Drought Sensitivity of Municipal Water Supply Systems in Ontario

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The sensitivity of municipal water systems to drought was explored in 1999, with particular attention to major urban centres in Ontario's Toronto-Niagara Region. A framework of sensitivity was developed, recognizing both water system characteristics, such as type of water source and storage capacity, and situational factors, such as population growth rates. The framework was developed from the literature, scoping interviews with officials in six southern Ontario municipalities, and in-depth interviews and document analysis in three case study municipalities: City of Toronto, Regional Municipality of York, and Regional Municipality of Niagara. The framework suggests that system characteristics that increase sensitivity to drought include groundwater and river water sources, older and/or poorly maintained water system components, and limited storage capacity relative to demand. Situational factors increasing drought sensitivity include rapid population growth and lack of demand management measures. Conversely, system characteristics that reduce sensitivity include interconnection of distribution systems and an abundant water source. Suggestions are offered for utilizing the framework as a checklist for assessing drought sensitivity of municipal water systems.

Keywords: drought, climate change, municipal water systems, sensitivity, water management

The impacts of urban drought and the responses of municipal water supply system managers to drought have been studied in many regions (Harnett 1980; Water Science and Technology Board et al. 1986; Gleick 1990; Schwarz and Dillard 1990; Shaw et al. 1992; O'Connor et al. 1999), including the Great Lakes basin, notably the Greater Toronto Area and Regional Municipality of Waterloo (Koshida et al. 1999). Much of the attention in the urban drought literature, however, has been on supply management and various water conservation measures, with less attention to assessing the drought sensitivity of supply systems, and particular system components, such as water source or system storage capacity. This is a significant gap in knowledge, especially in a region such as southern Ontario, where the frequency of drought is under-appreciated (Gabriel and Kreutzwiser 1993), and where the frequency of weather extremes, including drought, may increase because of climate warming

(Hofmann et al. 1998; Francis and Hengeveld 1998). In southern Ontario, in addition to more frequent dry spells, climate warming may result in reduced streamflows and groundwater recharge, lower Great Lakes water levels, and increased seasonal demand (McLaren and Sudicky 1993; Lee et al. 1996; Mills 1996; Hofmann et al. 1998; Southam et al. 1999).

The possibility of greater climatic variability poses a challenge to municipal water managers. Ignoring this possibility may result in costly redesign or expansion of infrastructure, not to mention the costs of water shortages. On the other hand, substantial overbuilding of facilities may be an unnecessary cost if climatic variability does not increase. In response to this dilemma, Gleick (1990, 223) argued that “we must explore the vulnerabilities of the existing water-supply infrastructure to existing climatic variability, and identify other commonsense [*sic*], inexpensive changes that make water supply more flexible and less vulnerable to a range of plausible futures.”

This paper investigates the sensitivity of municipal water supply systems to *drought* (i.e., a prolonged dry spell). Smit et al. (2000, 238) define sensitivity as “the degree to which a system is affected by, or responsive to, climate stimuli.” They note, however, that sensitivity often involves detrimental or harmful effects, and use the term vulnerability to refer to the degree to which a system is susceptible to damage or harm. In this paper, our concern with sensitivity is primarily with the adverse implications of drought for municipal water systems. Our aim is to identify and assess factors that influence the sensitivity of municipal water systems to drought and to develop a framework to assist municipalities in appraising their drought sensitivity.

There is a longstanding concern in the natural hazards literature with the capacity of individuals and governments to absorb the impacts of extreme natural events and to adjust and adapt to these events (e.g., Burton et al. 1978). This literature, and more recent work on adaptation to climate variability and change (e.g., Bohle et al. 1994; Burton 1997; Adger 1999; Smit et al. 2000), suggests that the sensitivity or vulnerability of human systems and locations to extreme events varies in response to complex interactions of biophysical, social, economic, technological and institutional factors. Adger (1999) argues that policies and other institutional factors are particularly important influences, and these can work both to reduce and, as Burton (1997) argues, to increase vulnerability. Specifically, in the context of municipal water systems, our research shows that sensitivity to drought is a function of both *system characteristics* and *situational factors*. *System characteristics* include type of water source, treatment processes, etc. *Situational factors* define the context within which the water supply systems operate, and include considerations such as population growth rates and political support for water conservation.

The Investigation

A literature review and preliminary interviews with eight officials in six southern Ontario municipalities served to identify water supply system components potentially sensitive to drought, as well as situational factors influencing the drought sensitivity of supply systems. Officials in the six municipalities, primarily water system managers chosen for their expertise and ability to influence management decisions, were consulted via personal and phone interviews, and were asked to comment on a preliminary list of system characteristics and modifying situational factors drawn from the literature. The six municipalities were chosen to reflect a range of water management contexts. They had populations ranging from just under 10,000 to just over 400,000. Two of the municipalities were dependent on rivers, while four were dependent on groundwater, supplemented by surface water. As two of the municipal water managers requested anonymity, the names of the municipalities are not reported.

This scoping of components and factors was key to structuring subsequent in-depth interviews with officials from three Ontario case study municipalities (Figure 1):

- City of Toronto — representing a large municipality, with older infrastructure, served by a reliable surface water source (Lake Ontario).
- Regional Municipality of York — a rapidly growing municipality served by groundwater and lake water sources, which currently is reaching the limit of its ability to meet projected growth from existing supplies.
- Regional Municipality of Niagara — a large municipality with a population served by a combination of surface and groundwater sources.

As the research was undertaken, in part, to support Environment Canada’s Toronto-Niagara Region Study on

Atmospheric Change (www.msc-smc.ec.gc.ca/airg/research_projects/index_view.e.cfm?IdKey+10), the three study municipalities were identified in cooperation with Environment Canada. Using primarily personal interviews, supplemented with telephone interviews, six municipal water managers in the three municipalities were asked to verify and prioritize various water supply system characteristics identified through the literature review and preliminary interviews, and to provide records, reports and other information in support of their positions. Additionally, these municipal water managers were asked to comment on situational factors. As with the preliminary interviews, interviewees were selected based on their expertise and ability to influence water management decisions. Reports and data supplied by the three municipalities were used to cross-check impressions and observations derived from the interviews and to fill in gaps.

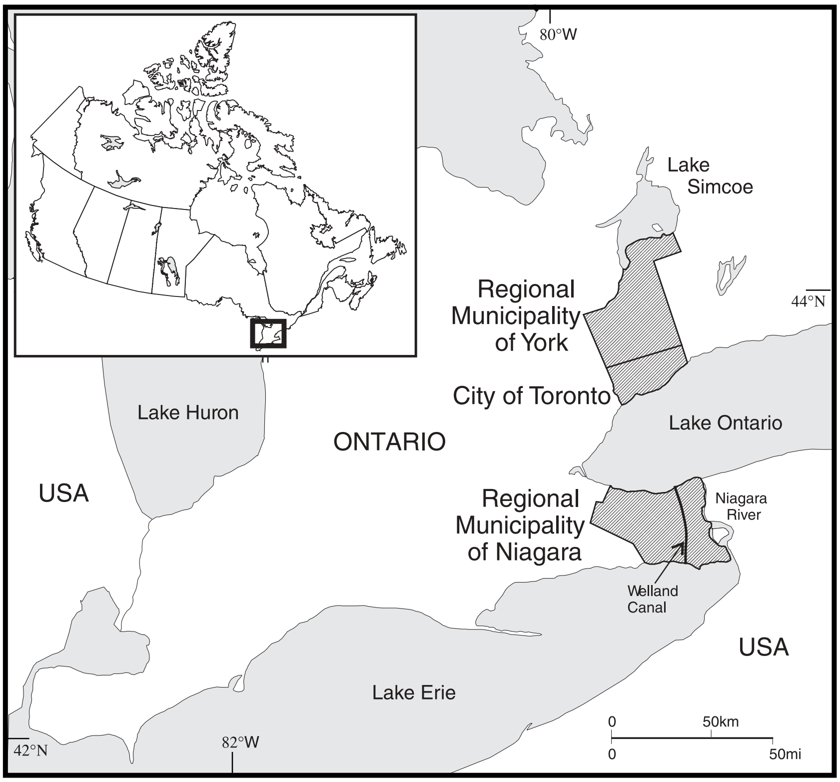

Figure 1: Study area municipalities.

Sensitivity of Municipal Water Supply Systems to Climate Variability

There is an extensive literature documenting the responses of municipal water system managers to drought. Although specific components of municipal water supply systems sensitive to drought may be mentioned, much of this literature focuses on supply augmentation and a variety of water conservation measures. Water source is important (Blackburn 1980; Reed 1982; Lettenmaier et al. 1990), and systems relying on rivers are often more affected by droughts than groundwater-reliant systems (Schwarz and Dillard 1990). O'Connor et al. (1999) found that surface water-reliant systems in central Pennsylvania were more sensitive to drought than groundwater-reliant systems. Water intakes, weirs and head gates may be impacted by declining lake or river levels (Schwarz and Dillard 1990; Lee et al. 1996). Water storage capacity (Al-Weshah and Shaw 1994) and water treatment capacity (Grigg and Vlachos 1993; Shepherd 1998) are other components that may be drought sensitive. Treatment processes using chlorination, for example, can produce trihalomethane — a carcinogen — when warmer water is treated (Schwarz and Dillard 1990).

There is much less literature that addresses the potential drought sensitivity of municipal water supply systems as a whole (Gleick 1990; Schwarz and Dillard 1990; Robinson and Creese 1993; O'Connor et al. 1999). Furthermore, a municipal water supply system is more than just the physical infrastructure. While pumping and storage capacity may be drought-sensitive components of a system, situational factors such as water pricing and other demand management arrangements, as well as increasing demand because of population growth, may influence the sensitivity of the system, or specific components, to drought.

In his evaluation of the possible impacts of climate change on water resources in the United States, Gleick (1990) drew several general conclusions regarding municipal water supply systems. Regions with limited water storage capacity (e.g., lakes, reservoirs, aquifers) relative to demand may be particularly vulnerable to drought. For example, Fiering and Matalas (1990) suggest that vulnerability is increased when storage capacity drops below 60% of annual stream flow. Locations where ground water pumping rates considerably exceed recharge rates are especially vulnerable to droughts. Water quality can also decline as a result of reduced recharge.

Regions presently experiencing highly variable streamflows will be particularly vulnerable to climate change, a conclusion also supported by Hurd et al. (1999).

Based on the literature review, a list of components of a municipal water supply system, and possible ways in which the system could be sensitive to climate-induced water shortages, was prepared. The interviewees in the six selected Ontario municipalities evaluated this list. Water managers were asked whether, in their judgement, any of the components of municipal water supply system listed were, or could be, sensitive to a climate-induced water shortage. Also, they were asked to identify any components not listed. These findings, summarized in Table 1, also serve as a preliminary assessment of the drought sensitivity of municipal systems.

In addition to identifying potentially sensitive components, interviewees also described several situational factors that make it harder for municipalities to meet demands during periods of water shortage or drought. Municipalities are facing increasing competition for their water supplies, e.g., from golf courses, sod farms and greenhouses/nurseries. Interviewees suggested that currently there is uncertainty in provincial legislation, regulations

Table 1: Drought-sensitivity of municipal water supply system components

Water System Component	Way in Which Component is Sensitive to Drought
Water source (ground, river, large lake, etc.)	Lower water levels increase pumping costs; may need to drill wells deeper; supplies may be inadequate to meet increased demand
Water intake pipe and screening	No sensitivity reported
Pipe systems/water mains	Increased pumping may increase leakage, especially in older systems
Pumping station(s)	Increased pumping stresses equipment, especially in older systems
Chemical storage and feeding	Treatment components/system may be inadequate if water quality declines (e.g., increased algae), or poor quality wells are returned to production
Flocculating basin	No sensitivity reported
Settling basin	No sensitivity reported
Spillways	No sensitivity reported
Rapid sand filtration tank(s)	No sensitivity reported
Backwash	May be impeded by reduced water supplies; backwash filters may require more frequent cleaning if water quality declines
Holding basins (distribution reservoirs)	Inadequate capacity to buffer increased demands and reduced supplies
Storage reservoirs/elevated tanks	Inadequate capacity to buffer increased demands and reduced supplies
House service connections	No sensitivity reported
Meters	No sensitivity reported
Disposal of treatment process waste by-products	No sensitivity reported

and policies and about water-taking priorities, particularly during low water periods. Difficulties exist when no legal or institutional provisions exist for water conservation (e.g., water rationing, retrofits, voluntary lawn watering bans). Where a water conservation program, drought contingency plan, and related legal provisions are not in place, water managers would be forced to respond quickly to a water shortage and may be more constrained in the actions they can take in response to the shortage. Lack of political will to enforce or implement conservation measures during periods of drought or water shortage can reduce capacity to respond to a drought. Education is key, as an informed public is more likely to be supportive of conservation measures. Finally, lack of adequate financial, technical and/or staff resources for implementing conservation measures makes satisfactory responses difficult.

Three of the six water managers interviewed stated that very few problems were experienced by their municipality during past droughts. Several reasons were offered. Some municipalities had two or three months worth of water reserves, and drought occurrences to date in Ontario have not lasted longer than this period. Water restrictions (e.g., odd-even day lawn watering) were in place all year round in one particular municipality and, in times of high water demand, a total ban was imposed on such non-essential activities as car and driveway washing. In one municipality, a water needs study was undertaken every five years. This kind of study allowed the municipality to deal with any problems that may arise, thus lessening its vulnerability to drought or water shortages. It requires plant operators and superintendents to prepare for eventualities, to correct deficiencies and to make improvements. One municipality responded that the drought that occurred in the summer of 1998 had no impact on the water supply (this municipality was dependent primarily on groundwater). An ongoing maintenance and capital replacement program prevented problems from occurring.

Drought Sensitivity of the Three Case Study Water Supply Systems

In-depth interviews were conducted during March and April, 1999, with six water department officials in the City of Toronto, Regional Municipality of York and Regional Municipality of Niagara. These interviews were structured around the water

Table 2: Characteristics of municipal water supply systems, 1998

System Characteristic	City of Toronto	York Region	Niagara Region
Population served	2,750,000[a]	597,000[b]	400,000+
Production capacity	2,300,000 m^3/day	Not available	614,900 m^3/day
Annual total production	539,442,000 m^3	93,821,000 m^3	83,461,000 m^3
Average daily production	1,478,000 m^3/day	257,000 m^3/day	228,700 m^3/day
Maximum daily production	138% of average for largest plant	193% of average for Lake Simcoe plants	146% of average for largest plant
No. of treatment plants	4	2	7
No. of wells	0	32	2
No. of pumping stations	18	14	16
Pumping capacity	9,000,000 m^3/day	Not available	Not available
Storage capacity	1,600,000 m^3	Not available	Not available
Water source	Lake Ontario	Lake Ontario, Lake Simcoe, ground	Lake Ontario, Lake Erie, Niagara River, Welland Canal, ground
Water treatment	chlorine	chlorine	chlorine

[a] Includes 365,000 residents of the Region of York.
[b] Includes 365,000 residents supplied by the City of Toronto system; 75% of the annual total production is from the City of Toronto system.

system components and situational factors identified through the literature review and preliminary interviews described above. Table 2 summarizes key characteristics of the water supply systems in the three case study municipalities, and the following sections assess the extent to which these systems are sensitive to drought. Some of the problems described may have been addressed since the interviews were conducted.

City of Toronto. The City of Toronto (Figure 1) (formerly the Municipality of Metropolitan Toronto) is Canada's largest municpality. The City's Works and Emergency Services Department is responsible for supplying water to approximately 2,385,000 residents of Toronto and 365,000 residents of the neighboring Region of York. In 1998, 539,442,000 m^3 of potable water were supplied via four filtration plants drawing water from Lake Ontario, 18 pumping stations, 10 major ground level storage reservoirs, four elevated storage tanks, approximately 487 km of trunk water mains, 5,347 km of distribution water mains, and 470,000 water service connections (City of Toronto 1999b; Municipality of Metropolitan Toronto 1996). The availability of abundant water supply from Lake Ontario meant that the storage of water in large constructed reservoirs was unnecessary. Storage facilities consisted of the in-system storage provided by filtration plants, ground level reservoirs and elevated tanks (City of Toronto 1999a).

According to interviewees, the City of Toronto's water supply system was not particularly sensitive to climate-induced water shortage. Table 3 highlights system components and situational factors that were reported to be somewhat drought sensitive, as well as components and processes thought to reduce sensitivity to drought.

Interviewees acknowledged problems with water treatment during dry spells, combined with warm lake water temperatures, which promoted algal growth. Granular filters were being installed at two treatment plants to address this problem (Palmer 1999). There had also been difficulties in meeting peak demands during prolonged dry spells. During the summer 1988 drought, some in-system storage reservoirs were under 10% of capacity, necessitating emergency water restrictions. However, interviewees pointed to key characteristics of the City's water system that reduced its vulnerability to drought, including an abundant source of supply from Lake Ontario and interconnection of water treatment plants (Table 3). Both interviewees reported that the lake level would have to drop "dramatically" or "about 10-12 metres" in order for the water supply system to be affected substantially.

Regional Municipality of York. York Region, located north of Toronto (Figure 1), is one of Canada's fastest growing municipalities, with a population increase of over 20% between 1994 and 1998 (Regional Municipality of York N.D.). It is comprised of an upper-tier regional municipality and nine area municipalities. The Water Branch of the Transportation and Works Department is responsible for supplying water to the Region's 597,000 residents. In 1998, 93,821,000 m^3 of potable water were supplied via two water treatment plants, 33 production wells, seven ground-level storage reservoirs, 29 elevated storage tanks, 14 pumping stations, and approximately 140 kilometers of trunk water mains (Regional Municipality of York 1999). It should be noted, however, that 75% of the water supplied was obtained from the City of Toronto system; of the remainder, 22% was supplied by the Region's wells, and three percent was drawn from Lake Simcoe (a large surface source). York Region wholesales the water to its area municipalities, who retail it to customers.

York Region's water system was found to be more sensitive to drought than Toronto's. Table 3 highlights components and factors contributing to sensitivity. Although the Region drew on three sources of water supply, these sources were not available equally to all area municipalities. Instead, municipalities tended to use those water sources that were geographically closest to them. Hence, some area municipalities relied on groundwater, others on Lake Ontario, and yet others on Lake Simcoe. Groundwater-reliant municipalities in the Region tended to be particularly vulnerable during a water shortage because water tables were drawn lower; golf courses and agriculture, for example, made considerable demands on groundwater supplies.

The components of the Region's water supply systems that tended to be more sensitive to drought were water mains and pipe systems, pumping stations, and storage reservoirs / elevated tanks. Algae-related odor and taste problems have been experienced with the Lake Simcoe supply, particularly during dry periods when water temperatures were warmer, prompting the Region to install an activated carbon treatment system at its

Table 3: Drought sensitivity of municipal water supply systems, 1998

Components and factors that are drought sensitive	**City of Toronto**	**York Region**	**Niagara Region**
pumping plants and storage reservoirs	high demand and fire emergencies can exceed capacity	pumps work harder during low levels in lakes and wells, increasing likelihood of failure	insufficient storage capacity during peak demand periods
treatment plants and processes	alterations required to deal with taste and odor problems related to algae; more frequent back-washing leads to breakdowns	alterations required to deal with taste and odor problems related to algae	alterations required to deal with taste and odor problems related to algae
water source		lower ground water levels due to competing demands and drought	
metering	large unmetered portions of residential sector in old parts of city contribute to high water use during droughts		lack of metering in certain areas leads to excessive water use during droughts
unanticipated failure of critical equipment	pumps can fail due to age, inadequate maintenance or electrical failure		pumps can fail due to age, inadequate maintenance or electrical failure; backup system can fail during peak demand periods
water mains and pipe systems	increased volume due to demand leads to increased leakage		
other components and factors		excessive demand due to rapid growth and drought	illegal connections to hydrants or water mains causes low flow and pressure during droughts
Components and factors that reduce drought sensitivity	**City of Toronto**	**York Region**	**Niagara Region**
water source	Lake Ontario is an abundant source of supply		Lakes Ontario and Erie are abundant sources of supply
raw water intakes	secure placement in deep water reduces vulnerability in case of lower lake levels		secure placement in deep water reduces vulnerability in case of lower lake levels
water use restrictions	voluntary and mandatory outdoor water use restrictions	voluntary and mandatory outdoor water use restrictions	voluntary and mandatory outdoor water use restrictions
ongoing conservation program	retrofitting of shower heads and toilet dams; education	retrofitting of shower heads, toilet dams and other devices ($10 million over six years)	
maintenance of equipment	ongoing maintenance program; routine maintenance restricted during droughts		ongoing maintenance program
expansion of infrastructure		ongoing capital program	ongoing capital program
interconnection of treatment plants	interconnected water distribution system permits sharing of treated water among plants during shortages		water transfer by truck, if necessary, from one treatment plant to another
other components and factors	seasonal treatment plant available to meet peak summer demands		small, drought-susceptible supply systems, including some wells, closed; water levels are monitored carefully

two treatment plants drawing water from Lake Simcoe. Perhaps the most significant situational factor contributing to the sensitivity of the Region's water supply system is rapid population growth, about a 25% increase over the past decade. The interviewee, responsible for the Water Branch, suggested that any reduction in the Region's infrastructure expansion and upgrading program would inscrease substantially the system's drought sensitivity.

Regional Municipality of Niagara. Niagara Region, located southwest of Toronto (Figure 1). is composed of the upper-tier regional municipality and 12 area municipalities. The Environmental Services Division, within the Regions's Public Works Department, supplies water to 400,000 residents in the Region. In 1998, 80,717,000 m^3 of potable water was supplied via eight water systems that included seven water treatment plants and one well system, together with the associated remote treatment and flow metering facilities, water mains (246 km), storage reservoirs (at least 18) and elevated tanks (10), and pumping stations (16) (Regional Muncipality of Niagara N.D.). Additionally, 1,225,000 m^3 of screened raw water was supplied to one of the area municipalities for industrial purposes. Water supply sources for the Region are Lake Ontario, Lake Erie, the Niagara River and the Welland Canal. The Region wholesales the water to its area municipalities, who retail it to customers.

Niagara's Region's water supply system was found to be more sensitive to drought than Toronto's, though less sensitive than York's. Table 3 summarizes system components and situational factors that were reported to be somewhat drought sensitive, and those components and factors thought to reduce sensitivity.

The Region of Niagara has secure water sources in Lakes Ontario and Erie. As water intakes are located at depths of 6.1 m to 9.1 m, lake levels would have to drop drastically for this infrastructure to become vunerable. Also, since formation of the regional municipality in 1969, the Region has closed more than a dozen smaller, more drought-susceptible water treatment plants, many drawing groundwater. Despite this restructuring, the Region has had some difficulty in meeting increased water demand during droughts due primarily to the capacity of existing pumps and storage facilities. This situation can be exacerbated, temporarily, by mechanical or electrical failures.. Two interviewees also reported that some tanker trucks illegally hookup to hydrants and water mains. Extensive agricultural irrigation within the Region, some of which is supplied by the municipal systems, was a further demand on these systems during droughts. One response had been restrictions on the scheduling of irrigation. However, the application of demand management measures was not facilitated by local perceptions of water abundance; one interviewee stated that it is hard to sell water conservation to residents "because the Niagara Peninsula is surrounded by a lot of water" [Lakes Erie and Ontario (Figure 1)]. The Region also experienced the same difficulties in treating algae-related odor and taste problems that Toronto and York experienced.

Preliminary Framework

An aim of this research was to develop a preliminary framework for assessing the sensitivity of municipal water supply systems to drought. Figure 2 offers a framework, which serves two purposes. First, it highlights system characteristics, situational factors and relationships between characteristics and factors, drawn from the literature and the interviews, that play a particularly important role in determining sensitivity. Second, while it must be stressed that the framework is based heavily on the experiences of only several Ontario municipalities, it may assist other municipalities in assessing the sensitivity of their own supply systems to drought.

Figure 2 suggests that the sensitivity of municipal water supply systems is a function of both *system characteristics* (e.g., water source; capacity of storage reservoirs) and *situational factors* (e.g., population growth rates; political will to apply demand management measures). Support for this concept was found in the literature (e.g., Gleick 1990; Schwarz and Dillard 1990). Both system characteristics and situational factors can directly influence sensitivity to drought. For instance, a system's ability to meet increased demand because of lawn and garden watering during drought conditions may be limited by its pumping capacity (a system characteristic). Additionally, the sensitivity of the system may be increased because of the inability (or unwillingness) of municipal officials to impose a mandatory lawn watering ban (a situational factor). System characteristics and situational factors also may exert an indirect influence on sensitivity. For example, a reliance on an abundant surface water source may discourage municipal officials from promoting demand management measures; or, rapid population growth may initiate a search for an alternative water source.

The system characteristics and situational factors highlighted in Figure 2 do not necessarily represent a complete set. Application of the preliminary framework in other locations likely will lead to appropriate additions and modifications. Situational factors probably are especially dependent on the particular case in question. For example, there is considerable variation among Canadian (Waller and Scott 1998) and Ontario (de Loë et al. 2001) municipalities in the application of demand management measures.

System Characteristics. Water system *source* is one of the most drought-sensitive components of a municipal water system. There are numerous references in the literature to problems associated with river and groundwater sources (Reed 1982; Blackburn 1980; Gilbert 1980; Larkin 1980; Robie 1980; Gleick 1990; Montana Drought Advisory Committee 1995). Interviewees in both the preliminary and in-depth interviews highlighted the importance of this system characteristic, noting that groundwater- and river-dependent systems were much more sensitive to drought than large lake-based systems.

Interviewees reported a number of other system components that are sensitive, or potentially sensitive, to drought. *Limited storage capacity relative to demand* and *older and/or poorly maintained system components* were also identified in the literature as sensitive to drought (Fiering and Matalas 1990; Smith and Boyd 1999; Lettenmaier et al. 1990; Taylor 1997; Reed 1982; Al-Weshah and Shaw 1994; Cullinane 1989). *Limited pumping capacity relative to demand*, *leaking distribution pipes*, *limited ability to treat water relative to demand*, *lack of interconnected treatment plants*, and *lack of back-up source and/or system* were also reported by interviewees. In municipalities that have more than one treatment plant, interconnection adds resilience to the supply system. Temporary plant shut down for maintenance and repair, for instance, can be more readily accommodated. Similarly, a back-up source, such as a well, could be invaluable in the event of a surface supply pipeline failure or inadequate surface supply during peak demand periods.

Situational Factors. Situational factors generally were not as extensively addressed in the literature as system components. *Rapid population and/or industrial growth* contributing to increased water demands, especially peak demand, is undoubtedly a major factor. This factor was acknowledged by interviewees and is discussed in the literature (Gleick 1990; Schwarz and Dillard 1990;

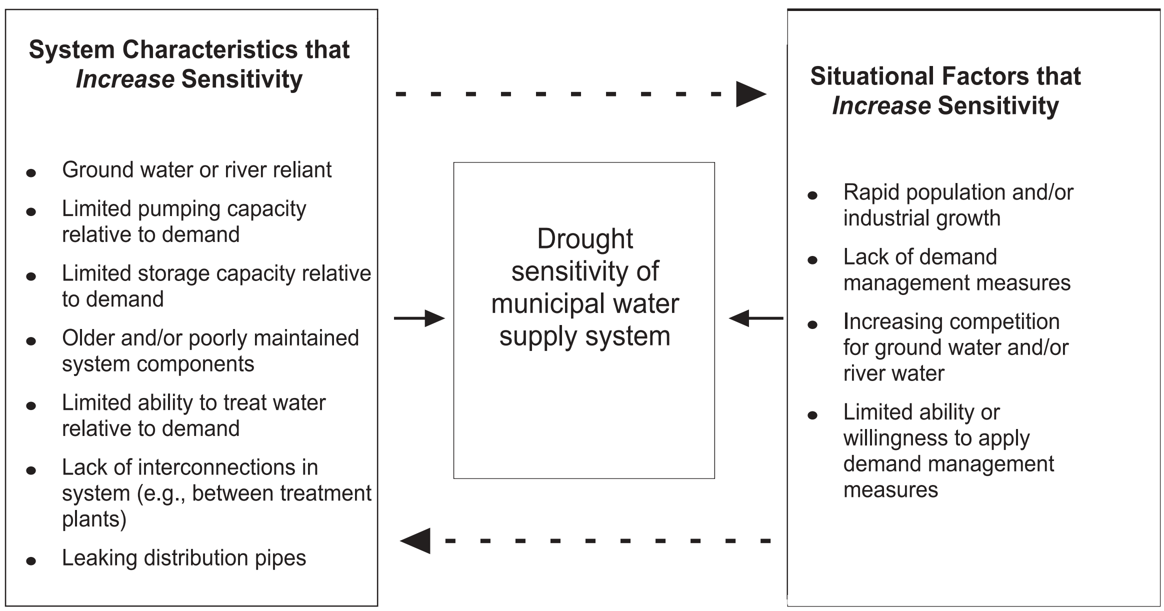

Figure 2: Preliminary framework of sensitivity of municipal water systems to drought

Deibert 1980). It is a fundamental factor that is addressed in much of the demand management literature (e.g., Loaiciga and Renehan 1997; Lund and Reed 1995; Woo 1992).

Other situational factors identified by interviewees included the *lack of demand management measures*, especially the ability to restrict water use during shortages, *increasing competition for ground water and river water*, and *limited ability to apply demand management measures*, for instance because of limited staff or lack of political will. These factors also were mentioned by Schwarz and Dillard (1990). Most of the urban water system managers they interviewed, for example, were skeptical about the likelihood of climate change, or the possibility that climate change might have an impact of urban water management.

Applying the Preliminary Framework

The preliminary framework has potential application as an assessment tool. It must be cautioned, however, that the characteristics and factors identified in Figure 2 have been drawn from preliminary interviews in six smaller- to medium-sized communities reliant on groundwater and river water, and from in-depth interviews in three larger urban areas drawing primarily from a large surface source, Lake Ontario. These nine municipalities are not necessarily representative of the range of municipal water systems in Ontario or in any other jurisdiction. Notably, very small communities are not represented. Furthermore, while the characteristics and factors identified as important in this study have been confirmed in the literature, the literature itself has emphasized large municipalities. The capacity of smaller municipalities to manage water supplies is a growing concern (Soelter and Miller 1999; Kreutzwiser and de Loë 2002; de Loë et al. 2002).

Nevertheless, by considering individual system characteristics and situational factors, and their interaction, municipalities may be able to gauge the sensitivity of their systems to drought. Municipalities that share a number of the system characteristics and situational factors identified in Figure 2 may want to review their circumstances more closely. Smaller municipalities, in particular, may wish to seek the involvement of other municipalities, watershed management authorities, officials in senior government agencies, or other experts in identifying cost-effective and practical ways of reducing the sensitivity of their water supply systems to climate-induced water shortages. Some actions, taken in advance of a crisis, may be sensible for a variety of reasons, in addition to reducing sensitivity to drought. For example, increased attention to demand management would be worthwhile as a way to defer the cost of constructing new works, and could also reduce sensitivity of systems to drought. Urban drought clearly is exacerbated by inappropriate development and wasteful water use practices.

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