Water Distribution System Capacity under Uncertain Climate Change
Ehsan Roshani¹, Yehuda Kleiner², Andrew Colombo³

¹,²,³ National Research Council, 1200 Montreal Road, Ottawa, CANADA
¹Ehsan.Roshani@nrc-cnrc.gc.ca

ABSTRACT

Various water distribution systems were analyzed through various scenarios to identify hydraulic capacity shortfalls in water mains, which result from climate change-driven demand increases. Results were compared against the status quo, in which only natural demand growth (i.e., due to urbanization and population growth) is considered. Watermains in need of renewal/replacement due to the extra demand were identified. Common patterns were explored and the results indicated that the distribution networks examined in this study are generally robust and contain sufficient hydraulic redundancy as to not be significantly affected for the additional demand that is associated with rising temperatures due to climate change. At the same time, this type of analysis does offer a tool to anticipate localized deficiencies in the systems and anticipate and prioritize actions for pipe renewal and rehabilitation. The suggested methodology is highly scalable and parallel processing significantly reduces the required computation time and enables the efficient implementation of Monte Carlo simulation to examine the significant variability that is inherent in this type of analysis.

Keywords: WDS, Uncertainty, Climate Change

1 Background

Climate change may result in increasing water consumption rates in the areas where the trends indicate that the general temperature is raising. Staats [1] showed that the per capita water consumption rate in Chapman, British Colombia was significantly correlated to ambient temperature, where an average rise in summer temperatures of 1°C caused a consumption increase of 34 liter per capita per day (LPCD). Akuoko-Asibey et. al. [2] estimated an increase of 40 LPCD for each 1°C rise, over 15 °C in the city of Calgary, Alberta. If true, such increases in water demand may impose higher stress on water distribution networks and their components.

While properly designed water distribution systems generally include some redundancy in hydraulic capacity to account for population growth and unforeseen contingencies, few if any, have considered the extra capacity that would be required to address loads caused by climate change.

According to the IPCC 5th edition report [3] temperatures could rise between 2 and 6 °C by 2100. Assuming a base maximum day demand (MDD) of 500 LPCD, such a temperature increase could result in a corresponding demand increase ranging from 14% to 45%.

The main goal of this research was to determine how well water mains in distribution systems are suited to handle these extra loads. To achieve this, future demand growth scenarios were generated, using various Representative Concentration Pathways (RCPs) suggested by the Intergovernmental Panel on Climate Change (IPCC)[3]. These scenarios were then applied to three real, moderately
large WDSs and the hydraulic capacity of each was evaluated under various demand scenarios that were generated using Monte Carlo Simulations (MCS) while considering climate impacts.

This work is part of a broader effort undertaken by the National Research Council of Canada (NRC) to investigate and adapt Climate Resilient Building and Core Public Infrastructures (CRB-CPI) to climate change. This work is envisaged to serve as a first step toward the development of a set of tools for water utility companies to evaluate their system vulnerabilities to changing climate. The paper describes the proposed approach (Section 2) as it was applied to case studies (Section 3). Results are analyzed in Section 4 and conclusions and proposed future research directions are provided in Section 5.

2 Methodology

Most large water utilities in Canada develop their distribution network according to master plans typically updated every 5 years, with planning horizons that range from 25 to 50 years. Figure 1 illustrates the range of temperature profiles predicted by the IPCC [3] based on various scenarios.

As can be seen, in the next 50 years the temperatures are predicted to rise by 0.7 °C (RCP2.6) to 3 °C (RCP8.5), which could translate into 3% to 18% increase in the per capita demand (assuming a 34 LPCD increase for each degree rise and MDD equal to 560 LPCD).

In examining the possible response of the network to future scenarios, one must consider three types of uncertainties, namely, magnitude of temperature increase (RCP scenarios), timing of these increases and the distribution of demands across the distribution network. Monte Carlo simulations were used to account for these uncertainties. The large number of computationally expensive hydraulic simulations is addressed by using a thread-based parallel processing technique. The following steps are executed:

1- Simulate the system with the status quo demand and record velocity and headloss for all watermains.
2- Select RCPs and compute the corresponding temperature increase and resulting demand increase.
3- With the mean demands computed in step 2, generate random demands for each demand node across the network.
4- Divide the simulations between available cores.
5- Run all hydraulic simulations.
6- Collect all simulation results.
7- Aggregated results (i.e., average velocity and headloss and their standard deviations) for each watermain.
8- Compare the aggregates with the status quo and record the impact on watermains.

There are several candidate hydraulic loading types that could be used in quantifying the hydraulic impact of added demand. One can use peak hour (PHD) in an average day demand, average hour in maximum day demand or peak hour in a maximum day demand. For this study average hour in maximum day demand (MDD) was selected, with a twofold rational. Firstly, increase in demand due to climate warming will manifest mainly in the summer, which is when MDD occurs. Average hour in MDD was selected rather than peak hour because many water utilities are willing to compromise on the level of service they provide at peak hour of MDD (which is the hour with the highest load of the year and typically represents a very short duration).

The IPCC report introduces about 300 scenarios covering a wide spectrum of possibilities, depending on future GHG emissions. On one side of this spectrum, with RCP2.6 temperatures are expected to rise by about two degrees by the end of the century. On the other side of the spectrum RCP8.5 predicts a rise of about five degrees by the end of the century. In our examination we selected four representative RCPs, namely 2.6, 4.5, 6.0 and 8.5. The examination was carried out for the year 2060 and the corresponding target temperatures were therefore (degree C) 1, 2, 2, and 3, respectively.

![Figure 2, Histogram of the demand distributions for one node with the base demand of 28.2 lps](image)

Step 3 addresses the uncertainty of the demand flow in a demand node. For each demand node the simulation generates a random demand that is taken from a normal distribution whose mean is the expected demand increase and standard deviation that was arbitrarily (for lack of data) assumed to be equal to one third of the difference between the baseline demand and the new average. Figure 2 illustrates an example for a node whose base demand is 28.2 lps and is expected to increase 12%, to 31.6 lps due to climate change. The mean of the normal distribution governing the demand in this node is 31.6 (SD is 1.12 lps).
Using a thread pool programming approach, each Monte Carlo scenario is sent to an available core (step 4), where EPANET2 [[4] is used to solve the hydraulic conditions. The result of each simulation is then sent back to the master thread for aggregation (step 5). For each pipe, the master thread calculates the average flow velocity and headloss as well as their standard deviation and records them on a GIS layer representing the pipes.

The proposed model was developed as an add-ins to HydraCAL framework which had previously been developed by, and is commercially available from, DataAb Inc. [[5]. HydraCAL was initially developed to assist designers with evaluating their design under automatically generated operating scenarios and benefits from parallel processing to speed up the required simulations. It also uses a simple but powerful GIS environment which allows visualization of various statistical and spatial analyses. Figure 3 illustrates a screenshot of HydraCAL with the newly added demand growth simulator.

![Figure 3, HydraCAL and Its New Add-ins for Evaluating Demand Growth](image)

### 3 Case studies

Three medium to large water distribution networks, A, B, and C, all in Canada, were examined in this study. The base demands were obtained from consulting firms that developed the master plans for these systems. These base demands considered population growth, land use, and where applicable demand reduction forecasts due to water conservation policies. Changes in system components, such as planned decommissioning of pipes or pumps were also considered. A demand increase of 34 LPCD per one degree of temperature increase was assumed for all three case studies. Table 1 provides the main characteristics. For each node in each network 1,000 demand scenarios were generated. A laptop computer with 8 cores was used for the simulations (approximately 3 minute simulation time per network).
Table 1, Case Studies Characteristics

<table>
<thead>
<tr>
<th>Network</th>
<th>Serving Population</th>
<th>Total Pipe Length (km)</th>
<th>Planning Year</th>
<th>Model Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1,400,000</td>
<td>4,100</td>
<td>2061</td>
<td>Detailed Model</td>
</tr>
<tr>
<td>B</td>
<td>2,700,000</td>
<td>2,876</td>
<td>2060</td>
<td>Some Pressure Zones are Detailed and Some are Skeletonized</td>
</tr>
<tr>
<td>C</td>
<td>1,300,000</td>
<td>2,950</td>
<td>2061</td>
<td>Detailed Model</td>
</tr>
</tbody>
</table>

4 Results and analysis

After aggregation, simulation results were compared to the baselines. Both headloss and flow velocity were used as criteria for identifying a pipe as significantly affected. A pipe was considered significantly affected if:

1) Pipe headloss at baseline was below or equal to 1.5 m/km and in 2060 average headloss increased above 1.5 m/km.

2) Pipe flow velocity at baseline was below or equal to 1.5 m/s and in 2060 average flow velocity increased above 1.5 m/s.

Table 1 provides results summary and Figure 4 illustrates pipes whose headloss was found to be affected. Results were aggregated by pipe diameter classes, which include small distribution pipes (less than 6” or 150 mm diameter), distribution pipes (6” – 12” or 150 mm to 300 mm diameter), small transmission pipes (14” – 36” or 350 mm to 900 mm diameter) and large transmission mains (more than 36” or 900 mm diameter).

Examination of results in Table 2 gives rise to a few observations:

- Across the board, the effect criterion of flow velocity 1.5 m/s is much less stringent than the headloss criterion of 1.5 m/km. This is evidenced in the low rates of pipes impacted based on flow velocity criterion compared to the much higher rate of impact based on headloss criterion.

- Among all examined networks, small distribution pipes are the least affected. This is probably because such pipes are typically used for short dead ends and cul-de-sac, where only a few homes are serviced by a pipe 2” or 3” in diameter. Such cases are inherently over-designed.

- Among the three networks examined, A is the most affected, followed by B and finally C is the least affected. However, the overall rate of affected pipes seems to be quite low and even with the most severe scenario (RCP 8.5) rate of total pipes affected is below 4% (with the stringent headloss criterion) in the worst network. This could be attributed to the fact that most utility companies, including the selected case studies, design their water mains conservatively. Moreover, small distribution pipes rarely feed fire hydrants, which are typically installed on pipes that are at least 6” (150 mm) diameter. This is significant because pipes in the distribution pipes class are sized to accommodate fire flows, which are invariably larger than peak demand flow. Therefore these pipes will typically be overdesigned with respect to peak flows.
Figure 4. The Selected WDSs. Red Links Indicate the Impacted Pipes for RCP8.5
(Figure 4) shows that pipes affected in Network A are distributed across the entire system, compared to the other two networks in which affected pipes are clustered locally. This could be explained by the fact that City A has the highest rate of intensification among the three, and provides an additional explanation to the fact that its pipes are already subject to hydraulic stress that is higher than the others.

Table 2 Results, Affected Water main Lengths

<table>
<thead>
<tr>
<th>Network</th>
<th>Pipe Diameter (mm)</th>
<th>Total Length in WDS (m)</th>
<th>Affected Pipe Length (m) (% of total) (Headloss)</th>
<th>Affected Pipe Length (m) (% of total) (Velocity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td>RCP2.6 (1 °C)</td>
<td>RCP4.5 &amp; 6.0 (2 °C)</td>
</tr>
<tr>
<td>D &lt; 150</td>
<td>1,558,401</td>
<td>1,924 (0.2%)</td>
<td>2,384 (0.3%)</td>
<td>4,181 (0.3%)</td>
</tr>
<tr>
<td>150 &lt;= D &lt;= 300</td>
<td>2,046,290</td>
<td>34,381 (1.7%)</td>
<td>64,666 (3.2%)</td>
<td>99,011 (4.8%)</td>
</tr>
<tr>
<td>300 &lt; D &lt; 900</td>
<td>348,116</td>
<td>17,753 (5.1%)</td>
<td>27,822 (8.0%)</td>
<td>44,312 (12.7%)</td>
</tr>
<tr>
<td>900 &lt;= D</td>
<td>146,841</td>
<td>1,795 (1.2%)</td>
<td>2,881 (2.0%)</td>
<td>9,531 (6.5%)</td>
</tr>
<tr>
<td>Total</td>
<td>4,099,647</td>
<td>56,312 (1.4%)</td>
<td>99,549 (2.4%)</td>
<td>158,272 (3.9%)</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td>RCP2.6 (1 °C)</td>
<td>RCP4.5 &amp; 6.0 (2 °C)</td>
</tr>
<tr>
<td>D &lt; 150</td>
<td>179,861</td>
<td>229 (0.1%)</td>
<td>473 (0.3%)</td>
<td>473 (0.3%)</td>
</tr>
<tr>
<td>150 &lt;= D &lt;= 300</td>
<td>1,515,885</td>
<td>11,070 (0.7%)</td>
<td>20,529 (1.4%)</td>
<td>31,983 (2.1%)</td>
</tr>
<tr>
<td>300 &lt; D &lt; 900</td>
<td>743,735</td>
<td>9,464 (1.3%)</td>
<td>20,385 (2.7%)</td>
<td>34,252 (4.6%)</td>
</tr>
<tr>
<td>900 &lt;= D</td>
<td>437,226</td>
<td>6,575 (1.5%)</td>
<td>13,910 (3.2%)</td>
<td>24,189 (5.5%)</td>
</tr>
<tr>
<td>Total</td>
<td>2,876,707</td>
<td>27,109 (0.9%)</td>
<td>55,053 (1.9%)</td>
<td>90,897 (3.2%)</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td>RCP2.6 (1 °C)</td>
<td>RCP4.5 &amp; 6.0 (2 °C)</td>
</tr>
<tr>
<td>D &lt; 150</td>
<td>895,384</td>
<td>1,924 (0.2%)</td>
<td>3,800 (0.4%)</td>
<td>8,269 (0.9%)</td>
</tr>
<tr>
<td>150 &lt;= D &lt;= 300</td>
<td>1,818,755</td>
<td>12,608 (0.7%)</td>
<td>13,704 (0.8%)</td>
<td>20,470 (1.1%)</td>
</tr>
<tr>
<td>300 &lt; D &lt; 900</td>
<td>149,557</td>
<td>885 (0.6%)</td>
<td>885 (0.6%)</td>
<td>2,564 (1.7%)</td>
</tr>
<tr>
<td>900 &lt;= D</td>
<td>86,256</td>
<td>(0.0%)</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Total</td>
<td>2,949,951</td>
<td>15,418 (0.5%)</td>
<td>18,390 (0.6%)</td>
<td>31,302 (1.1%)</td>
</tr>
</tbody>
</table>

5 Conclusions

Monte Carlo simulation is combined with parallel processing to evaluate the impact of climate driven demands on the capacity of water mains in three large water distribution systems. The results indicate that in general, these water distribution networks are designed robustly and can generally contain the extra hydraulic stress that is expected due to climate change. However, this type of analysis could help identify in the network pipes and locations whose level of hydraulic redundancy is less than the rest of the network and would therefore require earlier attention. The headloss criterion use in this work is much more stringent than the flow velocity criterion. Future work will include the examination of the sensitivity of the results to the values of the criteria that were reported here (i.e., 1.5 m/km of headloss and 1.5 m/s flow velocity). Future analysis will also
endeavor to examine whether different values for the criteria would result in a different distribution among pipe classes of affected pipes.

Additionally, this work was limited to the impact of extra demands on water main hydraulic capacity. Future research should consider examining the impact of increased demands on the spatial distribution of pressure, on fire flow scenarios, on other system components such as pumping stations and reservoirs, and on energy consumption. As well, other demand indicators, such as PHD could be examined.

All of the temperature estimations, resulted from the four RCPs, were generated using Global Climatic Models (GCMs), which due to their inherent nature and scale often result in averaged climatic values (i.e., they function as a low pass filter) that might differ from the outcome of more spatialized models (i.e., regional climatic models or downscaled simulations). Therefore, the impact of these models should be thoroughly investigated.

It is noted that the case studies in this work comprised only large and well-maintained WDSs in Canadian climate. Other types of systems might result in different outcomes. Finally, climate change could be associated with changes in precipitations, which also have potential of impacting water demand. These were ignored in this work but should be accounted for in future works.

6 References


