Peters & Chang, 2011; Mayer et al., 1999), making it very difficult to guarantee the representativeness of a sample of customer billing data. Moreover, complete billing data is often prohibitively difficult to obtain (Chini & Stillwell, 2016).
d) We contend that water conservation programs and water use restrictions should only be deemed 'effective' if their effects are visible at the city scale as reflected in water production rates.

Because water production data encompasses 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 outdoor water use by individual users, but rather as a gross seasonal surplus in municipal water production. This is considered a useful approximation of climate-driven water use within a given city, as no significant seasonal variation in indoor (base) water use, process uses or leaks is expected under normal circumstances (B. DeOreo, 2011; Mayer et al., 1999).

4.3.2. Metrics

In this text, the term *water demand* is the per-capita expression of mean daily water production and is presented in litres per capita per day (LCD), while *summer demand* (SLCD) and *winter demand* (WLCD) describe daily water demand values specifically in the summer and winter months. Here '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 municipal water use restrictions studied coincide during those months. In contrast, winter is defined according to the lowest average month method of DeOreo & Mayer (2012), which defines 'winter' as the three months of lowest water demand within each calendar year. Minimum-month winter demand is also sometimes referred to as *base demand*, and is assumed to represent indoor, climate-invariant water flows (and losses) across all user types (Maidment & Miaou, 1986; Shaw & Maidment, 1987). The annual average of daily LCD values is given the shorthand $\overline{\mathrm{LCD}_{\mathrm{y}}}$, while the annual average of daily SLCD and WLCD values are referred to as the *mean summer demand* ($\overline{\mathrm{SLCD}_{\mathrm{y}}}$) and *mean winter demand* ($\overline{\mathrm{WLCD}_{\mathrm{y}}}$), respectively.

The degree to which summer water demands exceed winter demands is often used to approximate the outdoor or otherwise climate-dependent surge in water use in summer months (Chini & Stillwell, 2018; Endter-Wada et al., 2008; Maidment & Miaou, 1986; Mayer et al., 1999; Mini et al., 2014). Though some researchers suggest that this method is of questionable utility in climates where warm winter weather allows for water to be used outdoors throughout the year (Gleick et al., 2003; Mayer et al., 1999), no such concern applies to Canadian cities, where sub-zero winter temperatures tend to preclude the use of water outdoors during those months. To enable a comparison between cities with widely divergent base demands, we quantify the summer surge in demand as the percentage by which mean summer demand $\overline{\mathrm{SLCD_y}}$ exceeds mean winter demand $\overline{\mathrm{WLCD_y}}$ in each city and each year.

Temporal trends in all metrics are determined by fitting a best-fit ordinary least squares regression line to time series data, where trends are considered significant if the regression coefficient for the slope is significantly different from zero at a 95% confidence level. In analysing water demands, *Winter trend* refers to the slope of the regression line fitted to $\overline{\mathrm{WLCD_y}}$ values over a multi-year period, while *summer trend* designates the slope of the line fitted to $\overline{\mathrm{SLCD_y}}$ values over that same timeframe. For the sake of comparability, trends were calculated over a reference period for which we have data from all cities, and are presented in results as annual rates of change in per-capita demand values (Δ LCD/year).

4.3.3. Detecting the influence of water use restrictions

The effect of permanent water use restrictions was explored by analyzing daily summer-season water demands before and after restrictions, where each SLCD value is expressed in terms of its ratio to the mean annual demand for that year ($\overline{\mathrm{LCD_y}}$) (Equation 1). The 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.

$$nSLCD = \frac{SLCD}{\overline{LCD_y}} \tag{1}$$

Where *n*SLCD represents individual normalized SLCD values. The impact of water restrictions (*bylaw effects*) was determined by comparing the distribution of daily *n*SLCD values in the years following the imposition of the restriction to that of the years that preceded it. The 'before' and 'after' periods were limited to the five years of data preceding 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 favour 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 three years and the 'before' period for city A spans four years instead of five.

Bylaw effects are then quantified by calculating the change in mean, median, standard deviation and the 95th percentile of the *n*SLCD distributions from the 'before' to 'after' subsets. The distance between the 'before' and 'after' distributions was further quantified by determining the Kolmogorov-Smirnov distance (D_{KS}) and the P-statistic of the two-sample Kolmogorov-Smirnov test (P_{KS}) between the cumulative distribution functions (CDF) of each subset (Wilcox, 2005). The two-sample Kolmogorov-Smirnov (KS) test is a non-parametric statistical test that determines maximum distance between two CDFs:

$$D_{KS} = max\left|F(x)_{before} - F(x)_{after}\right| \tag{2}$$

It should be noted that this method differs from that employed in some studies of the effectiveness of temporary drought restrictions, which often use short-term water demand forecasting models to predict a theoretical "expected use" value to which observed water demands under restrictions can be compared.

These comparisons are often drawn over time periods of a few months or years (Anderson et al., 1980; Haque et al., 2014; Jacobs et al., 2007; Kenney et al., 2004; Lee & Warren, 1981), whereas In longitudinal studies, this method requires assuming a constant trend in base use upon which summer-season demand patterns can be superimposed (Gutzler & Nims, 2005). In this research, assembled data from study cities did not conform to this assumption: sharp and unevenly distributed changes in the WLCD baseline in these cases limit the predictive capacity of both regression and time-series models for the simulation of summer water demands with the temporal precision required to understand the impact of day-of-week water restrictions. The statistical approach avoids this pitfall by relating daily summer demands to their respective annual average values to create a commensurable comparison of climate-driven demands before and after restrictions are applied.

4.3.4. Water demand during hot and dry periods in bylaw and non-bylaw cities

Because outdoor water use can intensify during periods of hot and dry weather, one of the main objectives of water use restrictions is to restrain surges in water demand during heat events. In order to gauge whether Canadian restrictions have been successful in this regard, we examined specific periods of exceptionally hot and dry weather affecting multiple cities simultaneously to determine whether water demand surges during these events were significantly lower in cities that enforce water use restrictions than in those that do not. As the study's semi-arid cities are too far apart to allow such a comparison, both clusters are drawn from within the humid cities group: City Cluster 1 groups cities G, E, F, and J and City Cluster 2 encompasses cities B, H, and D. All cities inside each cluster are located within 150km of each other and share general climatic similarities including AI values (which range from 1.0-1.08 in cluster 1 and 1.15-1.29 in cluster 2). For each cluster, an iterative process was undertaken to develop a functional definition for a hot and dry period (herein referred to as '*dry heatwave*') based on the data at hand, similar to the approach adopted by Ruth (2006): under this definition, a *hot and dry day* is one wherein no significant (>5mm) rainfall has been recorded for at least Y days preceding and inclusive of the day in question (where Y=median number of consecutive days that pass without significant rainfall within the climate dataset) and the maximum temperature exceeds N (where N= 90th percentile of daily maximum temperature values within the climate dataset), and a *dry heatwave* is a period within which every city in the cluster simultaneously experiences three or more hot and dry days in sequence. This threshold combination represents the most extreme hot/dry conditions for which more than 10 post-bylaw dry heatwaves could be identified within each cluster's climate and water production datasets.

With the 'dry heatwave' definition established, we compared the extent to which water demands surged during these events within clusters of climatically similar cities that impose differing degrees of water use restrictions. To normalize for differing demand baselines among cities and remove the impact of long-term trends in demand, each hot and dry day's SLCD value was expressed in terms of its ratio to that year's median SLCD 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:

$$hwSLCD = \frac{SLCD}{median_{SLCD_y}} \tag{3}$$

Where *hw*SLCD represents the ratio of water demand on a given summer day to the median summer day demand of that same year. Individual *hw*SLCD values are then averaged over the duration of each dry heatwave event to present an overall *demand surge* value for each city and each event ($\overline{\mathrm{hwSLCD}}$).

4.3.5. Data collection and city classification

Daily water production data was collected from a total of 12 Canadian municipalities as well as 3 municipal regions encompassing two or more smaller municipalities, herein grouped as "cities". Mid-sized 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 very small agglomerations (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 the city's history of enforcement (and promotion) of summer outdoor 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 and outliers removed.

Climate data for each city was 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, n.d.). 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 aridity index of each city was determined by finding the spatially averaged AI value for the city's geographical limits from within the CGIAR-produced Global Aridity Index dataset (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 aridity index (AI) of less than 0.5 (but greater than 0.2) as 'semi-arid', and those with AI>0.65 as 'humid' (United Nations Environment Programme, 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 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.

4.4. Results and Discussion

4.4.1. City data analysis

Fifteen participating cities from across 5 provinces provided a minimum of 14 and a maximum of 25 years of daily water production values for the study. Of these, five were classified as ‘semi-arid’, with aridity indices below the UNEP-designated threshold of 0.5, while the other ten 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 6 classes of population size (<50K, 50-100K, 100-250K, 250-500K, 500K-1million, >1million) and 4 classes of water price (<\$0.50/m^3, \$0.50-\$1m^3, \$1-2/m^3 and >\$2/m^3) based on the most recent information. For this classification, ‘price’ is defined as the current variable price charged to residential consumers for provision of drinking water only, and the first price tier is used in the case of block pricing. Four of the 15 cities do not have universal water metering and do not currently charge a variable price for water provided to 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 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, the cities within the 'humid' climate category were most likely to enforce strict water use bylaws, while three of the five semi-arid cities impose no restrictions on outdoor water use at all. 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 is available from before and after their introduction to evaluate their effectiveness.

The relative stringency (high/medium/low) of water use bylaws is established based on the number of hours of lawn watering permitted per week (in the case of no hourly restrictions, 12 hours is allotted to each watering day), the distribution of those watering hours throughout the week (assigned day(s) vs. odd/even day pattern), and the number of promotional tools used to remind water users about the restrictions. When bylaws make a distinction between watering hours permitted for manually-operated and automatic sprinkler systems, the larger of the two numbers was used. In the case of staged bylaws, which increase in severity according to water supply levels, the range of restriction levels is used to define bylaw severity. All of the eight bylaws evaluated are enforced through the issuance of tickets and/or fines.

Table 3.1: Study Cities

City	Years of data provided	Climate type (AI)	Population class (2016)	Water price class – ($CDN/m^3)	Water use bylaw enforced annually? (year imposed)	Hours of watering permitted /week	Days when watering is permitted	Number of promo-tional tools	Relative stringency
A	18	Humid (2.0)	50K-100K	<$0.50	Y (2004)	12	Assigned days	3	medium
B	25	Humid (1.3)	100K-250K	None	Y (2003)	6	Assigned days	9	high
C	14	Humid (1.2)	50K-100K	None	Y (2010)	14	Odd/even days	6	medium
D	17	Humid (1.2)	250K-500K	None	Y† (1971)	14	Odd/even days	4	medium
E	20	Humid (1.1)	500K-1M	>$2	Y (2005)	8.5	Assigned days	4	high
F	18	Humid (1.1)	250K-500K	>$2	Y† (1988)	42	Odd/even days	3	low
G	20	Humid (1.1)	100K-250K	$1-$2	Y (2002)	14/14/0 (staged)*	Odd/even days	7	high
H	13	Humid (1.1)	250K-500K	None	Y (2009)	36	Odd/even days	4	low
I	15	Humid (1.0)	>1 M	>$2	N	n/a	n/a	n/a	n/a
J	15	Humid (1.0)	250K-500K	$1-$2	N	n/a	n/a	n/a	n/a
K	15	Semi-arid (0.48)	100K-250K	$1-$2	N	n/a	n/a	n/a	n/a
L	15	Semi-arid (0.44)	<50K	$1-$2	N	n/a	n/a	n/a	n/a
M	18	Semi-arid (0.39)	50K-100K	<$0.50	Y (2015)	27/18/9/0 (staged)	Assigned days	6	medium
N	21	Semi-arid (0.37)	50K-100K	$1-$2	N	n/a	n/a	n/a	n/a
O	24	Semi-arid (0.34)	50K-100K	$0.50-$1	Y (2000)	38.5	Odd/even days	3	low

† indicates 'fossil' water restrictions that are too old to evaluate
* Shown are weekly watering hours permitted under stage 1/2/3/4 restrictions of increasing severity

4.4.2. Annual water demands and seasonal variations in demand

Results show that per-capita water demands, and especially summer-season demands, vary significantly across the 15 cities studied and tend to be higher in semi-arid cities than in humid cities, as expected (Figure 2a and 2b). When looking at the 2010-2015 period (inclusive) for which all cities have sufficient data, we find mean daily demand values ($\overline{\mathrm{LCD}}$ = mean of $\overline{\mathrm{LCD}_\mathrm{y}}$ over the 2010 – 2015 period) ranging from a low of 291 LCD in city E to a high of 645 LCD in city O (Figure 2b). This range is even broader among summer water demand ($\overline{\mathrm{SLCD}}$ = mean of $\overline{\mathrm{SLCD}_\mathrm{y}}$ over the 2010 – 2015 period) values, which range from a low of 311 LCD, also in city E, to over 1000 LCD in the most arid cities studied. This stands in sharp contrast to winter demands, which vary considerably less across the board: all but two cities studied show $\overline{\mathrm{WLCD}}$ values within the 300-450 LCD range ($\overline{\mathrm{WLCD}}$ = mean of $\overline{\mathrm{WLCD}_\mathrm{y}}$ over the 2010 – 2015 period). This provides some confirmation of the assumption that base (winter) 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.

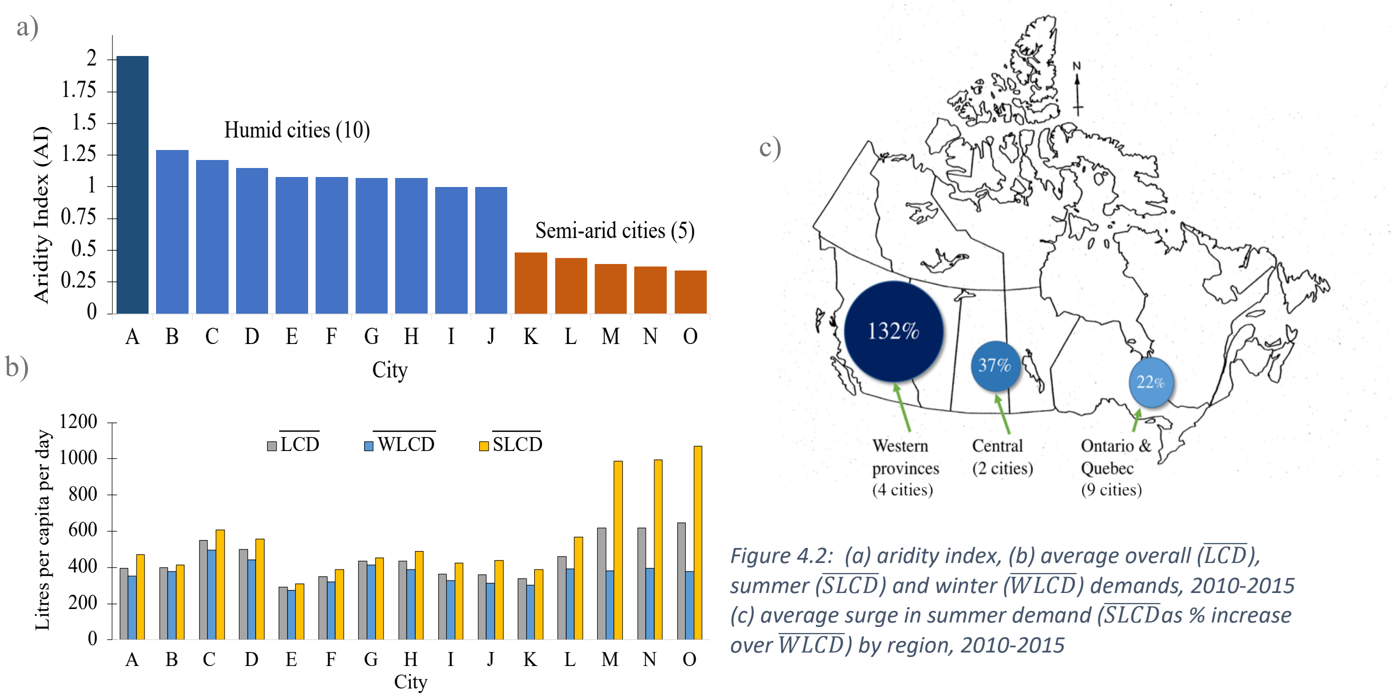

Figure 4.2: (a) aridity index, (b) average overall $(\overline{LCD})$*, summer* $(\overline{SLCD})$ *and winter* $(\overline{WLCD})$ *demands, 2010-2015 (c) average surge in summer demand* $(\overline{SLCD}$*as % increase over* $\overline{WLCD})$ *by region, 2010-2015*

The range in the seasonal distribution of demand across the study cities is notable: whereas in some humid cities summer demands exceed winter demands by as little as 10%, summer demand in city O is more than 180% higher than the winter demand (Figure 2b). As seen in figure 2c, the summer surge in water demand is significantly more pronounced in the western provinces than it is in central Canada and Ontario/Quebec, where mean summer demands $(\overline{\mathrm{SLCD}})$ were respectively only 37% and 22% higher than the mean winter demands $(\overline{\mathrm{WLCD}})$ for the 2010-2015 reference period. The divergence between summer and winter demand values in especially striking in the three most arid cities studied: when 2012 data from these cities is compared to that presented by Chini & 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 US like Colorado Springs (335%), Denver (348%) and Bakersfield, California (284%). Surprisingly, cities K and L, only slightly less arid than these three outliers, have relatively moderate summer surges in demand (29% and 45%, respectively). This suggests that summer surges in demand are a function of both climate and other factors (demographics, socioeconomic characteristics, etc.).

4.4.3. Temporal Trends in water demand

All 15 cities studied have witnessed an overall declining trend in annual average per-capita water demand ($\overline{\mathrm{LCD_y}}$) over the years of data provided (Figure 3a). These trends largely mirror results from the US-focussed studies mentioned previously (Rockaway et al., 2011; Sankarasubramanian et al., 2017), though in this case the steepest declines were not confined to wetter climate zones. 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 (Figure 3b). In this limited sample, the relationship between demand decline (2004-2014 trend in $\overline{\mathrm{LCD_y}}$) and starting demand (2004 $\overline{\mathrm{LCD_y}}$) was markedly stronger (R-squared =0.67) than the relationship between demand decline and water price (R-squared = 0.34).

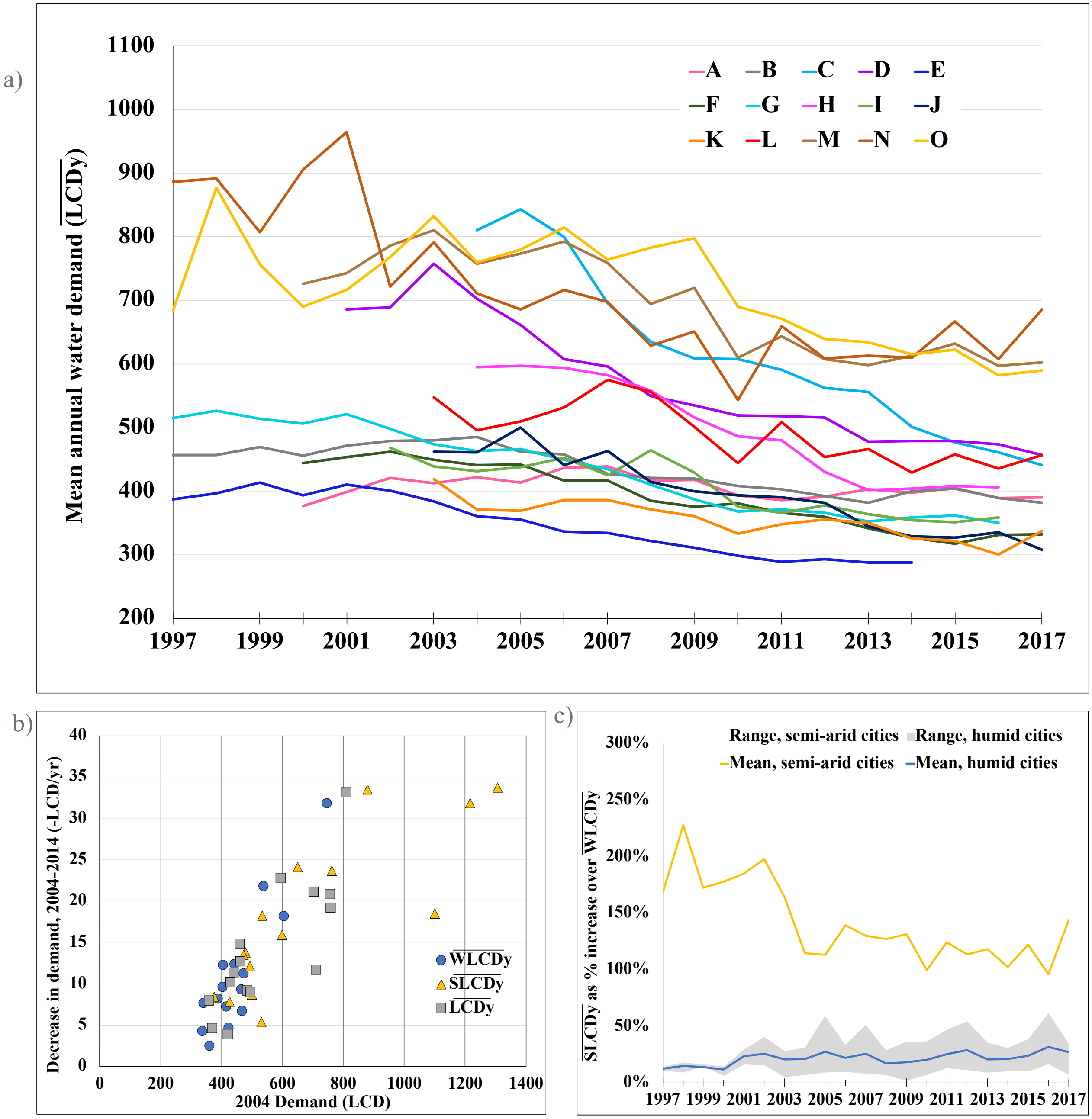

Figure 4.3: a) Mean annual water demand in all cities, 1997-2017. The decreasing trend in (LCDy) was statistically significant in all cities using the OLS regression method. b) Seasonal demand trends for reference period, 2004-2014 vs. their 2004 value c) Mean summer day demand as % increase over mean winter day demand, semi-arid and humid city groups (grey bands shows range of values in each group)

Annual trends in $\overline{\mathrm{SLCD_y}}$ and $\overline{\mathrm{WLCD_y}}$ for the 2004-2014 reference period also show varying rates of decline across the cities studied (supplementary information, Fig.S1, Annex A). Seasonal trends were all statistically significant except in the case of city A, where the slope coefficient for SLCD was not significant at the 95% confidence level. Interestingly, the decline in WLCD is found to be steepest within some of the sample's 'humid' cities while the decrease in SLCD was far more pronounced in the most semi-arid cities (M, N and O). This suggests that most of the decline in per-person water demand is likely attributable to climate-invariant water uses (e.g. indoor water conservation, leakage reduction) in humid cities, whereas the lion's share of water savings in arid cities is due to reductions in summer-specific demands including irrigation. As a result of these differing rates of decline, the seasonal variation in water demand has remained largely stable in the humid city group but has diminished in the semi-arid cities studied, albeit from a very high starting point (Figure 3c). 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 are witnessing 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.

4.4.4. Bylaw effects

4.4.4.1. 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 day demands (SLCD) following the imposition of water restrictions so that they more closely resemble the annual average ($\overline{\mathrm{LCD_y}}$)- in other words, a decline in *n*SLCD values (equation 1). Anticipated bylaw effects include an overall decrease of normalized demands (smaller mean and/or median *n*SLCD 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 *n*SLCD values), and/or a shortening of the upper tail of the distribution indicative of a decline in peak demands (lowered 95th percentile *n*SLCD value). Detailed statistical analysis of summer water demands from the pre- and post-restriction 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 4.4:

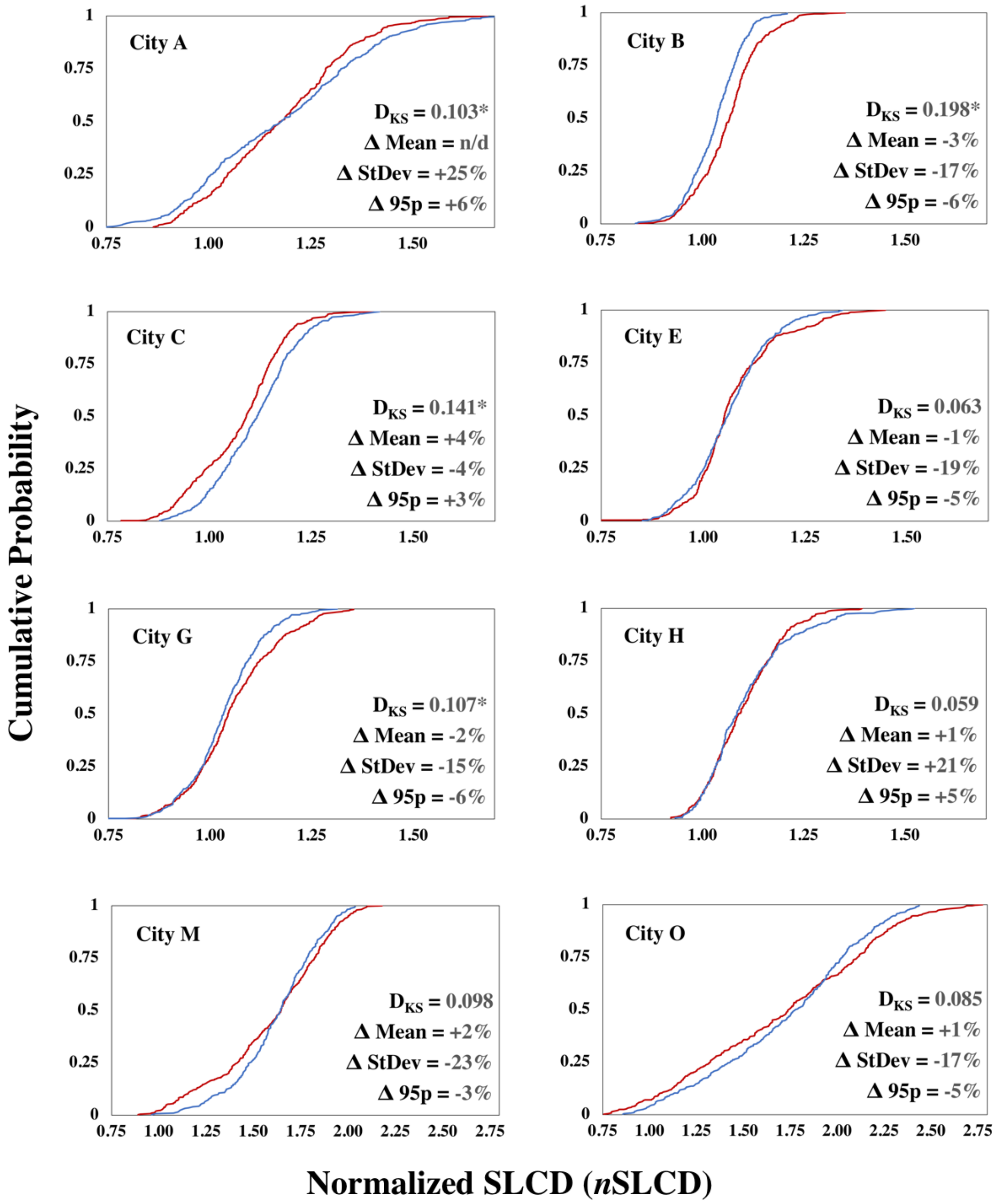

Figure 4.4: Cumulative distribution plots of SLCD as a function of $\overline{LCD_y}$ (nSLCD) before and after bylaw imposition in humid cities (top three rows) and semi-arid cities (bottom row- note difference in x-axis). Red line represents nSLCD values before bylaw, blue line after bylaw. Inset boxes show comparison metrics D_{KS} (Kolmogorov-Smirnov distance, where significance at 95% confidence level is denoted by an asterix), Δ Mean (change in mean), Δ StDev (change in standard deviation), Δ95p (change in 95th percentile value)

The analysis, which included five years of normalized SLCD demand values for each period and each city (with exceptions as noted), revealed that the two-sample Kolmogorov-Smirnov distance between the pre- and post-bylaw demand distributions was significant at the 95% level in 4 of the 8 bylaw cities studied, of which only two were significantly different in the anticipated (negative) direction (Fig. 4.4, Table S1). In all cases changes in mean and median demand between the two time periods was minimal, and some cities even saw net increases in multiple demand metrics following the imposition of bylaws (see Table S1 for full results). 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 4.4; Table S1) have seen small declines in mean and median demands alongside more significant reductions in both the standard deviation and 95th percentile values of the *n*SLCD 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 Kolmogorov-Smirnov test. In the third case (city E), demands declined most meaningfully in the upper tail region and the standard deviation of the demand distribution declined by nearly 20% following the imposition of restrictions, though D_{KS} was not significant at the 95% confidence level. Although mean water demands remained largely unchanged 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 & A; Figure 4.4; Table S1) also saw little difference in the mean and median of the normalized summer demands between the two time periods. However, 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 significantly (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 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, it has also become more variable at the daily scale with slightly higher peaks in demand. We argue that, in humid cities, when the stringency of bylaws is moderate they don't have a discernible effect on water demand, and other confounding factors, like price and demographics, are possibly responsible for the observed patterns. We did explore the relationship between trends in demand and price, but found no significant effect.

- The two semi-arid bylaw cities studied (Cities M and O; Fig. 4.4; Table S1, Annex A) have similarly seen little net shift in mean or median daily demands, but show a significant reduction in the spread of the distribution of daily *n*SLCD values after restrictions were imposed. In both cities, the standard deviation of normalized summer demands decreased by approximately 20 percent in the years following the imposition of restrictions, and both also saw reductions in the 95th percentile daily demand value. Both semi-arid 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). However, as with the humid cities, no significant change is apparent in the mean or median summer day demands in the years following bylaw imposition.

4.4.4.2. 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 clusters were used to develop the following threshold conditions for identifying *hot and dry days* following the method outlined previously (Section 4.3.4):

- Cluster 1 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

-Cluster 2 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, 14 and 13 individual dry heatwave events were identified within cluster 1 and 2 respectively. These events spanned a minimum of 3 and a maximum of 20 days during which all cities in the cluster 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 ($\overline{hw\mathrm{SLCD}}$), 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, $\overline{hw\mathrm{SLCD}}$ 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 SLCD 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.

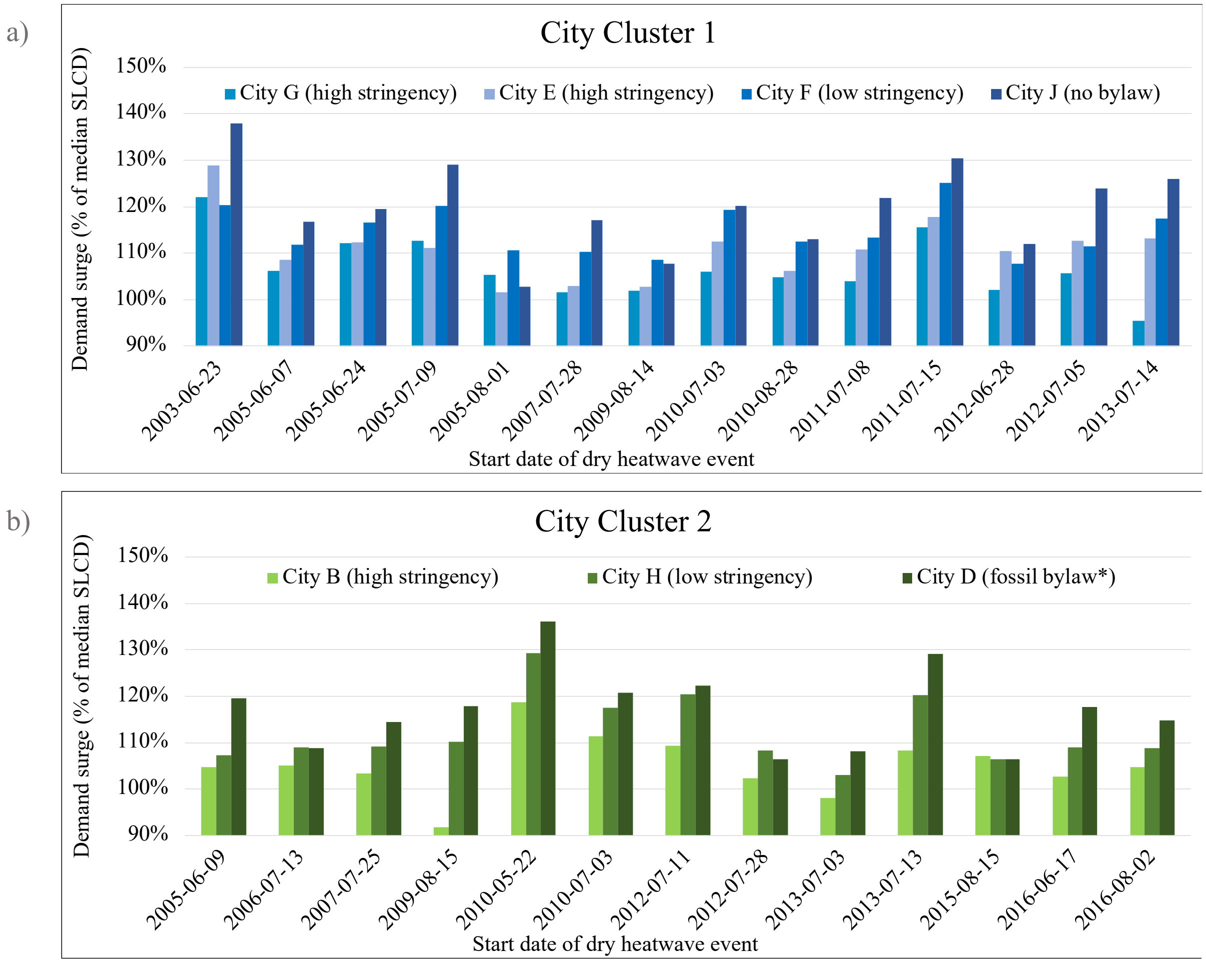

*Figure 4.5: Water demand surges during dry heatwaves in a) city cluster 1 and b) city cluster 2 *note that city D has a fossil bylaw introduced in 1971 that is classified as medium stringency (Table 4.1)*

4.5. Summary and Conclusions

We used daily water production data from 15 Canadian 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 200% 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 surge 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 datasets. 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 found in parts of the arid southwestern US.

Permanent water use restrictions had little impact on the mean and median water demand during the summer months in both humid and semi-arid cities, irrespective of the stringency of bylaw imposed. This stands is in contrast to previous literature that has largely demonstrated the effectiveness of temporary restrictions in curtailing overall water use during drought events (Kenney et al., 2004; Mayer et al., 2015). However, we also found evidence that stringent permanent water use restrictions can reduce demand surges during hot and dry periods when the need for water conservation is most apparent, which 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.

Permanent water use restrictions did impact the distribution of normalized daily summer water demand, with effects being greater for semi-arid cities and those with more stringent bylaws. Specifically, we found that in humid cities, stringent water use bylaws have been successful in reducing the demand variability, as captured by the standard deviation and the 95th percentile of the normalized summer daily water demands between the pre- and post- bylaw years. 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 influent 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.

Based on these observations, 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 North American 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 (Cromwell et al., 2007). 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.

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Bridging section

The preceding study showed that the permanent or seasonal water use restrictions enforced in most Canadian cities are not generally effective in tempering summer-season water demand surges. Overall, summer-season water demand increases were moderate in most ‘humid’ Canadian cities (that is, those located outside of the small pockets of semiarid climate that exist in the country): on a median summer day, water demands in several of those cities was only very slightly (10-15%, see Fig. 4.4) higher than average winter day demand. However, the upper extremes found within the distribution of daily-scale water demands are perhaps most interesting: when we zero in on short term periods of high heat and low precipitation in those same cities, we find summer daily demands that exceed the seasonal median value by 30-40% or more (Fig. 4.5).

The discovery of especially acute demand surges during abnormally hot and dry summer periods evokes new questions about how urban water demands may be affected by extended summer periods of drought-like conditions. If water demands increase significantly during brief, days-long periods of extreme heat and lack of rain, what might be the demand impact of extended warm summer periods that overlap with meteorological drought conditions? Considering that urban drought impacts can be driven by both reductions in supply and increases in demand, how do demand surges during summer drought events contribute to water shortage threats in Canadian cities?

The next study expands the timescales of the ‘dry heatwave’ analysis from Chapter 4 to the scale of summer droughts. As part of an overall effort to gain insight into the scale and severity of seasonal water shortage threats in the Canadian climate, this second data-driven study seeks to more precisely quantify the relationship between urban water demand and meteorological drought conditions that overlap with the summer watering period in Canadian cities.

Chapter 5:

Drought Demand Dynamics: Analysis of Changes in Water Demand During Short-term and Seasonal Droughts in Canadian Cities

Finalized paper to be submitted to *Urban Water Journal* (Taylor & Francis)

5. Drought Demand Dynamics: Analysis of Changes in Water Demand During Short-term and Seasonal Droughts in Canadian Cities

5.1. Overview

Urban water systems can experience water stress when a deficit in precipitation leads to decreased source water levels in lakes, rivers, wells, and reservoirs. Canadian cities are not exempted from these worries: though most parts of the country receive abundant rainfall on an annual basis, summer droughts driven by sub-annual periods of low precipitation, possibly compounded by anomalies in snowmelt patterns, are commonplace in different parts of the country. An *urban drought* is experienced when demand for water threatens to outstrip available supplies; however, little is yet known about how water demand dynamics during hot, dry summer months may contribute to the urban drought phenomenon in the Canadian context. This study makes use of a rich dataset of historic water production values from 15 Canadian cities to detect shifts in urban water demand during summer periods of meteorological drought. Results from correlation analysis revealed that excess summer water demands are very strongly correlated with climate variables at the monthly scale, with correlation coefficients ranging from -0.13 to -0.64 for drought persistence over various timescales, and from 0.35 to 0.92 for maximum temperature. Simple and bivariate regression testing shows that maximum summer temperatures are more influential on summer water demands than drought-like precipitation deficits in most of the cities studied; in this perspective, dry summer periods compounded by high heat are most likely to lead to large increases in demand and intensify water shortage risks for urban water systems. Somewhat surprisingly, water demands in the study's most arid cities were least sensitive to drought conditions, suggesting that discretionary water use is most volatile in cities where outdoor watering of urban landscapes is normally supplemented by rainfall during the summer months.

5.2. Introduction

Drought is a condition wherein a lack of precipitation, possibly compounded by an increase in temperature and/or evapotranspiration, causes the water supply:demand ratio of a human or natural system to reach a critical low threshold after which water users and ecosystems are impacted by a lack of water (Medd & Chappells, 2007; Van Loon et al., 2016; Wilhite & Glanz, 1985). Within an urban water system, the location of this critical supply:demand threshold is set by water utility managers, who determine at what point the combination of water storage levels, precipitation forecasts, and the expected demand for water services are indicative of a drought or threatened drought condition (Buurman et al., 2017; Medd & Chappells, 2007). Because urban water demand can be highly variable at short time scales especially during the hot summer months, drought events experienced within urban water systems (*urban droughts*) are expected to be influenced by changes in the demand side of the supply:demand equation (See Chapter 3). However, the contribution of demand dynamics to urban drought situations remains poorly understood.

Water demand in cities that feature both centralized municipal drinking water service and extensive landscaped area (lawns and gardens, both private and public) is generally understood to be composed of two main elements: 1) indoor water use, which is climate-insensitive and varies based on commonly installed water-using technologies, household size, socioeconomic factors, and changing water use preferences and attitudes, and 2) outdoor water use, which is highly sensitive to climate factors and almost entirely attributable to irrigation activities by residential, municipal and commercial water users (Savelli et al., 2023, Chang et al., 2014; Gober et al., 2015; Mayer et al., 1999; Mini et al., 2014; Ontario Water Works Association, 2008). Climate-driven outdoor water use during the summer (watering) months should have outsized effects on the urban supply:demand relationship because it tends to increase in response to high temperatures and low precipitation, the same conditions which contribute to decrease water availability during drought. In fact, Shandas et al., 2015 found that water managers surveyed from across the US identified the combined impacts of outdoor water use and long-term drought as among the most significant stressors to water systems in that country. This dynamic is also central to the study of urban adaptation to climate change impacts: Gober et al., 2015 present outdoor water use as ‘an adaptation problem’ that cities must confront as they seek to adapt to increasing hydroclimatic variability.

While the risk of long-term drought is lower in Canada’s relatively humid and temperate climate than it is in more arid regions, seasonal water stress conditions and summer droughts are common even in areas that are considered water-rich based on long-term averages, and these phenomena are expected to increase under the influence of climate change (Brauman et al., 2016; Hoekstra et al., 2012; Wada et al., 2011). While most Canadian regions are relatively water secure on an annual basis, the country’s population is highly concentrated around specific water bodies, and the temporal distribution of blue water flows is seasonally mismatched with periods of high urban and agricultural demand in some areas, creating the conditions for low water levels on sub-annual timescales (Trudel et al., 2016). One study of monthly water scarcity in a range of major global watersheds found that even the St. Lawrence watershed, North America’s largest by volume, is vulnerable to severe water stress (where aggregate demand threatens to outstrip available blue water flows) in August of each year (Hoekstra et al., 2012).

Temporary water shortage situations are a common, if little-discussed issue in Canada: over 25% of Canadian cities reported having experienced at least one temporary supply shortage when data was last reported in 2004, and more recent studies have shown that water treatment plants are vulnerable to low-flow conditions even in water-rich Quebec (Trudel et al., 2016, Carrière et al., 2006). Water shortage threats during periods of hot and dry weather have spurred aggressive outdoor water conservation efforts in cities across the country, focused on the introduction of summer water use bylaws and public education campaigns (Finley et al., 2020; Environment Canada, 2004). To date, little is known about how water demand dynamics may contribute to urban drought vulnerability in the context of Canadian cities.

5.2.1. Background

Previous studies that evaluated the impacts of drought conditions on urban water demand in single-city case studies have generally found that drought conditions and precipitation deficits evaluated at annual or sub-annual scales tend to increase summer water demand. Balling and Gober (2007) found that drought condition as indicated by the Palmer Drought Severity Index (PDSI) was significantly correlated (r=-0.52) with water demand in Phoenix, AZ, though the correlations between demand and temperature (r=0.55) and raw precipitation totals (r=-0.69) were stronger. Gutzler and Nims (2005) found that although average maximum temperature and raw precipitation variables exerted a similar degree of influence on urban water demand in Albuquerque, NM, the interannual *change* in summer-seasonal precipitation was the primary predictor for variations in summer demand at the monthly scale. Maidment and Miaou (1986) and Chang et al. (2014) conducted similar analyses in US cities with more temperate climates (located in Pennsylvania and Oregon, respectively) and found summer heat to be more closely associated with water demand than precipitation or lack thereof. Though no drought-focussed studies of demand have yet been conducted in Canada, studies that evaluate water demand model performance in Canadian cities point to a similar dynamic, where water demands respond primarily to maximum temperatures are less so to rainfall patterns (Adamowski, 2012, Chen et al., 2006).

Longer-term studies undertaken in Spain and the Southwestern US have found that urban water demand can gradually decrease over time when drought conditions persist for many years (Bernardo et al., 2015; Gonzales & Ajami, 2017; Hannibal et al., 2018). This demand response is likely related to the widespread water conservation campaigns and drought adaptation efforts deployed during extended drought events, and there is some evidence that demand can rebound after the drought ends (Gonzales & Ajami, 2017). Taken together, these findings suggest that while drought conditions may spur higher water use rates at shorter timescales, water users in cities that experience multiyear drought events may reduce discretionary water use over the longer term as they adapt to limited water availability and the water conservation initiatives of local water agencies.

In Canadian cities, water demand can be expected to exhibit a unique response to drought conditions and climate variables due to their geographic, sociodemographic and climatic differences from the cities studied previously; we also expect to find considerable internal variation among cities across the country. The situation of Canadian cities is also particular in that most experience true winter, which has the effect of concentrating all climate-driven water use within a few summer months each year. In this respect, we expect that the demand response to drought in Canadian cities will be limited to the summer season and can be conceptualized as a response to sub-annual *summer drought* periods at the seasonal scale or shorter.

Water demand modelling literature has long established that outdoor water demands tend to increase with higher temperatures (especially extreme/maximum temperatures) and decrease in response to precipitation events (Balling & Gober, 2007; Bougadis et al., 2005; House-Peters & Chang, 2011). However, drought represents a temporal persistence of low precipitation (combined with other factors) and not simply an expression of low total precipitation; indeed, drought's impact on water demand has been shown to be distinct from that of raw precipitation values in previous research (Balling & Gober, 2007, Gutzler & Nims, 2005). In order to evaluate drought's effects on water demand as separate from non-drought precipitation drivers of demand during the summer months, it is important to clearly define the temporal extent of ‘drought’ within the context of a summer watering period, as well as the most appropriate indicators/indices to measure drought conditions at that timescale.

In the Canadian context, where climate-driven water use is confined to a few summer months and preceded by annual snowmelt, we are most interested in the effects of summer droughts, where precipitation deficits combine with hot summer temperatures and to generate short-term water shortage threats for urban water systems (Cromwell et al., 2007; Finley et al., 2020). These situations are likely to increase in the future as studies show that concurrent drought and summer heat events are increasing in intensity and frequency across the globe (Mazdiyasni & AghaKouchak, 2015; Zscheischler et al., 2018).

Drought is most commonly identified through the use of various precipitation-related or combined precipitation- and evaporation-related index values. In assessing meteorological drought, the most widely used drought indices include the Standardized Precipitation Index (SPI), the Standardized Precipitation and Evaporation Index (SPEI), and the Palmer Drought Severity Index (PDSI) (World Meteorological Organization, 2012; Ontario Ministry of Natural Resources and Forestry, 2016; Paulo & Pereira, 2006). Each of these indices has unique advantages: SPI and SPEI are popular because they have low data requirements and can be compared across climate types, whereas PDSI is considered to be more directly representative of field conditions as relevant to agricultural and natural systems (Gurrapu et al., 2014; Paulo & Pereira, 2006). In the context of Canadian cities responding to summer drought conditions, SPI and SPEI are favored over the PDSI because of their advantages in measuring drought at sub-annual timescales and because both have been shown to correlate well with streamflow conditions in Canada (Gurrapu et al., 2014; Ontario Ministry of Natural Resources and Forestry, 2016).

Both SPI and SPEI quantify drought conditions as standardized deviations from a probability distribution function of historic climate conditions: for the SPI, the index measures departures in terms of precipitation only, whereas the SPEI incorporates evapotranspiration values as well to provide an indication of the combined conditions of heat and drought. Previous studies have used drought index values as independent variables within regression analysis to identify the portion of variance accounted for by drought conditions (Gonzales & Ajami, 2017, Hannibal et al., 2018). Because isolating the impacts of drought requires controlling for changes in other climate variables; SPI (which unlike SPEI does not incorporate any temperature-related variables) is most useful in identifying the impact of drought as independent from temperature. SPI is commonly measured at the 1, 3, 6, and 12+ month timescales, with the three-month value (SPI3) being the most representative of a summer drought event in the Canadian climate context (Ontario Ministry of Natural Resources and Forestry, 2016).

5.2.2. Study objective

Drought conditions influence urban water reliability from both sides: a lack of precipitation reduces the abundance of water sources while simultaneously driving changes in water use behaviours and aggregate water demand. As summers get hotter and hot summers get drier, it is important that we understand how water demand responds to drought as part of a strategy to ensure the reliability of urban water services.

The objective of this study is to quantify the degree to which water demands in Canadian cities are influenced by meteorological drought conditions that overlap with the summer watering season. Given that water demands in Canadian cities have been shown in previous work to be highest during the summer months due to a surge in climate-sensitive water use (Finley et al., 2020), the present analysis seeks to assess the degree to which already-elevated summer-seasonal water demands may be further intensified by summer drought conditions. The study makes use of a vast dataset of daily-scale water production values collected from 15 cities to identify and quantify the demand impacts of drought as experienced on both seasonal and monthly timescales in the Canadian context.

5.3. Methods

5.3.1. Data Collection and preparation

The water demand data used to conduct the analysis is described in detail in a previous study (see Finley et al., 2020, Chapter 4). Between 13 and 25 years of daily water production data was collected from 15 Canadian cities, including 12 individual municipal water utilities and three regional water systems serving two or more municipalities each (also designated here as 'cities'). Specifics about the dataset, including the criteria used for sample city selection, city climate classification, and the steps followed to prepare and clean the data are detailed in Chapter 4 (Finley et al., 2020).

As described in Chapter 4, climate data for each city were obtained from Environment Canada's historic weather database (Environment and Climate Change Canada, n.d.). Weather stations closest to the city centre were prioritized, and in cases where these stations had missing data, gaps were filled using data from the next-nearest station with complete data. Participating cities were categorized into two climatic groups according to aridity index (AI) and the UNEP climate classification system; within the sample, five study cities are classified as semi-arid (AI<0.5) and ten cities are classified as humid (AI>0.65) (see Finley et al., 2020).

As in previous work, all cities have been kept anonymous in the reporting of results. Cities are represented using a letter identifier assigned based on AI values, City A being the most humid and City O the most arid.

5.3.2. Metrics

In this paper, the term *water demand* refers to per-capita water production values over various time scales. *Per-capita* values are used to ensure that water demand trends are not obscured by changes in service population over the years of data studied. All water demand data and results are presented in litres.

Most of the methods employed in this study focus specifically on summer-monthly (and in some cases summer-daily) water demand values, where "summer" is defined as spanning the months of June-September of each year; these months were isolated as they represent the period within which outdoor water use is most widespread in Canadian cities (see Finley et al., 2020, Chapter 4). In most instances, we represent summer water demand values in terms of their exceedance over base (winter) water demands, calculated as the mean of the 3 months of lowest water demand within each calendar year (Mini et al., 2014). This approach is commonly used in studies of climate-driven water use as it provides a reliable estimate of summer-only water demands and serves to remove the impacts of time trends in overall water demands caused by factors unrelated to climate, notably upgrades to water-using technologies, structural changes to codes and standards, and evolving indoor water use habits (Gonzales & Ajami, 2017).

In order to enhance the comparability of results among the cities studied, monthly summer demand values were normalized within all city datasets. In previous work with this same dataset (Finley et al., 2020, Chapter 4), summer demand values were normalized by expressing them in terms of their multiplicative increase over winter (base) demand values:

$$nSDi,y = SDi,y\ /ADy \tag{3}$$

where $nSD_{i,y}$ represents individual normalized summer demand value for month *i* in year *j*, SDi,y is the summer-monthly demand value in litres per capita, and AD_y is the base demand value for that calendar year. In this context, an *n*SD value of 1.2 for July 2016 communicates that mean monthly demand in July was 20% higher than base demand for 2016 in that city.

While the *n*SD value remains useful in the present study as a means to understand the relative summer increases in water demand among the various cities studied, the use of linear regression modelling in the present study requires that the demand variable be standardized via a linear transformation to ensure that regression assumptions are respected. As a substitute, here we use a standard score value derived from the raw value of 'excess' water used in each summer month as a supplement over base monthly demand:

$$ESD_{i,y} = SD_{i,y} - AD_y \tag{4}$$

$$Z_{ESD} = ESD_{i,y} - meanESD\ /\ stdevESD \tag{5}$$

Like a statistical Z-score, the standard demand score value, Z_{ESD} has a mean of 0 and a standard deviation of 1; as such, it expresses monthly summer demand in terms of the number of standard deviations from the mean. The use of a standard score as the dependent variable within a multi-city analysis offers the potential for direct comparability between regression models built for cities with varying baseline levels of summer (and winter) water demand; that is, cities that tend to have a high mean *n*SD will provide model statistics and coefficients that can be directly compared with those cities with lower average summer demands where *n*SD hovers closer to 1.

5.3.3. Drought indices

We use Standardized Precipitation Index (SPI) values to represent meteorological drought conditions across Canada for the purposes of this study. This index value is deemed most appropriate because 1) it is independent of temperature, and thus facilitates the evaluation of the separate impacts of drought and heat on water demand, 2) it is context-independent and normalized, allowing for reliable cross-city comparisons (Ontario, WMO), 3) it is considered a reliable indicator of drought conditions at short timescales (World Meteorological Organization, 2012), and 4) it has demonstrated good correlation with hydrological drought conditions in the Canadian context (Gurrapu et al., 2014, Ontario Ministry of Natural Resources and Forestry, 2016).

SPI values for each city were calculated using the SPEI package for R (Begueira, 2017) using total precipitation data sourced from Environment Canada's historic climate database (Environment and Climate Change Canada, n.d.) fitted to the package's default (gamma) distribution. SPI values for the period covered in the analysis (years for which demand data is available) are calculated based on 30 years of antecedent monthly precipitation data in each case. To best represent the seasonal and shorter timescales of interest in the context of Canadian urban droughts, we use the smallest time intervals commonly used for this index: that is, the 1-, 3- and 6-month SPI values. We are interested in these drought periods as representative of drier than normal summer months (1-month SPI), drier than normal conditions during the summer growing season (3-month SPI), and extended drought conditions persisting through the late winter/spring and into summer (6-month SPI) (World Meteorological Organization, 2012).

5.3.4. Monthly regression analysis

In this analysis step, we use multiple linear regression (MLR) to quantify the influence of drought condition on summer-monthly water demand in each of the study cities. Given that rainfall and temperature variables are known to have the strongest influence on outdoor water demand patterns, we use univariate and bivariate regression models to compare the relative influence of drought and temperature variables on summer water demand values in each of the cities studied.

To determine the most appropriate climate variables to be used in the regression, we first conduct correlation analyses on drought- and heat-related variables of interest. Variables tested include mean maximum monthly temperature (MaxT, °C), total monthly precipitation (PRCP, mm) and 1-, 3-, and 6-month SPI values (SPI1/SPI3/SPI6, unitless). These parameters were chosen based on past research and according to the specific needs of the study:

- Maximum temperature has been found to be the most influential heat variable in estimating climate-driven water demand in multiple studies (Adamowski, 2008; Adamowski et al., 2012; Eslamian et al., 2016; Maidment & Miaou, 1986; Balling & Gober, 2007). Mean maximum temperature is reported in Environment Canada historical weather records and represents the mean of daily temperature maxima for each calendar month (Environment and Climate Change Canada, n.d.).
- Both water availability and water demand vary on short timescales in the context of urban drought events (Finley et al., 2020; Kallis, 2008). The 1, 3, and 6 month SPI values represent the shortest time scales used to indicate drought condition within drought literature (World Meteorological Organization, 2012).
- Total precipitation is included to evaluate if meteorological drought condition (as communicated by SPI) is more predictive of summer water demand than raw precipitation values.

The strength of the correlation between these variables and standardized excess water demand (Z_{ESD}) is assessed using the Pearson moment correlation coefficient, *r*. The precipitation variable found to correlate most strongly with demand in the majority of cities studied will then be used along with the temperature variable (MaxT) to build uniform bivariate regression models deployed to assess the influence of drought on water demands in each of the 15 cities studied.

We conducted two-step regression testing for all cities using the standard score Z_{ESD} as a dependent variable and the two climate variables independent variables. Because the drought variable is the parameter of specific interest for the purposes of this study, it was the first to be introduced in each case. The model fit (expressed as the R^2 value) for both a drought-only (univariate) model and the combined drought- and heat- (bivariate) model are compared to gauge the influence of drought before and after controlling for temperature. Regression coefficients and their respective significance values (expressed as *p* values within a 95% confidence interval) are used to assess the relative effect sizes of the drought and heat variables within the water demand regression equation for each city.

It is worthwhile to note that the deployment of simplified, bivariate linear regression for this analysis is not intended to provide a comprehensive accounting of all variables that may influence summer water demands. This format is favored to optimize the strength of regression models within a limited sample size, and to accord with the specific scope of the research objective, which focuses on identifying the specific influence of climate variables on summer water demands in Canadian cities. While other, non-climate variables may influence summer water demands in the cities studied (notably socioeconomic characteristics, lawn sizes, water price, etc.), these remain outside the scope of the current analysis. Further comparisons could benefit from the inclusion of non-climate variables, though it can be challenging to obtain complete and comparable longitudinal data about such factors over the multi-decadal time scale covered by the dataset, and it is difficult to ensure the representativeness of city-scale data (as required to perform cross-city analysis) for variables which are characterized by high spatial variability within urban areas.

The incorporation of drought index values meaningful only at monthly timescales or longer requires the use of monthly values as the basis for regression analysis, which yields relatively small sample sizes for model testing. In accordance with conventions for determining the minimum number of observations per tested variable to ensure sufficient power within regression analysis, we establish a minimum sample size of 60 for monthly regressions. This limit is set to allow for the inclusion of a maximum number of cities in the analysis while also following the guidance of both conventional and modified ‘rules of thumb’ for statistical methods as outlined in Wilson VanVoorhis et al., 2007.

To complement individual regression testing at the city scale, we also compiled a multi-city panel dataset to evaluate the overall influence of drought on water demand across all the cities studied. A pooled regression model was developed for all cities, incorporating variables for drought (as indicated by SPI), temperature (MaxT), city, and month. Within the multi-city model, we also tested the significance of dummy variables for high vs. low average summer water use (determined by overall mean *nSD*), the presence vs. absence of water use restrictions, and differing baseline aridity (semi-arid vs. humid cities, as defined in section 5.3.1). When these variables are found to be significant, the multi-city model is divided into corresponding groupings to evaluate the difference in drought impacts on demand in various city types and with or without applied restrictions.

5.4. Results and discussion

5.4.1. City characteristics

The cities included in this study are characterized in detail in Finley et al. (2020). For ease of reading, their essential features and summary details are repeated in Table 5.1 below:

Table 4.1: Study city characteristics

City	Climate type (AI)	Years of data provided	Population class (2016)	Mean BASE per-capita water demand, 2010-2015 (LCD)	Mean SUMMER per-capita water demand, 2010-2015 (LCD)	Mean summer MaxT, all years (°C)
A	Humid (2.0)	18	50K-100K	352	473	23.9
B	Humid (1.3)	25	100K-250K	376	415	23.5
C	Humid (1.2)	14	50K-100K	497	609	23.8
D	Humid (1.2)	17	250K-500K	444	558	24.6
E	Humid (1.1)	20	500K-1M	275	311	24.5
F	Humid (1.1)	18	250K-500K	321	389	24.8
G	Humid (1.1)	20	100K-250K	344	377	24.4
H	Humid (1.1)	13	250K-500K	390	488	24.7
I	Humid (1.0)	15	>1 M	326	425	25.4
J	Humid (1.0)	15	250K-500K	312	439	25.4
K	Semi-arid (0.48)	15	100K-250K	301	390	23.6
L	Semi-arid (0.44)	15	<50K	391	568	23.9
M	Semi-arid (0.39)	18	50K-100K	382	988	26.0
N	Semi-arid (0.37)	21	50K-100K	396	994	25.0
O	Semi-arid (0.34)	24	50K-100K	379	1070	26.8

As reported in that study, base (indoor) water demands expressed in per-capita (values (litres/capita/day, LCD) are similar among all 15 cities, ranging from 300-450 Litres/capita/day when averaged over the 2010-2015 period for which all cities submitted data. However, differences in outdoor, climate-driven water use rates are visible in the wide variability in summer water demand values, which when averaged over that same period range from 311 to over 1000 LCD (Finley et al., 2020). The three most arid cities in the sample (cities M, N, and O) have especially high summer water use; water treatment plants in these cities regularly produce over 2.5 times more drinking water in summer than during the winter months. Mean summer (June-September) maximum temperatures are also included in Table 5.1 to demonstrate how summer conditions vary within the humid and semi-arid city subgroups; it is worth noticing that the semi-arid group includes two cities (K and L) that are characterized by cooler summers than the rest of that group.

5.4.2. Regression analysis

Because the number of summer months within the years of data provided do not meet the minimum sample size of *n*>=60 as described in the previous section, cities C and H were excluded from the individual regression analysis step (though both are included in the multi-city regression). Consequently, a total of 13 cities underwent individual correlation and regression testing.

Prior to the analysis, all variable datasets were tested for normality using the Jarque-Bera test, where the skewness and kurtosis of sample distributions are tested for deviations from a normal distribution through the calculation of a test statistic, itself fitted to a chi-squared distribution (Garabaghi et al., 2019). No deviations from normality were identified among the independent or dependent variables based on a 2-tailed test of their respective Jarque-Bera test statistics at a 95% confidence level.

The Mann-Kendall nonparametric trend test and Sen's slope estimate were used to detect monotonic trends in the data (Cromwell et al., 1994). Because a gentle yet significant trend was found in the demand variable in some of the cities of the sample, we performed linear detrending on all demand datasets by removing the trendline formed by a simple linear regression relationship between year and (non-standardized) mean excess summer demand, meanESD_j (Balling and Gober, 2007).

Regressions were checked for autocorrelation by evaluating Durbin-Watson statistics and by plotting autocorrelation and partial autocorrelation functions (ACF and PACF plots) for each model. We find that the temperature variable introduces some degree of autocorrelation to all models that include the MaxT term; however, the degree of autocorrelation was not sufficient to warrant the inclusion of new variables into small-*n* individual city models at the risk of compromising the power of the regression analysis. Previous research has deemed water demand datasets to suffer from problematic levels of autocorrelation at daily timescales, but monthly demand models have not been subject to this same concern (Chang et al., 2014, Adamowski et al., 2012).

5.4.3. Correlation testing

In all cases, standardized summer-monthly excess water demand (Z_{ESD}) was found to be correlated with all climate variables tested, including mean maximum temperature (MaxT), total precipitation (PRCP), and drought index values SPI1, SPI3, and SPI6. These correlations, as represented by the Pearson correlation coefficient *r*, were all in the expected direction- that is, MaxT exhibited a positive correlation with summer water demand and all drought and precipitation variables exhibited a negative correlation. Table 5.2 presents the correlation coefficients of all climate variables with summer water demand in the cities studied. The strongest correlation among the precipitation/drought variables are presented in bold for each city.

Table 5.2: Pearson correlation coefficients for Z_{ESD} and all climate variables

Variable	**Temperature**	**Precipitation / drought**			
City	**MaxT**	**SPI1**	**SPI3**	**SPI6**	**PRCP**
A	0.88***	-0.49***	-0.47***	-0.21	**-0.64*****
B	0.35***	-0.13	**-0.26****	-0.20*	-0.12
D	0.77***	**-0.23**	-0.15	-0.16	-0.17
E	0.58***	-0.41***	**-0.49*****	-0.41***	-0.39***
F	0.76***	-0.57***	**-0.64*****	-0.50***	-0.59***
G	0.45***	-0.46***	**-0.46*****	-0.26*	-0.40***
I	0.74***	-0.36**	**-0.38****	-0.32*	-0.31*
J	0.81***	-0.39**	**-0.53*****	-0.44***	-0.45***
K	0.74***	-0.54***	**-0.62*****	-0.55***	-0.43***
L	0.84***	**-0.47*****	-0.44***	-0.43***	-0.40**
M	0.92***	**-0.49*****	-0.24*	-0.27*	-0.49***
N	0.92***	**-0.45*****	-0.39***	-0.39***	-0.45***
O	0.90***	-0.43***	-0.23*	-0.26**	**-0.45*****

Significance levels: * $p <= 0.05$, ** $p <= 0.01$, *** $p <= 0.001$

Results of the correlation analysis indicate a remarkably strong relationship between detrended, standardized summer-monthly water demand and climate variables in cities across Canada. Indeed, values of the Pearson's *r* correlation coefficient identified in this analysis exceed those found in other studies of this type carried out in the US (Balling & Gober, 2007, Chang et al., 2014). However, differences in data preparation and timescales should account for much of the difference in results; for example, Balling and Gober's 2007 Phoenix study, which found drought and temperature correlations of 0.52 and 0.55 respectively, examines the relationship between year-round monthly water demand residuals with annual climate data rather than distilling the data to measure the summer-only relationship as we have done here (Balling & Gober, 2007). Nonetheless, the scale of the correlations identified is indicative of a close relationship between climate variables and summer water use behaviours in all Canadian cities studied.

As seen in Table 5.2, there exists considerable variability across study cities in the strength of the correlation between summer-monthly water demands and climate variables tested. Water demand was strongly linked to maximum temperature in each case, with the strongest relationships seen in the most arid cities of the sample (cities M, N and O), where correlation coefficients exceeded 0.9 indicating a very strong relationship. Only one city showed a stronger demand correlation with the 3-month SPI value than with maximum temperature (city G), but the difference was not significant between the two. The consistent and strong correlation between summer excess water demand and heat (MaxT) in the Canadian cities studied contrasts with earlier drought and water demand modelling studies conducted in US cities, where precipitation was often found to be more influential on summer water demand than temperature variables (Balling and Gober, 2007; Gutzler & Nims, 2005; Chang et al., 2014; Kenney et al., 2008).

Drought and precipitation variables were nonetheless strongly correlated with summer water demand values in most of the Canadian cities studied. All cities but one (city D) had at least one drought variable that showed a significant correlation with summer-monthly water demand (Table 5.2). The 1- and 3-month SPI values dominated as the most influential variables in most cases, and the 3-month SPI value (SPI3) value accounted for the most variability in summer water demand in over half (7/13) of the cities studied. The most arid cities in the group tended to show a stronger relationship with short-term precipitation anomalies (PRCP and SPI1), while most humid cities (as defined in section 5.3.1) had a stronger relationship with the 3-month SPI value. 6-month SPI, representative of longer-term drought conditions persisting from late winter into the summer months, did exert some influence on water demands in most cases but was not found to exhibit the strongest correlation with demand in any of the cities studied. Interestingly, total monthly precipitation (PRCP) was most strongly correlated with water demand in only two cities, and these constituted the most humid and the most arid of the group (cities A and O).

Correlation testing also demonstrated that temperature and precipitation/drought are not independent variables, a finding that mirrors previous research in this and other fields (Balling & Gober, 2007; Gutzler & Nims, 2005). Cross-correlation between temperature (MaxT) and precipitation (PRCP) values were evaluated for each city using the same Pearson product moment correlation test; results show a weak positive or negative correlation ($-0.1 < r < 0.1$) in two cities (B and D), and a moderate negative correlation in the rest of the group ($-0.41 < r < -0.18$). Results were similar for the relationship between temperature (MaxT) and drought index values (SPI1/3/6), indicating that summer months in all cities were more likely to be either wet and cold or hot and dry. These relationships complicate the use of both temperature and precipitation or drought variables in a combined regression model, but extensive previous research has set a precedent of their use as independent variables in analysing climate drivers of water demand (House-Peters & Chang, 2011; Chang et al., 2014), and the median value of the correlation relationship for all cities was deemed sufficiently low (median $r = -0.25$ for MaxT/PRCP, -0.24 for MaxT/SPI3) to proceed with the analysis as designed.

Interestingly, the strongest correlation between temperature and drought values was seen in City A, the most humid of the group by a considerable margin. City A represents the only study city located in Canada's western coastal region, where annual rainfall can reach 2500mm (Environment and Climate Change Canada, n.d.). However, summer is the driest period of the year in this area, and summer water use in this community is high: as seen in Table 5.3, City A's mean *n*SD values are the second highest within the humid city group (as delineated in section 5.3.1). As visible throughout this section, analysis results for this city stand apart from others in the humid city group in multiple dimensions.

5.4.4. Bivariate regressions

Based on the findings that 3-month SPI (SPI3) was the drought index period most closely correlated with water demand in the majority of cities tested, we used this value along with the temperature variable MaxT to build a uniform bivariate climate regression model for deployment in all cities. Simple regression with the drought variable (SPI3) was performed first, then a combined MaxT/SPI3 bivariate regression added to compare model statistics after controlling for temperature. Model fits and bivariate model coefficients are shown in Table 5.3. The table also incorporates some key city characteristics (aridity index and average summer water demand, *n*SD) in order to contextualize the results. To aid in understanding, we also include a representation of each variable's 'demand effects in real terms', a translation of model coefficients in terms of percentage change in average excess summer water demand in each city (% change in mean ESD). However, it is important to understand that this representation has limitations in that the use of percentage values creates the appearance of larger impacts in cities with low mean ESD values. Both coefficients and percentage results are best understood as comparative representations of the scale of impact of each climate variable, as 1) the bivariate model does not include all relevant variables influencing water demands, and 2) the units of the variables are not equivalent, so that a 1°C change in MaxT represents a different interval than a 1-unit change in the SPI3 index value.

Table 5.3: Regression statistics for univariate and bivariate climate models

City	**Aridity Index (AI)**	**Mean *n*SD**	**R^2 of univariate SPI3 model**	**R^2 of bivariate model**	**Bivariate model coefficients**		**Demand effect in real terms (% change in mean *ESD*)**	
					MaxT	*SPI3*	*1 degree increase in MaxT*	*1 Unit (1SD) decrease in SPI3*
A	2.03	1.31	0.22	0.78	*0.350 ****	*-0.036*	*+17%*	*+2%*
B	1.29	1.11	0.07	0.18	*0.152 ****	*-0.223 ***	*+6%*	*+9%*
D	1.15	1.23	0.02	0.60	*0.356 ****	*-0.124*	*+13%*	*+4%*
E	1.08	1.12	0.24	0.47	*0.208 ****	*-0.400 ****	*+11%*	*+21%*
F	1.08	1.22	0.40	0.74	*0.274 ****	*-0.415 ****	*+11%*	*+16%*
G	1.07	1.10	0.22	0.33	*0.144 ****	*-0.335 ****	*+8%*	*+18%*
I	1	1.29	0.14	0.56	*0.278 ****	*-0.085*	*+10%*	*+3%*
J	1	1.37	0.28	0.74	*0.293 ****	*-0.281 ****	*+12%*	*+11%*
K	0.48	1.34	0.38	0.74	*0.215 ****	*-0.391 ****	*-+12%*	*+21%*
L	0.44	1.49	0.19	0.76	*0.274 ****	*-0.220 ***	*+14%*	*+11%*
M	0.39	2.50	0.06	0.86	*0.269 ****	*-0.094 **	*+8%*	*+3%*
N	0.37	2.43	0.15	0.88	*0.249 ****	*-0.168 ****	*+10%*	*+7%*
O	0.34	2.86	0.05	0.81	*0.263 ****	*-0.070*	*+9%*	*+2%*

Significance levels: * $p <= 0.05$, ** $p <= 0.01$, *** $p <= 0.001$

As seen in Table 5.3, climate factors account for over 50% of the variability in summer-monthly water demand in most of the cities studied: only three cities (cities B, E, and G) had R^2 values of less than 0.5 for the combined heat and drought regression model. These same cities have the lowest average summer water demands (*n*SD) of the group- summer water production rates in these three cities is only 10-12% higher than the winter baseline, suggesting that they have minimal levels of climate-driven water use during summer. Maximum temperature had a considerably stronger impact on water demands than drought condition in most cases, suggesting that heat is a more influential driver of summer water use behaviours than precipitation deficits in the majority of cities studied. In four cities (A, D, I and O), the coefficient for the drought variable did not reach statistical significance within the bivariate model. Based on simple regression model fits and bivariate model coefficients, drought condition was the stronger predictor of water demand in only four study cities (E, F, G and K), of which three are in the humid category and one has a semi-arid climate. The high variability in the effect size of the drought parameter among cities in the humid climate category is striking, suggesting that other, non-climate variables are influential in determining to what degree heat or precipitation deficits will drive outdoor water use decisions in those communities.

The relative influence of MaxT is strongest in the warmest and most arid cities in the group: in cities M, N and O, the effect size of SPI3 variables is very minor, whereas the addition of MaxT to the bivariate model accounts for more than 70% of the remaining variance in the demand value. This result suggests that drought condition is only very weakly influential on summer water demand in Canada's driest semi-arid cities. This finding contrasts with Chang et al. (2014)'s summary conclusion that based on their own research and that of previous studies, seasonal water demand in cities located in hotter and drier parts of the US seem to be most responsive to precipitation and drought, while seasonal demand in more temperate and humid climates is most sensitive to temperature. However, as suggested by Balling and Gober (2007), behavioural factors may play a role here: in very arid cities, there is likely to be a certain amount of outdoor water use that is ‘locked in’ due to the high prevalence of automated irrigation systems and long-held landscape watering habits. In these cities, it is possible that some level of landscape irrigation is considered a baseline, unchanging requirement for those with lawns and gardens, whereas residents and businesses in humid cities can count on precipitation to fulfill some of the outdoor watering need.

5.4.5. Multicity regression

The results of regression testing performed on the combined datasets of all 15 study cities largely reinforce the findings of the individual regressions described above. In the multi-city pooled regression model (controlling for city and month), over 50% of the variance in summer water demand is found to be related to a combination of maximum temperature and 3-month SPI. Two of the dummy variables introduced to test the difference between city groupings were found to be significant, so cities were divided into subgroups according to their climate category (delineated by AI into humid and semi-arid groups, according to climate classification system described in Finley et al., 2020) and mean summer excess water demand (where *High* and *Low n*SD cities are defined respectively as those with mean *n*SD values above and below the group median value of 1.29). Subsequent regressions with the SPI3/MaxT pooled model show that model fit is better in the semi-arid and high *n*SD subgroups as compared to the humid and low *n*SD groups respectively (Table 5.4). Reinforcing the findings of Finley et al., 2020 which found that water use restrictions have minimal impact on average summer water demands, the dummy variable for the presence or absence of water use restrictions was not found to be significant within the pooled model.

Table 5.4: Regression statistics for pooled multi-city model

City group	R^2	Coefficients*	
		MaxT	SPI3
All cities	0.57	0.226	-0.239
Humid cities	0.49	0.228	-0.268
Semi-arid cities	0.77	0.245	-0.163
Low *n*SD cities	0.42	0.213	-0.286
High *n*SD cities	0.71	0.238	-0.191

* *All coefficients significant at* $p <= 0.001$

As observed in the individual city regression results, there are indications within the pooled model that cities where temperature is more influential than drought conditions are characterized by semi-arid climates and high baseline summer water demands- that is, cities where outdoor watering is most prevalent. In contrast, summer water use is more dependent on precipitation anomalies in humid cities and those with low average summer water use; however, model fit statistics suggest that climate as a whole is less predictive of water demand in those communities. Again, this finding contrasts with previous studies that found precipitation to be most influential over water demand in more arid parts of the US (Chang et al., 2014); this contrast may attest to differences in water use behaviours or infrastructure characteristics in Canadian cities as compared to those of the arid cities that have been the subject of much outdoor water use research. Further cross-city and comparative research will be needed to explore the climatic, geographic and/or sociodemographic dimensions of these relationships.

Given the higher sample size available with a multi-city model (n=1084), we also tested the influence of other variables in determining summer water demand, including the raw AI value, network density (a proxy for lot/lawn size) and city size. In all cases the influence of these variables were found to be minor as compared to the climate variables of interest, and their addition to the pooled model resulted in an R^2 increase of less than 0.01 combined (data not shown).

5.5. Discussion

The analyses suggest that drought conditions do indeed contribute to increased summer water demand rates in Canadian cities, but that meteorological drought as defined only by raw precipitation deficit is not the most significant climate factor driving summer water demand dynamics. Together, climate factors account for the majority of the variability in water demands in most of the cities in the sample (Table 5.3). However, when we compare the relative demand impact of both heat and drought status within the Canadian climate context, we find that temperature is the more influential of the two variables in most of the cities studied, and that water demands increase most sharply when drought conditions are accompanied by hot weather (Tables 5.3 & 5.4). This finding is not all that surprising when we consider that excess summer water use in Canadian cities is known to be primarily driven by irrigation demand (Ontario Water and Wastewater Association, 2008), and as such can be expected to increase in reaction to urban water users' perceptions of landscape watering need; in turn, these perceptions are likely formed through consideration of both recent rainfall amounts and expected increase in plant evapotranspiration due to warmer temperatures (Maidment & Miaou 1986; Adamowski, 2008; Volo et al. 2015). Subsequent research on the influence of drought conditions on water demands (and in turn, the contribution of those changes in demand on the propagation of urban drought impacts) should thus incorporate the influence of at least two climate dimensions: meteorological drought and summer heat.

In terms of timing, we find that the drought variable that had the most significant influence on summer water demands in the majority of cities studied was the 3-month Standard Precipitation Index (SPI) value, which can be interpreted as representative of 'summer drought' in the highly seasonal Canadian climate. In contrast, longer-term drought conditions, represented in this study by the 6-month SPI value, were found to be significantly less influential on water demands. This finding reinforces the notion that, at least in the Canadian context, short-term precipitation anomalies experienced as summer droughts will produce the largest impact on the water demand side of the supply:demand relationship that drives water shortage threats. In real terms, it can be inferred that the water-use behaviours of Canadian city dwellers (and especially of those managing irrigated lawns and gardens) react most strongly to the short-term experience of hot, dry summers than they do to longer-term drought indicators such as dry winter conditions or reduced annual snowmelt. While it is not surprising that water demands increase during hot and dry summers, it is informative for city utilities to recognize that precipitation anomalies experienced as short-term or seasonal droughts will have a more acute impact on urban water use than accumulated water deficits experienced at longer timescales.

Somewhat surprisingly, we also found that meteorological drought condition is least impactful on water demands in the driest cities in the sample, where the monthly-scale variability in summer water use is instead very strongly correlated with maximum temperature. This finding suggests that climate-driven water decisions in those cities are dominated by heat-related considerations rather than by rainfall deficiency- in fact, water use in semi-arid cities was found to be relatively insensitive to drought after controlling for temperature (Table 5.3). This is an interesting result that could indicate that cities located in more arid climate regions may become most vulnerable to demand-side drivers of urban drought impacts during summer periods of extreme heat, regardless of meteorological drought condition. This could also be interpreted as reinforcing the notion that cities in normally water-rich climates may be more vulnerable to urban drought impacts during hydrological anomalies; in this case, both due to supply-side, structural factors (lack of storage and redundancy in urban water sytems- see Padowski & Jawitz, 2012) *and* due to differential demand-side dynamics that drive relatively larger increases in water use during periods of meteorological drought in those climate types. However, this particular result differs significantly from earlier studies conducted in arid regions of the US, Australia and Spain, which found that water use in drier climates was principally contingent on precipitation (Taylor et al., 2012, Balling & Gober, 2007, Gutzler & Nims, 2005). More extensive study of the water demand responses to climate in Canada's driest cities would be needed to confirm this dynamic.

In cities where the seasonal surge in water demand is already low, climate factors are less influential in determining summer water use rates than they are in cities that experience more significant demand increases in the summer months. As such, regression modelling with climate variables is significantly less informative in cities with low excess summer demand on average: these cities likely have lower prevalence of irrigated lawns and gardens, and as such, a lower degree of climate-driven water uses in summer months. Future research examining the contribution of demand shifts to urban drought impacts would benefit from an increased focus on cities that experience large variations in seasonal and climate-driven water demand.

5.6. Conclusions

Our results show that meteorological drought conditions increase water demand at the monthly and seasonal scale in Canadian cities. However, this conclusion is most informative when the dimension of summer heat is added: in all cities studied, water demands increased most significantly in response to a combination of drought and elevated maximum temperature. The degree to which these heat- and drought-driven increases in water demand will affect the supply:demand balance in each city will depend on a number of situational and structural factors affecting water supply resilience. However, it is notable that the contribution of demand-side dynamics in driving potential urban drought impacts is significant- in some cases, a one-standard deviation increase in the severity of meteorological drought as measured by SPI can increase excess summer water demand by as much as 20%.

Summer water demands in all cities reacted most strongly to short-term periods of drought representative of ‘dry months’ or ‘dry summers’ in the Canadian context. Interestingly, water demands seem to react differently to drought in the semi-arid and humid cities studied. Taken together, these results suggest that the demand-side contribution to urban drought risk in the Canadian cities studied is most acute during short-term summer periods of rainfall deficit combined with high heat, and especially in cities outside of semiarid climate zones.

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Chapter 6:

Conclusion

6. Conclusion

6.1. Responses to research questions

The research program that undergirds this thesis is rooted in the objective of uncovering more information about the scope and drivers of drought-related water shortage risks in Canadian cities. Based on available data and literature, it focuses on three research questions designed to establish the conceptual foundations that frame the problem of urban drought and to investigate demand-side indicators of water shortage threat in the urban Canadian context. The papers included in the thesis respond to these research questions as follows:

1. Considering that urban water shortage threats of varying severity are experienced in a wide variety of city types and climate zones, what conceptual frame can be used to characterise "urban droughts", how are they defined in relation to other forms of drought, and what endogenous factors contribute to drought impacts within city systems?

Chapter 3 sought to respond to this research question by exploring, extracting, and outlining the conceptual foundations that define the experience of urban drought within a range of literature sources and documented case studies. The resultant paper achieves this by:

a) Sharpening the definition of *urban drought* while fitting it more squarely within the categorization structure commonly used to delineate different drought types (see section 3.2). This effort advances the field of urban drought research by carving out a more precise, context-independent definition for precipitation-driven (or otherwise hydrologically-driven) urban water shortage threats as distinct from the broader concepts of *urban water insecurity, water scarcity* and *socioeconomic drought* that are variously used to describe the phenomenon in literature of diverse disciplines.

b) Delineating a conceptual framework for urban drought events that incorporates the influence of endogenous factors specific to the city and water system and that reflects the distinct spatial and temporal scales that shape the experience of urban water shortage threats (see section 3.3). The framework establishes a structure for recognizing urban drought impacts, then traces key interrelationships between physical water infrastructure systems, operational water management structures, and water users' demand patterns that ultimately determine the extent and severity of those impacts. The study represents the first conceptual analysis of urban drought events that specifically foregrounds the infrastructure systems and demand-side dynamics that shape their impact as independent from the hydroclimatic situation driving reduced water availability within the city's water supply sources.

c) Mining available urban drought case studies and relevant research to identify and classify the key endogenous drivers of urban drought recognized within available literature (see section 3.4). Endogenous drivers identified through this review were categorized as pertaining specifically to either the physical infrastructure system, operational infrastructure arrangements, or water demand dynamics. The identification of cross-cutting drivers of urban drought impacts within research and case studies emerging from vastly different geographical and climatic contexts helps to isolate and analyze the experience of drought within the city system as distinct from that of the wider regional or hydrological context.

Taken together, the results of this first study help to firmly situate the experience of urban drought within the more widely-studied meteorological, hydrological or agricultural drought categories while simultaneously developing the characterization of these events as distinctly urban phenomena where impacts may be generated by the specific infrastructural and water demand characteristics of the city itself. Importantly, the language and ideas elaborated in the first paper established the conceptual foundations needed to frame and contextualize the subsequent studies included in the thesis.

2. How effective are permanent or seasonal water use restrictions such as those applied in most major Canadian cities? Have the water use restrictions imposed in Canadian cities led to a reduction in outdoor water use overall, and have they been effective in curbing surges in demand that may accompany summer periods of exceptionally hot and dry conditions?

In 2004, the now-defunct Canadian National Water Research Institute published a report stating that "about 26% of municipalities with water supply systems reported water shortages during the 1994 to 1999 period, for such reasons as seasonal shortages due to droughts, infrastructure problems, and increased consumption." (Environment Canada, 2004). This statistic points to the existence of meaningful quantitative water threats affecting Canadian cities; however, the report (entitled *Threats to Water Availability in Canada*) was never reproduced or updated after that date, and surprisingly little academic or grey literature has since been produced to assess, quantify, or evaluate the scope of urban water shortage threats in the Canadian context. Because water utilities do not tend to publicise the scale of potential threats to continued water service reliability within their jurisdictions, there exists a real lack of documentation in Canada to help researchers and government bodies assess the scope and drivers of water shortage risk in the nation's cities.

Even though little data and evidence yet exists to assess the degree of water shortage risk that Canadian cities may experience during periods of low relative water availability, the widespread introduction of new outdoor water use bylaws across the country over the past two decades signals a level of concern about the sufficiency of urban water supplies during the summer months. Today over three-quarters of major Canadian cities enforce summer-seasonal or permanent water use restrictions of various stringency, all of which target the use of municipal water outdoors for such purposes as lawn and garden watering, property maintenance, car washing or pool-filling (see Table 1.1).

This second study in this thesis (Chapter 4) set out to answer a long-debated question in the Canadian water management community: are the water use bylaws established in so many cities across the country effective in achieving their aims of reducing excess summer water use and/or curbing demand surges during periods of threatened water shortage? Interestingly for the researchers, though perhaps somewhat disappointingly for participating cities, the study concluded that these restrictions in fact had little significant effect on overall summer-season demand profiles (see section 4.4.4.1). While some especially strict restrictions may have helped to reduce excess water production on the very highest peak demand days, the introduction of water use bylaws did not substantially alter overall water use patterns in the summer months as measured by mean or median daily demand values.

However, this research did provide some indication that seasonal or permanent water use bylaws such as those enforced in Canadian cities can indeed have a demand-tempering impact during periods of exceptionally hot and dry weather (assigned the term *dry heatwaves* in the study) when water demands tend to surge due to an intensification of outdoor water use (see section 4.4.4.2). These bylaw effects were most visible in cities that imposed stringent outdoor water use restriction models, such as those that permitted outdoor water use during only one or two assigned days per week (see Table 4.1, fig. 4.4). Cities that imposed the most stringent bylaws saw significantly smaller surges in daily-scale water demands during dry heatwave events (staying within 100-120% of the summer median value) while cities without bylaws or with old and poorly enforced restrictions saw demand surges of up to 140% of the summer median during those same events (see fig. 4.5).

Results from this second study provide some interesting insights into both the seasonal water demand patterns experienced in different Canadian cities and the effectiveness of the demand-side management measures enacted to reduce the risk of water shortages during the summer months. The last result outlined in the paper (see section 4.4.4.2), which showed that urban water demand surges can be most extreme during exceptionally dry and hot periods, provoked an interest in pursuing further research to assess the degree to which shifts in water demand might contribute to the already strained supply:demand relationship during periods of summer drought.

3. Given that urban drought involves an interplay between water supply and demand within the urban water system, to what degree do changes in water demand contribute to water shortage risk in the Canadian context? How much do water demands change during summer drought-like periods in Canadian cities?

The second study included in this thesis work (Chapter 4) provided some insight into the contribution of demand dynamics in the formation of urban water shortage threats in Canadian cities by confirming that a) urban water use rates are highest during the summer period in all cities studied (see section 4.4.2), b) during those summer months, water demand can further increase during periods of especially low rainfall and high heat (see section 4.4.4.2). Though these results provided a basis for understanding how water demands in Canada react to dry and hot summer weather, they offer no direct confirmation of their possible correlation with periods of meteorological drought, which are qualified as extended periods of rainfall deficiency reducible to a minimum timescale of monthly or seasonal periods with minimal rainfall, possibly aggravated by high temperature and evapotranspiration rates (see section 3.2.1).

In order to further dissect the relationship between urban water demands and meteorological drought within the Canadian context, the third study included in this thesis (Chapter 5) sought to uncover the correlation relationships between drought condition as measured by the Standardized Precipitation Index (SPI) and monthly-scale summer water demand values expressed as a standardized surplus over base (winter/indoor) water demands. This study's results showed that summer water demands in most of the cities studied are indeed negatively correlated with drought status, so as the SPI value drops (indicating increasing severity of drought status), water demand tends to increase (see section 5.4.3). However, the study also showed that maximum temperatures are in nearly all cases even more strongly correlated with water demands: in most cities in the sample, and especially in the most arid of the group, these high temperature maxima were more strongly correlated with water demand increases than either drought status or total rainfall values (see Table 5.2).

Regression analyses performed using climate and water demand data for each city confirmed that summer excess water demands are highly climate-sensitive in most Canadian cities (see section 5.4.4.). Model testing revealed that in ten of 13 cities studied, the combination of maximum temperature and short-term 'summer drought' status (as measured by the 3-month SPI value) accounted for more than 50% of the variability in normalized summer demands (and over 74% in eight of these) (see Table 5.3). Surprisingly, the drought parameter tended to be more influential on summer water demand values within the more humid-climate cities in the group: regression analysis showed that a decrease of 1-standard deviation in the 3-month SPI variable was associated with an increase of up to 20% in normalized demand in some of the sample's humid-climate cities (see Table 5.3). Conversely, drought status was surprisingly uninfluential in determining summer water demand in the few Canadian cities located in the most semiarid/warm-summer climate types. This result points to a need to further dissect the drivers of increased water demand in Canadian cities of various climate types, as it seems that while drought is indeed a contributing factor to surges in summer water demand, the scope of its influence is mitigated by factors such as city climate type, baseline outdoor water use, and summer heat (see Tables 5.3 & 5.4). Results from this study suggest that the degree to which summer heat and/or the occurrence and persistence of extreme heat events contributes to increased demand, and by extension the aggravation of urban water shortage threats, merits further investigation. While this research confirmed that meteorological drought status contributes to demand increases that may aggravate the strained supply:demand relationship that drives urban shortage threats, it also shows that the combination of both heat and drought may have an even greater impact in the Canadian context.

6.2. Original contributions to research

6.2.1. Theoretical/Conceptual contributions

The primary theoretical or conceptual contributions of the research contained in this thesis are the advances made in solidifying the terminology of urban drought while also expanding the concept via an exploration of its specific impacts, system-level interactions, and endogenous drivers (see Chapter 3). This work is the first to confidently deploy the term *urban drought* to describe any (cross-contextual) situation where hydroclimatic conditions characterized as drought under standard definitions create a situation where a threatened insufficiency of urban water supply as compared to demand impacts the day-to-day practices of urban water users (see section 3.2). It is also the first scholarly work to ascribe quantitative water threats in the Canadian climate to urban drought - that is, the same phenomenon that generates the more widely-publicized water shortage situations afflicting cities in places like California, Australia and South Africa; in this text, drought impacts generated in those more-researched contexts are similar in type, though potentially different in severity, from those experienced in Canadian cities to date.

6.2.2.Methodological contributions

The second paper included in this thesis (Chapter 4) introduces a novel methodology for comparing water demands before and after the introduction of water use restrictions. In previous studies of this type, researchers have generally employed one of two methods for evaluating the impact of restrictions on demand: the first, sometimes given the shorthand *direct comparison*, involves a series of simple mathematical comparisons made between water demand values in the period before and after the restriction is imposed (Jacobs et al. 2007; Polebitski & Palmer 2013; Castledine et al. 2014; Haque et al. 2014; Ozan & Alsharif 2013; Survis & Root 2012). Some studies that use the direct comparison method also include steps to improve the comparability of these periods by compensating for their differing timeframes and climate conditions: for example, this compensation can be approximated by standardizing water use according to the time of the year (Haque et al. 2014; Bruvold 2010; Polebitski & Palmer 2013) or by averaging several years of data together (Haque et al. 2014). The second method involves the use of a water demand model to derive theoretical 'unrestricted', water use values for comparison with observed, 'restricted' water use data (Kenney et al. 2004; Anderson et al., 1980; Spaninks, 2010; Shaw & Maidment 1987; Shaw et al. 1992; Lee & Warren 1981; Haque et al. 2014; Halich & Stephenson 2009; Moncur 1987; Little & Moreau 1991). These *modelled demand* methods promise to provide more precise comparison results by enhancing the compensation for climate and timeframe through model development; however, the various model types developed to test the use of the modelled demand method for this research provided inadequate compensation for the uneven longitudinal trends in base water demand observed in city data and failed to capture the high demand peaks that the study sought to capture (see section 4.3.3, Annex A).

The methodology used to detect water restriction impacts in the paper presented in Chapter 4 represents a refinement on the direct comparison method that provides added precision and depth. Instead of relying on a direct comparison of raw total water demand values between two time periods, the method used in this research a) provides a targeted comparison of only summer-season water demands within the before/after periods, each normalized as an increase over the yearly average base demand value; and b) favors a more comprehensive comparison by contrasting the entire distribution of summer-daily water demands in the years prior to and following the restriction's introduction, allowing for a full suite of statistical comparisons (mean, median, high/low percentile values, distribution distances) of the short-term demand patterns observed in each time period. By favoring a comparison between the full distribution of daily-scale, normalized summer water demand values, the method deployed in this study allows for cross-city comparability in results and produces a more fulsome picture of the potential shifts the wide range of daily-scale water demands that may be ascribed to the introduction of water use restrictions.

The second methodological contribution of the thesis research is first introduced in Chapter 3, where evidence from literature review is used to defend the use of shorter timescales to analyse urban drought as compared to those often used to assess its meteorological, agricultural or hydrological counterparts (see section 3.3.2). The methodological approach of favoring shorter timescales of analysis in the study of urban drought situations is then deployed in Chapter 5, where drought status at the scale of only 1, 3 or 6 months is used to detect drought-related shifts in urban water demand at summer-monthly timescales. Results from that study provide some support for the use of shorter timescales in evaluating (at least demand-side) drivers of drought impact in cities, as correlation results showed a closer relationship between urban water demand values and the 1-month and 3-month drought index (SPI1/SPI3) values as compared to the 6-month (longest-term) index value (SPI6) (see section 5.4.3).

6.2.3. Empirical contributions

The two data-driven papers included in this thesis involved extensive and in-depth analysis of vast troves of daily-scale water demand data collected from 15 cities spread across the country. This data analysis provided significant novel empirical contributions that advance our understanding of water demand patterns, trends, and relationships in Canadian cities of varying climate types. Among the empirical findings that provide new information about water demands in Canadian cities we can include:

a) The seasonal distribution of city-scale, per-capita water demands, showing that while most temperate, humid-climate cities produce less than 50% more water on the average summer day as compared to the winter baseline, some of the most arid and warm-summer cities in Canada produce up to 200% more water on a typical summer day than they do in the winter (see section 4.4.2).

b) The trend in the seasonal distribution of water demands in Canadian cities, which show that while the difference between summer and winter demand values have declined year over year in the semiarid city group since the year 2000, the degree of seasonal variation in demand within the more humid city group has remained largely stable over that same period. In other words, despite an overall decrease in annual per-capita water demand that is observed in most Canadian cities, the seasonal differences in demand have persisted in the more humid-climate cities, suggesting that there has been little significant decline in outdoor water use in those cities over the time period covered by the data.

c) The evaluation of the quantitative impact of water use bylaws (permanent or seasonally-applied water use restrictions) on summer-season water demand in the Canadian urban context, which is found to be minimal (see section 6.1.2). As described above, data analysis does however suggest that stringent water use bylaws may produce some reduction in the very high end of the daily demand distribution (lowered peak day demands) and may suppress the surge in water demand that can accompany very hot and dry summer periods.

d) The establishment of a relationship between meteorological drought status (as measured by the drought index SPI) and summer monthly water demand in multiple Canadian cities (see Chapter 5). Though previous water demand modelling research in Canadian cities has provided evidence of a relationship between water demand and temperature/antecedent rainfall (Adamowski 2008; Adamowski et al., 2012; Bourgadis et al, 2005), this work was the first to establish any such relationship with drought status itself.

6.2.4. Applied/Practical/Potential Policy contributions

A major potential policy contribution of the work presented in this thesis is the provision of statistical evidence that water use bylaws as commonly imposed in many Canadian cities are largely ineffective at achieving one of their principal aims – that is, the reduction of overall summer-season water use (see Chapter 4). When shared with the study's respondents and other parties involved in municipal water issues in Canada, this result provoked surprise only in some; Canadian municipalities do not tend to engage in detailed data analysis beyond the formulation of demand projections, and there have long been suspicions within the urban water management community that these bylaws, and especially the least stringent odd/even day bylaw formats, were not successful strategies for reducing summer-season water use rates. In parallel however, this research also provides some useful indication of how outdoor water use restrictions can become more effective: results suggest that more stringent bylaws can indeed produce reductions in peak daily water demands and during summer periods characterized by high heat and lack of rainfall (dry heatwaves). From a perspective of quantitative water security, the ability to curb strong upward swings in demand during summer periods of abnormally hot and dry weather (which often coincide threatened water shortage conditions) is perhaps of the greatest utility for water managers.

This research also provides some evidence that periods of short-term meteorological drought that coincide with the warm summer months will produce increases in water demand on short timescales (see Chapter 5). Though this is unlikely to come as a surprise for water management professionals, it may provide further support for the notion that monitoring meteorological drought status can be used to inform short-term water demand projections as needed to prepare for potential summer-season water shortage threats.

6.3. Future research directions

As stated in Chapter 1, the research contained in this thesis project represents an early foray into improving our understanding of the scale and scope of urban water shortage threats in the Canadian context. While this work helps to illuminate some of the demand-side relationships that may contribute to the degree of impact experienced during urban droughts affecting Canadian cities, there remains an urgent need to uncover more quantitative information about the supply-side dynamics that drive water shortage threats in this country. This information may take the form of data relating to reservoir or surface/ground water storage levels during differing timescales of meteorological drought, or the percentage of effective drinking water treatment capacity that remains during periods of low water availability and/or elevated demand. It would also be very informative to better understand the water storage (and/or demand) thresholds used by Canadian water managers to signal potential water shortage threats, especially with the objective of monitoring the relationship between progress toward or beyond these thresholds and hydroclimatic conditions in the surrounding watershed.

Following on this research's findings about a) the significance of summer heat in driving urban water demand increases and b) the potentially shortened timescales of activity for the formation of urban drought impacts, it would also be interesting to seek to integrate urban water shortage threats with recent research advances in the areas of ‘hot/summer drought’ and ‘flash drought’ (Lisonbee et al., 2021; Hanel et al., 2018; Pendergrass et al., 2021). These research areas are expanding on the concept of drought to reflect the scale of the contribution of extreme heat in an era of accelerating climate change; given the findings from the research presented in the papers included in this thesis, it would seem that the overlap between high heat and drought events on all timescales should be viewed as a source of significant water security risk for cities across the globe.

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Appendix A:

Supplementary information appended to *Curbing the Summer Surge: Permanent Outdoor Water Use Restrictions in Humid and Semiarid Cities* (Chapter 4)

Supplementary information (SI) appended to *Curbing the Summer Surge: Permanent Outdoor Water Use Restrictions in Humid and Semiarid Cities* (Chapter 4)

SI Contents:

Figure S1: Overall water demand, all cities, 1997-2017

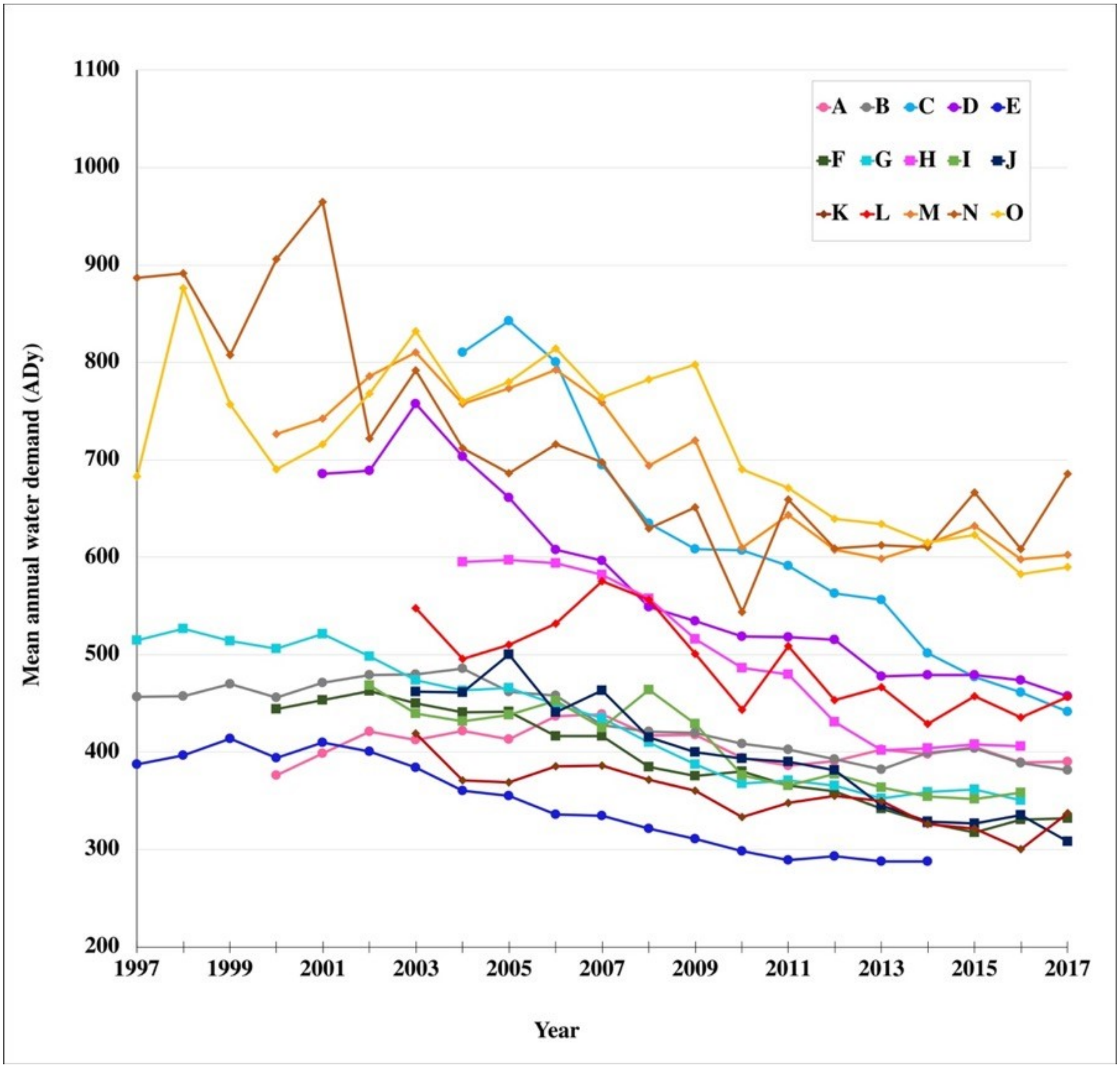


Table S1: Mann Kendall Trend test with Sen's Slope Estimate (2000-2017)

	City														
Trend *(units)*	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**
AD_y *(Δ LCD/yr.)*	-1.2	-6.5**	-28.3**	-16.5**	-9.7**	-9.5**	-11.6**	-20.4**	-8.7**	-12.1**	-6.2**	-7.9**	-12.9**	-11.0**	-13.1**
BD_y *(Δ LCD/yr.)*	-1.7**	-6.0**	-27.1**	-14.4**	-9.2**	-8.3**	-11.5**	-20.0**	-6.8**	-11.7**	-5.0**	-3.6**	-7.2**	-8.2**	-3.7*
SD_y *(Δ LCD/yr.)*	-0.16	-6.9**	-29.8**	-19.8**	-10.7**	-11.0**	-11.8**	-20.9**	-10.8**	-13.4**	-7.6**	-14.8**	-20.7**	-22.0**	-24.6**
SDS_y *(Δ ratio/yr.)*	6.1E-03	-4.3E-05	**6.4E-03 ****	-1.5E-03	-1.6E-03	-1.3E-03	-8.0E-06	**9.4E-03 ****	-2.7E-03	5.7E-03	-7.9E-03	-2.2E-02 **	4.6E-03	-1.6E-02	-2.4E-02 **
Production *(Δ m^3/yr.)*	**446****	-232*	-899**	-3028**	-1918**	-2177**	-643**	-3443**	-609	-743	-180	-180*	182	-188	-479

Note:
-Values in grey are non-significant
-Mann-Kendall test significance levels: * = >95%, ** = >99%.
-Significant increasing trends highlighted in bold.

Table S2: Kolmogorov-Smirnov Distance (D_{KS}) and Significance (P_{KS}) for Climate Parameters Before/After Bylaw

Daily max. temperature (℃)- difference from 'before' to 'after' period								
City	**A**	**B**	**C**	**E**	**G**	**H**	**M**	**O**
D_{KS}	**0.0761**	**0.0348**	**0.0631**	**0.0885**	**0.0779**	**0.0739**	**0.136**	**0.120**
P_{KS}	**0.187**	**0.934**	**0.336**	**0.0554***	**0.125**	**0.162**	**0.00617***	**0.00266***
Daily rainfall (mm) - difference from 'before' to 'after' period								
City	**A**	**B**	**C**	**E**	**G**	**H**	**M**	**O**
D_{KS}	**0.0641**	**0.0304**	**0.0783**	**0.0737**	**0.0458**	**0.0219**	**0.126**	**0.0522**
P_{KS}	**0.370**	**0.983**	**0.120**	**0.166**	**0.723**	**1.00**	**0.00858***	**0.558**

** indicates significant difference at 90% significance level*

Application of the "expected use method" for cities E, M and O

Cities E, M and O had significant difference in climate before and after bylaw implementation. Thus, for these cities we compared the direct comparison (CDF) method used in the paper with the model-based "expected use" (EU) method described in section 3.3. In the EU method, multiple linear regression (MLR) is used to develop a statistical relationship between water demands and one or more predictor variables. MLR is among the most widely-used techniques for water demand forecasting, and regression models based on climate variables (temperature and rainfall) and a one-day (or week, month) lag variable for previous water use have been used to simulate 'expected' water use in several studies of water conservation programs (Anderson et al., 1980; Little & Moreau 1991; Lee & Warren 1981; Kenney et al. 2004). Some of these studies found that antecedent rainfall (or lack thereof) was a significant predictor of water demand, owing to the persistence of rainfall's effects on watering behaviours (Anderson et al., 1980; Spaninks 2010; Steiner 1984), while other research comparing short-term MLR water demand models found best results by including a variable for the number of antecedent days without rainfall or by treating rainfall as a binary input (rain/no rain) rather than as a continuous variable (Jain et al. 2001; Adamowski & Karapataki 2010; Adamowski 2008).

To account for the fact that some cities had vastly different base demand baselines from year to year, in some models we include a term for outdoor water use (OWU), defined as the difference between summer day demand ($SD_{i,y}$) and that year's base demand (BD_y). Based on the findings of previous studies, the variables tested for regression modelling included:

Table S3: Variables tested for model development

Variable	Shorthand
Previous day's water use	LCD_{d-1}
Previous day's outdoor water use ($OWU = SD_{i,y}-BD_y$)	OWU_{d-1}
Average Daily Temperature	MeanT
Maximum Daily Temperature	MaxT
Rainfall (mm)	rainmm
# of antecedent days without rainfall	daysnorain
Rain Yes/No (binary)	rainy/n

Models were trained using 5+ years of data and used to predict expected summer water demands for the 5-year 'post bylaw period' included in Table 2. The table below shows the equation and fit of the best-fit model for each of these three cities as well as the results of the expected use method in each case. In this method, modelled demands for the 5 years following bylaw implementation are compared to observed demands over that same period, and the difference between the two is deemed to represent the effects of the bylaw on water demand. For ease of comparison, the results are presented in terms of *n*SDi,j using the same metrics presented in the paper.

Table S4: Results of the expected use method in cities E, M and O

	E	**M**	**O**
Climate category	humid	semi-arid	semi-arid
Bylaw stringency	high	medium	low
'Before' period	2000-2004	2010-2014	1995-1999
'After' period	2005-2009	2015-2018‡	2000-2004
Regression equation of best-fit model	$Y = -40 + 0.61 (OWU_{d-1}) + 2.05(MaxT) + 3.30 (daysnorain)$	$Y = 141 + 0.79(LCD_{d-1}) + 2.95(MaxT) - 61.15(rainy/n)$	$Y = -22.33 + 0.71(LCDd-1) + 13.93(MaxT) -122.39(rainmm)$
R^2	0.63	0.83	0.84
Δ Mean	-1%*	0%	-3%*
Δ Median	-1%	0%	-2%
Δ Std. deviation†	+18%	+8%	0%
Δ 95th percentile†	0%	0%	-2%

* Indicates significant difference at the 90% confidence level

‡ This period includes less than five years of data, as noted in section 3.3

†Note that because models tested were poor predictors of the extreme high and low demands observed in the dataset (as noted in section 3.3), these measures are considerably less reliable in a modelled comparison method than in the direct comparison method.

In the case of cities E and M, changes in mean and median were roughly analogous to those derived using the CDF method (Table 2). Though city M's change in mean is no longer positive in this result, the change is not significant using either method of analysis. In city O, the expected use method produces an estimated -3% change in mean demand, a result which is both significant and significantly lower than the +1% change shown in the paper. Overall, results from the two methods are comparable, and considering the uncertainties inherent in each (as well as the superior strength of the CDF method in describing the spread of demand distributions) we are confident in the finding that all three of these cities have seen only very minor bylaw effects in terms changes in mean/median demand, accompanied by more meaningful declines in peak demands and the spread of daily demand distributions (Table 2).

Sensitivity analysis for dry heatwave definition

A sensitivity analysis performed on a range of dry heatwave definitions showed the results to be minimally sensitive to the threshold values used to define the event. To conduct this analysis, we first selected the most ‘extreme’ threshold combinations of maximum temperature (Max T) and days without rainfall (DWOR) for which the highest number of dry heatwave events (periods of 3+ days wherein those thresholds are exceeded) could be identified within each city group (Table S5):

Table S5: Number of events identified for different dry heatwave definitions

		Number of events within bylaw enforcement period #Southern Group, #Northern Group		
		Max T (percentile)		
DWOR (percentile)		**70th**	**80th**	**90th**
	50th		**19, 13**	**13, 10**
	60th		**13, 9**	**7, 6**
	70th	**8, 9**	**11, 7**	**5, 4**
	80th	**9, 6**	**6, 2**	**3, 0**
	90th	**1, 0**	**1, 0**	**1, 0**

Then, we repeated the analysis for all of the definitions highlighted in yellow – that is, the most ‘hot/dry’ temperature and low-rainfall threshold combinations for which the most events could be identified within the post-bylaw period. As seen in Figure S2, we found that each threshold combination tested produced similar results to the one included in the paper (Fig. S2a). Though the magnitude of mean $HSD_{i,y}$ values vary somewhat under differing dry heatwave definitions, the relationship between cities remains consistent: the low-stringency or non-bylaw cities (F and J) show higher surges in demand than those with strict restrictions (G and E) during most dry heatwave events. Presented here are results from the 10 most recent events within the Southern Group using each of the threshold combinations highlighted in Table S5. (Note that only 8 events are included in the last figure due to a smaller number of events identified using that definition.) Similar results were found for the Northern Group of cities (results not shown).

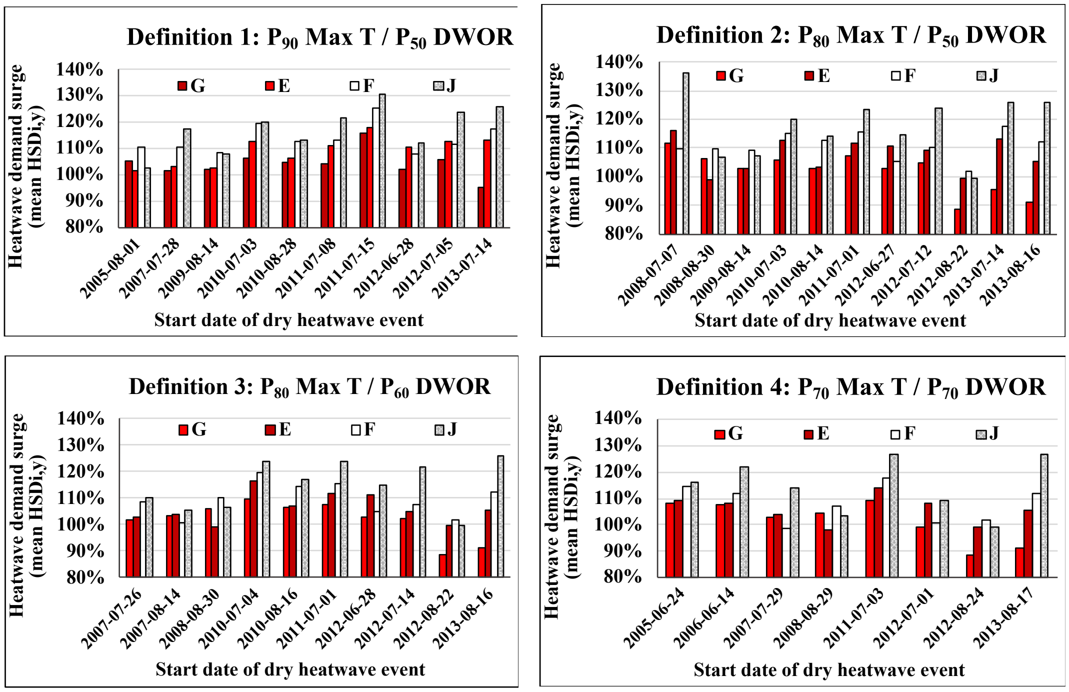
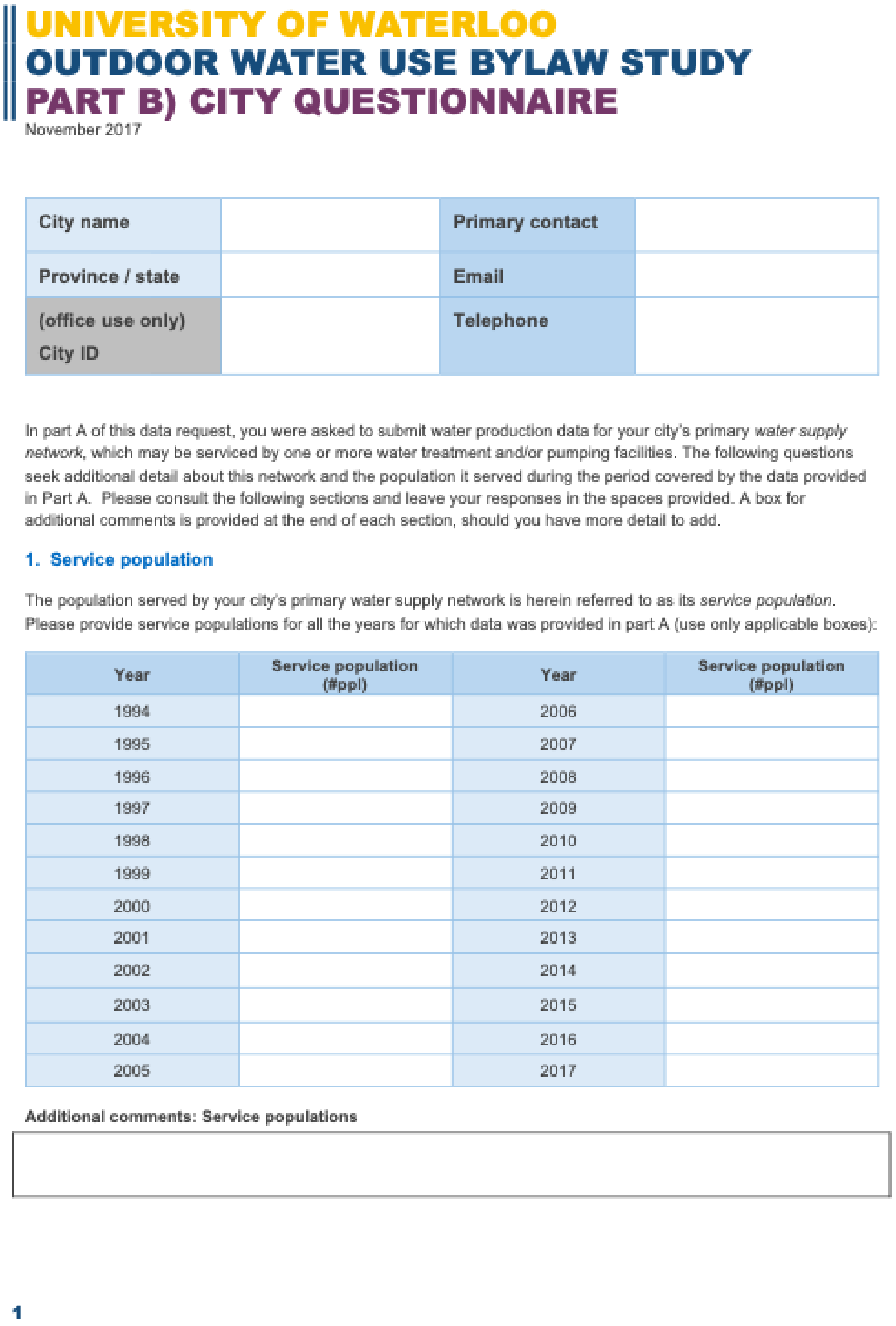


Figure S2: Water demand surges during dry heatwaves under varying threshold combinations of a) 90th percentile Max T and 50th percentile DWOR (included in paper) b) 80th percentile Max T and 50th percentile DWOR, c) 80th percentile Max T and 60th percentile DWOR, and d) 70th percentile Max T and 70th percentile DWOR

Appendix B:

City questionnaire

City questionnaire



UNIVERSITY OF WATERLOO
OUTDOOR WATER USE BYLAW STUDY
PART B) CITY QUESTIONNAIRE

November 2017

City name		**Primary contact**	
Province / state		**Email**	
(office use only) **City ID**		**Telephone**	

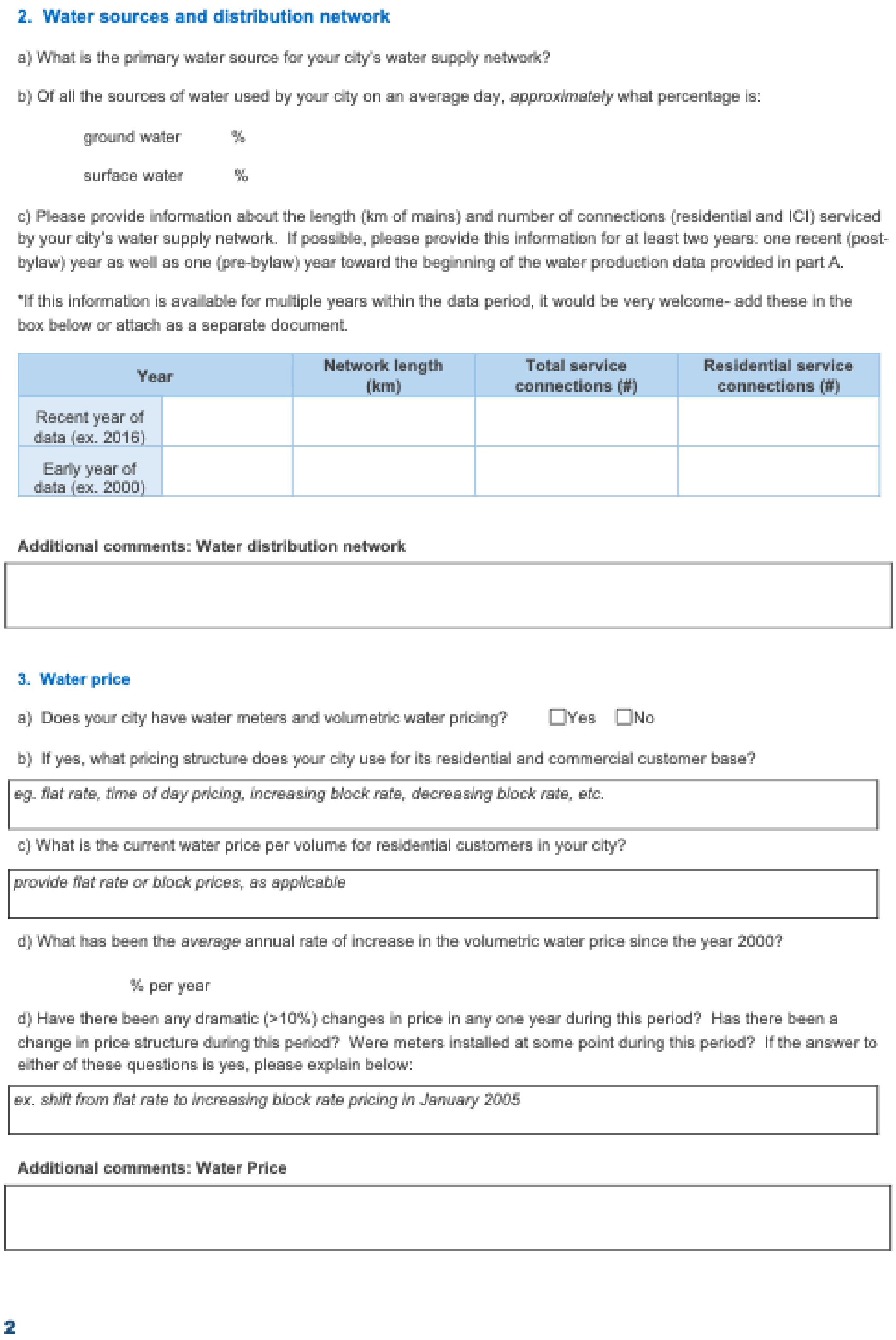
In part A of this data request, you were asked to submit water production data for your city's primary *water supply network*, which may be serviced by one or more water treatment and/or pumping facilities. The following questions seek additional detail about this network and the population it served during the period covered by the data provided in Part A. Please consult the following sections and leave your responses in the spaces provided. A box for additional comments is provided at the end of each section, should you have more detail to add.

1. Service population

The population served by your city's primary water supply network is herein referred to as its *service population*. Please provide service populations for all the years for which data was provided in part A (use only applicable boxes):

Year	Service population (#ppl)	Year	Service population (#ppl)
1994		2006	
1995		2007	
1996		2008	
1997		2009	
1998		2010	
1999		2011	
2000		2012	
2001		2013	
2002		2014	
2003		2015	
2004		2016	
2005		2017	

Additional comments: Service populations



2. Water sources and distribution network

a) What is the primary water source for your city's water supply network?

b) Of all the sources of water used by your city on an average day, *approximately* what percentage is:

ground water %

surface water %

c) Please provide information about the length (km of mains) and number of connections (residential and ICI) serviced by your city's water supply network. If possible, please provide this information for at least two years: one recent (post-bylaw) year as well as one (pre-bylaw) year toward the beginning of the water production data provided in part A.

*If this information is available for multiple years within the data period, it would be very welcome- add these in the box below or attach as a separate document.

Year		**Network length (km)**	**Total service connections (#)**	**Residential service connections (#)**
Recent year of data (ex. 2016)				
Early year of data (ex. 2000)				

Additional comments: Water distribution network

3. Water price

a) Does your city have water meters and volumetric water pricing? ☐Yes ☐No

b) If yes, what pricing structure does your city use for its residential and commercial customer base?

eg. flat rate, time of day pricing, increasing block rate, decreasing block rate, etc.

c) What is the current water price per volume for residential customers in your city?

provide flat rate or block prices, as applicable

d) What has been the *average* annual rate of increase in the volumetric water price since the year 2000?

% per year

d) Have there been any dramatic (>10%) changes in price in any one year during this period? Has there been a change in price structure during this period? Were meters installed at some point during this period? If the answer to either of these questions is yes, please explain below:

ex. shift from flat rate to increasing block rate pricing in January 2005

Additional comments: Water Price

2

4. Water use bylaw

a) Does your city have an outdoor water use bylaw in place? ☐Yes ☐No

If yes, please attach the bylaw document or provide a link to the bylaw wording here:

b) When was the bylaw first implemented in your city (mm/yy)?

c) Is the bylaw enforced through the issuance of formal warnings and/or fines? ☐Yes ☐No

d) Which information tools does your city use to communicate to residents about the outdoor water use bylaw:

☐ Bill inserts/other mailouts

☐ Radio and/or TV advertising

☐ Signs

☐ Other, please specify:

e) In your estimation, what percentage of water customers in your city are aware of the bylaw's restrictions? %

f) Has there been a change in the bylaw (change in watering days and/or watering hours) over the years covered in the data provided in part A? If yes, please explain those change(s) and when they occurred in the box below:

ex. reduction in daily permitted watering hours in June 2007

g) Finally, does your city enforce bans on:

☐ Once-through cooling systems? If yes, when was this restriction introduced?

☐ Non-recirculating fountains and splash parks? If yes, when was this restriction introduced?

Additional comments: outdoor water use bylaw

ANONYMITY

The data solicited for this research project will be used to complete an analysis of outdoor water use bylaw effectiveness and outdoor water use patterns in multiple cities. The results of this analysis (but not the data itself) will be published in journal articles and may be presented at academic conferences. If desired, the researchers can anonymize your city in the presentation of results, so that your city would appear in publications as, for example, 'City A', instead of by name. We are happy to grant anonymity at any time leading up to publication. Please check one of the boxes below:

☐ Do not anonymize my city- results can be published and presented under the city name

☐ Anonymize my city please- results should appear as 'City A', etc. in lieu of the city name

☐ Check with me again before publication- I may choose anonymity depending on analysis results

THANK YOU FOR YOUR PARTICIPATION!
Do not hesitate to contact Sara Finley at s3finley@uwaterloo.ca if you have any questions.

Completed by:

City contact signature ____________ Date ________

Received by:

University of Waterloo signature ____________ Date ________