TRUNK WATER MAIN FAILURE CONSEQUENCE MODELLING DURING NORMAL, PEAK AND FIRE FLOW CONDITIONS

by

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Abstract

Trunk water main failures pose a large risk to users as they often carry severe hydraulic, economic, and social consequences. The consequences can be increased when a fire event in the water distribution system coincides with a trunk water main failure event. Currently, municipalities have limited knowledge on the consequences associated with the failure of trunk water mains, as it has only recently emerged as an area of concern as water main assets reach or exceed their expected service life. Consequence modelling can provide municipalities with information to help with emergency planning and rehabilitation/replacement planning.

The aim of this thesis is to present a new methodology to characterize the consequences of trunk water main failures in water distribution systems. A new consequence index equation is used to calculate the severity of a failure event. A number of metrics were developed to characterize a range of consequences to the system and water users. A focus is placed on the hydraulic changes during water main failures and the ensuing consequences. The model examines failure during normal, peak and fire flow conditions in the network.

Two case studies were completed by applying the consequence model to the D-Town and City of Kingston water distribution systems. The purpose of these studies is to demonstrate the effectiveness of consequence modelling and provide the City of Kingston with information regarding trunk water main failures in their system, and thus help prevent high consequence events. An investigation of the relationship between pipe properties (location, pipe diameter, pipe length, proximity to large components) and consequence severity provided insight into trunk water main failure events. The results of these studies suggest that the location of the trunk water main failure is the largest contributing factors to the severity of consequence.

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Chapter 1

Introduction

Municipal water infrastructure in developed countries is deteriorating faster than it is being replaced, leading to water quality issues, reduced hydraulic capacity, increased leakage rates and frequent main breaks (Federation of Canadian Municipalities et al. 2003). Main breaks have become an increasing prominent issue as water main assets reach or exceed their expected service life. Trunk main failure in particular can entail serious negative consequences by both utilities and the public. Currently municipalities have limited knowledge on the consequences of trunk water main failures in their system.

Over the past decade North American cities have dealt with many unexpected catastrophic failure events. Included in these failures is the failure of a 910 mm pipe in Green Bay, Wisconsin in December 2012 resulted in 8 million gallons escaping from the system (Fox News 2013). This event has cost the Green Bay Water Utility $500,000 (US), representing only the direct costs of the failure (Fox News 2013). In January 2013 53 million litres were lost from a large diameter pipe failure in Minneapolis, Minnesota (Brandt *et al.*, 2013). It is estimated that this failure cost $500,000 (US) in repair of flooded cars alone (Brandt *et al.* 2013). This event also resulted in several businesses being shut down for the day of the burst resulting in loss of revenue and workers not receiving pay. A failure in Montreal of a 1200mm main, near the McGill University campus, caused several people to go to the hospital with minor injuries (CBC News 2013). The cost to the university alone is expected to be $100,000 (CND) and it will take month to fix all the damages from flooding (CBC News 2013). Without an understanding of the consequences of trunk water main failures these events will continue to occur without any ability to prevent them.

1.1 Consequence Analysis

Trunk water mains with diameters ranging from 300mm to 1500mm can entail serious consequences when compared with smaller pipes because they are integral parts of the system and convey large quantities of water to a large percentage of the population. Common consequences that result from these events include inconvenience to users, damage to the system, damage to property/ economic loss, and injury or loss of life (Filion 2005). These consequences arise due to water quality issues, flooding, insufficient pipe pressure/ fire flow, etc. and occur due to hydraulic, water quality or structural failure or a combination of the three.

The consequences of a trunk water main are realized not just at the location of failure but can be wide spread throughout the system. A portion of consequences are caused by changes to the networks hydraulics due to the large quantity of water being lost. The severity of consequence can vary depending on the number of people affected, the type of the land use affected, damage to other pipes in the system, etc. Other consequences unrelated to hydraulic changes that can be experience are traffic delays, water contamination, flooding, repair costs, etc.

1.2 Fire Flow Conditions

Water distribution systems have a basic purpose and function to deliver potable water to a community and to allow fire suppression. Modern systems are designed to provide water at a minimum acceptable pressure during peak demand conditions. This design criteria is normally taken as the greater of maximum hour peak demands, or maximum day demands and a fire at a critical node. While the coincidence of a fire and trunk water main failure event is rare, their joint occurrence can result in large losses especially if insufficient pressure is available for fire suppression.

In this research, a new consequence model was developed to examine the severity of different trunk water main failures in water distribution systems. Municipalities can use this consequence model to rank pipes according to the severity of consequences linked to their failure under both normal and fire flow conditions. The proposed model can be used to develop scenarios to assist municipalities in their emergency planning and management, and in conjunction with condition assessment data to help municipalities prioritize the replacement and rehabilitation of trunk water mains that entail severe consequences at the time of failure.

1.3 Thesis Objectives

The main objectives of this thesis are as follows:

1. To develop a new consequence model that examines the consequences due to hydraulic changes caused by a trunk water main failure in a water distribution system.

2. Examine the consequence during both failure and repair of a trunk water main.

3. Include the consideration of fire flow coinciding with a trunk water main failure and determine the associated consequences.

4. To examine the consequences linked to trunk water main failures in 2 large, complex water distribution systems.

5. To examine the link between pipe properties (location, pipe diameter, pipe length, proximity to large components) and consequence severity.

1.4 Original Thesis Contributions

1. Developed a series of metrics that help quantify the consequence of a trunk water main failure.

2. Developed a consequence index equation which calculates the severity of a trunk water main failure event in a water network.

3. Applied the consequence model to 2 large, complex water distribution networks.

4. Provided Utilities Kingston with consequence analysis results to help them in their emergency planning and their rehabilitation/ replacement planning.

1.5 Organization of Thesis

This thesis consists of 6 chapters including the present introductory chapter. An overview of each of the chapters follows below.

Chapter 2 is a review of the literature in consequence modelling of large-diameter pipes in water distribution systems failures. Consequence models included in the review focused on a single consequence, multiple consequences, or risk analysis of distribution networks.

Chapter 3 presents the methodology of the novel consequence model developed in this thesis. Details of the consequence index equation are presented along with the model metrics used for normal, peak and fire flow conditions.

Chapter 4 presents the first of two case studies where the consequence model is applied to the D-Town water distribution network (Marchi 2013). For the analysis all of the model metrics are

analyzed during peak and fire flow network conditions. The result of the case study point to links between failure location, fire location, and consequence severity.

Chapter 5 presents the second case study where the consequence model is applied to the City of Kingston water distribution network. Due to unavailable data a condensed metric analysis was completed focusing on the demand, population and land use during peak and fire flow network conditions. The results point to a link between pipe properties (location, diameter, proximity to large components) and consequence severity.

Chapter 6 concludes the thesis by providing an overall discussion and summary of the results. Future work that is possible in this area is discussed briefly.

1.6 Publications

Through the completion of my thesis I have submitted to the following conferences as indicated below:

Giangrande, V., Filion. (2014). "Trunk Water Main Failure Consequence Modeling of Hydraulic Failure with Fire Flow." 2014 CSCE Annual Conference. 28-31 May 2014 in Halifax, Nova Scotia.

Giangrande, V., Filion, Y. (2014). "Trunk Water Main Failure Consequence Modelling of Hydraulic Failure and Fire Flow." World Environmental and Water Resource Congress. 1-5 June 2014 in Portland, Oregon: pp 445-464.

Giangrande, V., Filion, Y. (2014). "Consequence Modelling of Trunk Water Main Failures under Peak and Fire Flow Conditions" ASCE Journal of Water Resources Planning & Management. (In preparation).

1.7 References

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Filion, Y. (2005). "Probabilistic approaches for safe-fail design of water distribution systems." *University of Toronto: Ontario, Canada.* Unpublished work.

Fox News. (2013). "Water Main Break Could Cost $500,000." Retrieved from http://www.fox11online.com/dpp/news/local/green_bay/green-bay-water-main-break-december-29-2012-could-cost-500000-dollars.

Marchi, A., et al. (2013). "The battle of the water networks II (BWN-II)." *J. Water Resour. Plann. Manage.* in press. doi:10.1061/(ASCE)WR.1943-5452.0000378.

Chapter 2

Water Main Failure Consequence Models: A Review of Previous Research

2.1 Introduction

With aging infrastructure, the concern of system failure has become an important issue. Municipalities have neglected water distribution systems replacing only 1-2% of the total system annually (National Research Council Canada 2003). This low replacements rate leads to pipe failure events that can produce large consequences. Large diameter water mains (with diameters ranging between 300 mm to 1,500 mm) are an integral part of water distribution networks since they convey water to large numbers of users. Their failure can carry serious economic, social, and public health consequences for users of a distribution system. The failure of large diameter water mains has shown to have major negative impacts including the inconvenience to users (residential, commercial and industrial), damage to the system, damage to property/ economic loss and injury or loss of life (Filion 2005). The high cost associated with these events has created a need for modeling tools that can characterize the economic and social consequences linked to the failure of trunk water mains in distribution systems. Several models have been developed to deal with this problem. Some of these models focus on one specific consequence in a robust manner. Other models examine several consequences and give a broader picture of the economic and social consequences by sacrificing accuracy in their predictions. The end purpose of many of the models is to incorporate the findings into a risk analysis that combines the probability of trunk water main failure with the consequences experienced after failure. Municipalities can use the findings from these models to allocate financial resources and prioritize their condition inspection and rehabilitation programs to reduce the risk and consequences of large-diameter failures.

The aim of this paper is to review past research on consequence modelling and analysis of large-diameter water mains. The paper reviews and offers an overview of past research in consequence modelling and discusses the areas where further research is needed.

2.2 Single-Consequence Models

Jowitt and Xu (1993) developed a method of identifying critical pipe failures that can carry severe consequences in a water distribution system. The impact of critical failure events on system hydraulics and water quality were simulated with a simplified method without recourse to a network solver and water quality routine. The model uses a known set of operational network flows to gather a more detailed understanding of the flow pattern termed the *microflow distribution*. Each microflow describes the flow of water in each pipe section and through each node including the demand at each node. Variables for nodal supply, nodal consumption and pipe element flow are used to define the micro flow distribution. Perfect mixing is assumed in accordance with previous work (Wilson 1970 & Jaynes 1957). Equation 2-1 represents the relationship between delivered demand, C_i, and the ultimate demand, C_i^*.

$$C_i = C_i^* \left[1 - a_i exp\left(-b_i \frac{SP_i}{P_i^*}\right)\right] \qquad (2\text{-}1)$$

SP_i is the service pressure at node i, and P_i^*, a_i, and b_i are all constants for each particular node. The first simulation uses normal conditions with all other simulations representing failure conditions for each of the pipe sections in turn. A case study of a 9-pipe network showed that nodal demands were met under normal conditions but that water main failures created severe shortfalls in demand.

The model by Jowitt and Xu (1993) was the first of its kind to analyze the hydraulic behaviour and consequences of water main failures. Several shortcomings of this method are outlined by Jowitt and Xu (1993). A comparison of the predicted microflow distribution simulation and actual full simulation under failure conditions showed that the model did not accurately identify the locations with demand shortfall and in most cases overestimated water deficits in the system. To use this model for practical applications, calibration of pressure dependency should be completed for nodal demands. Moreover, the model has only been applied to small networks and has yet to be tested with large, complex networks.

Filion *et al.* (2007) developed a new stochastic design approach to characterize the expected annual fire damages to residential, commercial and industrial users that occur during hydraulic failure situations in water distribution networks. Three different types of damages were considered: 1) damage that occurs when pressure drops below 14.0 m and a fire erupts, 2) damage that occurs when the pressure is between 14.0 and 26.0 m at a node inconveniencing users, and 3) damages that occur when pressures increase above the structural capacity of pipes that service industrial properties and cause flooding in those properties. A Monte Carlo Simulation (MCS) algorithm was used to calculate the expected annual damages represented by the general equation (2-2).

$$E[D] = \sum_{i=1}^{S} D_i p_S(s_i) \qquad (2\text{-}2)$$

D_i is damages, in dollars, incurred when the pressure state s_i occurs, $p_S(s_i)$ is the probability mass function of variable state s and S is the number of pressure states. The MCS framework developed by Filion et al. (2007) to calculate expected annual damages in a network is indicated in Figure 2-1. Time series of water demands, fire flows, and pipe breaks are generated with appropriate stochastic models. The stochastic model generates a time series of demand values by adding

together a base, seasonal, and random component of demands. Poisson processes were used to model random fire and pipe break occurrences.

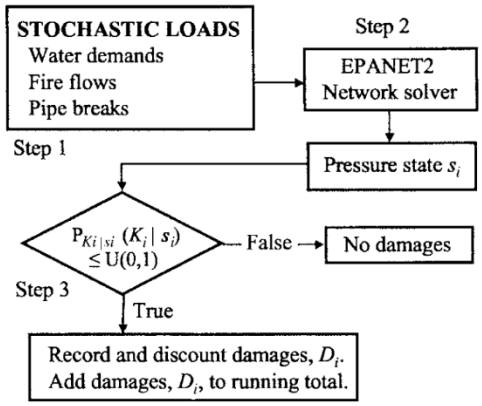

Figure 2-1: Structure for the Monte Carlo Simulation used to model annual fire damage (source: Filion et al. 2007).

The network solver EPANET2 (Rossman 2000) was used to evaluate pressures at nodes over time and over a range of demand, fire, and pipe break conditions. Expected annual damages were estimated by tallying the damages that occurred when pipe breaks and fires coincided with the violation of high and low pressure thresholds. The new stochastic design approach was demonstrated with the benchmark Anytown water distribution system (Walski et al. 1987). The results showed that increasing pipe sizes reduced the expected annual damages significantly in the Anytown water distribution network.

This model advanced network design practice by concluding that significant pipe break and fire events often occurred during low-demand periods rather than during high-demand periods, as is often assumed in network design. The stochastic model of Filion et al. (2007) could be coupled with a trunk water main failure model to get a more accurate picture of the probability of a fire during a failure event.

Filion *et al.* (2007) outlined several shortcomings of the current model. The authors pointed out that the stochastic design approach is hindered by the lack of available data to quantify damages, the complexity of the required calculations and the large computational demand. The model also simplifies failure events by only modeling the consequence that dominates for each pressure state and mode of failure. As displayed through other models, it is seen that a large number of consequences exist and it is important to understand the severity of each consequence.

Jeong and Abraham (2009) developed a model to help water utilities develop a rationing plan when the availability of water is lower following a catastrophic loss of a trunk water main or other water infrastructure. The non-dominated sorting genetic algorithm (NSGA-II) by Deb et al. (2000) was coupled with EPANET2 (Rossman 2000) to develop rationing plans for full-supply, 8-hour supply, 4-hour supply and no-supply in a 24 hour service period. The water rationing model calculates the consequences of each rationing plan while taking into account the impact level on the customer, the amount of people affected and the monetary loss. The proposed model was applied to a sample water network system to show the capabilities and importance of this type of modeling.

The consequence analysis model evaluates the consequence of trunk main failure (and other large water distribution system failures) and provides decision support to develop plans to mitigate the impact on customers. No other consequence model thus far has provided solutions to this problem. This model is also important in water distribution system research since it can be used to characterize the consequence of the failure of other components such as tanks and pumps.

The model by Jeong and Abraham (2009) has shortcomings. For one, it does not take into account water losses through leaking pipes and it cannot model pressure-dependent demand nodes. Another model shortcoming is that it does not include valves to shut off water to problem areas. The

program has also been shown to be computationally demanding for larger networks and could limit its practicality in a real-time application.

2.3 Multi-Consequence Model

Cromwell *et al.* (2002) developed the Grand Central Model (GCM) which is an iterative-based spreadsheet model that calculates the total societal costs that result from the failure of infrastructure systems. The model focuses on operating risks that are defined as failures under normal operation conditions. The GCM model considers three types of costs: (1) costs incurred by utilities directly, (2) high incidence/low impact social costs, and (3) low incidence/high impact social costs. Each cost type has its own worksheet with modules consisting of numerous input values that are applicable to different failure scenarios. The GCM also allows users to perform an analysis on a single component or a group of system components.

Low Incidence/High Impact Social Costs: The GCM model examines low-incidence/high impact events such as fire loss, waterborne illness, and property damage due to flooding. The fire cost module of the GCM takes into account the area that will lose firefighting capability if a fire hydrant is connected to the section of pipe taken out of commission during service operations due to the failure. It also captures the effects that a fire would have on residential and non-residential property separately because of the difference in structural and content values. The GCM model also examines health impacts linked to waterborne illness and injuries sustained at the location of the trunk main failure. It is emphasized (Cromwell *et al.* 2002) that the chance of waterborne illnesses occurring in modern distribution systems is extremely low. Property damage impacts includes flooding of buildings, cars and any property damaged at the site of pipe failure (e.g., car damaged

by sinkholes). The flooding damage from buildings assumes the content damage is directly proportional to the value of the structure.

High Incidence/ Low Impact Social costs: The GCM also examines high-incidence/low-impact events such as traffic delays and customer outages. The GCM has a module that examines traffic delays with respect to the time following water main failure and during repair. The GCM makes use of information for traffic delays from the State of Florida but data from other jurisdictions can be used with the GCM model. The GCM also examines customer outages and substitution costs for residential, dry industrial, wet industrial and critical customers. Residential customer interruptions were analyzed for the duration and number of residents affected and the amount of bottled water purchased. Dry and wet industries were analyzed in terms of the duration of the initial period with no impact and the duration between the start of impact and the full impact felt by the industry. (Note that wet industries reach maximal impact more quickly than dry industries since wet industries are heavily reliant on water.) It is assumed that impact of critical customers is similar to that of wet industries but that it includes costs (e.g., start-up costs) that occur outside of the time of the infrastructure failure.

Costs Directly Incurred By Utilities: Here the GCM considers administrative, legal, lost production, public safety, repair and return to service, and service outage mitigation costs that bear directly on the budgetary situation of the water utility who experiences a water main failure. The GCM considers administrative and legal costs which can be input into the GCM program using two different methods. The first is percent of legal claims methodology, which bases the cost on the percentage of legal claims filed. The second approach is the load salary estimation methodology, which bases the cost on an estimate of the legal and administrative costs associated

with the failure event. For both of these methodologies, an understanding of previous failure legal costs must be known if the user is modeling hypothetical scenarios, since this information is specific to water main failures. The GCM also considers a range of other costs such as the lost production costs, or the cost of lost water and the operational cost of cleaning and transporting the water. The GCM considers public safety costs associated with mobilizing emergency response staff at a failure site and the probability that their attendance will be necessary. The GCM also considers repair and return to service costs to repair the failed water main. This cost includes labour, materials, and return to service expenditures. In this module, the model user can include the costs of repair of other utilities that are damaged due to the trunk main failure.

The service outage mitigation cost module of the GCM allows for input of activities including alternative water supply services put in place by utilities for customers and customer relation costs associated with the failure event. These costs can vary widely depending on the utility and the type of failure event.

The GCM model by Cromwell et al. (2002) has shown to be the most complete model that examines the social consequences of water distribution system failures. It includes a wide range of consequences that allows for a robust analysis when information is available. This model allows user to choose what inputs can be discounted if they are not relevant since trunk main failures entail a unique set of consequences of importance. The range of input values provided for the user is also useful to allow for a better understanding of reasonable values. This model is best used for examining past events to help predict costs of future events and to understand the nature and severity of social impacts linked to a large diameter water main break. The costs include both

“hard” and “soft” costs for different modules allowing all social impacts to be represented in the model.

While the GCM by Cromwell et al. (2002) is robust and includes most social consequences linked to large diameter pipe failures, it is not without shortcomings. Model inputs consist of monetary values which must be accurate for the model to be helpful in decision making. This model is only capable of measuring consequence post-failure which is a useful tool in understanding failure events but does not shed light on failure prediction. Another short coming is the weighting of low incident/ high impact costs. These costs are given a low weighting because of low incident which ignores the fact that the impact is very high. These values such as fire cost and health impact should be given a larger weighting since the consequences can include injury, sickness or loss of life.

Gaewski *et al.* (2007) completed an analysis of the total cost of large diameter water main failure using a streamlined version of the GCM developed by Cromwell *et al.* (2002). The purpose of this analysis was to find the average cost of failure for pipes with diameter of 508mm and larger to allow water utilities to compare the cost with non-destructive inspection and replacement costs and to give a broader perspective on the conditions of their water distribution system. Thirty recent large-diameter pipe failures were analyzed by obtaining the necessary data from utilities to calibrate the GCM and calculate a total cost associated with these water main failures. Additional model inputs consistent across all the failure events were filled using best available public data and estimates from the range suggested by the GCM. Total cost was calculated as the sum of direct costs (costs paid for by the water utilities and their insurance carrier) and societal costs (costs paid for by the people affected either through actual dollar expenditures or by other terms).

The GCM analysis revealed total costs ranging from $6,000 to $8,500,000 with an average total cost of $1,700,000. A geometric mean of $500,000 was calculated to reduce the influence of the high and low values. The direct and social costs in most cases were evenly split in regards to their amount. The direct costs and societal cost breakdowns can be seen in Figure 2-2.

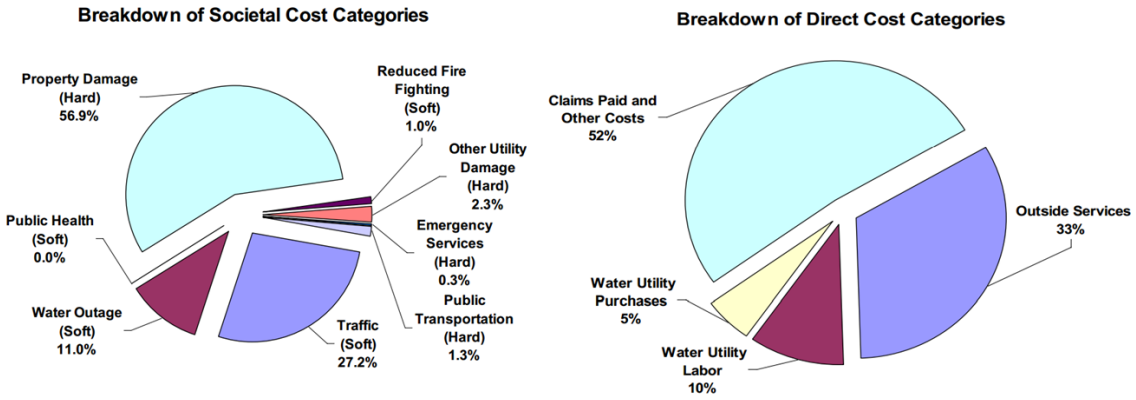

Figure 2-2: Charts showing the breakdown of both the social and direct costs associated with the failure of a large diameter water main (source: Gaewski *et al.* 2007).

These plots indicate the parameters that produce the highest cost, which in practice, can be related to the highest consequence. However, consequences that were not experienced in the sample size of failures can have a larger consequence than indicted in Figure 2-2. For example reduced firefighting only made up 1% of the cost because no fires were experienced during the 30 failures analyzed. However, if a fire occurs during the failure of a large diameter pipe and the necessary pressure is not available, the consequences will be severe and the damage costs will escalate significantly.

The analysis completed using the previously-constructed GCM advanced the understanding of historical large-diameter failures and the total costs linked to the consequences of failure. This research was the first to compile a large number of historical breaks to validate a model that covers a wide range of failure consequences. The research has also provided valuable knowledge to water

utilities on the cost of trunk main failures. The research has also shed light on what are the most costly consequences and how they vary from the consequences posited with general flooding data and other sources not linked to pipe failure.

The analysis completed also has shortcomings associated with it due to the model (as discussed above) and the data available. The sample size of water main breaks did not include all of the consequence mechanisms and this likely skewed the results. In the analysis, high-incidence consequences were considered more important than low-incident consequences. This does not properly represent the large severity that can occur due to low-incident consequences.

2.4 Risk Models

Cooper *et al.* (2000) developed the trunk mains burst risk model which characterizes the probability and consequences of failure of mains greater than 300 mm in diameter. The model focuses on the risk of failure within the Thames Water London Supply Region. A probabilistic approach was taken by examining past pipe failures and trying to explain the common conditions and factors involved in water main failure. It was found that the important factors in modeling probability were the number of buses per hour traveling above the water main, pipe diameter, soil corrosivity class and proximity of pipes to one another. Statistical analysis was conducted and an output score for each main length was stored in ArcInfo GIS. The consequence module of the model examines domestic properties, commercial properties, repair and reinstatement costs, and additional factors (including sensitive customers, key customers, tourist attractions and main arterial roads) focusing on flood damage. Postal codes were used to generalize areas by common characteristics. Ratable values (property taxes) and insurance reserve data were also used to

understand flood damage costs. A consequence score was calculated with (2-3) for residential consequences of water main failures

$$Domestic\ concequence\ score = [(Mean\ rateable\ value + Mean\ sum\ insured) \times Probability\ of\ basement] \quad (2\text{-}3)$$

Both mean ratable value and mean sum insured are used to understand the amount of property damage. The probability of a building having basement was determined by building age where different values were associated with different time periods of construction. The values were used in equation 6, where the domestic consequence score increases if the probability of a basement is higher. For negative consequences to commercial establishments, a commercial consequence score is calculated with (2-4)

$$Commerial\ consequence\ score = [(Total\ rateable\ value) + (Mean\ reatable\ value\ for\ each\ floor \times Loss\ of\ business\ factor)] \quad (2\text{-}4)$$

The total ratable value is used for basement and ground level floors to obtain a consequence score for postal code units. The mean ratable value for ground level and upper floors is multiplied by the loss of business to obtain a total consequence score. While at the time of writing a score system was not yet developed for additional consequence factors, Cooper *et al.* (2000) mentioned that it is possible to add them to the model if need be. A flood area model was developed to allow a basis for estimating the consequence of failure. The flood location and extent were the two components modeled. The trunk water main network was modeled hydraulically in order to calculate the volume of water that would escape a circumferential split with an orifice size the diameter of the pipe. This case represents the worst case scenario allowing for a conservative result when

considering flood location. A final value is obtained by subtracting a drainage function which represented the amount of water lost through the road and surface water drainage systems. The extent of flooding accounted for the flow rate at specific burst locations along with the road layout to see the direction of flow and understand when the amount of water is greater than what can be contained by the curbs. This area is entered into ArcInfo GIS intersecting the postal code layer with corresponding consequence score. The percentage of the postal code area that is affected by the main failure is the percentage of the consequence score that is the actual consequence score for that area. Multiplying the final consequence score and failure probability score together gives a pipe specific failure risk score.

This model represents the worst case scenario of flooding when a large diameter pipe bursts. With few other models taking into account flooding, Cooper *et al.* (2000) has provided a valuable model. The model takes into account the area of the pipe burst but also areas that may be affected from flood runoff. This gives a more robust characterization of flooding due to a catastrophic trunk water main event. It also takes into account both property and content values to allow for a more realistic rating of severity which, again, increases the robustness of the model. By representing the final outcome as a risk score, this model allows for risk values associated with different pipes in the system to be compared.

The model developed by Cooper et al. (2000) applies only to the Thames Water London Supply Region. It is unclear if the model could be transferable to other jurisdictions if calibrated with data from those other jurisdictions. Also, the model only considers one type of post-failure impact or consequence. This causes other large consequences to be ignored when examining the risk of failure throughout the system.

Beuken *et al.* (2008) developed a reliability-centered maintenance method to evaluate the feasibility of using quantitative risk analysis in assessing water distribution systems. The risk assessment included five risk evaluation matrices examining the probability and potential consequences of a spontaneous pipe burst. The matrices contain the risk classes *critical* and *non-critical* and can be varied by the user depending on the policies of a water utility. Probability was assessed as the number of bursts that occur along each pipe section per year regardless of the length. Five consequences are included in the model: interruption of supply, insufficient pressure, substandard water quality, and image and cost. The period of interruption and the number of connections affected are found using the tool CAVLAR developed by Kiwa Water Research to express the interruption of supply. Pressures in the system were examined during main burst and repair scenarios using a hydraulic model to calculate the number of connections affected. Substandard water quality was found by summing the ranking of customer complaints, area of low-flow velocity and areas of high flow. Public image was represented by the number of sensitive customers, such as schools, hospitals and industry, negatively impacted by the failure event. Cost included only the repair costs to the water distribution system and surrounding area, such as road, historical building and dyke repair. Once all five matrices are created they are consolidated through sundry methods such as the number of times critical, the average risk score, the maximum risk score, or by finding the weighted average risk score. A case study was completed using this model on the water distribution system of Montfoort, Netherlands, a small town with trunk water mains representing 12% of the network. From the analysis it was found that interruption of supply was not critical for any of the pipe sections in the network. In total, 39 out of 297 sections were considered critical in at least one of the five consequence criteria.

The risk analysis method of Beuken *et al.* (2008) showed that a quantitative assessment can be completed for water distribution networks. This method was previously believed to be unsuitable because networks are buried, span large areas and preventative maintenance is difficult and limited. This model took advantage of technological advancements to allow for better computer modeling and access to necessary information. Additionally, the consequences included represent network problems that are often not included in other models. New approaches were used to try and properly represent these consequences by using hydraulic modeling and the CAVLAR tool. This model can easily be used for different distribution systems and tailored to meet different municipality/ utility standards.

Beuken *et al.* (2008) outlined several shortcomings to improve upon to make the model practicable for water utilities. First, the computational demands of the model are high given the high volume of input data and many sub-modules that must be run in the model. Second, gaps exist between obtainable and desired data causing assumptions to have to be derived from available information making the final result less accurate.

Tchorzewska-Cieslak (2011) applied fuzzy-set theory to develop a model of risk management for water pipe failures. In this model failure is taken to occur when the flow to customers is not constant and/ or an unacceptable pressure exists in the system. The consequences considered are inconvenience to users, financial losses and water contamination (and the associated health affects). Risk is calculated as a function of frequency, consequences and network protection in (2-5)

$$r = \sum_{S=1}^{N} (P_i \ C_j \ E_k) \qquad (2\text{-}5)$$

where *r* is the risk function, *S* is the number of undesirable events, P_i is point value of the frequency of an undesirable event, C_j is the point value of the loss during an undesirable event and E_k is a point value of the degree of sensitivity. The point values are scaled according to a list of criteria where a large number represents large consequences. The probability parameter, losses parameter and sensitivity parameter have five, three and three linguistic characterizations respectively. The Mamdani-Zadeh type decision model (Mamdani 1977) was used for this model. Defuzzification is the last step in the model to convert the fuzzy set data into a form operators can use for decision making. The centre of gravity method was used to perform this last task. A set of water mains were analyzed using this model. They were analyzed based on diameter and split into three different categories: small than 150 mm, 150 mm to 400 mm and 400 mm and greater. The case study results suggested that the two smaller diameter categorizes were of medium risk whereas the pipes with a diameter of 400 mm or larger were of low risk. However when looking strictly at the consequence scores, the larger diameter pipes had a higher rating showing more severe consequences.

Using fuzzy set theory to model water distribution networks allows for input values with different scaling factors to be incorporated in the model. This model can also incorporate different expert data by including them as linguistic variables. The example results showed that the level of consequence increase as pipe size increased.

Tchorzewska-Cieslak (2011) discussed the limitations of the model in its current form. The usefulness of the model depends on whether a database of rules developed by experts exists or can be created. A larger database on the nature, risk and cost of consequences is needed to better calibrate this model. This information has been shown to be difficult to collect since many water utilities do not collect data on failure consequences. Lastly this model represents all consequence

as a single membership function which does not allow for different consequences to be taken into account.

A recent model developed by Friedl and Fuchs-Hanusch (2011) combines probability of failure, severity of failure and the probability of detection for large-diameter mains. A Failure Risk Index (FRI), a multi-criteria index, was created based on the risk methodology introduced by Zonensein *et al.* (2008) which is used to analyze flood risk in urban areas. Friedl and Fuchs-Hanusch (2011) applied the method to a case study for an Austrian water supply company. The indicators can vary according to the location of the analysis but should represent data that is easily obtainable. For the sake of simplicity, the input values and output FRI are represented by non-dimensional values ranging from 0 to 100. The probability of failure parameters included were the number of previously-detected failures on a pipe segment, vintage, pipe joint type, ground water impact, operating pressure, location when installed, prospective changes to the pipe and changes to the surrounding system. The consequences of failure parameters considered for each pipe section were the location of installation, level of supply redundancy, designation of surrounding land, vulnerability of the remaining water distribution system and the exposure of the bordering area. The parameters included for the probability of detection of a failure included: information available about water loss in a specific area and the quantity and time interval of inspection, and the expert knowledge of inspection. The FRI values showed increased risk with larger values. The FRI is calculated with (2-6)

$$FRI = O^{qO} S^{qS} D^{qD} \qquad (2\text{-}6)$$

where FRI is the Failure Risk Index, O, S and D are sub-indexes representing occurrence, severity and detection respectively, and qO, qS and qD are weighting factors that match their corresponding

sub-index. The calculated FRI for each pipe is designated as having either a high or acceptable risk of failure. It is important to note that the weighting of each sub-index should be completed by the expert who intends to use the model since the FRI is system dependent.

The model by Friedl and Fuchs-Hanusch (2011) focuses on both probability and consequence. All of the parameters were chosen to be easily accessible to water utilities responsible for managing water distribution systems. Friedl and Fuchs-Hanusch (2011) were attempting to improve on other models with needed parameters that are difficult to obtain. This attempt did underscore the importance of data availability and user-friendliness of the model. The authors used their model to calculate a single FRI value for the entire system, which did not shed light on the geographic distribution of consequence. A better understanding of the geographic distribution of consequence could be obtained if FRI values were calculated for individual trunk water mains.

Fare and Zayed (2010) developed a hierarchical fuzzy expert system (HFES) model that considers the uncertainties in water main attributes. The model is similar to the one proposed by Kleiner *et al.* (2006). The model by Fare and Zayed (2010) includes 16 input values, 11 probability of failure factors and five consequence of failure factors, to evaluate risk of water main failure. The consequence factor considered were cost of repair, damage to surroundings/business disruption, loss of production, traffic disruption and type of serviced area. Each weight was obtained from information collected through a questionnaire completed by experts in the field. A qualitative approach was taken for the model since it can be difficult to attach a monetary value to certain consequences of failure. Altogether, five models were created (shown in Figure 2-3) to calculate a final output of risk of failure associated with a section of pipe. Data for the models was collected

from past literature and experts within water utilities as well as the use of a case study on a water distribution system in Moncton, N.B.

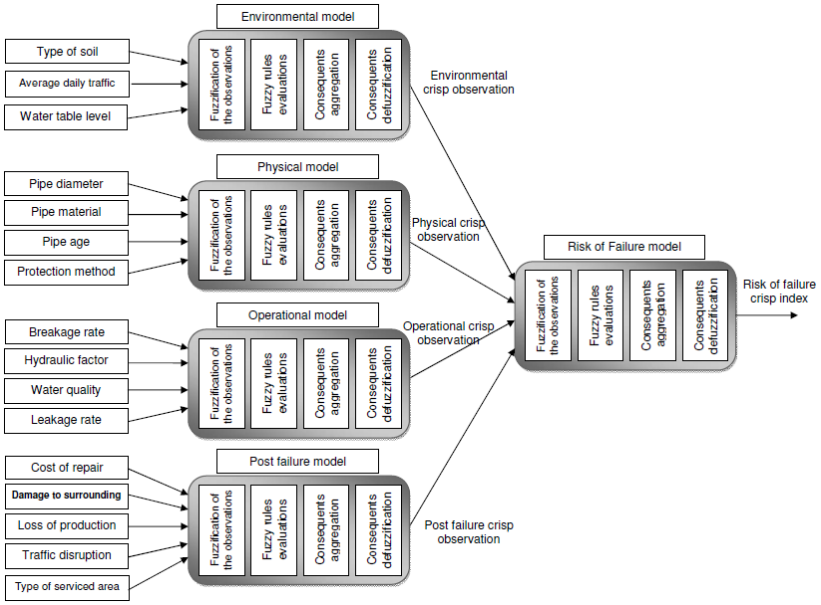

Figure 2-3: Structure for the five models used to obtain a risk of failure output (source: Fare and Zayed 2010).

Data from industrial, commercial and residential users were used to construct membership functions to model water main failure consequences. Membership factor functions allow for real input data to be converted into a fuzzy number value in the period [0, 1]. The Mamdani fuzzy rules system type (Jin 2003) was used to combine different factors' performance to generate fuzzy rules represented by (2-7)

$$\mu_{R^j}(x_1, x_2, x_3, \dots, x_n, y) = \mu_{A_1^j} \wedge \mu_{A_2^j} \wedge \mu_{A_3^j} \dots \mu_{A_n^j} \wedge \mu_B \qquad (2\text{-}7)$$

where R^j is the jth rule and A_i^j, B_j are the fuzzy subsets representing the input and output values. Using a maximum operation in (2-8), each consequent membership function is then aggregated

$$\mu_R(x_1, x_2, x_3, \dots, x_n, y) = \bigvee_{j=1}^{N}[\mu_{Rj}(x_1, x_2, x_3, \dots, x_n, y)] \qquad (2\text{-}8)$$

where V is a maximum operator, R is the consequent membership function representing one of the following standardized functions: extremely low, very low, moderately low, medium, moderately, high, very high, and extremely high. Then the center-of-sum defuzzification process is used to convert fuzzy consequents into crisp values using (2-9)

$$Crisp\ Risk\ Output = \frac{\sum_{n=extremely\ low}^{extremely\ high} Truncated\ Area_n \times Centroid_n}{\sum_{n=extremely\ low}^{extremely\ high} Truncated\ Area_n} \qquad (2\text{-}9)$$

This method is used for each of the five models. A risk of failure scale was proposed ranging from 0 to 10 where 0 is the least risky condition and 10 is the riskiest condition regarding pipe failure. This model can help municipalities make an informed decision on the condition of different sections of pipe.

Fare and Zayed (2010) completed a model showing that fuzzy-based models are beneficial to decision making. The multi-consequence model was incorporated with the four probability models to develop a risk assessment model. A shortcoming of this model is that it places a much larger emphasis on the probability of failure when compared to consequences when calculating the overall risk of a pipe section. Additionally, by not focusing on large diameter mains, the magnitude of consequences does not properly represent trunk water main failures. To be an effective tool in modelling large-diameter water main failure consequences, this model would have to be modified to capture the important differences between small and large diameter pipe failures.

Recent work by Kanta and Brumbelow (2013) presented a risk-optimization algorithm using dynamic programing to extend knowledge on the vulnerabilities in water distribution networks

when fire and failure events coincide. Multiple failure modes were included in the analysis to include accidental failure due to pipe-soil interaction and seismic activity, and intentional failure resulting from a malicious attacks of the system. The algorithm focuses on finding the failure scenarios that result in the greatest risk while having the highest probability of occurring (2-10).

$$R = (J\{u_1, u_2, \ldots . u_n\}) x\ P\{u_1, u_2, \ldots . u_n\} \qquad (2\text{-}10)$$

where *R* is system risk, *J* is the damage function and *P* is total annual probability of failure. The model sets out to maximize *R* allowing for the greatest risk to be calculated. The probability portion of the model was determined using a fault tree (Pate-Cornell 1984). The damage function (2-11) characterizes consequences by determining the systems pressure or lack of pressure during a fire and failure event.

$$J = \frac{Q_{req} - Q_{avail}}{Q_{req}} \qquad (2\text{-}11)$$

where Q_{req} is the required fire flow at an active fire hydrant and Q_{avail} is the available flow at an active fire hydrant. This equation is used to represent the consequences that could result from diminished system performance. The consequences include damage or loss of houses, businesses and loss of life. EPANET2 (Rossman 2000) was used to model the system hydraulics. Modifications were made to allow pressure-driven demands for nodes that were experiencing reduce pressure. The model is capable of analyzing multiple failures simultaneously. The authors also assessed potential mitigation strategies to reduce the weakness of a network.

The model by Kanta and Brumbelow (2013) was applied to the hypothetical Micropolis (Brumbelow et al. 2005, 2007) network. Vulnerable pipe sections were identified in multiple sections of the water distribution network. The results indicated that the proximity of the fire

hydrant to critical pipes with high failure probability greatly increased the level of risk. The system showed to have no robustness in fire protection during attack/ failure scenarios.

The model by Kanta and Brumbelow (2013) presented a unique method of calculating risk in water distribution system including both failure and fire in the risk assessment. As fire flow is important in system design, this model shows that it should also be considered during network risk analysis. A focus was placed on hydrant demands allowing for pipe vulnerability to be assessed. This method is distinctive and showed to be useful to developing an understanding of the water distributions systems vulnerabilities. Kanta and Brumbelow (2013) included mitigation strategies to allow for improved risk management. This could prove to be very useful to municipalities in replacement and rehabilitation planning.

The model only examined the demand at fire hydrant in the system, ignoring how the rest of the nodal demands are affected. This provides a narrow understanding of the consequences that result from a failure event. Also water loss at the failed pipes was not considered which would underestimate the level of consequence and risk calculated especially for large diameter water mains.

2.5 Further Advances in Consequence Modeling

Many of the current models designed to analyze the consequence of a trunk water main failure event are not capable of characterizing the full extent of these failure events. Several of these models robustly analyze a single, specific post-failure consequence but ignore many other types of consequences. To be more practical and helpful, current models should more broadly analyze different types of consequences linked to trunk water main failures. On their own, existing failure models do not provide much information to utilities regarding the broad spectrum of consequence.

By contrast, the models that do capture multiple consequences tend not to provide an in-depth characterization of individual consequences.

Almost all of the current models only look at failure of large diameter mains in terms of structural failure and hydraulic failure to adjacent nodes. In the future, models should try to incorporate the capability to capture cascading hydraulic failure through the rest of the network caused by the initial failure event.

Consequence weighting has a large influence in the overall severity rating of each pipe section. Most model consequence weightings reflect the probability of a consequence occurring. For example, traffic delays have a high probability of occurring so they receive a higher weight when compared to a consequence like fire damage which has a very low probability of occurring. This method reflects the most common consequences but downplays consequences that have a low rate of incidence with large consequence. To get a robust understanding of each failure event it is pertinent that weightings represent low probability, high impact events with higher values. If the weighting does not properly represent low incident high impact events the model will underestimate the possible consequences.

Many models currently make use of monetary values to characterize consequences. This common unit cannot be properly used for all consequences, such as loss of life. It is suggested that future models make use of scaled input values to allow experts to provide informed input on a relative scale and magnitude. Scaled inputs also allow for consequences that do not have "hard" costs to be included, as they do not have to be translated into a monetary value. Models requiring monetary values also run the risk of being inaccurate if certain predetermined values change over time due to a change in the marketplace value or inflation/deflation.

Data collection has shown to be a problem since many utilities and municipalities are not collecting data that is essential for these models to provide accurate and helpful results. Also, to properly define the social impacts, additional data is needed from other sources such as insurance companies, the public, etc. Also data specific to large diameter water main failures needs to be separated from other failure events because difference consequences result from these failures when compared to small diameter pipes.

2.6 Summary

Currently there are a limited number of models that examine the consequences of trunk water main failure. The current paper has provided a review of previous research in consequence analysis of large-diameter water mains. The review suggests that single consequence models provide an in-depth characterization of a single consequence where the focus is placed on the hydraulic performance of a system during a failure event. The multi-consequence models are based on the model developed by Cromwell *et al.* (2002) and characterize the severity of system and social consequences. The risk models combine the probability of failure and consequences of a water main and place and include a limit number of consequences which do not allow for a proper rating to be established.

In the future, models need to incorporate consequences that characterize severity throughout the entire distribution system and not just at the location of failure. Utilities should try to focus on data collection with the view of developing failure-consequence models to assist with capital infrastructure planning efforts. Further, models should focus on the characterization of consequences in trunk water mains where the consequences and severity of failure are larger than

in small-diameter pipes. By continually advancing this field of research more precise and encompassing models will allow for a reduction in failure events.

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Chapter 3

Water Main Failure Consequence Model

3.1 Introduction

Water main failures and their severe consequences are becoming an important concern as linear assets age and deteriorate. Water main failures can lead to inconvenience to users, monetary losses, and injury or loss of life. These large consequences can effect both the public and the management of municipal water systems. There is a need for consequence modelling of water main failures to provide utilities with a better understanding of failure consequences and damages in their water distribution systems.

This chapter presents a number of metrics that characterize the severity of a trunk water main failure under a range of demand scenarios. The metrics quantify the consequences that occur due to hydraulic changes during a failure event. The first set of metrics examines the consequences of a water main failure during peak demand conditions in the network. The second set of metrics examines the consequences of a water main failure during a fire event. The third set of metrics examines the time-averaged consequence of a failure event under normal conditions in the network.

The metrics developed in this research thesis have the aim to help municipalities and water utilities responsible for water distributions system to understand the economic and social consequences linked to water main failure. The main objective of this work is to assist them in determining which water mains have the most potentially severe consequences of failure. This information will help

in developing condition assessment and replacement and rehabilitation programs and schedules, with the limited resources available.

3.2 Metrics to Analyze Water Main Failure under Peak Demand Conditions

The first set of metrics characterizes the severity of the consequences of a trunk water main failure under peak demand conditions. The analysis focuses on the hydraulic consequences of three failure types: low-pressure failures, high-pressure failures and complete service disruption. Other consequences such as flooding, traffic delays, construction costs, and legal costs are not included in this analysis. A hydraulic analysis is performed with the EPANET2 (Rossman 2000) model to obtain the pressure and flow data to evaluate the metrics. Each metric is assigned its own rating criteria such that a higher numeric value corresponds to a more severe consequence.

Several decisions must be made before applying the consequence metrics to a water distribution system. Specifically, trunk water mains of interest and critical times in the diurnal pattern must be identified. Which trunk water mains are chosen will vary depending on the criticality of the water mains and focus of the analyses. This selection process should consider a pipe's location, size, age, proximity to important network features, etc. The selection of critical times is also important, but generally peak hour, minimum hour, and average day demands are important times in a service day to consider. The minimum acceptable water pressure must also be determined. This value can be found in the water distribution standards and can vary depending on location and guidelines.

For each modelled failure, two scenarios are analyzed to account for the changing situation during a failure event. The first scenario evaluates the hydraulics during the first stage of the failure event, when water is being lost from the system through the burst location. The second scenario evaluates the network hydraulics during repair of a failed pipe. The pipe failure scenario is modelled by

increasing the demand at the upstream node to the trunk water main under analysis just prior to failure. The pipe repair scenario is modelled by allowing zero flow through the trunk water main under analysis. The pipe failure and pipe repair scenarios create two different sets of hydraulic conditions in the network. For each scenario, the hydraulic performance of the system is then calculated for each trunk water main failure and at each time period of interest. These scenarios are modelled as a snapshot in time. Consequences also depend on length of time in a failed state which could be included in future research. These results can then be input into the consequence index equation, discussed below.

The consequence index equation (3-1) was developed to quantify the severity of each trunk water main failure consequence. It is used for all of the metrics focusing on nodal pressures. The equation is

$$CI=\sum_{i=1}^{N}\left[\left|\frac{H_i-H_{min}}{H_{min}}\right| K_i^{max}\left(\frac{Q_i}{Q_{tot}}\right)\right] \qquad (3-1)$$

where *CI* is the consequence index of a specific metric, H_i is the pressure head at node *i*, H_{min} is the minimum acceptable pressure, K_i^{max} is the consequence parameter, Q_i is the demand at node *i* and Q_{tot} is the total demand in the water distribution system. The $(H_i - H_{min})/H_{min}$ term represents the severity of the event, such that when the pressure head is at or below the minimum pressure head, the failure entails the most severe consequence. The Q_i/Q_{TOT} term is a scaling factor that relates the significance of the event, such that nodes with large demands (as a percent of total) carry more significance in the index. The consequence parameter, K_i^{max}, quantifies the metric being analyzed in the calculation, representing the maximum consequence parameter value for each node in the

system. The consequence index equation is a first approximation. To determine the exact shape of the severity term more research is required.

Nodes only receive a consequence index score if the pipe failure has caused significant pressure changes that result in negative consequences. The focus of the analysis is on situations resulting in pressure below the minimum acceptable level and above the maximum acceptable level. The consequence index equation modification (2) allows for these parameters to be taken into account.

$$CI = \begin{cases} \sum_{i=1}^{N} \left[\left| \frac{H_i - H_{max}}{H_{max}} \right| K_i^{max} \left(\frac{Q_i}{Q_{tot}} \right) \right], & H_i > H_{max} \\ 0, & H_{min} < H_i < H_{max} \\ \sum_{i=1}^{N} \left[\left| \frac{H_i - H_{min}}{H_{min}} \right| K_i^{max} \left(\frac{Q_i}{Q_{tot}} \right) \right], & 0 < H_i < H_{min} \\ \sum_{i=1}^{N} K_i^{max} \left(\frac{Q_i}{Q_{tot}} \right), & H_i < 0 \end{cases} \qquad (3-2)$$

The demand and population metrics, outlined below, are not affected by pressures above the maximum acceptable amount. Therefore, the $H_i > H_{max}$ term does not apply to the consequence calculations for these metric.

Four metrics were developed for peak hydraulic conditions to estimate the severity of consequences for each pipe failure. The metrics represent potential consequences that are caused by hydraulic changes throughout the system due to a failure event. Each metric is calculated using the consequence index equation (3-1). The 4 metrics are:

1. **Demand Metric:** the demand metric compares the pressure in the system against the demand at each node. This metric indicates a higher severity when high-demand nodes are experiencing low/negative pressure due to a trunk main failure event. The consequence

parameter, K_i^{max}, in equation (3-1), for this metric is equal to 1, since demand is already represented in the equation.

2. **Population Metric:** the population metric indicates the number of people at each node with insufficient water pressure. The consequence parameter, K_i^{max}, for this metric is equal to the maximum amount of people who can experience insufficient water pressure at each node.

3. **Land Use Metric:** the land use metric indicates the severity of consequence due to insufficient pressure for the land use at the each node in the network. This metrics reflects generalized network consequences based on land use. For example residential units normally experience moderate consequences in the form of inconvenience to the user during low pressure events. In manufacturing facilities with industrial processes that rely on a water supply within a range of pressures, a low-pressure failure can translate to economic losses in production. The consequence parameter value, K_i^{max}, for each land use is a number from 0 to 100 and should be determined by expert elicitation. A value of 0 corresponds to the case where low-pressure events produce no consequences in the system and a value of 100 correspond to the case where low-pressure events produce the most severe consequences in the system.

4. **Economic Loss Metric:** the economic loss metric characterizes the severity of financial losses by industrial and commercial businesses caused by insufficient pressure. Residential units are not considered in this metric. For industrial land use, this metric represents the production loss linked to insufficient pressures. For commercial land use, this metric represents the sales loss linked to insufficient pressures. The consequence parameter value

for industrial and commercial land use ranges from 0 to 100, where the value 0 corresponds to no negative consequences and a value of 100 corresponds to the most severe consequence possible in the system. The consequence parameter values can be quantified through expert elicitation.

Cumulative Distribution function (CDF) plots are used to give further information on the consequences associated with each node in the system. These plots show the severity at each node in the system with a value of 0 representing no consequence and increasing values representing increased consequence with a maximum value varying depending on the metric. The x axis represents the metric severity. The y-axis represents the percent of nodes that have a consequence severity value below a specific value on the x-axis.

3.3 Metrics to Analyze Water Main Failure under Fire Flow Conditions

Of particular concern during a trunk water main failure event is the possibility (however unlikely) of a fire event occurring at the same time. If a fire event occurs elsewhere in the system during a trunk water main failure event, the consequences can be amplified as pressure and flow may be insufficient for firefighting. Without the necessary pressure and flow, the consequences of fire damage, including damage/loss of property, displacement from dwelling, interruption of businesses, job loss and injury or loss of life, can be much more severe.

The second part of the consequence model examines the potential for severe consequences when a fire event coincides with a trunk water main failure. To this end, a series of metrics are used to quantify the consequences due to the failure of a trunk water main under fire flow conditions. The focus of this analysis is on hydraulic changes in the system due to the combination of a trunk water main failure and a fire flow event, and the resulting consequences. The consequences occuring at

system nodes include low pressure, high pressure, no service and insufficient fire flow. The metrics developed for peak demand conditions are used, with the addition of fire flow to characterize the added stress on the system during a fire. In addition to the selection of trunk water mains and critical times of peak demands, critical fire locations must also be selected. The fire locations can be selected geographically based on land use/ district metering areas (DMAs) or based on fire data.

As before, the EPANET2 model is used to simulate the system hydraulics but with the addition of fire flow demand at the node closest to the fire location. As before, a pipe failure and pipe repair are simulated to evaluate the consequence index. For both the pipe failure and pipe repair scenarios, a fire is simulated at a node of interest in the system by adding a fire flow demand (Fire Underwriters Survey 1999) to the existing demand. The fire flow location is simulated at any node in the water distribution network with no relation to the location of the trunk water main break.

3.3.1 Consequence of Fire at Non-Fire Nodes

The consequence index equation (3-1) is used to characterize the consequences to the entire system when a water main failure coincides with a fire in the system. The consequence index equation is applied to all nodes of the system, excluding the fire flow location. The four metrics (demand metric, population metric, land use metric and economic loss metric) used under maximum day demand is used to evaluate the consequences of the water main failure under fire flow conditions. The consequences include low pressure, high pressure, no service and insufficient fire flow at non-fire nodes. The minimum pressure head under fire flow conditions is 140 kPa, a lower value than under normal operating conditions in accordance with the Ontario Ministry of the Environment (2008) guidelines and American Water Works Association standards (Oberoi 2009).

3.3.2 Consequence of Fire at a Fire Node

A more detailed analysis is completed to characterize the consequences of a fire at the fire location at the time of a water main failure in the system. The fire consequence index equation (3-3) was developed to assess the consequences at the location of the fire event

$$CI_{FF} = \left[\left|\frac{H_{FF} - H_{min}}{H_{min}}\right| K_{FF}^{max}\right] \qquad (3-3)$$

where CI_{FF} is the fire consequence index of a specific metric, H_{FF} is the pressure head at the fire node, H_{min} is the minimum acceptable pressure during fire flow (usually 140 kPa), and K_{FF}^{max} is the consequence parameter (Ontario Ministry of the Environment 2008). The term (H_{FF} – H_{min})/H_{min} represents the severity of the event and increases in value the closer the pressure head is to 0 m. No scaling factor is included in the calculation because the consequence at each fire node is examined individually. This equation does not account for any baseline fire damages but assumes with adequate pressure no damages are incurred. In reality, there is likely a baseline level of damages even when pressures are above the minimum at the fire location.

For the fire consequence index equation, a focus is on those situations where the pressure is below the minimum acceptable level for firefighting capabilities. When pressure is above the acceptable level, no additional negative consequences are produced. The fire consequence index equation modification (3-4) takes into account these criteria.

$$CI_{FF} = \begin{cases} 0, & H_{FF} > H_{min} \\ \left[\left|\frac{H_{FF} - H_{min}}{H_{min}}\right| K_{FF}^{max}\right], & 0 < H_{FF} < H_{min} \end{cases} \qquad (3-4)$$

A fire flow metric was developed to represent the consequences at the fire node when there is insufficient fire flow:

- **Economic Damages Metric:** the economic damages metric examines the potential economic losses caused by insufficient pressure at the fire node. Building envelope and content losses are both included in the consequence calculations. The consequence parameter will represent the monetary value lost during the fire event.

3.4 Overall Trunk Water Main Rating

Trunk water mains are rated against each other based on the consequence index values calculated for each metric. There are 3 stages of ranking to allow for different levels of comparison, shown in Figure 3-1.

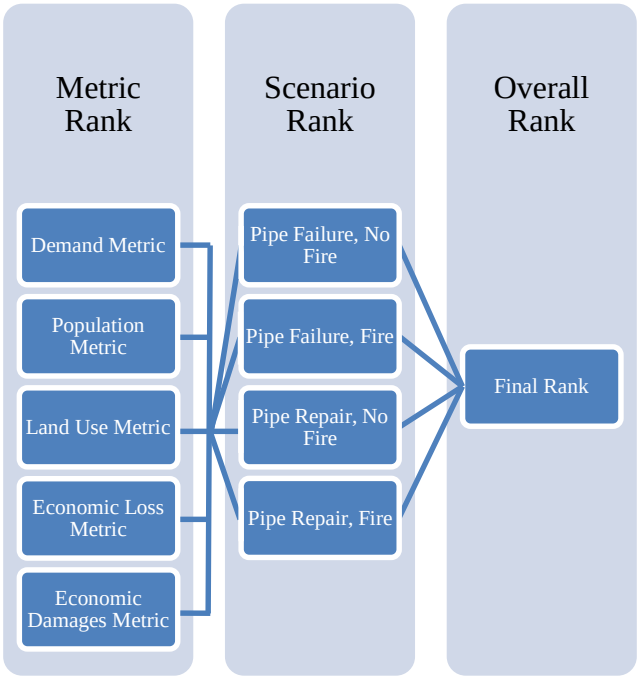

Figure 3-1: Outline of the 3 stages of rank and the subsections for each stage.

A metric rank is calculated for each metric where the pipes are ranked based on their consequence index values. This style of ranking allows for pipe consequences to be compared from metric to metric regardless of different initial rating criteria. The metric ranks can then be consolidated to obtain a scenario rank for each of the scenarios that are examined (pipe failure with no fire, pipe repair with no fire, pipe failure with fire, pipe repair with fire). The last stage is the overall ranking where the scenario ranks are combined to allow for a comparison for all analyzed trunk water mains under all scenarios. Each level of ranking can provide valuable information and the overall rank can characterize all scenarios, however it less precise than the metric ranking or scenario ranking. For N number of pipes being analyzed, a ranking of 1 represents the trunk water main failure with the most severe consequences and a ranking of N is the main failure with the least severe consequences.

3.5 Time-Average Metrics under Normal Conditions

In large systems, peak diurnal demands are often not synchronous across pressure zones or district metering areas (DMA). To gain an understanding of trunk main failure consequences throughout a typical day or time period of service, it is helpful to perform time-averaging calculations on consequence metrics at nodes in different pressure zones or district metering areas. Here, the EPANET2 model is used to simulate the pressures and flow in the system throughout the diurnal period when a pipe has burst or a pipe is undergoing repair. (The same approach is used as in the analysis under peak operating conditions.) The time-averaged consequence index equation (3-5) was developed to quantify each metric over the entire diurnal pattern

$$CI_{TA} = \frac{1}{T}\sum_{t=0}^{T}\sum_{i=1}^{N}\left[\left|\frac{H_i(t) - H_{min}}{H_{min}}\right| K_i^{max}\left(\frac{Q_i(t)}{Q_{tot}}\right)\right]\Delta t \qquad (3-5)$$

where CI_{TA} is the time average consequence index of a specific metric, T is the time in hours of the diurnal period, H_i is pressure head at node i at time t, Q_i is the demand at node i at time t and Δt is the networks hydraulic time step. The term $(H_i(t) - H_{min})/H_{min}$ represents the severity of the event for each time step while the $Q_i(t)/Q_{TOT}$ term is a scaling factor that relates the significance of the event over each time step.

Demand, population, land use and economic loss metrics are used to determine consequence for the time-average analysis under normal hydraulic conditions. These metrics focus on failure events where pressure is below minimum acceptable levels or when pressure exceeds maximum acceptable levels. To account for this, the time-average consequence index equation modification (3-6) is

$$CI_{TA} = \begin{cases} \frac{1}{T}\sum_{t=0}^{T}\sum_{i=1}^{N}\left[\left|\frac{H_i(t)-H_{max}}{H_{max}}\right| K_i^{max}\left(\frac{Q_i(t)}{Q_{tot}}\right)\right]\Delta t, & H_i(t) > H_{max} \\ 0, & H_{min} < H_i(t) < H_{max} \\ \frac{1}{T}\sum_{t=0}^{T}\sum_{i=1}^{N}\left[\left|\frac{H_i(t)-H_{min}}{H_{min}}\right| K_i^{max}\left(\frac{Q_i(t)}{Q_{tot}}\right)\right]\Delta t, & 0 < H_i(t) < H_{min} \\ \frac{1}{T}\sum_{t=0}^{T}\sum_{i=1}^{N}\left[K_i^{max}\left(\frac{Q_i(t)}{Q_{tot}}\right)\right]\Delta t, & H_i(t) < 0 \end{cases} \quad (3-6)$$

The demand, population and land use metrics only experience negative effects when pressures drop below minimum acceptable levels. Therefore, the $H_i(t) > H_{max}$ term does not apply to the consequence calculations for these metrics.

3.6 References

Fire Underwriters Survey. (1999). "Water supply for public fire protection." *CGI Risk Management Services, Markham, Ont., Canada*. Retrieved from http://www.scm-

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Chapter 4

D-Town Water Distribution Network Case Study

4.1 Introduction

Consequence modelling can be helpful to plan strategies to mitigate water main failure events with severe consequences that affect municipalities and water users. The consequences can vary from inconvenience to users, economic losses, damage to property or loss of life. With the possibility for such large negative impacts, it is important for municipalities to use available models to help better understand their water networks under conditions of water main failure.

Chapter 4 presents the analysis of the D-Town Water Distribution Network (Marchi 2013). Here, the consequence model and the set of metrics presented in Chapter 3 are used to examine 8 trunk water main failure events during peak and fire flow conditions. The chapter presents the results from the analysis completed and presents the overall findings from this case study.

4.2 Overview of Metrics Modelled

An overview of the scenarios modelled for the D-Town Water Distribution Network is presented in Table 4-1. The scenarios and demand loading conditions are indicated in the left-most column and the metrics used are indicated in the top row of the table.

Table 4-1: Metrics used for each scenario considered in the D-Town distribution system study.

	System-Wide Consequences								Consequences at Fire Location
	Demand metric	Population metric	Land use metric	Economic loss metric	Time-averaged economic loss metric	Time-averaged demand metric	Time-averaged population metric	Time-averaged land use metric	Economic damages due to fire damages
Minimum hour demand in DMA[1] 5	x								
Global minimum hour demand and minimum hour demand in DMA 1, 2, 3 and 4	x								
Maximum hour demand in DMA 3	x								
Maximum hour demand in DMA 5	x								
Global maximum hour demand and maximum hour demand in DMA 1, 2 and 4	x	x	x	x					
Global maximum hour demand with fire simulation[2]	x	x	x	x					x
All time periods during normal conditions					x	x	x	x	

[1] DMA stands for district metering area

[2] Fire flow was modelled at nodes J434, J496, J141, J320 and J56 located at the centroid of DMAs 1, 2, 3, 4 and 5 respectively.

Table 4-1 displays the data modelled for normal, peak and fire conditions in the network. It also shows the time periods of interest in which each metric was analyzed. A focus is placed on analyzing the system during a specific time period however time averaging analysis was also completed allowing for the entire diurnal period to be considered.

4.3 Description of D-Town Test System

The new consequence modeling framework developed was applied to the D-Town Water Distribution Network (Marchi 2013) indicated in Figure 4-1. The D-Town network has 5 district metering areas (DMAs), 461 pipes (75 of which are trunk water mains), 399 nodes, 1 reservoir, 7 tanks, 12 pumps and 4 valves. The network services approximately 69,000 people. The water mains (shown in red in Figure 4-1) represent the large-diameter mains in the D-Town network. Two small-diameter mains have been added to the system to allow for each DMA to be connected to the rest of the system at a minimum of two connection points. These mains were added to allow for a connection between DMAs 2 and 5 and DMAs 1 and 4. The pipes selected for failure simulation are P13, P19, P22, P767, P102, P237, P86, and P348 and are labeled in Figure 4-1. These pipes were selected after an analysis was completed to represent pipes of varying consequence throughout the entire network.

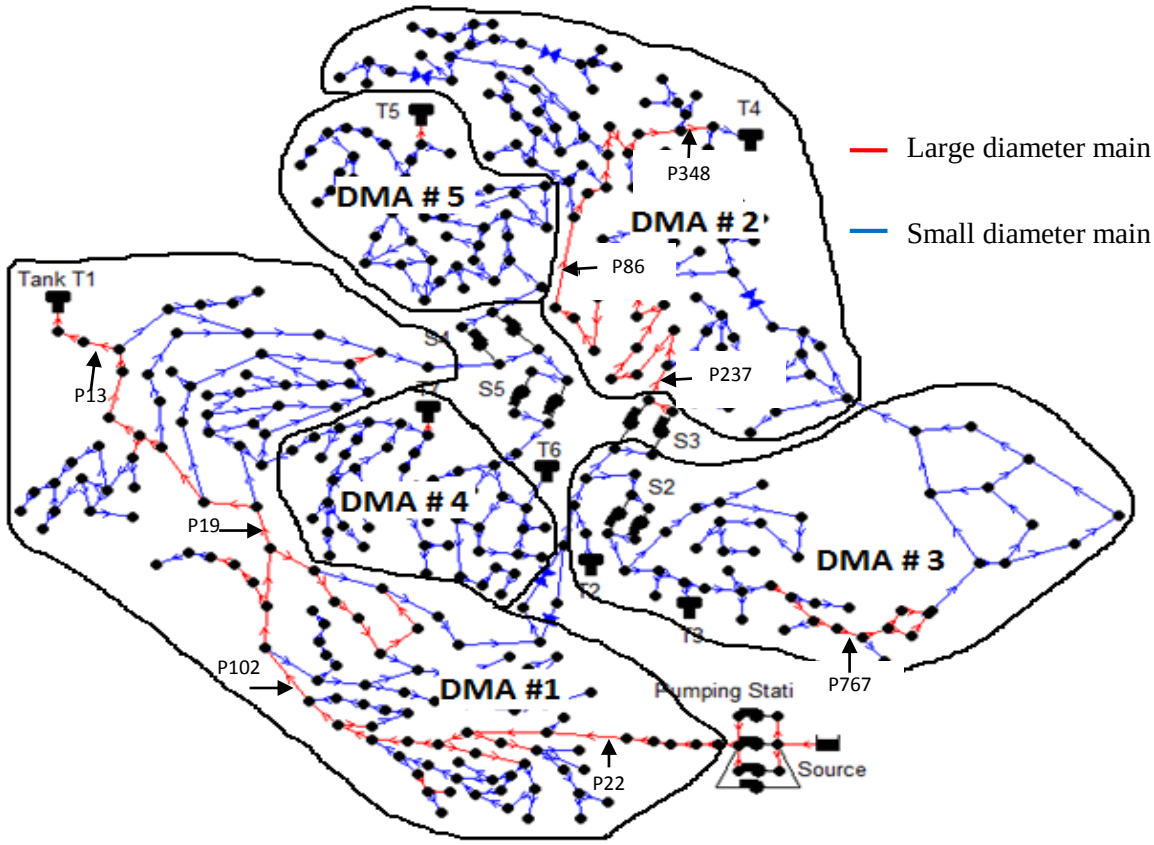

Figure 4-1: D-Town Water Distribution Network with outline of 5 DMAs.

EPANET2 was used to evaluate the baseline conditions for a weekly (168 hour) diurnal pattern. This pattern is a composite of demands that occurs during weekday flows, weekend flows and seasonal flows. Due to varying diurnal patterns in each DMA, several time periods were found to produce peak conditions. Five time periods were found to be critical: 166 hr (maximum demand for whole system), 117 hr (maximum demand for DMA 5), 105 hr (maximum demand for DMA 3), 53 hr (minimum demand for the whole system) and 3 hr (minimum demand for DMA 5).

4.4 Consequence Modelling under Peak Demand Conditions

During peak demand conditions, the 8 failure locations were analyzed to obtain severity ratings for each pipe sections modelled. EPANET2 (Rossman 2000) was run to obtain pressure and

demand values and evaluate the metrics for each of the 8 water mains during pipe failure and pipe repair. The minimum required pressure was set to 25 m in accordance with the design guidelines set out for the D-Town system (Marchi 2013). The consequence index equation (3-1) was used to evaluate each metric.

An example of the distribution of pressures that occur during a failure event (water main P19 at 166 hours) is indicated in Figure 4-2. Surrounding the failure location is an area of low pressure surrounded by negative pressure. This can be expected since the failed pipe is restricting flow from the source reservoir to other locations in the network. Another low-pressure area exists in DMA 2 surrounding a tank that has drained completely due to the failure event. This depiction of a failure event is typical for all trunk water main failure events in the D-Town network, with a different number of nodes at each pressure depending on the severity of the event.

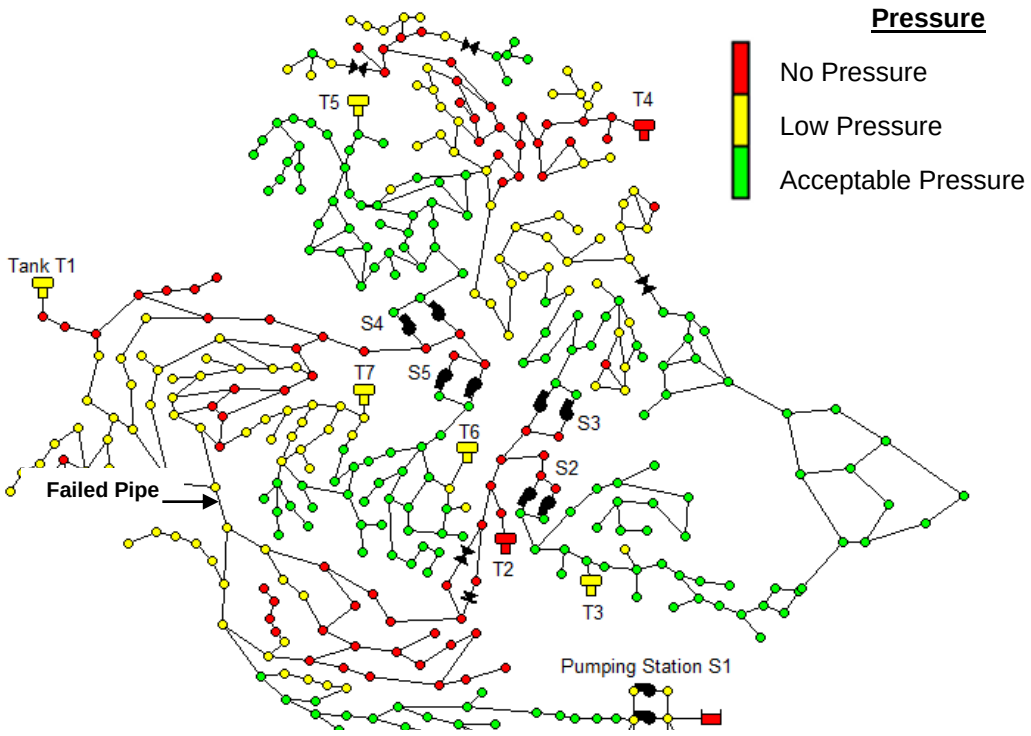

Figure 4-2: D-Town Distribution Network showing nodal pressure patterns as a result of a failure of trunk water main P19 during hour 166.

4.4.1 Demand Metric

The demand metric examines the level of consequence at each nodes with low pressure heads based on the demand at each node. The demand metric consequence parameter is 1 since the scaling factor in the consequence index equation (3-1) takes into account the demand at each node in the system. The consequence indexes are presented in Table 4-2 as percentage values by multiplying the indexes by 100 to allow for easier interpretation of the data. Consequence index values of 0 represents no system consequence where a value of 100 corresponds to the case where the entire system experiences a complete service disruption.

Table 4-2: Consequence index values for both failure and repair conditions.

		DMA ID	Water Main Failure					Water Main Repair				
			Time (hr)									
			3[1]	56[2]	105[3]	117[4]	166[5]	3	56	105	117	166
Pipe ID	P13	1[6]	0[7]	2	1	23	13	0	0	0	0	0
	P19	1	0	2	4	32	39	0	39	41	65	65
	P22	1	0	0	0	0	3	2	99	99	99	99
	P767	3	0	0	1	1	0	0	0	3	4	1
	P102	1	0	8	70	98	99	0	88	88	88	88
	P237	2	0	1	24	50	37	23	22	33	36	35
	P86	2	0	2	24	47	35	0	15	27	30	28
	P348	2	4	4	24	48	36	0	0	0	0	0

[1] Minimum demand for DMA 5.
[2] Minimum demand for the whole system.
[3] Maximum demand for DMA 3.
[4] Maximum demand for DMA 5.
[5] Maximum demand for the whole system.
[6] Indicates in which DMA the failed pipe is located.
[7] Consequence index values reported as percentages by multiplying by 100 for ease of interpretation.

4.4.1.1 Impact of Demand Loading

The increase in severity with regard to time occurs because of varying changes in demand loads. Hours 3 and 56 represent the times of minimum demand with hour 56 having the lowest average

system wide demand. Hours 105, 117 and 166 are the maximum demands with hour 117 having the lowest average system wide maximum demand and hour 166 having the highest average system wide demand. During failure hours 3 and 56, the system shows significantly lower consequence levels for most failure locations. For example the highest percentage of the system seen during times of minimum demand is 8% where times of maximum demand see up to 99% of the system negatively affected. The lower consequence values occur during minimum demand conditions because frictional losses are lower and pressure head at nodes tends to be higher. During pipe repair, higher consequences are observed for all time periods with the exception of hour 3. During pipe repair, no water is conveyed through the failed trunk water main which causes more significant pressure head drops in the D-Town system. Overall an increased demand resulted in a larger percentage of the network to be negatively affected because of a loss of pressure head in the system.

4.4.1.2 Impact of Failure Location

The location of the pipe also has a significant effect on consequence severity. Pipe P767 is the least critical pipe since it negatively affects less than 5% of the system. This is in large part because Pipe P767 does not connect the system to any major components (e.g., pumping stations, reservoirs, etc). Conversely, pipe P102 is the most critical, since it negatively affects 99% of the system. The large consequence linked to the failure of pipe P102 is owing to the fact that it connects the source reservoir to the rest of the system with no alternate route for the water to flow. By shutting off flow from the source reservoir it is only a matter of time before the tanks run dry causing complete service disruption. Pipes in the same DMA show varying consequence index values. For example pipes P13 and P102 are both located in DMA 1 but while pipe P13 has low consequence during a failure event (with all consequence index scores below 23%) pipe P102

causes up to 99% of the system to be negatively affected. This occurs because pipe P102 connects the source reservoir to the rest of the system where pipe P13 only connects tank T1 to the system, so when it fails, water can be brought into DMA 1 from the source reservoir and tanks of neighboring DMAs. Overall an increased level of consequence is observed in the D-Town network when failure occurs to trunk water mains that are not looped and connected to important system features (reservoirs and tanks).

4.4.1.3 Impact of Main Failure and Repair

On average, the water main failure condition produces more severe consequences than the water main repair condition. The exception to this rule are pipes P22, P13, and P348 which show more severe consequences during the repair condition than the failure condition. Pipes P22, P13, and P348 are connection points to the water source and tanks that service large DMAs 1 and 2. The difference in failure and repair consequence index is owing to the fact that during failure, water is still conveyed through the failed pipe. During water main repair, the water source connection is completely removed from the system, which produces a more severe consequence.

Figures 4-3 and 4-4 indicate cumulative distribution function (CDF) plots of the severity term of the consequence index at the 399 nodes of the D-Town system at time = 166 hours for the 8 water main locations under pipe failed and pipe repair conditions. The CDF plots represent the severity at each node in the system due to a trunk water main failure event. The x-axis represents the level of consequence and the y-axis reports the percent of nodes that have a consequence value below a specific value on the x-axis. A value of 0 means that no nodes has a consequence value below a specific value and a value of 100 means that all the nodes (100%) has a consequence value below a specific value on the x-axis.

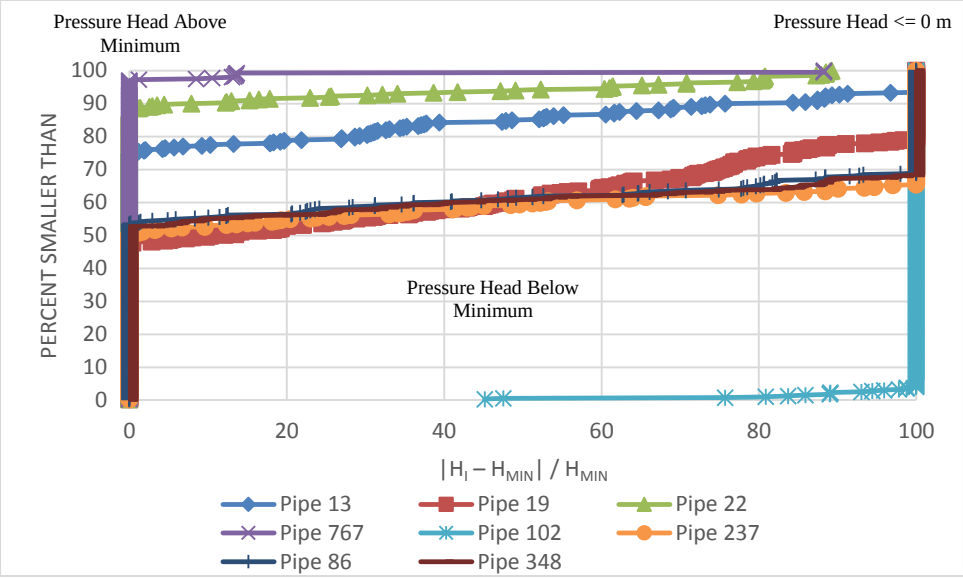

Figure 4-3: CDF plot of severity term of the consequence index at nodes in the D-Town system at time = 166 hours for the 8 water main locations under failed conditions.

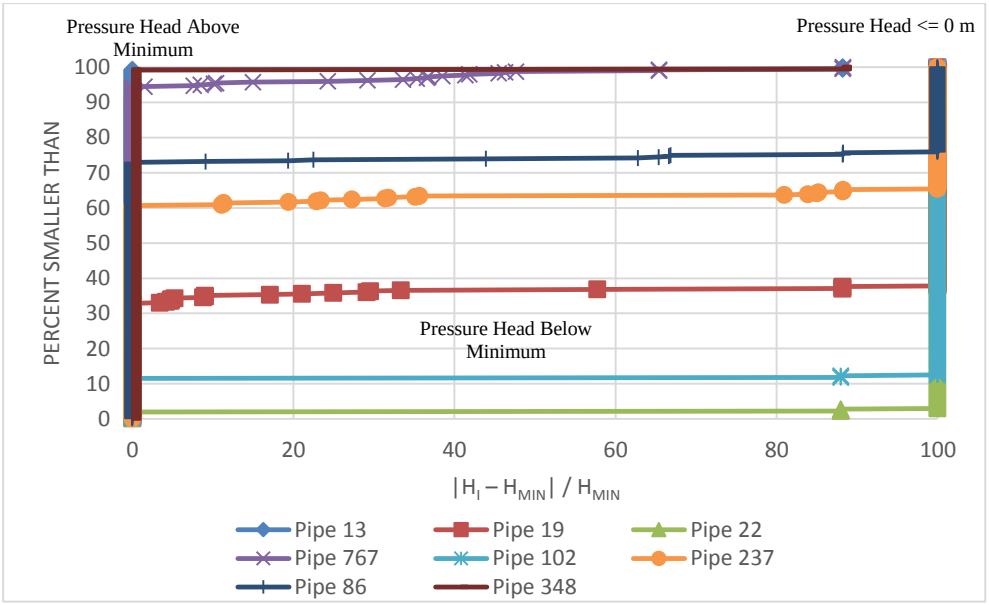

Figure 4-4: CDF plot of severity term of the consequence index at nodes in the D-Town system at time = 166 hours for the 8 water main locations under repair conditions.

Figure 4-3 indicates that when mains P19, P237, P86 and P348 fail, approximately 50% of the nodes are above the minimum pressure head of 25m, while the remaining 50% of nodes are at a

lower pressure between H_{min} and 0 m. Pipe P102 has the largest number of nodes affected with over 98% experiencing unacceptable pressure heads. Conversely, when mains P13, P22 and P767 fail, approximately 75-99% of the nodes have pressure head above the minimum. The results suggest that the location of the trunk water main failure have a strong effect on consequence level, where pipes connected to integral D-Town network features (source reservoir and, tanks) tend to produce the most severe consequences during failure. The absence of alternate flow paths and pipe looping also tends to increase consequence severity for these water mains. Severity is observed in all pipe burst scenarios because water is escaping from the system causing significant drops in pressure head.

The results in Figure 4-4 indicate that under water main repair conditions, nodes either experience a pressure head above the minimum or provide low pressure heads of 0 m, with only a few nodes that provide pressure head between H_{min} and 0 m. Specifically, trunk water main failures P22, P102 and P19 have 0-30% nodes at pressure head above min, and 70-99% nodes with pressure head of 0. All of these pipes connect the source reservoir to different parts of the system with no alternative flow path. During repair, no water is conveyed through the pipe which results in large consequence levels. Further, trunk water main failures P237, P86, P348, P767 and P13 have 60-100% nodes at pressure head above min, and 0-40% nodes with pressure head of 0. These pipes benefit from looping and thus create alternate flow paths which reduce the number of affected nodes in the D-Town network. As mentioned above, when a water main is in failure, it still can convey some water and provide pressures to the system. When critical mains that service large areas are under repair, they are unable to convey water and pressure to some parts of the system. It is this condition that explains the almost binary pressure state for the majority of nodes in Figure 4-4.

4.4.2 Population Metric

The population metric quantifies the number of people inconvenienced by changes to the system's hydraulics caused by the failure event. To estimate the population data for each node in the network, an average day demand was calculated at each node and divided by the average water use of Canadians (329 L/ person • day) (Environment Canada 2013). The population at each node was then used in the consequence index equation as the consequence parameter. The values from the consequence index calculations are represented in Table 4-3. As indicated in the model overview, this metric was only examined during global maximum hour demand (at time 166 hr).

Table 4-3: Population metric consequence index values for both failure and repair conditions at hour 166.

		DMA ID	Trunk Water Main Failure	Trunk Water Main Repair
Pipe ID	P13	1[1]	34[2]	0
	P19	1	101	182
	P22	1	7	270
	P767	3	0	3
	P102	1	270	240
	P237	2	105	99
	P86	2	99	71
	P348	2	101	0

[1] Indicates in which DMA the failed pipe is located.
[2] Consequence index values representing the population demand that is negatively affected by insufficient pressure.

4.4.2.1 Impact of Main Failure and Repair

The number of people affected per node varies in each case, with dissimilar results seen during pipe failure and pipe repair. Pipes P13, P102, P237, P86 and P348 all have a larger consequence during water main failure, while pipes P19, P22, and P767 have greater severity during pipe repair. The pipes that experience large levels of consequence during failure are all close to important

network features (source reservoir, tanks and pumps) where the loss of water during failure results in a larger consequence then pipe repair conditions. Pipe P22 shows the largest difference in index values between water main failure and repair. The consequence index value during failure is 7, whereas during repair it is 270, the largest value seen for all cases. Other metrics show a similar discrepancy for pipe P22. These results are caused by the location of pipe P22, which is connected to the source reservoir. During water main failure, water can still be conveyed through the pipe, since the pipe still has some residual hydraulic capacity. However, during repair no water is capable of being conveyed from the reservoir to the rest of the network, thus causing the increased severity and higher consequence index value. This trend is also observed to a lesser degree during failure of pipes P19 and P767.

4.4.2.2 Impact of Failure Location

Pipes P19, P22 and P102 all entail the largest consequences since these three pipes all connect the main reservoir to the rest of the system with no alternative pipe connection. Failure of pipe sections P13 and P767 result in the lowest consequence index values, with values ranging from 0 to 34. These pipes are not in central locations in the system, resulting in more localized and less significant consequences.

Figures 4-5 and 4-6 show CDF plots for the severity term multiplied by the population consequence parameter during hour 166 for all of the systems nodes. Figure 4-5 shows the results for failure conditions and Figure 4-6 shows the results for repair conditions.

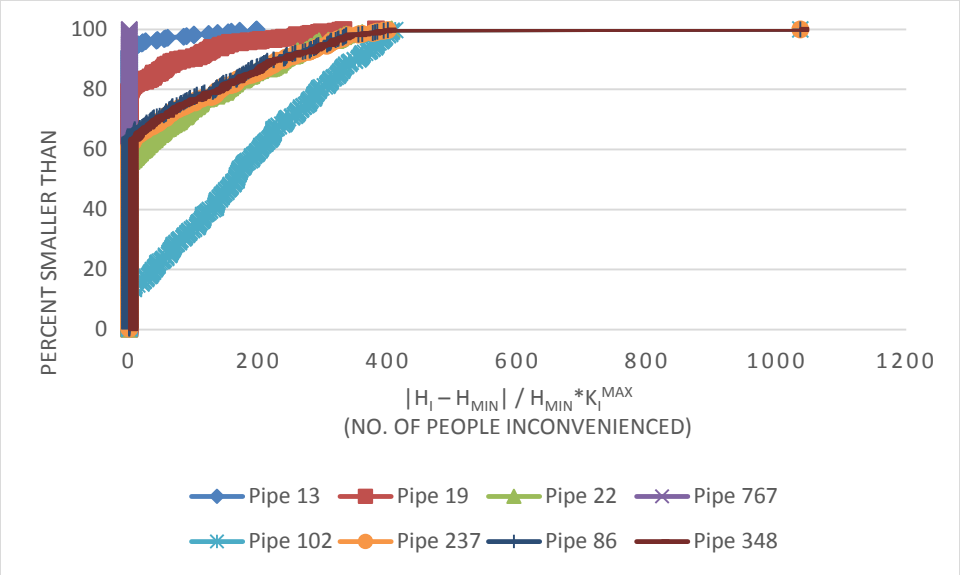

Figure 4-5: CDF plot of the population severity term at all nodes in the D-Town system at time = 166 hours for the 8 water main locations under failure conditions.

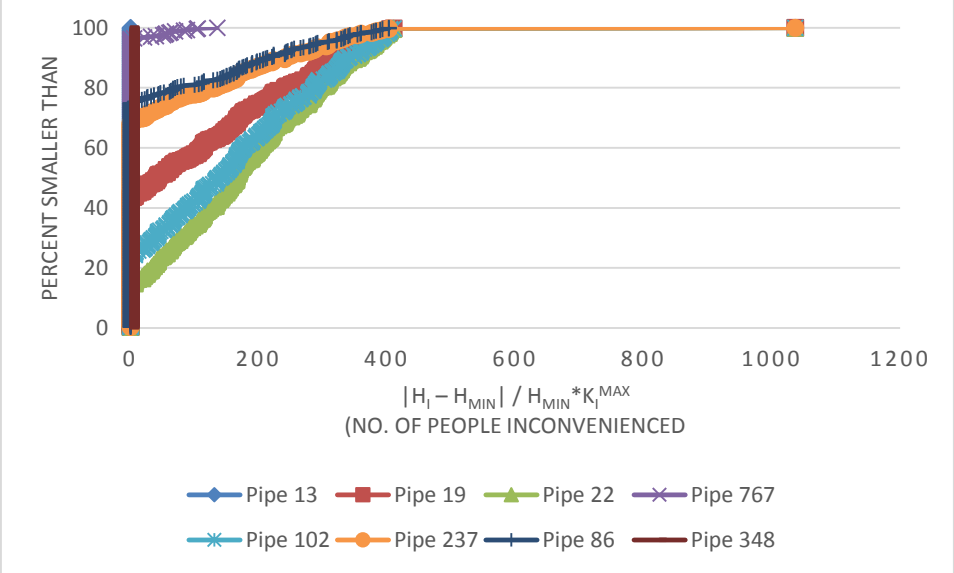

Figure 4-6: CDF plot of the population severity term at all nodes in the D-Town system at time = 166 hours for the 8 water main locations under repair conditions.

The number of people inconvenienced during a water main failure event was estimated by accounting for both the changes in water pressure caused by the failure event and the population at each node. The largest number of people at any one node in the system is 1036 at node J93 located in DMA 2, making this node very important when estimating the consequences of a failure

event. During repair conditions, there are a greater number of nodes at which users are inconvenienced by low pressures than during pipe failure conditions. For the repair phase of pipes P19, P22 and P102, over 50% of the nodes have users which are inconvenienced by low pressures. For each of these 3 water main failures, there is at least one node with over 1,000 users who are inconvenienced by low pressures. In comparison, when modeling pipe failure conditions at all of the water main locations (with the exception of pipe P102) less than 50% of the nodes experience a drop in pressure. Figures 4-5 and 4-6 indicate that at most nodes in the network fewer than 400 people per node are inconvenienced by low pressures during both a water main failure and a water main repair. This is owing to the fact that most nodes provide water to fewer than 400 people per node, and some nodes do not serve any users.

4.4.3 Land Use Metric

The land use metric categorizes each node depending on the land use for the area that it serves. Since the original D-town case study did not have any social data, a synthetic social data layer was developed based on hydraulic and water use data (Ministry of the Environment 2008, Environment Canada 2013 & The World Bank 2013). The social data layer for the D-Town system in indicated in Figure 4-7. DMAs 1, 2 and 3 were assigned residential land use with critical customers (6 schools, 5 retirement homes and a hospital). DMA 4 is a commercial district with a government services location (critical customer). DMA 5 is an industrial area. Consequence parameter values were developed for each land-use category in the D-town network to demonstrate the application of the land-use metric (Table 4-4).

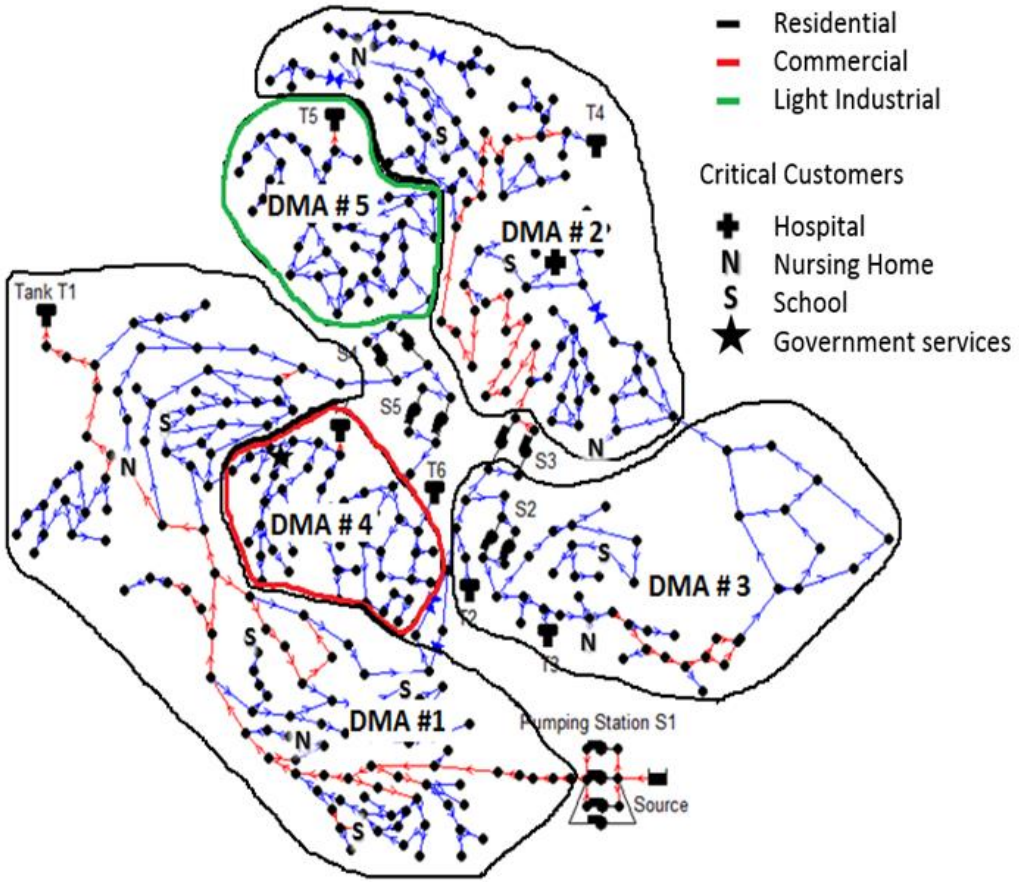

Figure 4-7: D-Town water distribution network with outlined land use.

Table 4-4: Consequence parameter values for land uses.

Land Use	K_i^{max}
Residential	50
Commercial	75
Industrial	80
Critical customer	100

The consequence parameters, pressure values and demand information was used to analyze the severity of consequence of the 8 failure locations of interest. The consequence index values for both pipe failure and repair scenarios for a trunk water main burst are presented in Table 4-5. The analysis was completed only for the time of largest demand in the system (hour 166).

Table 4-5: Land use consequence index values for both failure and repair conditions at hour 166.

		DMA ID	Trunk Water Main Failure	Trunk Water Main Repair
Pipe ID	P13	1[1]	7[2]	0
	P19	1	21	41
	P22	1	1	59
	P767	3	0	1
	P102	1	59	53
	P237	2	21	22
	P86	2	19	18
	P348	2	20	0

[1] Indicates in which DMA the failed pipe is located.
[2] Consequence index values representing the land use demand that is negatively affected by insufficient pressure.

4.4.3.1 Effects of Failure Location on Main Failure and Repair

The severity of the consequences under pipe failure and repair conditions varies depending on the location of the pipe. Trunk water mains P13, P102 and P348 experienced a larger consequence under pipe failure conditions. Pipe P348 shows the largest difference in consequences between the two scenarios, with a consequence index value of 20 during failure conditions and a value of 0 during pipe repair. Pipes P102 and P13 show less variation in index values between pipe failure and pipe repair conditions, with consequence index values varying less than 7 between the two scenarios. For trunk water mains P348 and P13, a more significant pressure drop is seen under failure conditions than under repair conditions, despite the fact that no flow is conveyed during repair. Water loss during pipe failure causes increased impact because both of these pipes connect storage tanks to the rest of the network. The water loss drains the tank reducing pressure throughout the DMA, creating worse consequences than if these components were just disconnected from the system. Pipe P102 shows high consequence values under both pipe failure and pipe repair because it is a connection point for the source reservoir. However, the water loss during pipe failure causes

larger consequences than conditions produced during pipe repair. Pipes P767, P237 and P86 show minor changes between the two scenarios, with consequence index values varying by 1. The consequences experienced by these pipes for the land use metric are not too severe, ranging from 0 to 22. The low level of consequence and low variation between pipe failure and pipe repair is because these pipes are located in areas away from important network features and are looped, allowing water to still be conveyed throughout the entire system. Pipes P19 and P22 have a higher level of consequence during pipe repair than during pipe failure, with differences in consequence index as high as 58. The large change in consequence index values is caused by the integral location of these pipes, connecting the main reservoir to the system without alternative flow paths. To reduce the potential high level consequences of the failure of these water mains, additional pipes could be added to the system to create alternate routes.

4.4.3.2 Impact of Land Use Distribution

The land use consequence index values range from 0 to a possible consequence of 100 (representing a system with no pressure and critical customers being serviced at each nodes). Table 3 shows a range from 0, for a pipe having no consequence, to 59, the most severe consequence observed in the system. The trends observed in the land use consequence index follows those seen for the other metrics (Tables 4-2 and 4-3). This indicates that the severity term of the consequence index equation has a large influence over the results. This is expected because the change in pressure head is the cause of the negative consequences in the system. The land use consequence parameter values have a greater influence when compared to the consequence parameter values of the previous metrics. For example, analysis of pipe P86 results in slightly larger consequence during repair then failure conditions. This is not the case for the demand or population metric.

CDF plots were constructed to show the percent of nodes that experience a range of consequence levels. Figures 4-8 and 4-9 indicate the land use severity for the 8 water main failure locations under pipe failure and pipe repair scenarios, respectively.

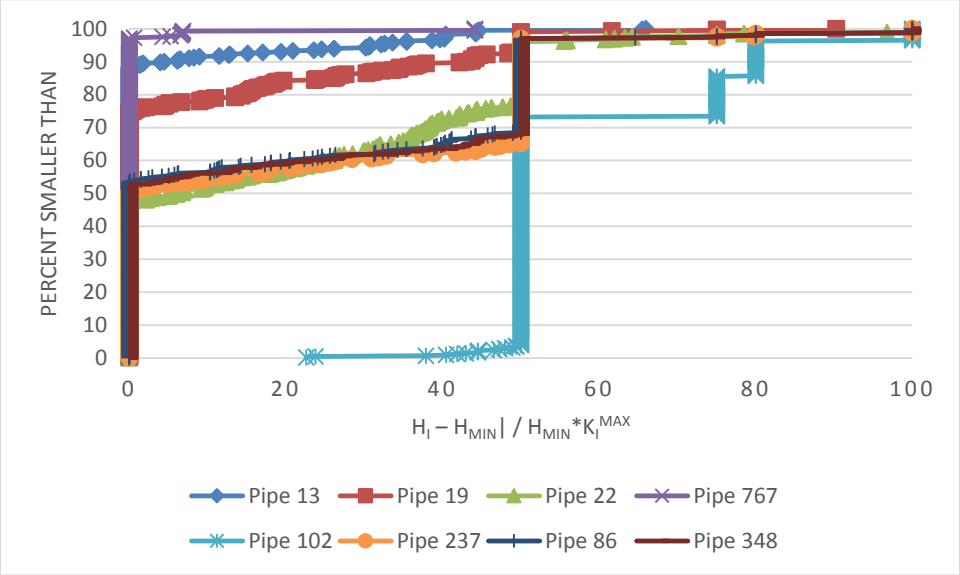

Figure 4-8: CDF plot of the land use severity term at all nodes in the D-Town system at time = 166 hours for the 8 water main locations under failure conditions.

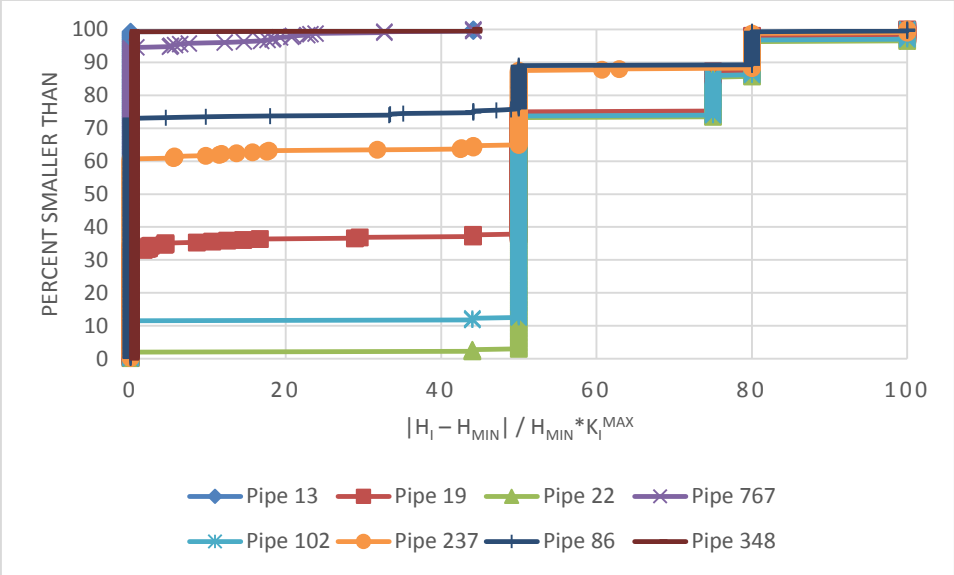

Figure 4-9: CDF plot of the land use severity term at all nodes in the D-Town system at time = 166 hours for the 8 water main locations under repair conditions.

4.4.3.3 Impact of Land Use Distribution

The D-Town land use distribution has an effect on the consequence index values that result from this metric analysis. The different land uses are sectioned by DMA and not dispersed throughout the network. Therefore if a pipe failure or pipe repair affects a DMA, that DMAs land use is largely affected. For example DMA 4 is designated commercial land use and during failure of pipe P102 and repair of pipes P102, P19 and P22 DMA 4 experiences large consequences causing the commercial nodes to all experience a pressure below the minimum acceptable level. Other failures such as pipe P767 do not affect the water pressure in DMA4 and therefore no commercial land use nodes experience an effect. The industrial land use shows the same trend, making up all of DMA 5. The largest portion of the land use severity values have a value of 50 representing residential land use with a pressure head of less than 0 m. This results because 75% of the nodes are designated residential land use occupying DMAs 1, 2 and 3. Critical customers are dispersed throughout DMAs 1, 2, 3 and 4 allowing for a larger variation in consequences during different failure events.

4.4.3.4 Impact of Main Failure and Repair

During pipe repair, more nodes experience unacceptably low pressure head values, with the failure of 3 of the trunk water mains (pipes P22, P102 and P19) negatively affecting over 60% of the nodes. During pipe failure only the burst of pipe P102 results in a large consequence with100% of the nodes experiencing a negative consequence, while failure conditions for all of the other pipes, at least 45% of the nodes still experience acceptable service. During failure conditions, more nodes experience land use severity values ranging from 0 to 50 than under repair conditions. This trend is evident in the severity chart of Table 4-6 that shows the number of nodes that experience acceptable pressure, unacceptable pressure and a pressure head of less than 0 m during pipe failure and pipe repair conditions of trunk water main P19 at time 166 hours.

Table 4-6: Severity of consequence for different land uses during failure of trunk water main P19 under failure and repair conditions at time 166 hours.

	Trunk Water Main Failure			Trunk Water Main Repair		
	Acceptable Pressure	Below Acceptable Pressure	Pressure <= 0	Acceptable Pressure	Below Acceptable Pressure	Pressure <= 0
Residential	112[1]	102	77[2]	124	18	149
Commercial	33	14	2	0	0	49
Industrial	42	1	0	0	0	43
Critical Customers	4	7	5	7	1	8

[1]Light coloured shading denotes a low-severity consequence and dark coloured shading denotes a high-severity consequence.
[2]Numerical value denotes number of nodes.

When under pipe repair conditions, trunk water main P19 causes a majority of the nodes to have pressure head of less than 0m for all land uses. This is not the case under pipe failure conditions. This trend matches the CDF plots (Figure 4-8 and 4-9) and is a result of the difference in hydraulic conditions occurring during pipe failure and pipe repair. Pipe P19 is an important connection to

the networks source reservoir and, therefore, during repair conditions, water cannot be conveyed from the source reservoir causing increased consequences when compared to pipe failure. For other pipes the opposite is observed, and the location of the failed pipes has a large influence on severity of consequence. For pipes P86, P237 and P348, more nodes experienced lower pressures during failure conditions than during pipe repair conditions. All of these pipe sections were located away from key network features and alternative flow paths are available.

4.4.4 Economic Loss Metric

The economic loss metric assigns a value to each node which represents the potential financial losses during a trunk water main failure. These losses can occur during low and high pressure events caused by the failure. For this analysis only low pressure was examined. The metric focuses on the losses experienced by industry, through production loss, and commercial businesses, due to loss in sales. All critical customers can also experience economic losses. Monetary loss due to the effect on residential land use areas is ignored in the model. Since no social data layer was available for the D-town network, a rating system (Table 4-7) was developed for illustrative purposes. The rating system ranges from 0 to 100 with higher values representing increasing severity. For a real system the consequence parameter values would have to be developed by someone with expert knowledge of the system.

Table 4-7: Consequence parameter values for economic loss metric.

Economic Losses	K_i^{max}
Residential	0
Commercial	50
Industrial	80
School	10
Hospital	30
Retirement Home	20
Government Services	10

The consequence index equation was used to determine the consequences of each of the 8 trunk water main failures (Table 4-8). The economic loss metric was modelled during the systems highest demand (hour 166).

Table 4-8: Economic loss consequence index values for both failure and repair conditions at hour 166.

		DMA ID	Water Main Failure	Water Main Repair
Pipe ID	P13	1[1]	0[2]	0
	P19	1	1	17
	P22	1	0	17
	P767	3	0	0
	P102	1	17	17
	P237	2	2	10
	P86	2	2	9
	P348	2	2	0

[1] Indicates in which DMA the failed pipe is located.
[2] Consequence index values representing the economic loss demand that is negatively affected by insufficient pressure.

4.4.4.1 Impact of Main Failure

Fewer nodes receive a consequence rating when compared with other metrics because residential land use, which makes up a majority of the system, is assumed to experience no economic losses. Under pipe failure conditions, pipe P102 is the only location that produces significant

consequences, with a consequence index value of 17. The water lost during the burst of pipe P102 causes increased consequence index value because it is a connection point to the reservoir with no alternative flow path. All other pipe failures result in less severe consequences because they continue to convey water even after failure or have alternate flow paths available to transport water to necessary destinations.

4.4.4.2 Impact of Main Repair

During pipe repair, large consequence index values are produced by the failure of trunk water mains P19, P22, P102, P237 and P86. This trend is the opposite of that seen by all the other metrics analyzed. The economic loss metric therefore is not largely influenced by pressure data but by the consequence parameter values and location of the industrial, commercial and critical customers in the network. During repair of trunk water mains P348, P767 and P13, no consequences are produce because they are located in peripheral areas of the network with no integral connection to the industrial and commercial districts. All of the other trunk water mains are essential to the water supply to the industrial and commercial districts, distributing water to DMAs 4 and 5.

Figures 4-10 and 4-11 are CDF plots indicate the severity of each node of the D-town network for the economic loss metric for failure and repair conditions, respectively. The severity term multiplied by the economic loss consequence parameter of the consequence index equation is shown for all 8 trunk water main failure locations.

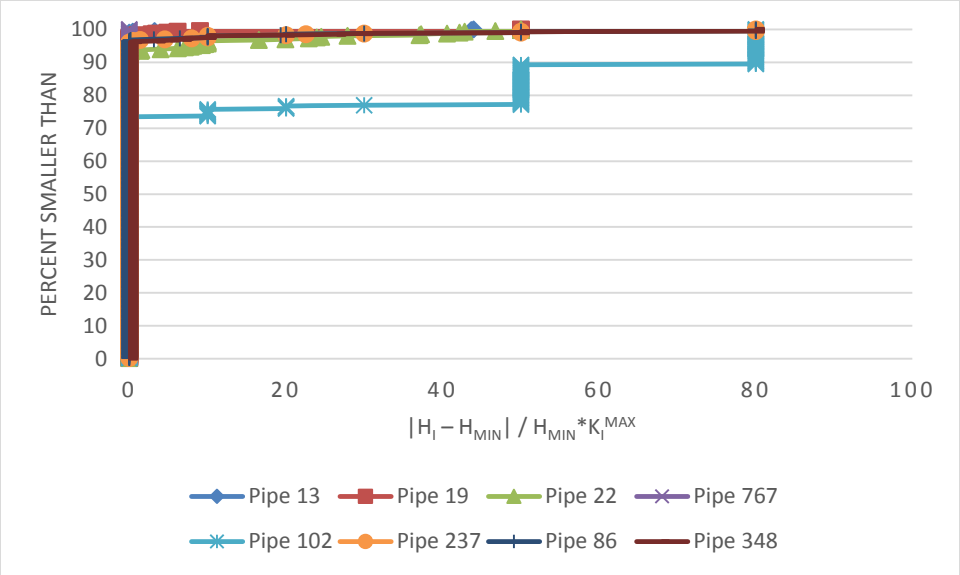

Figure 4-10: CDF plot of the economic loss severity term at all nodes in the D-Town system at time = 166 hours for the 8 water main locations under failure conditions.

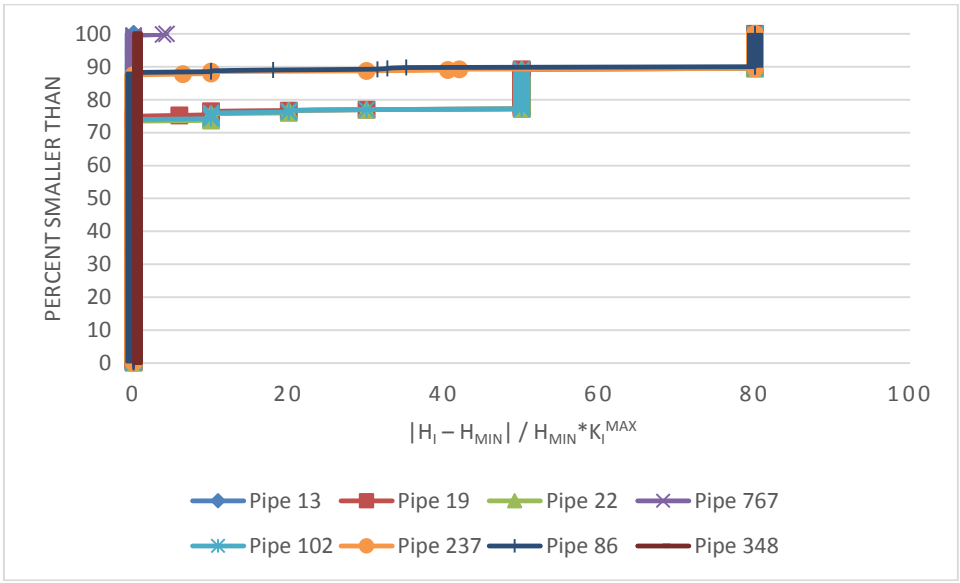

Figure 4-11: CDF plot of the economic loss severity term at all nodes in the D-Town system at time = 166 hours for the 8 water main locations under repair conditions.

The CDF plots during pipe failure and pipe repair show similar trends, with at least 10% of nodes having severity values of 50 and 80. These values represent a water pressure head of less than 0m at nodes that service commercial and industrial customers, respectively. For both pipe failure and

pipe repair, over 70% of the nodes do not experience negative consequences. This is largely due to the residential nodes, of which there are 293, that are not affected by economic losses. Pipe failure of trunk water main P102 produces the most significant consequence and affects both commercial and industrial nodes. All other pipe failures result in losses affecting less than 10% of the system. During pipe repair, 5 of the pipes (P19, P22, P102, P237 and P86) cause over 10% of the network to be negatively affected. The failures of pipes P102, P86, P237, P19 and P22, cause over 15% of the commercial district and 10% of industrial land use nodes to experiences a pressure head of less than 0 m. To reduce these potential losses, utilities could invest in the repair or replacements of integrals trunk water mains to commercial and industrial regions, thus reducing potential future monetary losses.

4.5 Water Main Failure under Fire Conditions

A fire simulation was run for each trunk water main failure at 5 locations in the system at the "centroid" of each DMA. A fire flow was applied at nodes J434, J496, J141, J320 and J56 located in DMAs 1, 2, 3, 4 and 5 respectively. Each fire location was evaluated during water main failure and repair conditions. EPANET2 was used to analyze the hydraulic conditions in the system at hour 166 of the diurnal period, correspond to the maximum day demand with fire flow. This hydraulic condition is used as one situation that governs worst case scenario in conventional design of water distribution system. The consequence index equation is used to calculate the severity of the 8 failure locations under the 5 fire scenarios for the demand metric. The minimum pressure is taken as 14.3 m in accordance with guidelines of acceptable pressure during a fire event (Ministry of the Environment 2008, Oberoi 2009).

4.5.1 Demand Metric

The demand metric was used to model the consequences that occur when a trunk main failure and fire event coincide. The metric characterizes how the loss of water, due to failure and fire flow, affects the ability of the system to meet user demands. The consequence parameter for the demand metric is equal to 1 since demand is take into account in the scaling factor of the consequence index equation (3-1). The consequence index equation values are presented in Table 4-9 as percentage values by multiplying the indexes by 100 for ease of interpretation.

Table 4-9: Consequence index values for both failure and repair conditions during a fire event.

		DMA ID	Water Main Failure					Water Main Repair				
			Fire Flow DMA Number									
			1[1]	2[2]	3[3]	4[4]	5[5]	1	2	3	4	5
Pipe ID	P13	1[6]	10[7]	37	34	29	17	0	6	0	11	3
	P19	1	31	41	41	57	59	65	64	70	64	64
	P22	1	2	18	2	18	7	99	99	99	99	99
	P767	3	0	11	1	8	3	0	21	26	9	2
	P102	1	99	99	99	99	99	88	88	88	88	88
	P237	2	54	56	60	83	55	34	34	39	48	34
	P86	2	35	35	40	54	50	28	28	28	41	28
	P348	2	36	36	41	54	51	1	6	2	9	1

[1] Fire located in the centroid of DMA 1.
[2] Fire located in the centroid of DMA 2.
[3] Fire located in the centroid of DMA 3.
[4] Fire located in the centroid of DMA 4.
[5] Fire located in the centroid of DMA 5.
[6] Indicates in which DMA the failed pipe is located.
[7] Consequence index values reported as percentages by multiplying by 100 for ease of interpretation.

4.5.1.1 Impact of Fire Location

The consequence index values of a trunk water main break under fire conditions show that fire location can affect the overall consequence severity. For lower consequence pipes, fire location

changes the level of consequence experienced by customers. For example, the failure of trunk water main P13 produces index values that range from 10 to 37 depending on the location of the fire. In this case, a number of factors affect the consequence value linked to the failure of pipe P13. The first factor is the loss of tank T1 as a water source and the hydraulic impact on DMA 1 and the other surrounding DMAs in the system. The other factor is close proximity of DMAs 4 and 5 that rely on the source of water from tank T1. For water main failures in critical locations, all five fire locations produce uniformly high consequence index values. For example, when pipe P102 is failed, 99% of the system is experiences an interruption to their water service for all the simulated fire locations. Hydraulically the system is already at a high level of stress from the trunk water main failure that disconnects the source from the rest of the system. Under these conditions, adding a fire flow at the five locations only introduces small variations in consequence severity in the system. When comparing the non-fire and fire scenarios it can be observed that the consequence severity is either the same or higher during the fire scenario. This would be expected since fire flow imposes an added stress on the system.

4.5.1.2 Impact of Failure Location

The pipe location has a significant effect on the severity of consequences during fire flow conditions (as it has during peak demand condition). For example pipe P102 and P22 have the largest consequence during failure and repair conditions respectively because they are both integral pipes that connect the source reservoir to the system and that are not looped. Pipe P767 has the smallest consequence during failure and pipes P13 and P348 during repair because the pipes serviced are looped allowing water to be conveyed even when these mains are in a failed state.

Figure 4-12 indicates a CDF plot that compares non-fire and fire scenarios during both failure and repair conditions when pipe P767 has failed (fire flow is located in DMA 2).

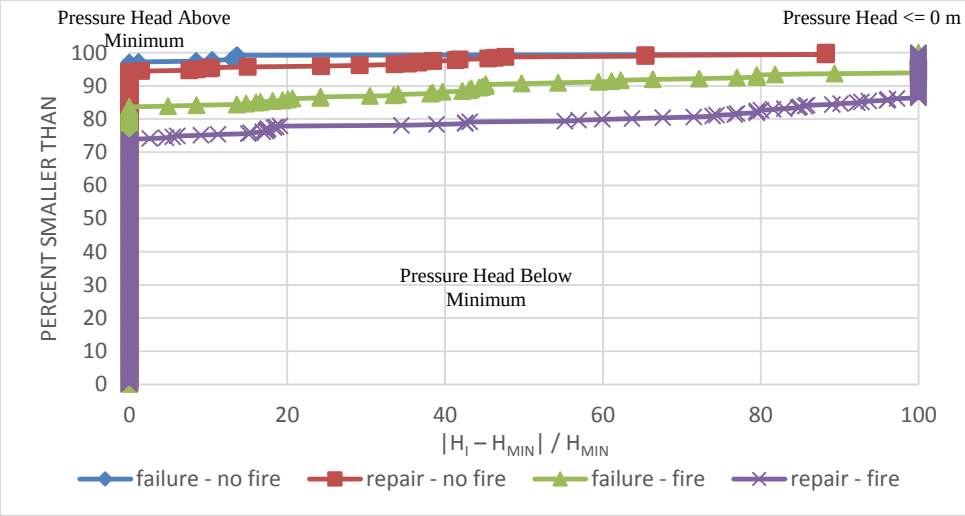

Figure 4-12: CDF plot of severity term of the consequence index at nodes in the D-Town system at time = 166 hours for the failure of pipe P767 with a fire in DMA 2.

By representing all 4 scenarios for 1 failure and 1 fire location in the same plot, the different severities can be compared. The fire scenarios cause a more severe consequence during both pipe burst and pipe repair conditions. During peak conditions, both the failure and repair plots display similar consequence with less than 5% of the system experiencing pressure below an acceptable pressure head. The low severity experienced during pipe failure and pipe repair is because pipe P767 is looped having alternative flow paths. Conversely, during fire flow in DMA 2 there is over 10% more nodes that experience an unacceptable pressure during pipe repair when compared with pipe burst conditions. This shows that during pipe repair, the system is more vulnerable to additional hydraulic stresses impose by a fire flow loading on the system.

Other CDF plots displayed a different trend than observed in Figure 4-12. Failures of critical pipes P19, P22 and P102 produced CDF plot curves that overlapped closely for all 4 scenarios (pipe

failure with no fire, pipe repair with no fire, pipe failure with fire and pipe repair with fire). This is owing to the fact that these 3 critical pipe failures disconnect the water source from the rest of the system, and, under these circumstances, adding an additional fire flow does little to vary the severity of consequences between scenarios.

4.5.2 Population Metric

To obtain population data for this network, an average day demand was estimated at each node and divided by the average water use of Canadians (329 L/ person • day) (Environment Canada 2013). The population affected at each node was then used in the consequence index equation as the consequence parameter. The values from these calculations are represented in Table 4-10.

Table 4-10: Consequence index values for both failure and repair conditions during a fire event for the population metric.

		DMA ID	Water Main Failure					Water Main Repair				
			Fire Flow DMA Number									
			1[1]	2[2]	3[3]	4[4]	5[5]	1	2	3	4	5
Pipe ID	P13	1[6]	26[7]	102	88	79	43	0	16	0	27	8
	P19	1	81	115	111	151	165	181	180	193	180	180
	P22	1	5	45	6	50	18	1	270	271	271	271
	P767	3	0	29	1	21	7	0	56	78	24	7
	P102	1	270	269	270	270	270	240	240	240	240	240
	P237	2	148	152	164	229	149	97	96	109	136	97
	P86	2	100	99	112	150	137	71	71	70	108	72
	P348	2	102	101	114	152	139	1	18	6	25	1

[1] Fire located in the centroid of DMA 1.
[2] Fire located in the centroid of DMA 2.
[3] Fire located in the centroid of DMA 3.
[4] Fire located in the centroid of DMA 4.
[5] Fire located in the centroid of DMA 5.
[6] Indicates in which DMA the failed pipe is located.
[7] Consequence index values representing the population demand that is negatively affected by insufficient pressure.

4.5.2.1 Impact of Failure Location

The consequence index values show that the pipe location has a large effect on the severity of consequences. All fire scenarios show varying consequence severity depending on the location except for the failure of pipe P102 during both failure and repair. The largest consequence take place during failure and repair of pipe P102 and the repair of pipe P22 with values above 240. This occurs because these pipes are connected to the source reservoir with no alternative water flow route. Pipe P767 has the smallest consequence during failure and pipe P348 during repair, with values lower than 30, because these pipes are looped in the system and therefore water can still be conveyed to necessary locations during a burst event.

4.5.2.2 Impact of Main Failure and Repair

Significant differences in severity are observed between water main failure and repair conditions at different pipe locations. Pipes P19, P767 and P22 are connected to a reservoir and/ or are not looped resulting in higher consequence during repair. This occurs because during failure, some water is still conveyed through the pipe whereas during repair no water is conveyed. The rest of the pipes have a higher consequence during failure because water loss during failure creates pressure drops in the system that do not occur during repair. This result underscores how the method can help to identify parts in the network that should be made redundant to prevent such consequences.

The fire location has only a small effect on the severity of consequence. CDF plots illustrate this by showing the percentage of all 398 nodes at different severity levels for the 5 fire DMA locations during the failure (Figure 4-13) and repair (Figure 4-14) of trunk water main P19.

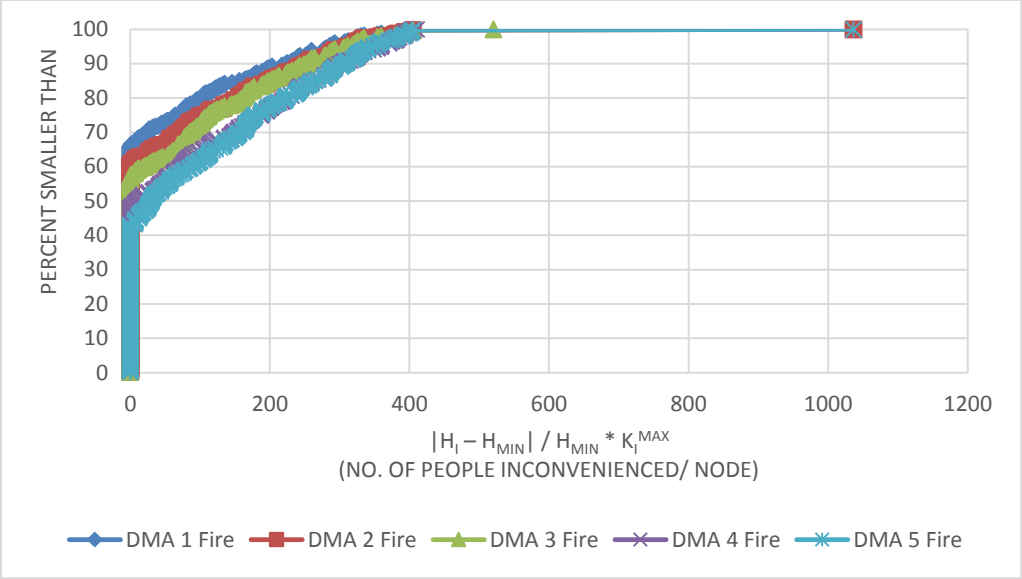

Figure 4-13: CDF plot of the severity term in the consequence index at nodes in the D-Town system at time = 166 hours for the 5 fire locations (DMAs) during failure of water main P19.

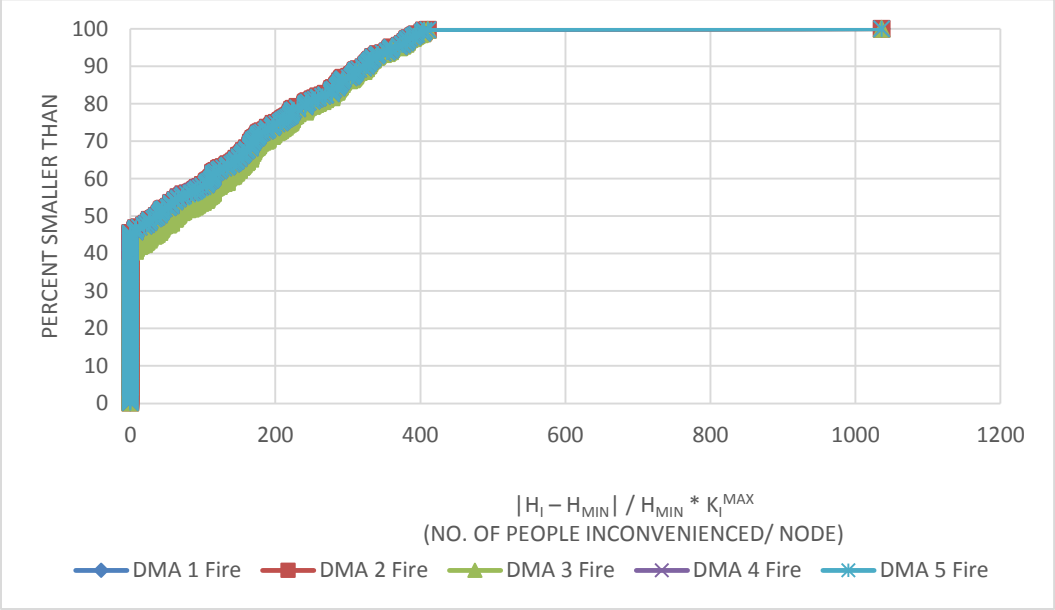

Figure 4-14: CDF plot of the severity term in the consequence index at nodes in the D-Town system at time = 166 hours for the 5 fire locations (DMAs) during the repair of water main P19.

These plots reflect the number of people inconvenienced at each node when a water main failure coincides with a fire flow in the system. In Figure 4-13, approximately 50% of the nodes experience pressure heads above the minimum acceptable level except for when there is a fire in DMAs 1, 2 and 3 during a water main failure. The plots in Figure 4-13 show that fewer than 400 people will be affected at 99% of the nodes when there is a fire at the 5 fire locations.

The results in Figure 4-14 suggest that during the repair of water main P19, fire at the 5 locations will have practically the same severity. These results occur because pipe P19 is integral at connecting the source reservoir to the rest of the system with only one other connecting pipe. During failure some water is conveyed through the pipe causing the proximity of fire to affect the severity. During repair no water is conveyed by the pipe resulting in the same severity regardless of fire location.

4.5.3 Land Use Metric

Since GIS data was not available for this network, a hypothetical social layer (indicated in Figure 4-7) was constructed based on hydraulic information and network layout. DMAs 1, 2 and 3 have a designated residential land-use with critical customers (6 schools, 5 nursing homes and a hospital) distributed within the said DMAs. DMA 4 has a designated commercial land-use with government services (critical customer) and DMA 5 has a designated industrial land-use. The consequence index equation was used to calculate the severity of low pressure caused by a failure event during fire flow. Consequence parameter values (Table 4-4) are the same as for peak conditions. The results are presented in Table 4-11.

Table 4-11: Consequence index values for both water main failure and repair conditions during a fire at the 5 DMA locations for the land use metric.

		DMA ID	Water Main Failure					Water Main Repair				
			Fire Flow DMA Number									
			1[1]	2[2]	3[3]	4[4]	5[5]	1	2	3	4	5
Pipe ID	P13	1[6]	5[7]	20	18	19	11	0	3	0	8	2
	P19	1	16	22	22	33	35	41	41	43	41	41
	P22	1	1	9	1	13	5	59	59	59	59	59
	P767	3	0	6	0	6	2	59	59	59	59	59
	P102	1	59	59	59	59	59	53	53	53	53	53
	P237	2	32	33	35	51	32	22	21	24	32	22
	P86	2	20	19	22	33	30	22	21	24	32	22
	P348	2	20	20	22	33	30	0	3	1	7	0

[1] Fire located in the centroid of DMA 1.
[2] Fire located in the centroid of DMA 2.
[3] Fire located in the centroid of DMA 3.
[4] Fire located in the centroid of DMA 4.
[5] Fire located in the centroid of DMA 5.
[6] Indicates in which DMA the failed pipe is located.
[7] Consequence index values representing the land use demand that is negatively affected by insufficient pressure.

4.5.3.1 Impact of Fire Location

The fire location has less influence over the severity of consequences when the land use index is used for the D-Town network. Pipe P102 has the same index values for all fire locations during failure and pipes P22, P767 and P102 show no change in values during repair. This occurs because residential land use makes up a large portion of the system but has a consequence parameter value of only 50. With lower consequence parameter values the disparity in consequence created by different fire flows is reduced.

4.5.3.2 Impact of Failure Location

The pipe location again creates significant differences in consequence severity. Pipe P13 has the lowest index values (all below a value of 20) when in failure and pipes P19, P22, P767 and P102

show index values as high as 59 when in a failed state. Pipes P19, P22 and P102 are all source reservoir connection pipes with no alternative flow path causing them to result in increased consequence. Pipe P13 causes limited severity because it is located on the peripheral of the system, does not obstruct source water flow and located near residential customers, a school and retirement home which are all in close proximity to the source reservoir. Pipe P767 shows a significant increase in consequence index value during repair when compared to the population metric value. This is because when this pipe fails it reduces or stops all supply water to many critical customers including a hospital, a retirement home and school. Pipes P237, P86 and P348 under failed conditions have middle-of-the road consequence index values because they are all located in DMA 2 which services mostly residential customers with 2 retirement homes, 2 schools and the hospital.

A severity chart for the pipe repair of trunk water main P237 during a fire in DMA 3 is presented in Table 4-12. A severity chart indicates the number of nodes that are above the minimum acceptable pressure, below the minimum acceptable pressure, and have a pressure of zero for each land use.

Table 4-12: Severity of consequence for different land uses during repair of pipe P237 with a fire present in DMA 3.

	No. of Nodes With Acceptable Pressure	No. of Nodes Below Acceptable Pressure	Pressure <= 0	Total No. of Nodes
Residential	178[1]	7	107	292
Commercial	47	2	0	49
Industrial	0	0	43	43
Critical Customers	9	0	6	15

Consequence

no consequence
mild consequence
severe consequence

[1] The number of nodes within each category.

The severity chart shows that when pipe P237 is being repaired, most of the nodes are either above the minimum acceptable pressure or experienced a pressure head of less than 0m with less than 10 residential and commercial nodes that provide a pressure head between Hmin and 0 m. The industrial land-use category was linked to the most severe consequences with all of the nodes experiencing a pressure head of less than 0m. This is because pipe P237 conveys water towards one of two connection points for DMA 5 (the industrial district). With only one remaining supply pipe pressure head severely drops causing a significant consequence. In the commercial district only 2 nodes out of 49 experience a pressure below the minimum acceptable level. This is because the repair of pipe P237 does not affect flow of water into DMA 4 (the commercial district) and therefore very few nodes experience consequence. Nine critical customers maintain an acceptable pressure levels during pipe repair of trunk water main P237 with 6 critical customers experiencing completed serve interruption. Since critical customers are distribute throughout the entire network a split in severity occurs based on the proximity of the critical customer to pipe P237. Different trends occur for different fire and failure locations in the network. The DMA in which pipe failure and fire occurs influences the level of consequence because each DMA has a unique distribution of land uses. For example during repair of pipe P767 with a fire in DMA 4, all nodes that service industrial users have a pressure head above 14.3 m while over half the nodes that service commercial users are below the minimum acceptable pressure. This occurs because DMA 4 is the commercial sector of the D-Town water distribution network. With varying data it is important that analysis of a significant number of failure and fire locations is completed to get a robust understanding of the consequences when this information is being used for network improvement.

4.5.4 Economic Loss Metric

The economic loss metric consequence index values were calculated using the consequence parameter values presented in the peak condition analysis (Table 4-7). The results are reported in Table 4-13.

Table 4-13: Consequence index values for both water main failure and repair conditions during a fire at the 5 DMA locations for the economic loss metric.

		DMA ID	Water Main Failure					Water Main Repair				
			Fire Flow DMA Number									
			1[1]	2[2]	3[3]	4[4]	5[5]	1	2	3	4	5
Pipe ID	P13	1[6]	0[7]	1	0	7	6	0	16	0	27	8
	P19	1	0	1	0	7	9	17	17	17	17	17
	P22	1	0	0	0	7	4	17	17	17	17	17
	P767	3	0	0	0	4	2	0	0	1	4	2
	P102	1	17	17	17	17	17	17	17	17	17	17
	P237	2	9	9	9	17	9	10	10	10	16	10
	P86	2	2	2	2	9	9	9	9	9	15	9
	P348	2	2	2	2	9	9	0	0	0	4	0

[1] Minimum demand for DMA 5.
[2] Minimum demand for the whole system.
[3] Maximum demand for DMA 3.
[4] Maximum demand for DMA 5.
[5] Maximum demand for the whole system.
[6] Indicates in which DMA the failed pipe is located.
[7] Consequence index values representing the economic loss demand that is negatively affected by insufficient pressure.

4.5.4.1 Impact of Failure and Fire Location

Since the residential nodes are assigned an economic losses consequence parameter value of 0, the index values are lower than those of the other metrics. The location of the fire has a large influence on the consequences, with fires in DMAs 4 and 5 causing more severe consequences for most water main failure locations. This is especially true during failure conditions, where all the analyzed pipes, excluding pipe P102, experience higher levels of consequence when a fire takes

place in DMAs 4 and 5. This increased level of consequence is caused by local losses surrounding the fire location at nodes that are designated as commercial or industrial land use. Contrary to the trends seen for all other metrics, the largest consequence index value, 27, was experienced during pipe repair of pipe P13 in conjunction with a fire in DMA 4. This value is almost double the next highest consequence index value in Table 4-13. The reason pipe P13 has the largest consequence is because the failure and fire combination cause pressure head losses in DMAs 4 and 5 due to the close proximity to these DMAs of both the pipe and the fire. The proximity of the pipe to important network features during pipe repair also has an effect on the level of consequence. Pipes P22, P19 and P102, all of which are connection points to the source reservoir, have consequence index values as high as 17, with little to no variation with different fire locations.

4.5.4.2 Impact of Land Use Distribution

All pipes analyzed, with the exception of pipe P348, experience a higher consequence index value during pipe repair than during pipe failure. The magnitude of the differences vary depending on the pipe location, with differences ranging from 1 for pipe P237 with a fire in DMAs 1, 2, 3 or 5, to 20 for pipe P13 with a fire in DMA 4. This demonstrates that the commercial, industrial and critical customers are more largely affected by the no-flow conditions during pipe repair for the pipes examined for the D-Town system. This trend is not the same as that seen for other metrics where there is more variation in consequence severity experienced between pipe failure and pipe repair. This displays the importance the land use distribution with regards to the resulting level of consequence.

4.5.5 Economic Damages at Fire Node

To obtain a consequence value for the 5 modelled fire locations, the fire consequence index equation (3-3) was used. A data layer of building envelope and contents loss was constructed for demonstrative purposes in this case study. The values were determined with average residential, industrial and commercial costs in Ontario, specifically the Toronto region (The Canadian Real Estate Association 2014, Toronto Real Estate Board 2014). Contents values were added as a percentage of the envelope cost. The final results are fire consequence index values displayed in monetary value of envelope and contents loss. Figures 4-15 and 4-16 display the results for the 8 failures and 5 fire events during pipe failure and pipe repair, respectively.

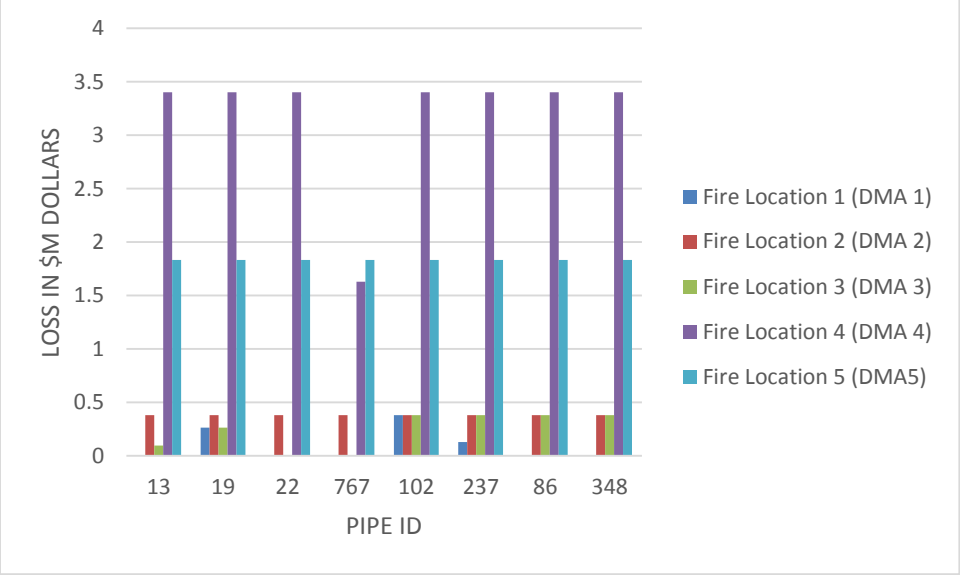

Figure 4-15: Fire consequence index values for 8 failure and 5 coinciding fire events during failure.

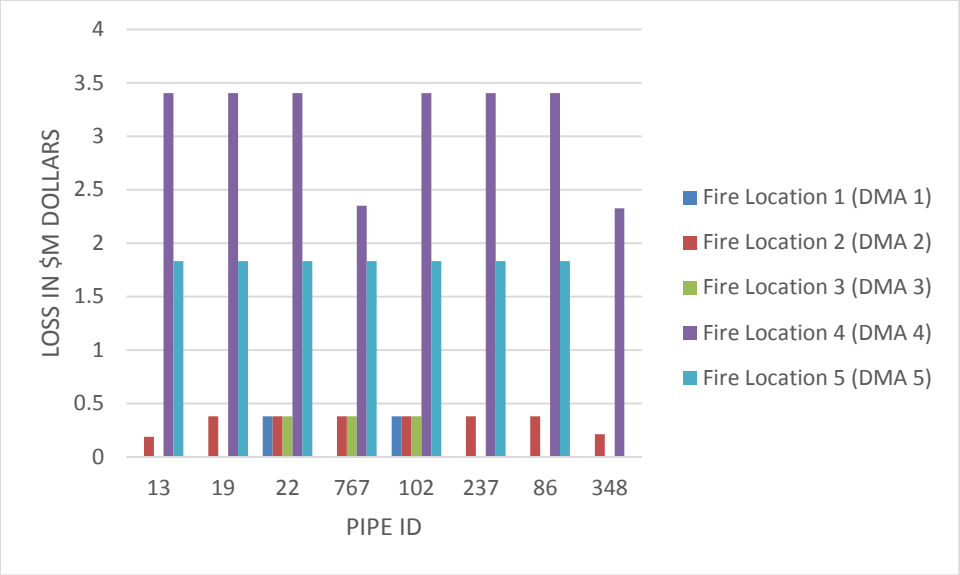

Figure 4-16: Fire consequence index values for 8 failure and 5 coninciding fire events during repair.

Figures 4-15 and 4-16 depict large discrepancies in fire consequence index values depending on the fire location, regardless of the water main failure location. This is as a result of the different building types that exist at each of the fire location and the different monetary value associated with each one. A fire at the centroid of DMA 4 or 5 has the largest consequence result since a fire at these locations affects commercial or industrial buildings. The fire locations in DMAs 1, 2 and 3 are all residential buildings, resulting in significantly lower monetary loss when a fire occurs. The least significant damages occur during pipe failure of pipe P767 and during pipe repair of pipes P767 and P348. This is because these events allow for some residual water pressure and more fire protection at the fire locations. The most significant damages occur during the failure of pipe P102 and during repair of pipes P22 and P102. During these events, each of the five modelled fire locations receive a pressure head of less than 0 m, that results in the maximum levels of economic losses. With most of the fire locations experiencing a maximum level of consequences, the impact of a fire event and failure event coinciding in the D-Town network is very high.

4.6 Overall Pipe Ranking

To allow for a general consequence classification of the 8 trunk water mains considered in this investigation, each pipe was assigned an overall rank. The rank denotes a pipe's consequence severity relative to the other pipe failure locations examined in the study. Each pipe was ranked from 1 to 8, were 1 represents the trunk water main failure that results in the most severe consequences and 8 represented the least severe. In Table 4-14, 5 different rankings are presented for each pipe analyzed. The first four ranks show the scenario ranks for peak conditions during pipe failure, peak conditions during pipe repair, fire flow conditions during pipe failure and fire flow conditions during pipe repair. The last column depicts the overall rank, which is a combination of the four previous ranks which were all weighted equally.

Table 4-14: Consequence classification of 8 pipes modelled under peak and fire flow conditions and overall ranking at hour 166.

		Peak Condition		Fire Conditions		Overall
		Failure	Repair	Failure	Repair	
Pipe ID	P13	6	7	6	8	8
	P19	2	3	4	3	2
	P22	7	1	7	1	4
	P767	8	6	8	6	7
	P102	1	2	1	2	1
	P237	3	4	2	4	3
	P86	5	5	5	5	5
	P348	4	7	3	7	6

The values illustrated in Table 4-14 show that varying levels of consequence can result for the same trunk water main failure under pipe failure and pipe repair conditions. For example trunk water mains P22 and P348 have very different rankings under different conditions. Pipe P22 shows a larger consequence during pipe repair and pipe P348 shows a larger consequence during pipe

failure. The rankings for pipe P86 were relatively uniform across loading conditions, with pipe P86 ranking 5th in all scenarios. The difference between the rankings for peak and fire flow conditions was minimal. The largest difference was for pipe P19 during pipe failure, with a rank of 2 during peak conditions and a rank of 4 under fire flow conditions.

The overall ranking is not an appropriate representation of all of the scenarios considered except for pipes that experienced a similar ranking under all four cases considered. However it does give a general idea of the level of consequence when compared to the other pipes in the system. This information can assist utilities in prioritizing water main rehabilitation and replacement plans in their distribution systems.

4.7 Time Average Consequence Modelling

The time average metrics are an important tool for networks where peak demand does not occur simultaneously throughout the system, such as the D-town network. Each DMA follows a different diurnal pattern resulting in varying levels of consequence throughout the water distribution network at a single point in time. All of the time average metrics were calculated for only DMA 3 to allow for a more focused analysis. The analysis was completed under average day demand for the 8 failure locations for both pipe failure and repair conditions. The time-averaged consequence index equation in (3-5) was used to determine the consequence for all of the examined time average metrics. The minimum acceptable pressure head was 25 m in accordance with the network's design guidelines (Marchi, 2013).

4.7.1 Demand Metric

The demand metric was analyzed using the time average approach. A time-averaged consequence index value for the demand metric was determined for each time period, using a time step of 15

min. The diurnal pattern for DMA 3 is presented in Figure 4-17, showing variation in demand over the 168 hour time period. Figures 4-18 and 4-19 present the index values during pipe failure and pipe repair, respectively.

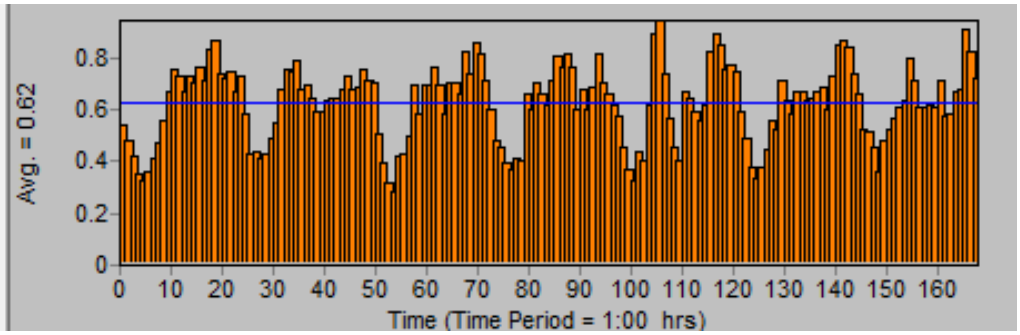

Figure 4-17: Diurnal pattern for DMA 3 in the D-Town water distribution network.

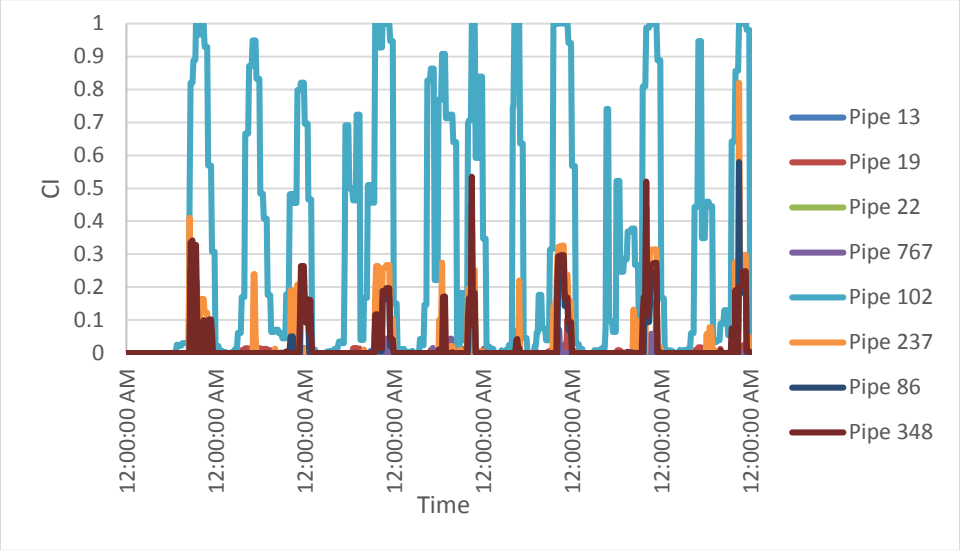

Figure 4-18: Time average consequence index values for 8 trunk water main failures during failure conditions in DMA 3.

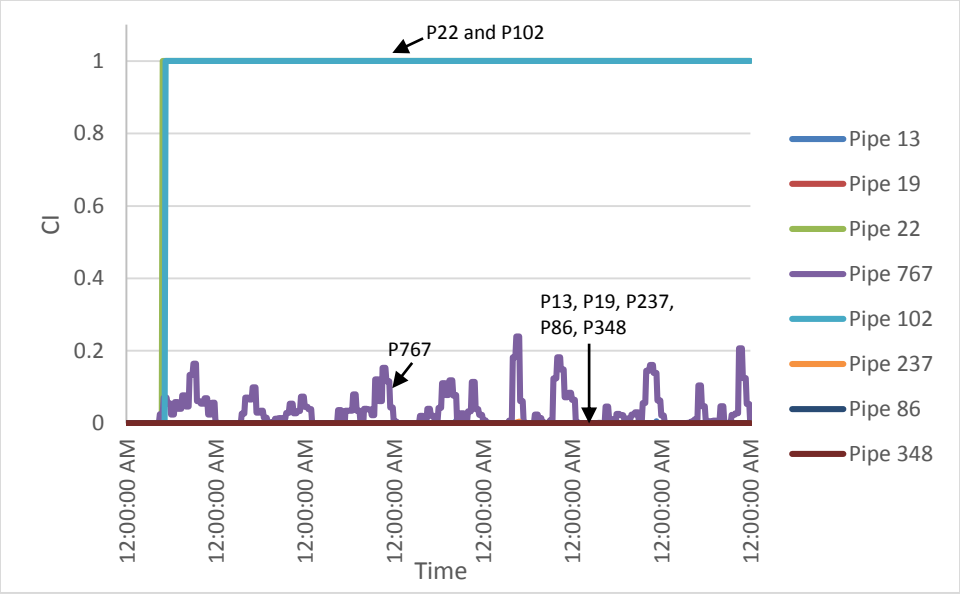

Figure 4-19: Time average consequence index values for 8 trunk water main failures during repair conditions in DMA 3.

Analyzing the system over each time step shows that there are multiple times of increased consequence throughout the diurnal pattern. During pipe failure conditions more fluctuations in severity are observed throughout the 168 hour time period. The index values have similar trends as those seen in the diurnal pattern. This is expected because in off peak demand times system pressures are high reducing severity during a failure event and during peak demand conditions For pipe P102 each peak demand time periods result in the entire system experiencing a pressure head of less than 0 m, causing a consequence index value of 1 to be obtained. Hour 166, which was modelled as the systems time of highest consequence, does coincide with the highest severity for most of the trunk water main failure events in DMA 3. However, this trend could differ for analysis of other DMAs in the network due to the varying diurnal patterns. The results obtained for pipe repair conditions vary from those obtained during pipe failure conditions. During pipe repair a majority of the failure locations result in little to no consequence throughout the entire diurnal time

period. The only significant consequence is observed during repair of trunk water mains P22, P767 and P102. Pipe P767 shows varying consequence index values with the most significant consequences occurring at hour 105, where 25% of the system is negatively affected. Hour 166 shows the second largest consequence index value, affecting 20% of the network. Pipe P767 did not show as significant consequences during peak conditions. However, this pipe is located in DMA 3 and therefore produces larger localized losses which are represented by this analysis. The failure of pipes P22 and P102 result in no consequence to the system for the first 10 hours. However, at a time of 10 hours all of DMA 3 experiences a pressure head of less than 0 m, which continues for the remainder of the diurnal time period. Pipes P22 and P102 showed the highest levels of consequences throughout the entire analysis. This is because these critical pipes connect the source reservoir to the rest of the network. The results indicate that pipe repair during peak hour 166 did not coincide with the most severe consequences for DMA 3. Time average analysis identifies important consequences that occur during off-peak times that might otherwise be missed in a snapshot analysis. The analysis of DMA 3 showed that losses are more localized during pipe repair conditions than they are during failure conditions.

4.7.2 Population Metric

Time average analysis was completed for the population metric as well. To acquire a comprehensive understanding of the maximum consequence and understand how time affects this metric, a comparison between the time-averaged consequence index value, the consequence index value for the analysis of peak hour 166 and the maximum consequence index value that occurs during each failure scenario is presented. The results are reported in Table 4-15 for failure and repair conditions of the 8 modelled trunk water mains focusing on nodes in DMA 3.

Table 4-15: Population metric consequence index value comparison of time average, peak hour 166 and maximum index values for 8 trunk water main failures during pipe failure and pipe repair conditions.

			Failure			Repair		
		DMA ID	Time Average	Peak Hour 166	Maximum Index Value	Time Average	Peak Hour 166	Maximum Index Value
Pipe ID	P13	1[1]	0[2]	5	6	0	0	2
	P19	1	1	5	34	0	0	1
	P22	1	0	0	3	221	235	235
	P767	3	0	0	14	7	27	235
	P102	1	77	232	235	220	235	235
	P237	2	7	62	190	0	0	1
	P86	2	4	48	127	0	0	0
	P348	2	6	52	115	0	0	0

[1] Indicates in which DMA the failed pipe is located.
[2] Consequence index values representing the population demand that is negatively affected by insufficient pressure.

The time average results show lower consequence values than previous consequence index results because they represent the entire diurnal time period, and not just the peak demand at hour 166. This trend is most obvious during failure conditions, where periods of both high and low severity throughout the 7 day time period result in a lower average severity. Hour 166 does not represent the worst case scenario for any of the large-diameter water mains under failure conditions. The difference between the maximum index values from the time averaged analysis and the values from the analysis of hour 166 range from 1 (for pipe P13) to 128 (for pipe P237). This shows that for DMA 3 the systems maximum hour demand (hour 166) does not correspond to the worst case loading scenario. During pipe repair, the results of the analysis of hour 166 more appropriately represent the worst case scenario, with consequence index values only varying by a margin of 2. Conversely, pipe P767 has a maximum index value of 235 but during hour 166 only receives a consequence index value of 27. During repair, the time average values are also similar to the

maximum index values. This demonstrates that over the 7 day time period the consequences are relatively constant under pipe repair conditions. This information can be used by municipalities to know which pipes require a short repair time allowing for a limited effect on the system.

4.7.3 Land Use Metric

Time average analysis was performed for the land use metric. The time-averaged consequence index values were calculated and are presented in Table 4-16 along with hour 166 consequence index values and the maximum consequence index value that occurs over the diurnal period. The values displayed are for the severity during failure and repair of the 8 trunk water mains considered.

Table 4-16: Land use metric consequence index value comparison of time average, hour 166 and maximum index values for 8 trunk water main failures during failure and repair conditions.

			Failure			Repair		
		DMA ID	Time Average	Peak Hour 166	Maximum Index Value	Time Average	Peak Hour 166	Maximum Index Value
Pipe ID	P13	1[1]	0[2]	1	1	0	0	0
	P19	1	0	1	9	0	0	0
	P22	1	0	0	1	48	51	51
	P767	3	0	0	4	2	6	51
	P102	1	17	51	51	48	51	51
	P237	2	2	15	42	0	0	0
	P86	2	1	11	30	0	0	0
	P348	2	1	12	28	0	0	0

[1] Indicates in which DMA the failed pipe is located.
[2] Consequence index values representing the land use demand that is negatively affected by insufficient pressure.

Similar results are observed for the land use metric as were seen for the population metric. The results shows that both demand and pressure play a large role in the time average consequence

index values versus population or land use consequence parameters. During pipe failure, the time average values produced significantly lower levels of consequence when compared to hour 166 and the worst case scenario. The maximum consequence index values produced more severity than hour 166, in most cases. For pipe failure of trunk water mains P13 and P102, hour 166 had the same consequence as the maximum index value, with values ranging from 1 to 51. Pipe P13 is located at the opposite end of the system from DMA 3 resulting in minimal consequence at all times. Pipe P102 produces a larger consequence that is maintained throughout most times of failure because it is a connection pipe for the source reservoir which is crucial in providing water to DMA 3. Pipe failure of trunk water mains P237, P86 and P348 resulted in the most significant differences in severity between hour 166 and the maximum index value with consequence index values over 50% lower at hour 166. These failures are all located in DMA 2, which neighbors DMA3. On average these failures did not affect the severity because they were not located in DMA 3 however during peak conditions the severity of failure increased and had a larger effect on the nodes in DMA 3.

During pipe repair only pipe P767 shows significantly different consequence index values for the three circumstances. The failure of pipe P767 has low severity values for the time average and hour 166 results, with values of 2 and 6, respectively. However, the maximum consequence experienced by the system is significantly higher, with an index value of 51. This occurs because pipe P767 is located in DMA 3 but is isolated in the system causing consequence levels to stay low in most cases, except the most critical case. Repair of trunk water main failures P13, P19, P237, P86 and P348 create no consequence to DMA 3 throughout the entire 7 day time period. This information is important to municipalities showing that these failures will not affect any user negatively in DMA 3 and therefore are of lower importance during pipe repair when focusing on

this DMA. Pipes P22 and P102 have substantial consequence index values during pipe repair for the land use metric for all 3 situations. The consequence index values for both pipes are 48, 51 and 51 for the time average, hour 166 and worst case scenario respectively. The similarity between these values demonstrates that DMA 3 experiences a large negative affect throughout most, if not all, of the diurnal time period. This large consequence is experienced because these pipes connect the source reservoir to the rest to the system. The results from the pipe repair case establish that the analysis completed at hour 166 is capable of depicting the worst case scenario throughout the entire time period. This data gives municipalities a broader understanding of the consequences that occur throughout the entire diurnal time period. It can be useful in creating detailed improvement and replacement plan for large-diameter pipes to reduce severe consequence to the system.

4.8 Conclusion

The results of the D-Town water distribution case study demonstrate how a smaller scale water distribution system is affected by trunk water main failures during peak demand and fire flow conditions. Eight trunk water mains were modelled under pipe failure and pipe repair conditions. First, failure location played the largest role in level of consequence with a larger severity resulting when failures occurred near important network features. Second, pipe repair conditions produced larger consequence than pipe failure because the D-Town system is not well looped. Therefore, when no water is able to be conveyed through the failed pipe, as under repair conditions, larger pressure drops occur. Third, the combination of a trunk water main failure and a fire event produces an increased consequence in the system, showing that the system does not provide adequate hydraulic capacity for fire flow. Lastly, maximum system demand does not always result in the largest consequence when DMAs have varying diurnal patterns, which shows that time average analysis is an important tool to better understand consequence severity. The consequence model

used in this analysis can provide valuable information to utilities that can help improve rehabilitation and replacement planning.

4.9 References

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Chapter 5

Characterizing the Consequences of Trunk Water Main Failures in the City of Kingston: A Case Study

5.1 Introduction

There is a different response to trunk water main failures between large-scale and small-scale water distribution systems. Large-scale networks service a larger population, which can lead to a significantly larger affected population when a failure event takes place. To mitigate the consequences of failure events, it is important for municipalities to know which water mains in their system produce the largest consequences when failure does occur. Such information can be used to develop water main rehabilitation and replacement plans.

The aim of this chapter is to apply the water main failure consequence model of Chapter 3 to the City of Kingston water distribution network. The consequence model is used to examine the severity of consequences linked to 19 trunk water mains in the City of Kingston distribution network. The consequences of water main failures are examined during maximum hour demand, minimum hour demand and fire flow conditions. The results from both this case study and the overall findings from the analysis are discussed in detail.

5.2 Overview of Metrics Modelled

A full analysis of all the metrics outlined in Chapter 3 could not be completed with the available data. An abridged analysis was completed to obtain a preliminary understanding of the consequences of different trunk water main failure events. Table 5-1 indicates the scenarios that were modelled and the metrics that were included in the analysis.

Table 5-1: Metrics used for each scenario considered in the City of Kingston water distribution system study.

	System Wide Consequences		
Demand Loading	Demand Metric	Population Metric	Land Use Metric
Maximum Hour Demand	x	x	x
Minimum Hour Demand	x		
Fire Flow at 3 Locations[1] + Maximum Day Demand	x	x	x

[1] Fires simulated at nodes J10860, J17052 and J13780 labeled in Figure 5-1.

5.3 Description of Case Study

The novel consequence model was applied to the City of Kingston water distribution network, indicated in Figure 5-1, to provide the City of Kingston with knowledge on the potential consequences of trunk water main failures in their system. The Kingston network services approximately 124,000 people and is made up of 12,189 pipes (3,299 of which are large diameter water mains), 11,176 nodes, 31 pumps (making up 5 booster stations), 10 tanks and 2 reservoirs. The water mains indicated in red in Figure 5-1 are the trunk water mains in the City of Kingston system. The City of Kingston water distribution network has 3 distinct sections: Kingston West which serves the western part of the City, Kingston Central which serves the old, historic part of the City, and Kingston East which serves the Canadian Forces military base and the eastern part

of the City. Kingston West is hydraulically disconnected from the rest of the system and is fed by the Kingston West Water Treatment Plant (WTP). Kingston Central is supplied by the King Street WTP and water is transferred from Kingston Central to Kingston East across the Great Cataraqui River via the James Street Booster Station and 2 large-diameter water mains.

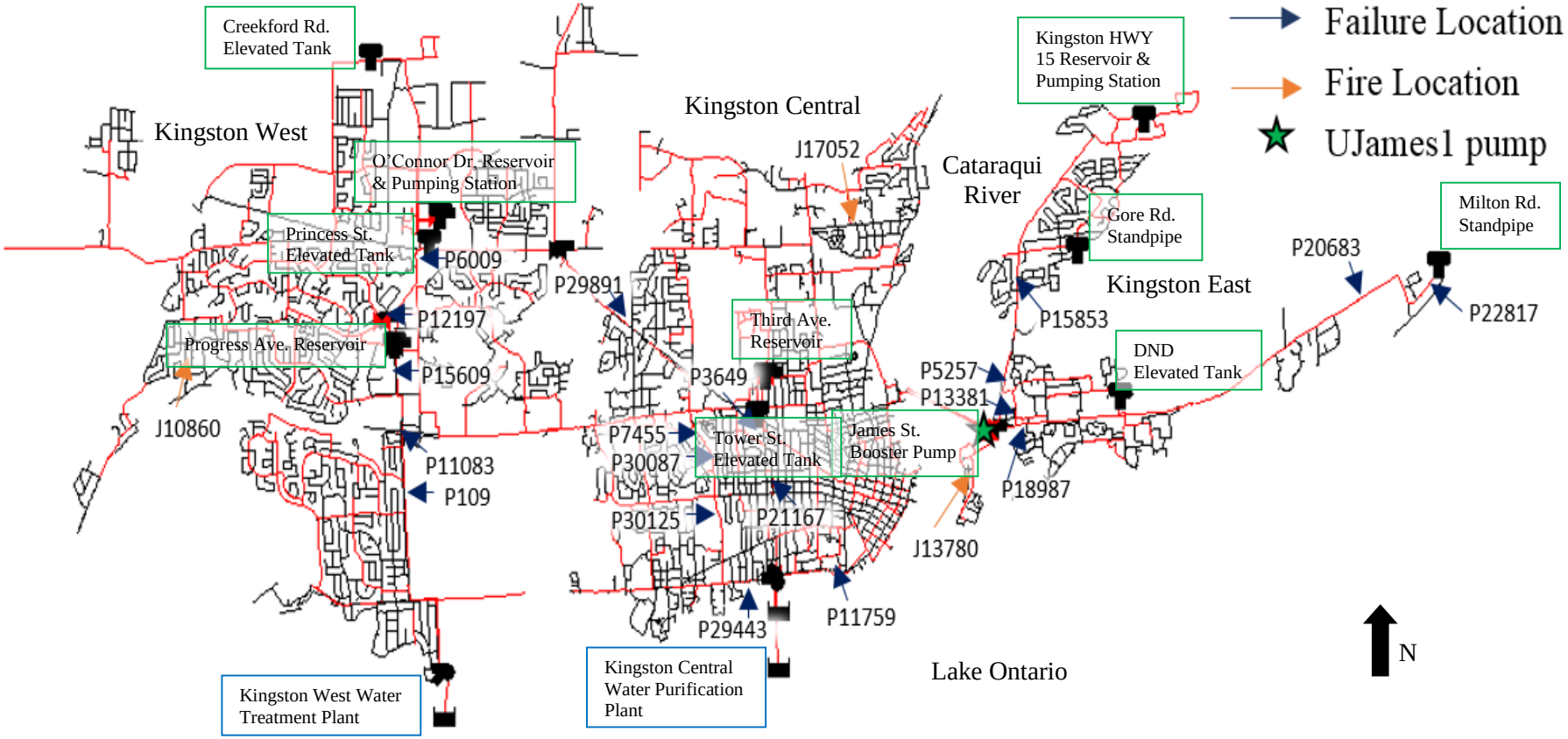

Figure 5-1: Kingston water distribution network with 19 pipe failures scenario locations labelled.

EPANET2 (Rossman 2000) was used to perform steady-state analyses to evaluate the worst case and minimum loading scenarios for the Kingston water distribution network. The model accounts for water leakage which for more accurate results to be calculated. The pipes selected for failure simulation are P29443, P30125, P30087, P7455, P109, P11083, P15609, P12197, P6009, P29891, P11759, P3649, P21167, P15853, P13381, P5257, P18987, P20683, and P22817. These pipe IDs correspond to the network model and are labeled in Figure 5-1. Times of interest modelled were maximum hour demand, minimum hour demand and maximum day demand with fire flow, with peaking factors of 2.48, 1.65 and 0.7 of average day demand, respectively, in accordance with design standards for municipal water distribution systems (Ministry of the Environment 2008).

Several changes to the EPANET2 model were made to the model of the Kingston distribution network, an all-pipes model, provided by Utilities Kingston to allow the modelling process to be completed. UJames1 pump (located in the east end) was causing system unbalances, to rectify this problem the pump curve was increased to create for system equilibrium. Hydraulically this change means that if flow in the pump exceeds the original pump curve, the pump will continue to provide a head value. Tank water levels were set to control minimums to model worst-case scenario for a failure event. The changes are documented in Appendix A to allow for future work to be completed using the Kingston water distribution model.

5.4 Consequence Modelling under Maximum and Minimum Loading Conditions

Maximum and minimum hour demand conditions were simulated for the 19 failure locations to obtain severity ratings for each of the pipe sections. EPANET2 (Rossman 2000) was used to perform steady-state hydraulic analyses to obtain pressure and demand values and to evaluate the metrics for pipe failure and pipe repair for each of the 19 trunk water mains. The minimum required

pressure under maximum hour and minimum hour demand loading conditions was set to 27.5 m in accordance with Ontario Ministry of the Environment (2008) guidelines. The consequence index equation (3-1) was used to evaluate the demand and population metrics.

5.4.1 Demand Metric

The demand metric was used to evaluate the consequences that occur when a failure occurs during maximum hour and minimum hour demands in the system. The metric quantifies the effect of changes in water pressure caused by the failure event on the satisfaction of system demands. The demand metric consequence parameter is 1 because the scaling factor in the consequence index equation (3-1) accounts for the demand at each node in the network. Additional analysis was completed for the demand metric to observe trends between the consequence index values and network parameters (pipe diameter, pipe length and pipe location). The resulting consequence index equation values are presented in Table 5-2. For clarity, the values are shown as percentages, by multiplying the indexes by 100.

Table 5-2: Consequence index values for both pipe failure and pipe repair conditions during maximum and minimum hour demands.

		Network Section	Trunk Water Main Failure		Trunk Water Main Repair	
			Maximum Hour Demand	Minimum Hour Demand	Maximum Hour Demand	Minimum Hour Demand
Pipe ID	P29443	Central[1]	1.4[2]	0.1	1.3	0.1
	P30125	Central	1.8	0.2	1.0	0.1
	P30087	Central	1.6	0.2	1.0	0.1
	P7455	Central	1.5	0.1	1.1	0.1
	P29891	Central	1.0	0.1	0.9	0.1
	P11759	Central	1.1	0.1	1.0	0.1
	P3649	Central	3.8	2.9	24.2	0.1
	P21167	Central	1.0	0.1	0.9	0.1
	P109	West	1.4	0.2	1.0	0.1
	P11083	West	1.9	0.2	1.3	1.3
	P15609	West	1.4	0.2	0.9	0.1
	P12197	West	1.0	0.1	0.9	0.1
	P6009	West	1.0	0.1	0.9	0.1
	P15853	East	0.9	0.1	0.9	0.1
	P13381	East	0.9	0.1	0.9	0.1
	P5257	East	0.9	0.1	0.9	0.1
	P18987	East	0.9	0.1	0.9	0.1
	P20683	East	0.9	0.2	0.9	0.1
	P22817	East	0.9	0.1	0.9	0.1

[1] Indicates in which section of the Kingston network the failed pipe is located.
[2] Consequence index values reported as percentage values by multiplying by 100 for ease of interpretation.

5.4.1.1 Impact of a Failure Event

The consequence index values in Table 5-2 indicate the percentage of the demand that is not met due to the trunk water main failure. All of the failures events caused part of the system to experience pressures below the minimum acceptable level. The consequence severity varied from 0.1-2% of system demand met at pressures below the 27.5 m minimum. The exception to this was the failure of pipe P3649, for which the percentage of the system negatively affected ranges from

0.1% to 24.2%. These generally low percentage values may make the consequences of these failures seem insignificant. However, the system is large and small index value can have an effect on many people. For example, 1% of the system services approximately 3,700 homes and businesses.

5.4.1.2 Impact of Main Failure and Repair

A comparison of the results for pipe failure and pipe repair conditions show that pipe failure conditions create larger consequences, except in a few cases. During pipe repair, water is redistributed in new directions, which allows demands to be met since the Kingston network is well looped. However, during pipe failure conditions, water is being lost in the system which results in larger pressure drops and higher consequences. Under pipe repair conditions, trunk water mains P3649 (during maximum hour demand) and P11083 (during minimum hour demand), the level of consequence is considerably higher than under the same demand conditions during failure. This is because these two pipes are located in integral locations in the system that connect parts of the system to a tank. During pipe failure conditions, some water is still conveyed through the pipe, resulting in smaller consequences than during pipe repair condition, when no water is conveyed through the pipes and the tank is disconnected from parts of the network.

5.4.1.3 Impact of Failure Location

Water main failures in Kingston West and Kingston Central entail more severe consequences than failures in Kingston East, especially during maximum hour demand. This is because pipe failures that are central to the system have wider spreading consequences. The east end is isolated from the west sections and does not provide source water flow to Kingston Central, therefore the hydraulic changes caused by a trunk water main failure are more localized.

5.4.1.4 Impact of Demand Load

As expected, during maximum hour demand, the level of consequence experienced is significantly higher than during minimum hour demand. This is because the demands during maximum hour conditions are 3.5 times greater than during minimum hour conditions. This trend is most significant during pipe failure because the water loss and larger demands both decrease the water pressure and increase the consequence severity. Conversely, pipe P11083 produces the same consequence index value under pipe repair conditions for both maximum and minimum hour demand. This pipe connects the southern part of Kingston West (where the source reservoir feeds the network) to the northern part of Kingston West and is in close proximity to Progress Ave. Reservoir. Because this pipe is in a critical location, its failure produces large consequences to the surrounding area regardless of the demand.

To further analyze the factors that affect the level of consequence of a failure event, the consequence index values were plotted against different pipe characteristics (pipe diameter, pipe length, and pipe location). Figure 5-2 shows the plot of the consequence index values versus pipe length during pipe failure and pipe repair conditions.

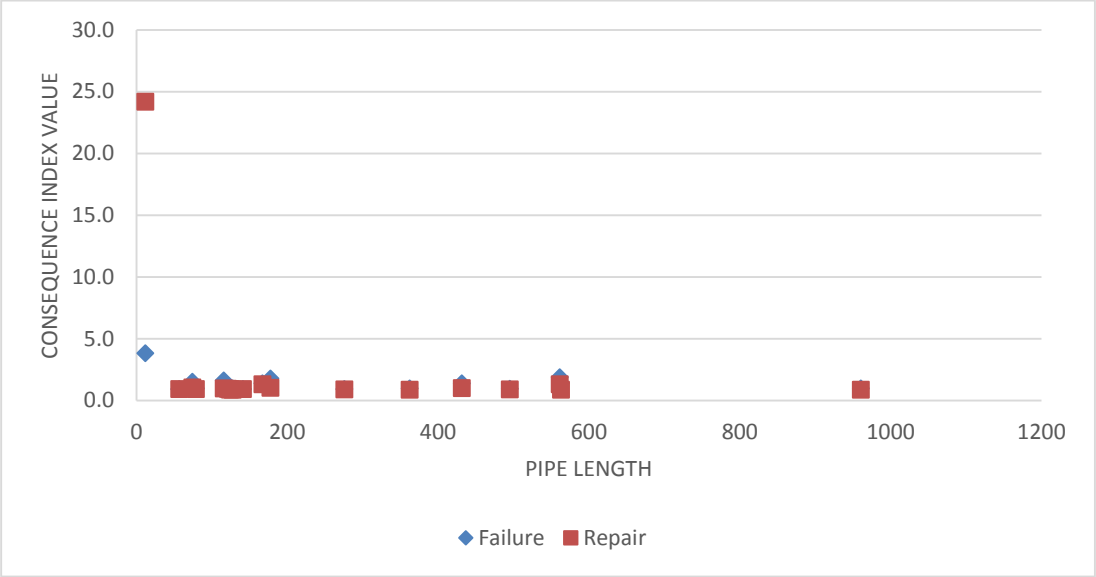

Figure 5-2: Pipe length plot of the correlation between consequence index values (during pipe failure and repair) and length of the failed pipe.

Figure 5-2 displays the level of consequence associated with the lengths of the 19 pipes modelled for both failure and repair conditions. No trend between pipe length and level of consequence is evident in the Kingston network.

Figure 5-3 depicts the relationship between the consequence index values and the pipe diameter for the 19 pipe failures analyzed. Data from pipe failure and pipe repair conditions are included.

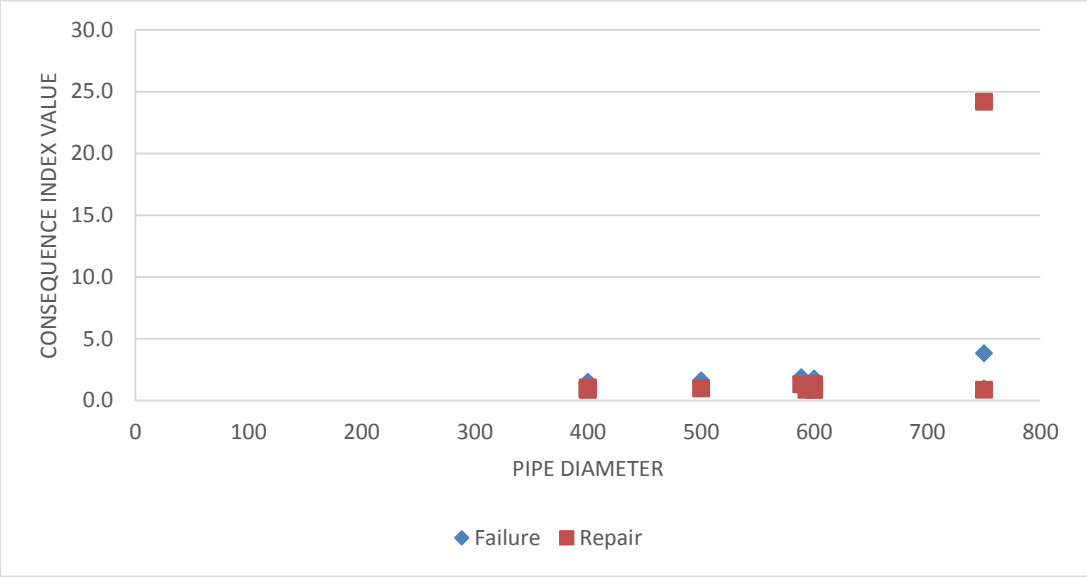

Figure 5-3: Pipe diameter plot of the correlation between consequence index values (during pipe failure and pipe repair) and pipe diameter of the failed pipe.

During the failure of a trunk water main, it can be observed that a slight increase in severity occurs with an increase in diameter. This occurs because a larger diameter pipe results in greater water loss from the system during a failure event. During pipe repair conditions, no clear trend is discerned. On average, a pipe repair entails a slightly less severe consequence than pipe failure. This is owing to the fact that the Kingston network is well looped and that this redundancy of flow path means that water service to users is largely preserved during pipe repair. This result is consistent with the consequence index values reported in Table 5-2.

Figure 5-4 shows water main failure and repair locations in the Kingston water distribution system and the percent of demand delivered with pressure head below minimum associated with each water main failure and repair. The figure gives a visual representation of the severity consequences associated with each geographic location of water main failure and repair.

Figure 5-4: Consequence maps depicting the location of each failure and the percentage of demand delivered below minimum pressure head for both pipe failure and pipe repair conditions under maximum hour demand.

The results in Figure 5-4 suggest that consequence severity is somewhat uniform between failure locations. Specifically, the results in Figure 5-4 show that when pipe fail in Kingston West and Kingston Central, generally 1-5% of demand is delivered at a pressure head below the minimum. When pipes fail in Kingston East, less than 1% of demand is delivered at a pressure head below the minimum. There are multiple factors that affect the severity of the consequences under pipe

repair conditions that do not have the same influence under pipe failure conditions. The proximity to tanks and reservoirs has a large effect on the severity, where pipes in close proximity to tanks and reservoirs, which convey water to the rest of the system have increased levels of consequence. For example pipe P3649 has the largest consequence during repair and is the closest pipe for the Tower Street tank. Alternatively, pipes that are looped with multiple alternative flow paths tend to have a low severity of consequence because water can still reach end users. Pipe P2167, located in Kingston Central, is close to the Kingston Central Water Purification plant however experiences low severity because is well looped. Lastly, pipes that are central to the rest of the system have more severe consequences because they can affect larger sections of the network. For example all of the pipe failures in Kington East result in low severity because they are not central to the system, reducing the ability for wide spread consequences. All trunk water main failures in Kingston East have low consequence severities because water main repairs in these locations are peripheral to the rest of the system and their effect tends to be localized.

5.4.2 Population Metric

The population metric was used to analyze the population affected by each failure in the City of Kingston water distribution network. The consequence parameter for this metric is the maximum number of people at each node that could experience low water pressure or interrupted service by a failure event. Population data and water distribution information were used to determine the population serviced at each node in the system. The consequence index equation was used to calculate the severity of each failure for both pipe failure and pipe repair conditions. The results are indicated in Table 5-3.

Table 5-3: Consequence index values for pipe failure and pipe repair conditions under maximum hour demand for the population metric.

		Network Section	Trunk Water Main Failure	Trunk Water Main Repair
Pipe ID	P29443	Central[1]	2.7[2]	2.8
	P30125	Central	2.4	2.2
	P30087	Central	2.4	2.0
	P7455	Central	2.4	1.9
	P29891	Central	2.0	1.9
	P11759	Central	2.2	1.9
	P3649	Central	1.9	27.9
	P21167	Central	2.0	1.8
	P109	West	2.2	2.0
	P11083	West	2.5	2.2
	P15609	West	2.2	1.9
	P12197	West	2.0	1.9
	P6009	West	2.0	1.9
	P15853	East	1.9	1.9
	P13381	East	1.9	1.9
	P5257	East	1.9	1.9
	P18987	East	1.9	1.8
	P20683	East	1.9	1.9
	P22817	East	1.9	1.9

[1] Consequence index values reported as percentages by multiplying by 100 for ease of interpretation.
[2] Population metric consequence index values under pipe failure and pipe repair conditions.

5.4.2.1 Impact of Population Distribution

The City of Kingston's population was assumed to be distributed uniformly across all the nodes of the distribution network. This was done because distribution of households and users per node was not available. The assumption of uniform population distribution is what explains the small variation in consequence index values across the trunk water main failures indicated in Table 5-3.

5.4.2.2 Impact of Main Failure and Repair

Trunk water main failure produced more severe consequences than pipe repair in the water mains examined. System looping and the availability of alternate flow paths means that water loss during pipe failure leads to more dramatic drops in pressure than during pipe repair in the Kingston distribution network. The two exceptions to this are pipes P29443 and P3649, which produced more severe consequences during pipe repair. The reason for a slightly larger consequence index value for pipe P29443 is discussed above. Pipe P3649 produced a significantly larger consequence during pipe repair than during failure given that pipe P3649 connects Tower Street tank to the rest of the Kingston Central pressure zone. During failure, pipe P3649 is still able to convey water to Kingston Central which produces less severe consequences. The repair of pipe P3649 means that Tower Street tank---an important source of water to Kingston Central---is disconnected from the Kinston Central pressure zone, and leads to more dramatic drops in pressure head.

5.4.2.3 Impact of Failure Location

The water main failure location has a large impact on the population consequence index values. The results in Table 5-3 suggest that water main failures that occur in the same area of the system tend to produce consequences of similar severity. Water main failures in Kingston East produced the least severe consequences in large part because this part of the system is on the periphery of the rest of the network and only serves a small portion of the Kingston population. Water main failures in Kingston West have more severe consequences than failures in Kingston East, but the severity of consequences varied depending on the location within the Kingston West area. Water main failures in Kingston Central produced the most severe consequences. For example, the failure

of pipe P29443 produced a severity index of 2.7 in large part because this trunk main conveys flows from the King Street WTP to the Kingston Central pressure zone.

The repair of pipe P3649 produced a severity index of 27.9 largely because pipe P3649 connects the Tower Street tank to the rest of the Kingston Central pressure zone and under repair conditions, water cannot be conveyed to Kingston Central.

Figures 5-5 and 5-6 show CDF plots of the number of people that experience inconvenience from pipe failure and pipe repair, respectively. The plots display the severity term multiplied by the population consequence parameter during maximum hour demand.

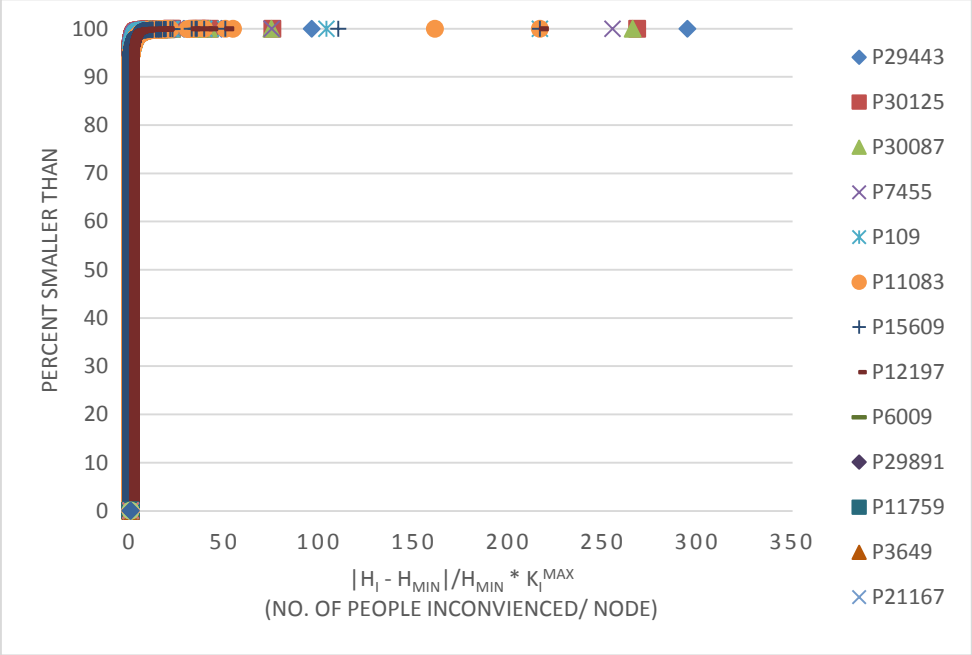

Figure 5-5: CDF plot of number of people inconvenienced at nodes in the Kingston system at maximum hour demand for the 19 water main locations under pipe failure conditions.

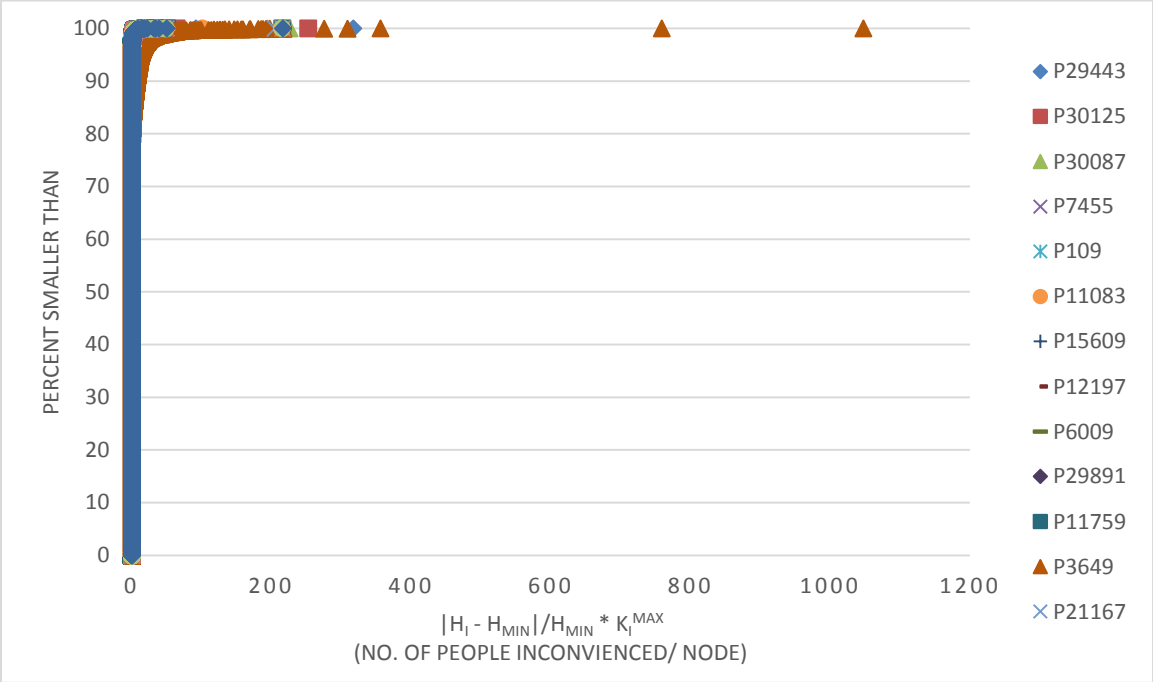

Figure 5-6: CDF plot of number of people inconvenienced at nodes in the Kingston system at maximum hour demand for the 19 water main locations under pipe repair conditions.

By incorporating both the change in pressure head caused by the trunk water main failure and population information, the number of people inconvenienced at each node during a water main failure event can be evaluated. Figure 5-5 shows that during pipe failure, less than 5% of the nodes convey water at an unacceptable pressure. Pipe failure conditions for pipe P29443 causes the largest consequence at a single node where 300 people experience loss of water pressure.

A comparison of Figure 5-5 and 5-6 suggests that pipe repair causes fewer nodes to experience low pressures than pipe failure. In general, during pipe repair, only about 2% of the system experiences a pressure drop below the minimum acceptable level. Pipe P3649 is the only pipe that does not follow this trend; when it fails, over 10% of the nodes experience low pressures with a

disruption to users. This causes the largest consequence at a single node for all hydraulic conditions where over 1000 people experience low pressures.

5.4.3 Land Use Metric

The land use metric categorizes each node in the system depending on the land use that it serves. The City of Kingston has land use types that include: commercial, government and institutional, open area, parks and recreation, residential, and resource and industrial. The layout of the social data layer is shown in Figure 5-7.

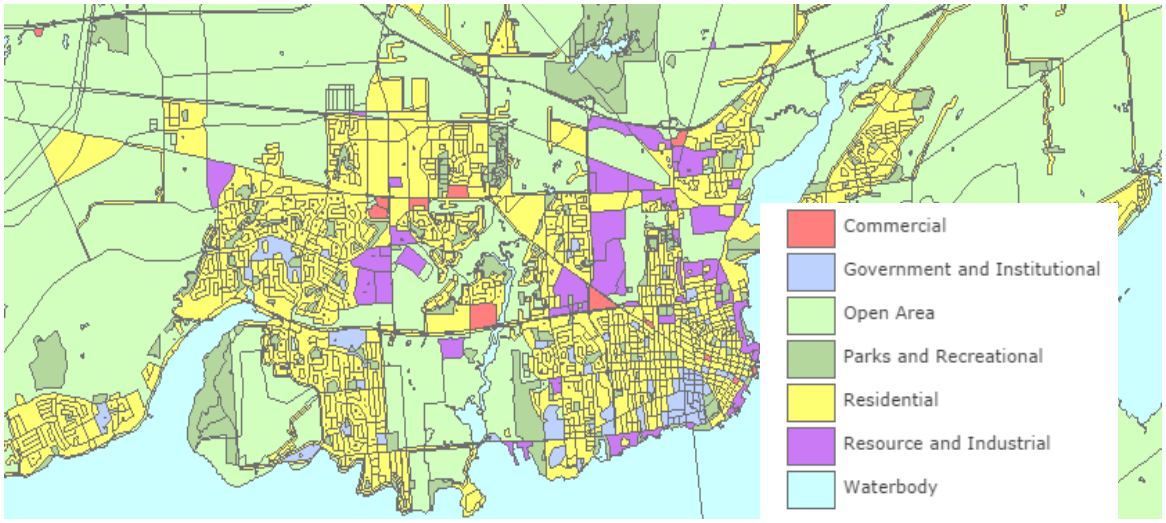

Figure 5-7: Land use distribution for the City of Kingston (source: DMTI Spatial Inc. 2013).

Since the consequence index equation was not used in the analysis, consequence parameter values were not generated. Instead the percentage of nodes that experience unacceptable pressures during peak demand for pipe failure and pipe repair conditions for each land use are reported in Table 5-4 and 5-5.

Table 5-4: Percentage of nodes that experience consequence for different land uses under maximum hour demand during pipe failure conditions.

		Residential	Parks and Recreation	Open Area	Resource and Industrial	Commercial	Government and Institutional
	P29443	12[1]	7	12	13	45	5
	P30125	10	7	12	12	35	5
	P30087	10	7	12	12	34	5
	P7455	10	7	12	12	36	5
	P109	11	8	12	13	36	5
	P11083	13	9	13	17	44	6
	P15609	12	8	12	13	39	5
	P12197	9	7	12	9	22	5
	P6009	9	7	12	9	22	5
Pipe ID	P29891	9	7	12	10	24	5
	P11759	10	7	12	11	31	5
	P3649	9	7	12	9	22	5
	P21167	9	7	12	10	25	5
	P15853	8	7	12	9	20	5
	P13381	12	7	12	13	45	5
	P5257	8	7	12	9	20	5
	P18987	8	7	12	9	20	5
	P20683	8	7	12	9	20	5
	P22817	8	7	12	9	20	5

[1] Percentage of nodes for each land use that experiences a pressure head below 27.5 m.

Table 5-5: Percentage of nodes that experience consequence for different land uses under maximum hour demand during pipe repair conditions.

		Residential	Parks and Recreation	Open Area	Resource and Industrial	Commercial	Government and Institutional
Pipe ID	P29443	11[1]	8	12	13	39	5
	P30125	9	7	12	10	27	5
	P30087	9	7	12	10	25	5
	P7455	9	7	12	10	25	5
	P109	9	7	12	9	23	5
	P11083	11	8	12	11	34	5
	P15609	8	0	12	9	22	3
	P12197	8	6	12	9	22	4
	P6009	8	6	1	9	22	4
	P29891	8	7	12	9	20	5
	P11759	8	7	12	9	20	5
	P3649	43	39	27	46	61	62
	P21167	8	6	12	8	19	5
	P15853	8	6	12	9	20	5
	P13381	8	6	12	8	20	5
	P5257	8	6	12	9	20	5
	P18987	8	6	12	8	20	5
	P20683	8	6	12	8	20	5
	P22817	8	7	12	9	20	5

[1] Percentage of nodes for each land use that experiences a pressure head below 27.5 m.

5.4.3.1 Impact of Failure Location

The location of the failure event causes variations in the percentage of nodes of each land use that are experience consequences resulting from a pressure head below 27.5 m. Failures in the same general area result in similar percentages of nodes affected for each land use. Failed pipes located near important network features results in a larger percentage of nodes experiencing reduced water pressure. Pipes P11083 and P29443 are both important pipes that connect Kingston West and

Kingston Central respectively to the Kingston West WTP (P11083) and Kingston Central WTP (P29443) and their failures result in severe consequences. These failures increased the percentage of nodes of each land use that are negatively affected as much as 20%. Other pipe failures in proximity to the water treatment plants also produce more severe consequences. For example, pipe P109 located near pipe P11083 and pipes P11759 and P30125 located near P29443 produced an increase in the consequence severity index value as high as 10% when compared to other failure locations.

Repair of pipe P3649 produced the most severe consequence, where over 60% of nodes with government and institutional land use designations experiencing a pressure head below the minimum acceptable level. This is owing to the fact that the repair of pipe P3649 hydraulically disconnects the Tower Street tank from the Kingston Central zone and causes a dramatic drop in pressures in Kingston Central.

5.4.3.2 Impact of Main Failure and Repair

Water main failure generates more severe consequences at nodes with land use designation than does water main repair. The location of the failure event has a large impact on the consequences, where the failure of pipes that connect reservoirs and tanks to the rest of the system tend to generate more severe consequences. This occurs because water loss causes reduced network pressures and reduces the conveyance of water from reservoirs and tanks to the rest of the system. Pipe P11083 shows this with all land uses having a greater number of nodes affected during pipe failure when compared to pipe repair. Commercial land use shows the largest increase in severity with 10 more nodes experiencing low pressure during pipe failure.

Water main repair tends to produce less severe consequences and a lower number of nodes that experience unacceptable pressure head in large part because the Kingston network is well looped and has a high level of redundancy in flow paths. This looping and redundancy means that water can reach the end user even when a major trunk main is under repair and is unable to convey flow, P3649 is the exception to this general trend. When pipe P3649 is under repair, 27-62% of nodes of all land use designations are experiencing a pressure head below 27.5 m, while P3649 is in failure, only 5-22% of nodes of all land use designations are experiencing low pressure. This in large part because the repair of pipe P3649 disconnects Tower Street tank from Kingston Central and causes dramatic drops in pressure.

5.4.3.3 Impact of Land Use Distribution

The City of Kingston has a mix of different land uses throughout the entire network (Figure 5-7). The main land uses in the system are residential, industrial, commercial and institutional with open and park land use mostly on the periphery of the network. Commercial land use is most affected by water main failure since most commercial areas are located in Kingston Central along major arterial roads that carry large diameter water mains. Parks and recreation, open area and government and institutional land uses show little fluctuation in the number of nodes affected for different failure locations. The number of nodes for each of these land uses is low with government and institutional land use having the least severe consequences (average of 5% of nodes with government and institutional land use designation affected). This occurs because these land uses are mostly located along the periphery of the system with only a small number of government and institutional nodes close to all of the failure events.

5.5 Consequence Modelling under Fire Conditions

A fire scenario simulation was completed for each of the 19 trunk water main under analysis. Three fire locations (J10860, J17052 and J13780) were chosen based on their location and potential level of hydraulic consequence to the system. The analysis of different fire locations throughout the entire system is required to obtain an understanding of the locations that have a maximum effect on the systems hydraulics. For this study, one location was selected in each area of the water network (Kingston West, Kingston Central, and Kingston East). Each fire was simulated individually by adding a fire flow of 64L/s, in accordance with Ontario Ministry of the Environment Guidelines (2008), to the existing demand at the node, one fire event at a time. The fires were assumed to occur during the period of maximum day demand. Therefore, a maximum day factor of 1.65 was applied to the systems demand (Ministry of the Environment 2008) during the fire events. The consequence index equation (3-1) was used to calculate the severity of each water main failure and fire combination. The minimum acceptable pressure during fire flow was taken as 14 m of pressure head (Ministry of the Environment 2008).

5.5.1 Demand Metric

The demand metric was used to characterize the effect on the system hydraulics and the network's ability to meet user demands that occur when a fire and water main failure coincide in time. The consequence parameter for this metric is 1 because demand is already taken into account in the scaling term of the equation. The consequence index values for each fire and failure combination are presented in Table 5-6 for both pipe failure and pipe repair conditions. The consequence index values have been converted to percentage values for ease of interpretation.

Table 5-6: Consequence index values for both pipe failure and pipe repair during fire flow for 3 fire locations.

		Network Section	Trunk Water Main Failure			Trunk Water Main Repair		
			Kingston West[1]	Kingston Central[2]	Kingston East[3]	Kingston West	Kingston Central	Kingston East
Pipe ID	P29443	Central[4]	0[5,6]	0	0	0	0	0
	P30125	Central	0	0	0	0	0	0
	P30087	Central	0	0	0	0	0	0
	P7455	Central	0	0	0	0	0	0
	P29891	Central	0	0	0	0	0	0
	P11759	Central	0	0	0	0	0	0
	P3649	Central	0	0	0	0.47	4.06	0.58
	P21167	Central	0	0	0	0	0	0
	P109	West	0.01	0	0	0	0	0
	P11083	West	0.11	0	0	0.01	0	0
	P15609	West	0.01	0	0	0	0	0
	P12197	West	0	0	0	0	0	0
	P6009	West	0	0	0	0	0	0
	P15853	East	0	0	0	0	0	0
	P13381	East	0	0	0	0	0	0
	P5257	East	0	0	0	0	0	0
	P18987	East	0	0	0	0	0	0
	P20683	East	0	0	0	0	0	0
	P22817	East	0	0	0	0	0	0

[1] West end fire located at J10860.
[2] Central area fire located at J17052.
[3] East end fire located at J13780
[4] Indicates in which section of the Kingston network the failed pipe is located.
[5] Consequence index values reported as percentages by multiplying by 100 for ease of interpretation.
[6] Consequences calculated with fire flow during maximum day demand.

5.5.1.1 Impact of Failure Location

The consequence index values in Table 5-6 show that no consequences result from a majority of the simulated failure and fire combinations. The only pipe failures conditions that have some level of consequence are those of water mains P109, P11083, P15609 that connect the southern part of Kingston West to the rest of the Kingston West system. For all of these failures the consequence

is low, with less than 0.11% of demand that delivered at a pressure head below the minimum of 14 m in the worst case scenario. The reason why there is no or low consequence observed is because the minimum acceptable pressure during a fire event is lower than in peak or normal conditions. Also this shows that the Kingston network has adequate hydraulic capacity (function of sizing of mains and their looped layout) for fire protection even during a trunk water main failure. Contradictory, pipe P3649 affects up to 4% of the system during repair condition showing that adequate hydraulic capacity could be improved on.

Pipe P11083 is the water main with the highest severity consequence (0.11%) during pipe failure since it connects the Kingston West WTP to the rest of the Kingston West system. Pipes P109 and P15609 are also in integral locations in the system, delivering water from the source reservoir to the rest of the system. However, there are loops in the system which reduce the consequences from the failure of these two pipes by allowing water to continue to be conveyed to the rest of the system. During repair conditions, Pipe P3649 produces the most severe consequences (0.47-4.06%) since it is the only pipe that connects the Tower Street tank to the rest of Kingston Central.

5.5.1.2 Impact of Fire Location

Generally, the proximity of the fire location to the water main failure had an impact on the consequence severity experienced in the network. Specifically, when pipes P109, P11083 and P15609 located in Kingston West fail, the network experiences some degree of consequence severity when the fire is also located in Kingston West. When these same pipes are in failure and the fire is located in Kingston Central and Kingston East, the network experiences no consequences. Similarly, the network experiences the most severe consequences when pipe P3649 (located in Kingston Central) is in failure and a fire erupts in Kingston Central. It is noted that the

system does experience some degree of consequence severity when pipe P3649 is in failure and when a fire erupts in the adjacent areas of Kingston West and Kingston East. The results suggest that drops in pressure head are most dramatic when the failed water main and fire are in close proximity to each other.

5.5.1.3 Impact of Main Failure and Repair

The location of the fire has an impact on the consequences when in close proximity to a pipe. However, it had no effect when comparing the magnitude of the consequences experienced between failure and repair conditions. Pipe failure conditions created more severe consequence for pipes P109, P11083 and P15609. These are the same results seen during the non-fire flow scenarios. The increase consequence during pipe failure conditions is caused by the water lost from the system during the burst event. Pipe P3649 shows significantly higher consequence values during pipe repair because it is a critical pipe that connects the Tower Street tank to the Kingston Central pressure zone. This is, again, the same results seen during non-fire conditions in the system, when pipe repair conditions for this also caused severe consequences.

5.5.2 Population Metric

The population metric was used to analyze the number of people that receive water service at a pressure head below the minimum by the combination of a trunk water main failure and fire event. The consequence parameter for the population represents the maximum number of people at each node inconvenienced by hydraulic changes in the system. For this metric, only repair conditions of trunk water main P3649 (located in Kingston Central) was examined as it was the only scenario that created significant consequences. The consequence index values for this water main failure

are indicated in Table 5-7. Results from minimum and maximum hour demand and fire flow conditions are included to allow for a comparison of the different scenarios.

Table 5-7: Consequence index values for pipe repair of trunk water main P3649 under maximum hour demand, minimum hour demand and fire flow conditions for the population metric.

Maximum Hour Demand	Minimum Hour Demand	Fire Flow + Maximum Day Demand		
		West[2] End Fire	Central Area Fire	East End Fire
27.9[1]	0.1	0.5	3.6	0.7

[1] Population metric consequence index values during pipe repair of trunk water main P3649.
[2]These loading conditions correspond to maximum day demand and fire at a particular location.

Consequence index values are presented for the pipe repair of trunk water main P3649 under maximum and minimum hour demand and during all 3 fire flow scenarios. Maximum hour demand shows the most severe consequences, more severe than any of the failure and fire combinations, with a consequence index value of 27.9. This condition produces the most severe consequence because maximum hour demand is the highest demand in the system (of all 5 scenarios) and the minimum acceptable pressure of 27.5 m under maximum hour demand conditions is a difficult standard to meet under those conditions. Minimum hour demand produces the smallest consequences since the system is under the least amount of hydraulic stress during this time, in the absence of fire and low demands. The different fire flow scenarios produce a range of consequence index values, showing that the percentage of the population inconvenienced is influenced by the fire location. A fire event in the central section results in the most severe consequence, with a consequence index value of 3.6. This is over 5 times greater than the consequence index value that results when there is a fire in Kingston West and Kingston East. This increase in consequence

severity is owing to the fact that pipe P3649 is located in Kingston Central in close proximity to the fire location in Kingston Central.

To better demonstrate how the population is inconvenienced when water main P3649 fails, Figure 5-8 indicates the CDF plot of consequence index values under different demand plus fire loading conditions.

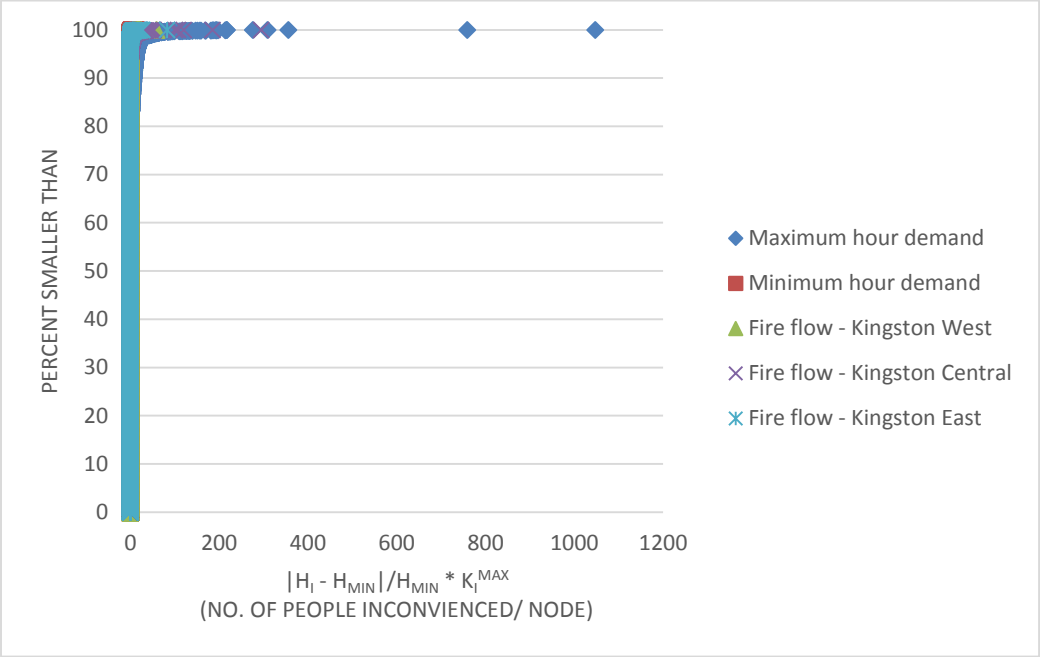

Figure 5-8: CDF plot of severity term of the consequence index for the population metric for pipe repair of trunk water main P3649 during maximum hour demand, minimum hour demand and fire flow conditions.

This CDF plot shows the number of people inconvenienced at each node due to low water pressure. Each point on the graph represents a system node and the number of people affected at each node is represented by the x-axis. Maximum hour demand affects the largest percentage of the population with over 10% of the systems nodes experiencing reduced pressure head causing a total

of 30, 031 people to experience consequences. Under high demand conditions the system experiences lowered system water pressures resulting in increased severity. Minimum hour demand affects very few nodes, with only 184 people affected in total because with a lower demand the system water pressures are higher than during regular demand conditions resulting in reduced consequences. During combined failure and fire flow conditions the fire located in Kingston Central has the largest consequence, with up to 300 people affected at a single node and 3435 people in total experiencing consequences. The reason why increased consequence is experienced for this fire location is because it is located in close proximity to the failure location which is also located in Kingston Central. The fires located in Kingston West and Kingston East produces slightly lower consequences, affecting 590 and 732 people, respectively. These fires are located away from the failure location causing smaller pressure drops to be experienced by the network. The scale of failure and fire events is made clear by examining the total number of people affected. In most cases, only a small percentage of the system experiences changes in water pressure however this can still cause a significant number of people can be affected.

5.5.3 Land Use Metric

The consequence index equation was not used to calculate the land use metric because consequence parameter values were not available. The percentage of nodes with unacceptable pressure for each land use are presented in Table 5-8 for maximum hour demand, minimum hour demand and fire flow conditions for the repair of pipe P3649.

Table 5-8: Severity for different land uses under maximum hour demand, minimum hour demand and fire flow conditions for pipe P3649 during pipe repair conditions.

	Maximum Hour Demand	Minimum Hour Demand	Fire Flow + Maximum Day Demand		
			West[1] End Fire	Central Area Fire	East End Fire
Residential	43[2]	3	4[3]	10	4
Parks and Recreation	39	2	4	20	4
Open Area	27	8	4	7	4
Resource and Industrial	46	3	2	3	2
Commercial	61	6	22	76	23
Government and Institutional	62	1	1	3	1

[1] These loading conditions correspond to maximum day demand and fire at a particular location.
[2] Percentage of nodes for each land use that experiences a pressure head below 27.5 m.
[3] Percentage of nodes for each land use that experiences a pressure head below 14 m.

The fire location influence on the number of nodes for each land use that experience consequence severity. When a fire erupts in Kingston Central the consequences that result vary from those results depicting non-fire scenarios. During maximum hour demand the largest consequence was experienced for government and institutional land use, with 62% of these nodes affected. During a combination of repair of pipe P3649 and fire flow in Kingston Central, the commercial land use nodes experience the most severe consequences with 76% of all commercial nodes having a pressure head below 14 m. Parks and recreation was the next highest affected, with 20% of the parks and recreation nodes that experience water pressure below the acceptable level. The rest of the land uses had significantly lower consequences, with 10% or less of each being affected. The

reason for the varying consequences between different scenarios occurs due to the location of the failure/ fire. Since the different land uses are not evenly distributed throughout the system the severity is affected based on the types of land use in close proximity to the failure/ fire event. Fires in Kingston West and Kingston East only caused significant pressure drops at nodes with a commercial designation with 22-23% of the commercial nodes experiencing consequences, respectively.

5.6 Conclusion

The City of Kingston water distribution network case study provided an understanding of how a larger scale water distribution network is affected by trunk water main failure during peak demand and fire flow conditions. Nineteen trunk water mains were analyzed under pipe failure and pipe repair conditions. The results showed that the location of the failed pipe had an impact on the consequences, where an increased severity occurred for trunk water mains located in close proximity to important network feature. Second, pipe failure conditions resulted in increased consequence when compared to pipe repair conditions. This is because the system is well looped and, therefore the water lost during pipe failure causes increased consequence over repair conditions where water is not conveyed through the pipe. A combination of a pipe failure and a fire event resulted in less severe consequences then only pipe failure because a lower required pressure of 14 m was used in the analysis. This shows the system has an adequate hydraulic capacity for fire flow. An increased consequence during fire flow occurred when the pipe failure and fire location were in close proximity to each other. Failure during maximum hour demand produced the largest consequences since the system experiences its largest hydraulic stresses during this time. The information obtained from the consequence model can provide the City of Kingston with more insight into the vulnerability of their system.

5.7 Recommendations

The City of Kingston and Utilities Kingston can obtain valuable information from this case study to assist with emergency planning and rehabilitation and replacement planning. As the City of Kingston network further approaches end of service life the probability of pipe failure continues to increase. The recommendations from this analysis are:

1. All pipes located near important network features (tanks, source reservoirs, etc.) should be well looped to provide alternative flow routes in case of a failure event.

2. An additional pipe should be added to connect the Tower St. tank to reduce the trunk water main failure severity of pipe P3649.

3. If a failure occurs the time of water loss from the system should be reduced as much as possible as higher consequences were evident during pipe failure conditions.

4. An analysis should be completed looking at all 3299 trunk water mains. This will provide a complete understanding of which pipes should be of higher interest.

5.8 References

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Chapter 6

Summary and Conclusions

6.1 Introduction

Due to aging water distribution networks the concern for trunk water main failure has become an increasingly prominent issue. Currently, municipalities possess limited knowledge on trunk water failure events and the potential consequences. Trunk water main failures pose a risk to users as they can often result in significant hydraulic, economic, and social consequences. Even larger consequences can occur when a fire event in the water distribution system coincides with a trunk water main failure event. Consequence modelling can provide municipalities with information regarding trunk water main failures, and thus help prevent high consequence events.

Chapter 2 provided an overview of previous work that has been completed in the field of consequence modelling of water mains. A focus was placed on models that examine consequences associated with large diameter water main failures. Research in this field is sparse as it is now an emerging area of concern. Several types of models were reviewed, including single consequence models, multi-consequence models, and risk analysis which includes both probability of failure and the associated consequences. The literature review also discussed research needs in the area of consequence modelling of trunk water main failures.

Chapter 3 provided an overview of the methodology used in the consequence model that was developed for this thesis. The model determined the severity of different trunk water main failures in network under both peak demand and fire flow conditions. A series of metrics were developed to characterize a range of consequences resulting from the hydraulic changes during a failure event.

The consequence index equation was presented to determine the severity of the consequences across the entire water distribution network for each metric. EPANET2 was used to determine demand and pressure information used in the consequence index equation. A fire consequence index equation was also presented to calculate the economic losses that can occur at the location of the fire due to insufficient water pressure required for fire flow.

Chapter 4 presented a case study of the D-Town water distribution network. The methodology presented in chapter 3 was used to analyze 8 trunk water main failures distributed throughout the system. The location of the failure was found to have the largest effect on the overall consequences. Pipes connecting the source reservoir to the rest of the system resulted in the largest consequences, with up to 99% of the system being affected. Five fire locations were examined and it was found that the location of the fire significantly affected the consequences of the trunk water main failure events that had lower consequences when no fire was considered. The consequence severity varied between different fire locations causing up to 29% more of the network demand to be affected at the most severe fire location. An overall ranking was determined for each of the trunk water mains considered in the case study to denote each pipe's relative severity of consequence compared to the other pipes examined in the study

Chapter 5 presented a case study of the City of Kingston water distribution network. A condensed analysis was completed due to the lack of available data necessary to complete a full analysis of all the metrics in the model. The case study focused on the demand, population and land use metrics under peak demand and fire flow conditions for 9 trunk water mains of interest to Utilities Kingston. It was found that pipes located near important network features (source reservoirs and tanks) produced the largest consequences, affecting up to 24% of the nodes in the network. Three

fire locations were examined to understand how a failure and fire event coinciding affects the network hydraulics. It was found that the Kingston network has adequate hydraulic capacity for fire flow since no consequences were experienced in most cases, with the most severe case affecting less than 5% of the system. This information can be used by the City of Kingston to develop a better understanding of the system hydraulics when additional stress is added to the network.

From the two case studies four preliminary conclusions were made regarding the relationships between system characteristics and the resulting severity of the consequences for the analysis in this thesis. First, the location of the failed trunk water main has a large impact on the resulting consequences for the case studies examined. When pipe failures occur near important network features (source reservoir, tanks, pumping stations) a larger percentage of system nodes experience reduced water pressure and, therefore, an increased consequence. Second, the Kingston network, a looped network, experienced larger consequences during pipe failure when compared to pipe repair which is the opposite of the results seen for the D-Town networks with fewer loops, which experience larger consequences during pipe repair. During pipe repair, water is redistributed in new directions, which allows demands to be met. However, during pipe failure, water is being lost from the system which results in larger drops in pressure head and higher consequences. Third, when modelling the combination of fire flow and a failure event for both networks, an increased consequence occurs when the fire and failure locations are in close proximity to one another. Also, during a fire event, if the system has adequate hydraulic capacity for fire flow the consequences are greatly reduced when compared to systems that are not designed to properly operate under fire flow conditions. Lastly, for both case studies when trunk water main failures occurred during times

of high demand, more severe consequences occurred because of the combined stresses from high demand and water main failure causing reduced pressure and flow.

6.2 Research Contributions

The research completed for this thesis has furthered the field of trunk water main failure consequence modelling in 3 major ways. The first major contribution is the development of a new consequences model that focuses on the hydraulic consequences that result from a trunk water main failure event. The model uses EPANET2 and developed metrics to produce a ranking of trunk water main of interest in a network. Included is the consideration of fire event coinciding with a trunk water main failure and the associated consequences. This analysis can provide utilities with valuable information when developing rehabilitation and replacement plans.

The second major contribution is the application of the consequence model to two large scale water distribution systems. These applications of the model are important to demonstrate the effectiveness of the consequence model. These studies also provided links between pipe/network properties and consequence severity. Different results were observed between the two networks because of the different hydraulic capacities and system layouts.

The third major contribution was providing beneficial information to the City of Kingston on trunk water main failures in there system. By completing an abridged analysis, preliminary results were obtained for both peak demand and fire flow conditions. The relationships between pipe/network properties and consequence severity can be used to assist the City of Kingston in their emergency planning and rehabilitation/ replacement planning.

6.3 Future Research

The new consequence model developed has provided insight into the severity of trunk water main failures. Further work can be completed to allow for more accurate results to be determined and to provide additional information on pipe failure consequences. This model focused on times of maximum and minimum demands however additional demands should be analyzed. Individual diurnal patterns that highlight weekday, weekend and seasonal flows should be modelled separately. This will provide more information on when increased consequence occurs not just during a specific diurnal pattern but over longer time periods with varying hydraulic conditions. Each pipe failure was modeled as a snapshot which does not provide information into the consequences occurring due to varying times of failure and repair. Information on average time of pipe failures and pipe repair conditions should be obtained and incorporate into model to more accurately characterize consequence. For the two case studies completed, a select number of pipes were chosen to reduce time of analysis. Further work could be completed to decrease the computational demand of the model to allow for all trunk water mains in a system to be analyzed. This would allow for more robust knowledge to be obtained resulting in more informed planning by municipalities. Studying two case studies allowed for a preliminary understanding of how trunk water mains affect different systems. More networks should be tested to allow conclusions to be drawn on how these failure affect system in general terms. These test networks should include different levels of looping with a different number of major components in the network to understand if trends exist throughout all networks.

Appendix A

As added reference for future work with the City of Kingston water distribution network below are the changes made to the water distribution model.

1. The UJAMES1 pump curve was changed to prevent exceeds maximum flow errors. The original pump curve is shown in Figure 1. The changed pump curve is show in Figure 2.

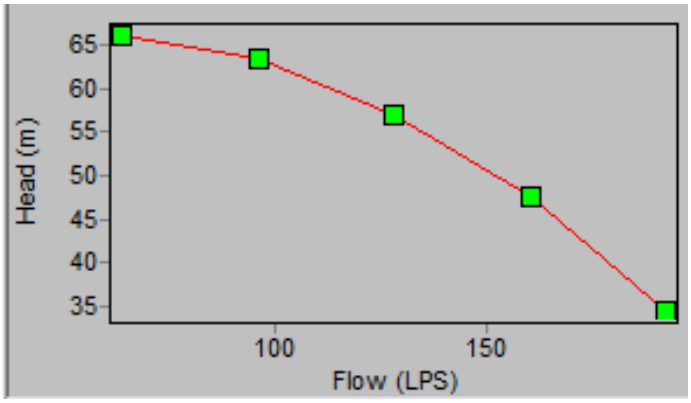

Figure A-6-1: Original pump curve for the UJAMES 1 pump.

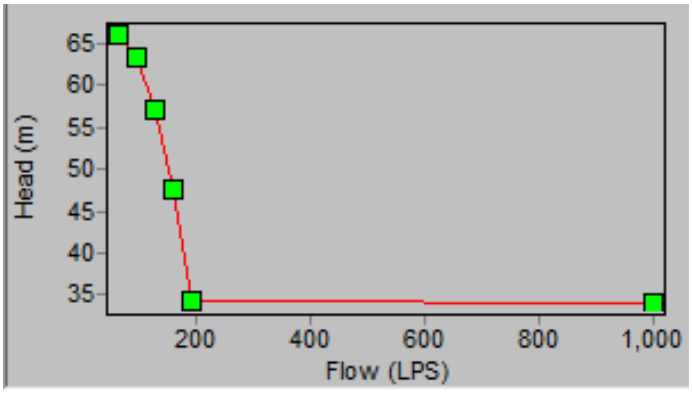

Figure A-6-2: The changed pump curve for the UJAMES 1 pump used in the analysis.

2. The status of pipe P30507 was changed from open to close. This was done to properly model the disconnection of Kingston West from the rest of the network.

3. The 24 hour diurnal pattern was removed to allow for steady state hydraulic analysis to be completed during maximum hour demand minimum hour demand and maximum day demand plus fire flow.