Modelling to support the Operations of Water Distribution Networks (WDNs) and their adaptation to Climate Change: Physics-based resilience analysis of WDNs

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Brief Summary

Access to safe and affordable drinking water, one of the most important pillars of public health and economic well-being, is enabled by a robust, resilient, and reliable water distribution network. However, water supply utilities are struggling to fulfil their mandate of providing drinking water at reliable quantity, pressure, and quality, owing to increasingly aging potable water infrastructure among other factors (see Figure 1). 28% of water mains in North America are more than over 50 years old [1], with 25% of Canadian drinking water infrastructure in fair or worse condition, and about 10% in poor or very poor condition [2]. In North America alone, water main break rates, i.e., rates of pipe bursts or leaks, have increased by 27% since 2012 [1], with about $5.7 billion worth of water lost annually due to leaks [3]. Notwithstanding these existing challenges, climate change (CC) impacts with their inherent uncertainty associated with, but not limited to, scope, magnitude and nature, act as a formidable variable in the decision-making framework of water utilities.

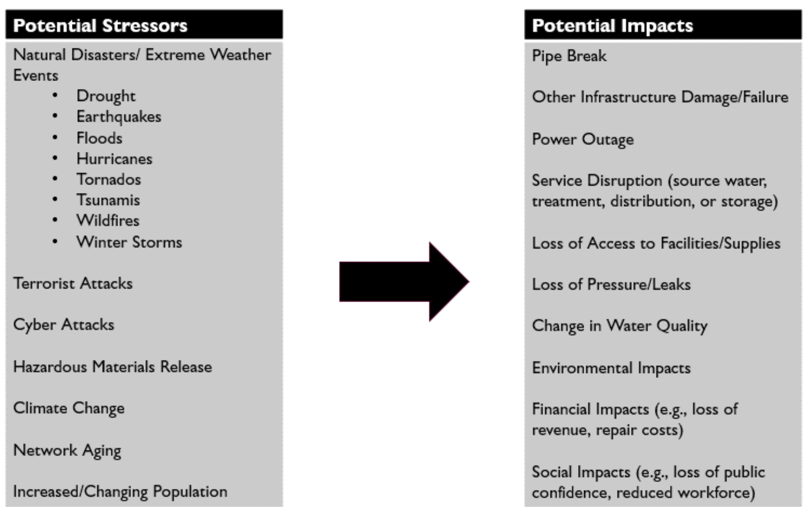

Figure 1: List of potential stressors or disruptions and impacts on a water distribution network. (adapted with permission from [4, p. 5])

Research Questions (RQs) - The two research questions addressed in this study are – RQ1) What may be the impact of climate change (CC) on WDNs; and RQ2) How hydraulically resilient are the operations of a given WDN undergoing individual and combined CC-induced impacts, e.g., combination of systemic change/s and disruption. The systemic or long-term impacts addressed include – a) changing source water availability; and b) infrastructure aging, while the disruption or the temporary impacts include municipal- or household-level fires.

RQ1: Impact of Climate Change of WDN - The study provides an account of the CC-induced impacts on WDNs in two broad categories – a) Overarching Issues, which include CC impacts on water availability,

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water consumption demand and infrastructure damage; and b) WDN Operations. The impacts on WDN operations are in response to the impacts of the overarching issues, which pose consequential risk to both the structural and operational integrity of the WDNs.

A typical WDN sources raw water from reservoirs, surface waters such as rivers or lakes and groundwater before sending the raw water to a drinking water treatment plant. According to a synthesis report [5], due to increased variation in temperature, e.g., causing more extreme droughts or intense flooding risk, and precipitation, there could be reduced summer and fall reservoir levels, reduced base flows during summer and fall into the surface waters, reduced recharge of aquifers, and increased levels of evapotranspiration from surface waters; leading to depleted reservoir capacity and decreased surface water and groundwater flows. Thus, these CC-induced impacts have the ability to exacerbate water scarcity and reduce the overall availability of source water for municipal use. The extreme levels of water scarcity, i.e., when a city is unable to meet the water demand of the populace alternately referred to as Day Zero in popular parlance, are already a reality for many global cities such as Johannesburg and Mexico City [6]. Further, it is found that there is – a) high positive correlation between summer daily water demand and daily maximum temperature, b) positive correlation between demand and population, and c) negative correlation between daily demand and rainfall presence or absence and intensity. As CC is expected to lead to temperature rise, marked by sporadic rainfall events and increased drought episodes, the increases in total water consumption, especially during summers, are predicted. Moreover, the impact of climate change on population is uncertain, making the operations of water utilities more challenging.

Another critical concern is the threat posed to the structural integrity of WDN infrastructure due to CC impacts such as increased frequency and intensity of climate extremes, i.e., both high and low, changing precipitation patterns, sudden weather events, and wildfires [7]. These impacts of climate change can further exacerbate the routine disruptions, such as the pump failures and power breakdown in water treatment plants caused by power outages, pipe breaks caused by aging or deteriorating pipe materials, where different types of pipe materials react differently to high or low temperature extremes, and negative consequences for water quality levels due to accelerated disinfectant decay related to increased temperatures, and contamination and erosion due to flooding and erosive events. As these disruptions become more frequent, there are increased stresses on the maintenance efforts of water utilities, necessitating a transition from reactive maintenance practices towards preventive WDN maintenance and infrastructure management efforts [8].

RQ2: Hydraulic Resilience Analysis of WDN - The study conducts hydraulic resilience analysis, using two physics-based modelling approaches[4] - demand driven modelling (DDM)[5] and pressure-driven demand modelling (PDM)[6], to evaluate the effects of aging infrastructure and reduced water availability on the real-life calibrated model of Net6 WDN [9], [10], undergoing fire flow demand disruption, of varying intensity, at one of its service nodes having maximum base design demand. The Net6 WDN is typical of a small-sized American water utility serving approximately 150,000 people. The CC-induced aging infrastructure is simulated by changing the roughness of the WDN pipes, while the simulation for the reduced source water availability, assumed to be caused by decreased precipitation owing to CC, is undertaken by reducing the reservoir capacity by ten percent. The resilience is measured in terms of the

[4] For this purpose, WNTR [17], a Python-based modelling tool, employing physics-based modelling fundamentals is used.
[5] Based on satisfying the design water demands.
[6] Based on satisfying demands contingent on the available pressure in the WDN.

metrics – Modified Resilience Index, measuring surplus power to face disruptions, and Water Service Availability, measuring the degree to which expected demand is met.

PDM has been found to be more robust than DDM in modelling not only increased fire flows, emblematic of increased stress or abnormality, but also normal operating scenarios. This observation is consistent with findings in literature [11]. Thus, PDM is preferred for resilience analysis. In addition, PDM may lead to more consistent and rational boil water[7] or network pressure advisories [12], [13], and is proposed for improving pressure management, minimization of loss due to leaks and better understanding of capacity expansion[8]. Thus, based on the PDM simulation results for the Net6 WDN operations undergoing various long-term change scenarios and fire flow demand combinations; the following conclusions may be made – a) fire disruption has a relatively greater detrimental impact on resilience, when compared with aging of pipes or reduced water availability; b) the higher the degree of aging, the greater the loss of WDN hydraulic resilience; c) reduced water availability has almost negligible impact on the resilience; and d) the Net6 WDN has been found to be largely resilient to not only increased fire flows but also CC-induced stressors such as aging and reduced source water availability. The last conclusion holds true even when both the stressors and the fire flows are combined.

The findings emphasize the importance of integrating resilience-focused strategies, similar to WDN resilience estimation studies, during hurricanes, by Klise et al. [14] and during firefighting, pipe damage and loss of the water source, by Chu-Ketterer et al. [15], into WDN management; particularly in estimating the impact of CC-induced stressors. Additionally, the study highlights the significance of PDM as a modelling approach for enhancing the hydraulic operational decision-making of water utilities, aimed at adapting water utilities to evolving CC-induced perturbances, as well as other operations and maintenance practices.

Way forward - The impacts of climate change on WDNs are complex and multifaceted, affecting water availability, treatment, distribution operations, and consumption patterns. Effective adaptation strategies, robust modelling, and proactive maintenance are crucial for ensuring the resilience and reliability of water distribution networks in the face of climate change. It is also important to underline that these adaptation strategies need to minimize their greenhouse gases footprint by optimally managing the emissions resulting from pumps or generator operations sourced from fossil-fuel based energy sources [4]. Due to climate change, there is potential for not only increased energy costs but also decreased energy output [5], posing a challenge to the fiscal sustainability of water utilities too. Accordingly, the USEPA [16] advocates for and facilitates climate-ready water utilities through its Climate Ready Water Utilities (CRWU) Initiative[9]. This adaptive response framework, based on an integrative and multipronged approach, involves awareness of climate impacts, adaptation and mitigation strategies, policy support, community involvement, and external partnerships to enhance the resilience of water utilities.

[7] BWAs are advisories issued by local health officials or municipalities to the consumers about the potential or real health risks associated with drinking water [18].

[8] These have not been modelled in this study.

[9] Additional associated links and resources that might be of readers' interest: *Creating Resilient Water Utilities (CRWU)* Website *maintained by EPA* | *Emergency Response for Drinking Water and Wastewater Utilities* Website *maintained by EPA* | *AWWA* Manual *on Climate Adaptation for Water Utilities* [19] | *AWWA* Manual *on Emergency Planning for Water and Wastewater Utilities* [20]

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