8-2016

Empirical Analysis of Large Diameter Water Main Break Consequences

Sreeganesh Reddy Yerri

Clemson University, syerri@g.clemson.edu

Follow this and additional works at: https://tigerprints.clemson.edu/all_theses

---

Recommended Citation

Yerri, Sreeganesh Reddy, "Empirical Analysis of Large Diameter Water Main Break Consequences" (2016). *All Theses*. 2427.
https://tigerprints.clemson.edu/all_theses/2427

This Thesis is brought to you for free and open access by the Theses at TigerPrints. It has been accepted for inclusion in All Theses by an authorized administrator of TigerPrints. For more information, please contact kokeefe@clemson.edu.

EMPIRICAL ANALYSIS OF LARGE DIAMETER WATER MAIN BREAK CONSEQUENCES

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Civil Engineering

---

by
Sreeganesh Reddy Yerri
August 2016

Accepted by:
Dr. Kalyan R. Piratla, Committee Chair
Dr. Leidy Klotz, Co-Chair
Dr. Kapil Chalil Madathil

ABSTRACT

The recent ASCE report card gave a near failing “D” grade to drinking water infrastructure in the U.S. and reported that about 240,000 water main breaks occur annually. The economic, environmental and societal consequences of some of these water main breaks have been hard to comprehend in the context of risk assessment and rehabilitation planning. In an attempt to understand the various impacts of such failures and subsequently estimate the overall impact cost, this study synthesized the reported consequences of 20 large diameter water main breaks in the U.S., most of which have occurred in the recent past, and subsequently estimated the overall cost of the impacts in dollar amount. Furthermore, this study identified the factors that aggravated the overall impact cost of water main failures and also compared the direct costs with the indirect costs. Direct costs are paid by the utility in the form of emergency repair expenses, whereas the indirect costs are left to be borne by the society. Several factors were found to influence the overall impact cost of water main failures. It was also found that the share of indirect costs is more than that of direct costs on an average for the 20 case studies. Knowledge of true failure costs will better prepare water utilities in appropriately prioritizing the deteriorating assets for repair. Documenting the impact costs of more number of water main failures will serve as a database that water utilities and other agencies can use for capital improvement planning.

DEDICATION

I dedicate this thesis to my beloved parents

ACKNOWLEDGEMENTS

Firstly, I would like to formally acknowledge the support, guidance, and direction that I have received from my advisor, Dr. Kalyan R. Piratla. His insight and consultation has guided me through the challenges in this project. I also extend my thanks to Dr. Leidy Klotz and Dr. Kapil Chalil Madathil for accepting to be on my thesis committee and for their support.

I would like to thank my family, and in particular my parents Mr. Mallikarjuna Reddy Yerri and Mrs. Suneetha Yerri without the support and encouragement given by them this work would not have been possible. I would like to acknowledge my good friend Ms. Phalguni Yamuna Moganti for her unconditional support and motivation which helped in achieving my goal. I would also like to thank my friends who supported me throughout my masters.

TABLE OF CONTENTS

	Page
TITLE PAGE	i
ABSTRACT	ii
DEDICATION	iii
ACKNOWLEDGEMENTS	iv
LIST OF TABLES	vi
LIST OF FIGURES	viii
CHAPTER 1: INTRODUCTION.....	1
1.1 Study Objective and Methodology	4
1.2 Organization of this Thesis.....	5
CHAPTER 2: STUDY METHODOLOGY	6
2.1 Previous Research	6
2.2 Consequences of Water Main Break (COWAMB) Model.....	9
CHAPTER 3: CASE STUDIES	23
CHAPTER 4: ANALYSIS	77
CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS.....	82
REFERENCES.....	94

LIST OF TABLES

	Page
Table 2.1: Suggested data ranges for property damage data inputs.....	22
Table 3.1: Deduced data inputs with influence factors.....	24
Table 3.2: Cost of Various Failure Impacts in Case Study #1	26
Table 3.3: Cost of Various Failure Impacts in Case Study #2.....	29
Table 3.4: Cost of Various Failure Impacts in Case Study #3.....	32
Table 3.5: Cost of Various Failure Impacts in Case Study #4.....	35
Table 3.6: Cost of Various Failure Impacts in Case Study #5.....	38
Table 3.7: Cost of Various Failure Impacts in Case Study #6.....	41
Table 3.8: Cost of Various Failure Impacts in Case Study #7.....	43
Table 3.9: Cost of Various Failure Impacts in Case Study #8.....	46
Table 3.10: Cost of Various Failure Impacts in Case Study #9.....	48
Table 3.11: Cost of Various Failure Impacts in Case Study #10.....	51
Table 3.12: Cost of Various Failure Impacts in Case Study #11	53
Table 3.13: Cost of Various Failure Impacts in Case Study #12.....	56
Table 3.14: Cost of Various Failure Impacts in Case Study #13.....	58
Table 3.15: Cost of Various Failure Impacts in Case Study #14.....	61
Table 3.16: Cost of Various Failure Impacts in Case Study #15.....	63
Table 3.17: Cost of Various Failure Impacts in Case Study #16.....	66
Table 3.18: Cost of Various Failure Impacts in Case Study #17.....	68
Table 3.19: Cost of Various Failure Impacts in Case Study #18.....	71

List of Tables (Continued)	Page
Table 3.20: Cost of Various Failure Impacts in Case Study #19	73
Table 3.21: Cost of Various Failure Impacts in Case Study #20	75
Table 4.1: Impact related data for water main break cases	78

LIST OF FIGURES

	Page
Figure 3.1: Water main break location along with effected routes for case study #1.....	25
Figure 3.2: Percentage distribution of overall impact costs in case study #1	27
Figure 3.3: Water main break location along with effected routes for case study #2.....	28
Figure 3.4: Percentage distribution of overall impact costs in case study #2	30
Figure 3.5: Water main break location along with effected routes for case study #3.....	31
Figure 3.6: Percentage distribution of overall impact costs in case study #3	33
Figure 3.7: Water main break location along with effected routes for case study #4.....	34
Figure 3.8: Percentage distribution of overall impact costs in case study #4	35
Figure 3.9: Water main break location along with effected routes for case study #5.....	37
Figure 3.10: Percentage distribution of overall impact costs in case study #5	38
Figure 3.11: Water main break location along with effected routes for case study #6.....	40
Figure 3.12: Percentage distribution of overall impact costs in case study #6	41
Figure 3.13: Water main break location along with effected routes for case study #7.....	42
Figure 3.14: Percentage distribution of overall impact costs in case study #7	44
Figure 3.15: Water main break location along with effected routes for case study #8.....	45
Figure 3.16: Percentage distribution of overall impact costs in case study #8	46
Figure 3.17: Water main break location along with effected routes for case study #9.....	47
Figure 3.18: Percentage distribution of overall impact costs in case study #9	49
Figure 3.19: Water main break location along with effected routes for case study #10...	50
Figure 3.20: Percentage distribution of overall impact costs in case study #10	52

List of Figures (Continued)	Page
Figure 3.21: Percentage distribution of overall impact costs in case study #11	54
Figure 3.22: Water main break location along with effected routes for case study #12...	55
Figure 3.23: Percentage distribution of overall impact costs in case study #12	56
Figure 3.24: Water main break location along with effected routes for case study #13...	57
Figure 3.25: Percentage distribution of overall impact costs in case study #13	59
Figure 3.26: Water main break location along with effected routes for case study #14...	60
Figure 3.27: Percentage distribution of overall impact costs in case study #14	61
Figure 3.28: Water main break location along with effected routes for case study #15...	62
Figure 3.29: Percentage distribution of overall impact costs in case study #15	64
Figure 3.30: Water main break location along with effected routes for case study #16...	65
Figure 3.31: Percentage distribution of overall impact costs in case study #16	66
Figure 3.32: Water main break location along with effected routes for case study #17...	67
Figure 3.33: Percentage distribution of overall impact costs in case study #17	69
Figure 3.34: Water main break location along with effected routes for case study #18...	70
Figure 3.35: Percentage distribution of overall impact costs in case study #18	71
Figure 3.36: Water main break location along with effected routes for case study #19...	72
Figure 3.37: Percentage distribution of overall impact costs in case study #19	74
Figure 3.38: Water main break location along with effected routes for case study #20...	75
Figure 3.39: Percentage distribution of overall impact costs in case study #20	76
Figure 4.1: Mean percentage distribution of overall costs.....	79
Figure 4.2: Percentage distribution of direct vs. indirect costs of water main breaks	81

CHAPTER 1: INTRODUCTION

Water plays a crucial role in human survival, economic wellbeing and public health. Almost 97% of the water present on earth's surface is held in oceans in the form of salt water; and out of the remaining 3%, over 65% is inaccessibly held in glaciers and polar caps [Gleick, 1993]. Rest of the freshwater available on earth is constituted in the form of lakes, rivers and other water bodies. Accessible freshwater is collected, treated and distributed for human consumption, industrial processes, irrigation, and firefighting among many other purposes. The movement of freshwater from a water body to the place of its eventual consumption requires humungous infrastructure that is mainly constituted by raw water collection pipelines, water treatment facilities, water pumps, storage tanks, transmission and distribution pipelines. All these engineered structures that facilitate the treatment and movement of water from its source to destination are together referred as water infrastructure.

Water infrastructure is a vital component of any community development plan and it is common that it is planned for and built to last for a very long period of time. Majority of water infrastructure is buried underground leading to many challenges that arise from the need for its access for installation and repair purposes, and the resulting inconvenience to the society. Given the need for this infrastructure to last for a very long period of time, all potential challenges with its operation and management need to be considered during the design phase itself to make appropriate adjustments before the system is put in place.

Water infrastructure is one of the most critical lifeline infrastructures a community is dependent on and it is vital that it continues to perform in the face of various uncertainties arising from natural or anthropogenic causes. Many of the water infrastructure systems that are currently operational in the United States are very old with some being in a very critical state needing a major overhaul to sustain the quality of life desired by the citizens (ASCE, 2013). The poor state of water infrastructures is mainly due to the sub-optimal design choices made by the asset owners many decades ago which is exacerbated by inadequate maintenance and lack of financial resources to undertake timely rehabilitation. As a result, many water infrastructure systems are serving beyond their intended design life which leads to an undesirable consequence of various components failing and posing reliability and emergency preparedness challenges to water infrastructure managers. It is estimated that the cumulative cost of degraded water/wastewater infrastructure on households could be as high as \$59 billion from 2013 to 2020, whereas the economic effect on businesses could be as high as \$147 billion (ASCE, 2013).

As water infrastructure systems age, the components deteriorate due to a combination of factors that include but not limited to: (a) natural material degradation over time and subsequent loss of structural integrity, (b) lack of proper maintenance, (c) fatigue loading and subsequent localized structural damage, (d) design defects or construction errors that weaken the system over time, (e) adverse operating schemes, and (f) adverse environments the system is exposed to (e.g. corrosive soil cover for pipelines) (Yazdekhosti et al., 2014). Due to lack of economic and reliable condition assessment

tools, many water infrastructure managers are unaware of the condition of their pipeline infrastructure and as a result, may not be adequately prepared for their failures when they occur. It is reported that there are 240,000 water main failures in the U.S. annually (ASCE, 2013). The fact that the recent ASCE report card gave a near failing “D” grade for the condition of drinking water infrastructure in the U.S. sums up the current state of drinking water infrastructure in the U.S. (ASCE, 2013).

The failure of water infrastructure components, especially when not expected, have severe consequences. In United States, the direct costs alone incurred due to water main failures are estimated to be \$2.6 billion per year [Sabol, 2011]. The indirect costs that include but not limited to costs of lost water service, flooding of streets, loss of business revenue due to both lack of water and closure of roads for emergency repairs, damage to public and private properties, and personnel injuries, all of which put together would make the overall cost of a water main failure much higher than just the direct costs.

It is important to note that these indirect costs are usually left to be borne by the society and are not completely owned up by water infrastructure (or utility) managers. This realization raises an important question of *whether water utility managers should consider the overall cost of a component failure when prioritizing the critical infrastructure components that need to be revamped as part of their capital improvement planning or simply consider the direct cost that they usually own up*. This is an important question to answer given that the “actual” benefit of rehabilitating critical pipelines prior to reaching the end of their useful design life may be higher than the cost of rehabilitation

if the indirect costs are considered in rehabilitation planning and decision making. The cost of emergency repair when the deteriorated asset fails unexpectedly will be much higher than the cost of planned rehabilitation. The benefit – in terms of reduced failure consequences – will also be much higher in the case of planned rehabilitation as opposed to letting the asset to fail. It can be deduced that planned rehabilitation will be cheaper and highly beneficial. Unfortunately, not many utility owners account for the indirect costs in their rehabilitation planning; this could well be due to the lack of tools to estimate the “actual” consequences of water main failures, but it could also be because of the lack of intent. Nevertheless, there seems to be a clear need for a framework to estimate the “actual” costs of water main failures, especially for large diameter pipelines which have proven to be highly consequential.

1.1 Study Objective and Methodology

Unfortunately, knowledge on the consequences of current water main failures is limited to plan any well-versed rehabilitation strategy. Especially, there is inadequate knowledge on the indirect costs of water main failures which are usually borne by the society as a whole. To address this knowledge gap, the objective of this study is to empirically evaluate the direct and indirect costs of large diameter water mains failures in the U.S. through documenting failure case studies. Based on the synthesized consequences of 20 large diameter water main failures, out of which 18 occurred in the last decade, analysis on direct and indirect costs is performed. A statistical analysis on the overall costs of consequences revealed interesting insights that may be useful to water utility managers in the planning of their infrastructure rehabilitation. Various factors that

aggravated the overall consequences of large diameter water main failures have also been identified through the empirical data analysis.

1.2 Organization of this Thesis

This thesis is divided into five chapters. Chapter 1 presents an overview of the problem studied and states the specific objectives of this study. Chapter 2 presents a brief review of relevant literature and also describes the model used in this study for analyzing the consequences of large diameter water main failures. Chapter 3 documents the case studies of 20 large-diameter main failures that have occurred in the U.S. in the recent past and analyzes the costs of those failures. Chapter 4 presents an analysis of the overall results of 20 case studies with the objective of identifying useful trends. Chapter 5 concludes the study by providing recommendations and highlighting the study limitations.

CHAPTER 2: STUDY METHODOLOGY

The overall cost of large diameter water main breaks is estimated using a simplified adaptation of a previously proposed model. This chapter presents a brief review of relevant previous studies followed by a description of the adapted model from literature.

2.1 Previous Research

A few previous studies attempted to develop cost models to estimate the overall (i.e., direct and indirect) costs of infrastructure failures. Cromwell et al.'s study is the most significant one that is related to water infrastructure, specifically pipeline failures (Cromwell et al., 2002). They developed the Grand Central Model (GCM) as part of the research project supported by the then American Water Works Association Research Foundation (AwwaRF). Various categories of cost, namely service outage and mitigation costs, repair and return to service expenses, police and emergency costs, cost incurred due to lost product, utility emergency response costs, and administrative and legal costs of damage settlements, were included as part of GCM (Cromwell et al., 2002). Various inputs are required to effectively employ the GCM model for estimating the overall costs of water main failures. While some of the GCM inputs may be available with water utilities, it is not uncommon to lack a few and due to this reason, the GCM model also included suggestions for possible ranges for various model inputs when reliable data is not available (Cromwell et al., 2002).

In the GCM model, the cost of service outage and mitigation is estimated based on the unit price of bottled water for residential customers, cost of alternative supply for non-residential customers, and average hours of work and number of personnel on public relation duties. Return to service module calculates the material, labor, and repair costs of the failure based on the number of repair/emergency response staff attending to the repair of the failed main, work hours, material and equipment costs; wages and fringe values are suggested in the GCM model. Cost due to treating and pumping the estimated volume of water that is lost through the main break is calculated in the lost product module using information on pipe diameter, operating pressure, area of break, operational cost, and nature of discontinuity. Unit costs of legal claims and administration along with the estimated legal claim probability are used to calculate the administrative and legal costs of damage settlements. Other important inputs in the GCM model include number of public safety staff on the repair scene and their wages, annual average daily vehicular trips, estimated hourly traffic flow, duration of disruption, detour time, population at risk, and properties damaged. While GCM model is thorough, it is very extensive and complicated for practical usage.

A later study conducted by Gaewski and Blaha collected data for 30 case studies in collaboration with various water utilities to analyze overall impact costs of large diameter water main breaks in the U.S. (Gaewski and Blaha, 2007). Overall impact costs were classified into direct costs and societal costs; GCM model developed by Cromwell et al. (2000) was used to estimate the societal costs. Gaewski and Blaha (2007) reported that most of the water utilities are lacking in techniques to track failure costs and that the

utilities which do keep track of the failure costs certainly do not consider societal costs as a factor in rehabilitation planning and risk assessment practices. With a geometric mean of \$500,000, overall impact costs for 30 case studies they analyzed were estimated to be in between \$6,000 and \$8.5 million (Gaewski and Blaha, 2007). It was highlighted that property damage and traffic delay were two main factors that influenced the societal costs due to water main breaks. Strong correlations were reportedly observed between the cost of lost product and the utility response time and also between population density and health impact costs (Gaewski and Blaha, 2007).

Recently, Grigg provided general explanation on the failure risk issue of water mains (Grigg, 2013). Challenges regarding data availability to estimate the consequences of failures were highlighted in his study (Grigg, 2013). Coombs suggested that the cost of rehabilitation is seldom less than the cost of repair unless the societal costs were considered (Coombs, 2014). Matthews also reported that about 50% of the costs of underground infrastructure construction or repair work were accounted by the traffic delay costs, a societal component of consequences (Matthews, 2010).

Matthews et al. recently identified various knowledge gaps on water main breaks and the need for uniform procedures for collecting appropriate data at the time of failures (Matthews et al., 2015). They recognized the need for having a unified data format, which will help all the utilities to collect correct and reliable data in a standard manner for future references, as a major research need (Matthews et al., 2015). While the failure costs of water main breaks, as perceived by water utilities, rarely include the indirect or the societal costs, they are also only collected and used at local level and not at regional

and national levels for the purposes of tracking and analyzing for useful trends. In an attempt to complement the existing databases on water main failure costs, this study synthesizes data on 20 large diameter water main failures and analyzes the data for useful trends that would help water utilities in more appropriately predicting failure costs as part of their rehabilitation planning. Additional insights on the factors that influence the overall impact costs and the fraction of overall costs left to be borne by the society are also presented in this study.

2.2 Consequences of Water Main Break (COWAMB) Model

A simple Microsoft Excel-based model called COWAMB is developed in this study to estimate the costs of environmental, economic and societal consequences resulting from water main failures. COWAMB model is a simplified adaptation of the GCM model proposed by Cromwell et al. (2002). The GCM model is extensive and complicated for estimating the water main break consequences (Gaewski and Blaha, 2007). The COWAMB model mainly minimized the number of inputs required to estimate the cost of overall impacts of water main breaks while some inferences and assumptions, which are consistent with the GCM model, were made.

The basic inputs required for the COWAMB model include failure location, pipeline material, pipeline diameter, operating pressure, outage and repair durations, and prevailing cost of water supply. It is helpful to have additional data for making accurate predictions; such data includes the distribution of different types of dwellings affected and number of consumers affected by possible supply outage and water flooding, average

vehicle delay time due to traffic detours, and number of health issues reported in the service area. In cases where accurate input data is lacking, reasonable values from the suggested ranges of GCM model are assumed mainly based on the severity of the failure assessed through available data.

COWAMB is comprised of six impact categories whose costs are separately estimated from a given set of data inputs. The mathematical formulations for estimating each of these categories are presented in the following paragraphs. Some of these mathematical formulations are adapted from the GCM model.

Lost Product

Significant amounts of water is lost through water main breaks and this lost product is defined in this study as the volume of water lost through the broken pipe during the period between the actual failure and time when the utility operator isolates the failed pipeline section for repair. Pipe diameter, operating pressure, the size of the break or burst, and the time elapsed between failure and isolation of the pipe section are some of the factors that influence the lost product volume. The embedded costs of lost water include the investment made in collecting, treating and pumping the water into the distribution system; and these costs are irrecoverable.

If the amount of lost product is not reported for a given case, the surface area of the water main failure is assumed to be quarter of the pipeline cross sectional area. Upon estimating the surface area of the break, orifice flow equation is employed to calculate the outflow through the break (Raymond and Harvey, 1918). Depending on the location

of the failure, operating cost of water is appropriately varied. Purchase cost of water is considered to be the value of fresh water withdrawal from the source. Cost associated with the lost product is calculated as the sum of operating cost, i.e., pumping and treatment cost invested by the Water Utility, and purchase cost of the water. Orifice flow equation is presented in the flowing equation:

$$Q = \frac{A \times 8.02 \times 448.8 \times \sqrt{2.31P}}{144}$$

Where,

Q = Flow of water, gallons per minute

A = Area of the orifice, square inches

P = Operating pressure, PSI

The following inputs are explicit to this cost category:

1. Pipe Diameter: The diameter of the failed pipeline.
2. Operational Pressure: The normal operational pressure for the failed pipeline section.
3. Area of Break: The portion of the area of the break, split or pipe burst through which water flows under pressure.
4. Operating Cost: Cost per thousand gallon accounted for treatment and distribution of water.

$$C_{LP} = \frac{(V \times OC)}{1000} + (V \times C_W)$$

Where,

C_{LP} = Cost of lost product, \$

V = Lost water volume, gallons

OC = Operating cost, \$/1000gallons

C_W = Cost of water, \$/gallon

Repair and Return to Service:

Prominent factors that influence the *repair and return to service* costs are labor, material and equipment costs. Labor costs depend on the number of laborers that worked on the failed pipeline and the wages paid to each of them; similarly, quantity of material, type and duration of equipment used determine other category of repair costs. Other minor categories which influence the repair cost are transportation charges, fringe benefits for the workers, and cost of miscellaneous tools used in the repair. The weighted cost is the combination of the base salary of the average *repair and return to service* worker, material costs, equipment and training multiplier, and fringe benefits, which are defined as a percentage of the base salary. Depending on the location, base salary of the average *repair and return to service* worker and percentage of material costs, equipment and training multiplier and fringe are selected from the suggested data ranges of GCM. Cost of repair and return to service expenses is calculated using the following formula:

$$C_{RR} = \frac{WS \times (1 + FS + Eq + MC) \times D \times RS}{WH} + R_C$$

Where,

C_{RR} = Cost of repair and return to service, \$

WS = Wage and salary, \$

FS = Fringe, %

Eq = Equipment and training multiplier, %

MC = Material costs, %

D = Duration of repair period, hours

RS = Repair personnel on scene

WH = Annual working hours, hours

R_C = Repair cost, \$

Travel Delay:

Travel delays may occur due to the failure and the subsequent repair of water mains. Water main failures gush out a large amount of water onto the streets which may disrupt normal traffic flow. Additionally, the emergency repair work may also result in closing of one or more traffic lanes. The resulting traffic delay expenses are estimated

based on the average traffic flow during the disruption, the average delay per vehicle and the average delay cost per vehicle per hour.

It is assumed that the duration of travel delay is equal to the duration of water service disruption, mainly because traffic issues would persist from the time of the break occurrence until the pipeline is repaired and recommissioned. The average delay cost per vehicle per hour is computed from the average number of passengers in the vehicle and the hourly vehicular operational cost, a measure of the cost of time (Cromwell et al., 2002). Depending on the magnitude of the break and type of road, detour time is assumed from the suggested data range in the GCM model (Cromwell et al., 2002). Average delay cost per hour is calculated by multiplying average delay cost per vehicle per hour with average traffic flow. Travel delay expenses are estimated as the product of average delay cost per hour and duration of disruption.

The following inputs are explicitly required for the travel delay impact cost category:

1. Annual Average Daily Trips (AADT): In a 24-hour period the average daily volume of traffic traveling past a given point.
2. Average Vehicle Delay or Detour Time: As a result of the water main failure, the time delay experienced by the passengers due to the closed lanes.
3. Proportion of Daily Trips per Hour during the disruption period: It is an estimate of the average traffic flow. This can be expressed as a percentage of the AADT.
4. Passengers/vehicle: The average number of passengers traveling in delayed vehicles.

Cost of travel delay is calculated by the following formula.

$$C_{TD} = (TF \times VO \times P \times D_D \times DT)$$

Where,

C_{TD} = Cost of traffic delay, \$

TF = Estimated traffic flow, trips/hour

VO = Vehicle operational cost per hour, \$/hour

P = Passengers per vehicle, passengers

D_D = Duration of disruption, hours

DT = Detour time, hours

Supply Outage and Substitution:

Depending on the probable amount of water used and cost of a substitute potable source, water supply outage costs are estimated in this category. Key components that are required to estimate the cost of this category are number of buildings and individual customers affected due to the supply outage. Bottled water is considered in this study as a substitute for potable source of water. It should be noted that the cost of supply outage reflects the inconvenience of lack of water for customers while the failed pipeline is being repaired, whereas cost of lost product reflects the inability of the water utility to monetize water that is lost to the environment due to the failure. Unit cost of water used in calculating the supply outage costs is an environmental value assumed for freshwater

withdrawal. Number of customers affected due to the break is estimated based on the affected properties and residents in respective properties. Gallons of water used by each customer per day and the total number of customers affected gives total volume of water usage, by which total cost of supply outage can be calculated using unit cost of water from an alternate source. Total cost spent on alternate source of water during failure is calculated from cost of bottled water per gallon and total number of customers affected due to the failure. Supply outage and substitution cost is the combination of cost spent on alternate source and cost of water due to outage. Cost of supply outage and substitution expenses is calculated by the following formula.

$$C_{SOS} = (A_P \times C_{BW}) + (V_{WU} \times C_W)$$

Where,

C_{SOS} = Cost of supply outage and substitution, \$

A_P = Affected population due to break,

C_{BW} = Cost of bottled water, \$

V_{WU} = Volume of water usage, gallons

C_W = Cost of water, \$/gallon

Health Risk:

Health impact cost is estimated by following the principles and assumptions of the GCM model (Cromwell et al., 2002). Population at risk as a percentage of total population exposed to water contamination-based illnesses is obtained from the literature

to calculate the cost of health risk [Cromwell et al., 2002]. Depending on the location, severity of the break and exposed population that is calculated based on the number of affected dwellings, population at health risk is reasonably estimated. The estimated populations at health risk are then categorized into severely ill (a maximum of 2%) and normally ill classes (Cromwell et al., 2002). Estimated lost wages, doctor fees and hospital charges associated with these classes are reasonably assumed based on the location factor and are used to calculate the total cost of health risk associated with each water main break (Cromwell et al., 2002).

There are two ways that health issues may occur; first, unforeseen pressure fluctuations which are related to the failure may risk people for possible exposure to waterborne illness and secondly, physical injury that may occur at the failure location. It has to be noted that any type of health impacts, particularly waterborne ones, are less likely and the same has been reflected while estimating the infection percentage. However, in order to provide a suitably comprehensive estimate for societal costs, this cost category has been included. An estimate of economic impact of the outbreak of waterborne illness within a hypothetical population which is at risk by the water main failure is required to evaluate the theoretical impact of waterborne illness. Provision of data regarding illness severity and health care costs could give more accurate estimate. All the data inputs in this cost category are deduced from suggested data ranges in the GCM model. Calculated health risk costs are dependent on hospital charges, physician and professional charges, and on lost wages. Cost of health risk is calculated by the following formulas.

Lost hours:

$$L_H = W_D \times P_R \times P_{LR} \times I \times I_x \times D_x$$

Where,

L_H = Lost working hours, hours

W_D = Work day hours, hours

P_R = Population at risk

P_{LR} = Percentage of low risk population, %

I = Infection percent, %

I_x = mild/moderate/severe infection percent for low/high risk population, %

D_x = Duration of illness, days

Lost wages:

$$L_W = L_H \times W_R$$

Where,

L_W = Lost wages, \$

L_H = Lost working hours, hours

W_R = Hourly wage rate, \$/hour

Physician and professional charges:

$$P_C = P_R \times P_{LR} \times I \times I_x \times P_x$$

Where,

P_C = Physician and professional charges, \$

P_R = Population at risk

P_{LR} = Percentage of low risk population, %

I = Infection percent, %

I_x = mild/moderate/severe infection percent for low/high risk population, %

P_x = Patient costs for mild/moderate/severe infection, \$

Hospital charges:

$$H_C = P_R \times P_{LR} \times I \times I_x \times H_D \times DC_H$$

Where,

H_C = Hospital charges, \$

P_R = Population at risk

P_{LR} = Percentage of low risk population, %

I = Infection percent, %

I_x = mild/moderate/severe infection percent for low/high risk population, %

H_D = Hospital days, days

DC_H = Daily charge of hospitals, \$/day

Total health risk expenses:

$$C_{HR} = \frac{(L_W + H_C + P_C)}{CP}$$

Where,

C_{HR} = Cost of health risk, \$

L_W = Lost wages, \$

H_C = Hospital charges, \$

P_C = Physician and professional charges, \$

CP = Supply contamination probability

Property Damage:

The cost of property damage incurred as a result of a water main failure is estimated in this category based on the amount of water lost. Property damage could occur in two primary locations, at the failure location and in the adjacent areas to the failure location. At the failure location, property damage is associated with the property directly affected by the water main break. For example, all vehicular damage and structural damage caused due to the undermining of the water main failure are considered in this category. Property damage in the areas adjacent to the failure location is measured

as the damage to the structures due to flooding caused by the break. For every 7,571 m³ (or 2 million gallons) of water lost, 1% value of any building in the surrounding area is reasonably assumed to get damaged due to flooding. The data on the number and type of buildings affected depends on the magnitude of the break, and the average property values depend on the failure location. Properties affected due to flooding and average property values could largely vary depending on magnitude of the break and location factor, so wide range of data is suggested data ranges in COWAMB model and is presented in Table 2.1. Both, the number of properties affected due to the flooding and average value of the property, affect the total cost of damages to properties. Cost of property damage is calculated by the following formula.

$$C_{PD} = [(P_{Rd} \times V_{Rd}) + (P_O \times V_O) + (P_{Rt} \times V_{Rt}) + (P_H \times V_H) + (P_S \times V_S)] \times P_p$$

Where,

C_{PD} = Cost of property damage, \$

P_{Rd} = Number of residential properties affected,

V_{Rd} = Average value of residential property, \$

P_O = Number of offices affected,

V_O = Average value of office, \$

P_{Rt} = Number of restaurants affected,

V_{Rt} = Average value of restaurant, \$

P_H = Number of hospital properties affected,

V_H = Average value of hospital property, \$

P_S = Number of schools affected,

V_S = Average value of school, \$

P_P = Percentage of property affected, %

Table 2.1: Suggested data ranges for property damage data inputs

No. of properties affected due to flooding	Suggested Data Range	
	Lower Bound	Upper Bound
Residential	50	500
Office	50	500
Restaurants	50	500
Hospitals	1	20
Schools	1	20
Average value of the property:		
Residential	\$ 20,000.00	\$ 300,000.00
Office	\$ 3,000,000.00	\$ 25,000,000.00
Restaurants	\$ 500,000.00	\$ 6,000,000.00
Hospitals	\$ 15,000,000.00	\$ 40,000,000.00
Schools	\$ 5,000,000.00	\$ 30,000,000.00

It should be noted that costs associated with repairing roads and damaged vehicles as a result of water main breaks, and the resulting damage claims are not included in the COWAMB model in its current form; although these were included in the GCM model.

CHAPTER 3: CASE STUDIES

Report of 20 large diameter water main break case studies that have occurred in U.S. in the recent past is presented in this chapter. The 20 cases documented in this chapter epitomize a diverse sample that involves pipe materials such as grey cast iron, and prestressed concrete cylinder pipe (PCCP) and steel, and diameters ranging from 762 mm to 3048 mm. In this study, overall impact costs of 20 large diameter water main breaks are calculated using the COWAMB model. Majority of the data required for computations are acquired either from published literature or media reports gained through significant internet search. In some cases, where the required data is unavailable, reasonable values were deduced based on the magnitude of the break, location factor, while complying with the suggested data ranges in the GCM model. Table 3.1 presents more details on the inferences made in the analysis of this study along with the influential factors that served as the basis for the inferences. This chapter describes each of the 20 case studies in detail.

Table 3.1: Deduced data inputs with influence factors

Cost Category	Deduced Data Inputs	Influence Factor
Lost Product	Operating cost of water	Location
	Purchase price of water	Location
Repair and Return to Service	Wage and salary assumption of repair personnel	Location
	Fringe assumption	Location
	Equipment and training multiplier	Location and magnitude of break
	Material costs	Location and magnitude of break
	Annual work hours	General assumption
Travel Delay	Annual average daily trips (AADT)	Type of road and magnitude of repair
	Proportion of Daily Trips per Hour During the Disruption	Type of road and magnitude of break
	Vehicle Operational Cost per Hour	Type of road and magnitude of break
	Passengers/Vehicle	General assumption
	Detour time	Type of road and magnitude of break
Supply Outage and Substitution	Unit price of bottled water	Location
	Customers affected due to outage	Magnitude of break
	Water usage of customers per day	General assumption
Health Risk	Percentage of low risk population	Magnitude of break
	Infection percent	Magnitude of break
	Mild/moderate/severe infection percentage in low risk population	General assumption
	Mild/moderate/severe infection percentage in high risk population	General assumption
	Average illness duration of mild/moderate/severe infection	General assumption
	Average patient costs of mild/moderate/severe infection	Location
	Average hospital days of moderate/severe infection	General assumption
	Average hospital day charge of moderate/severe infection	Location
Property Damage	Average value of each property	Location

Case study #1: Sunset Boulevard, Los Angeles, California, 2014:

A 100-year-old 914mm steel pipeline in West Hollywood has ruptured sending muddy water down Sunset Strip and prompting a series of street closures and also caused 4.5-meter-wide sinkhole (Parker, 2014). The discharge from the broken main was estimated to be $2,178\text{m}^3/\text{hr.}$, resulting in $6,814\text{m}^3$ of lost water (Hailey and Ryan, 2014). The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.1.

Figure 3.1: Water main break location along with effected routes for case study #1

Hundreds of cars and buildings on the University of California in Los Angeles campus were damaged due to this break and the resulting flooding (Parker, 2014). It has taken nearly six hours for repairing the broken pipeline (Parker, 2014). No injuries were reported due to the break. Water also spilled onto nearby Santa Monica Boulevard, although that street was not immediately closed.

Lost volume of water, repair cost, and repair period of the water main break data was available from multiple sources. Lost product and repair and return to service costs were estimated using the COWAMB model based on the available data. Other inputs such as operating pressure, repair staff on scene, total population at risk, and number of properties damaged due to flooding were reasonably deduced based on the location, magnitude of the break.

Various categories of failure impact costs are summarized in Table 3 and it can be seen that the overall impact cost of this failure is estimated to be about \$3.3 million.

Table 3.2: Cost of Various Failure Impacts in Case Study #1

Category	Cost
Lost Product	\$ 23,400.00
Repair and Return to Service	\$ 1,004,384.62
Travel Delay	\$ 680,400.00
Customer Outage & Substitution Expenses	\$ 1,220,902.50
Health Cost	\$ 207,049.29
Property Damage	\$ 200,700.00
TOTAL	\$ 3,336,836.41

The overall failure costs are also categorized into direct and indirect cost. Direct costs are the repair costs typically paid by the utilities; e.g., lost product, repair and return to service. Indirect costs are left to be borne by the public or insurance companies related to the property; e.g., travel delay, supply outage and substitution expenses, health impact cost, and property damages. The direct costs accounted for only 31% of the overall impact costs for this failure case while the indirect costs accounted for 69%, as can be inferred from Table 2.

Figure 3.2. Percentage distribution of overall impact costs in case study #1

Percentage distribution of overall impact costs for this case study is shown in Figure 2. It can be observed from Figure 2 that customer outage and substitution expenses and travel delay costs together accounted for more than 55% of the overall

impact costs, which is due to flooding of the University and other high traffic routes as result of this failure.

Case study #2: UCLA Campus, Los Angeles, California, 2014:

A 762 mm steel pipeline was ruptured in UCLA campus, Westwood. Flooding in the amount of 181,058 m³ also caused significant damage to the nearby properties stranding hundreds of vehicles in the parking structures and historic Pauley Pavilion's court (Lloyd, 2014). Traffic delays and road repairs were reported due to water gushing on to the Sunset Boulevard after the break and a 20-foot wide and 10-foot deep sinkhole was blew open in Westwood due to the water main break (Lloyd, 2014). The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.

Figure 3.3: Water main break location along with effected routes for case study #2

It has taken about four hours to isolate the failed section of the pipeline for repair in this case. The discharge in the meantime has flooded athletic fields, underground garages that housed several cars, and various walkways on the University of California in Los Angeles campus. Due to higher traffic density, it has taken longer time to repair damaged roads resulting in increased travel delay costs. Closing of Sunset Boulevard between Veteran Avenue and Hilgard Avenue due to repairs caused traffic problems. 900 cars and two parking structures were reported as damaged due to flooding (Lloyd, 2014).

Information on lost water volume, and properties damaged due to flooding were available to estimate impact costs of lost product, and property damage. Significant data like repair cost, number of repair personnel, population affected due to outage, population at risk and number of properties damaged were not available and hence deduced reasonably depending on the location factor, traffic volume, magnitude of the break.

Cost associated with the break is categorized and showed in Table 3.3.

Table 3.3: Cost of Various Failure Impacts in Case Study #2

Category	Cost
Lost Product	\$ 155,449.19
Repair and Return to Service	\$ 8,260,884.62
Travel Delay	\$ 12,397,000.00
Customer Outage & Substitution Expenses	\$ 4,161,600.00
Health Cost	\$ 1,576,227.55
Property Damage	\$ 2,271,949.72
TOTAL	\$ 28,823,111.08

Percentage distribution of overall impact costs for this case study is shown in Figure 3.4. From COWAMB analysis over the water main break costs, it is concluded that only 30% of the total costs are accounted as direct costs and 70% as indirect costs.

Figure 3.4: Percentage distribution of overall impact costs in case study #2

Total of 28 million is estimated as the loss due to the water main break. Travel delay expenses cover a major share of 43% of overall loss, has an extensive impact as flooding closed few streets and Sunset Boulevard which has high annual average daily flow. Though loss due to lost product is only 1% of the overall cost, the indirect effects due to flooding showed major impression comprehensively.

Case study #3: Connecticut Avenue in Chevy Chase, Maryland, 2013:

A break in 33-year-old 1524 mm PCCP pipeline was occurred in Connecticut Avenue in Chevy Chase, Maryland. Break led a jet of water four to five stories into the

air and blasted over asphalt on Chevy Chase Lake Drive, leaving a 20-foot-deep crater (Shaver, 2013). The intersection of Connecticut Avenue and Chevy Chase Lake Drive was closed due to the break for about six days after which it was reopened for traffic. As a result, travel delay costs were greater in this case. The system lost more than 2,27,124 m³ of water during the break. Nearly 1.8 million residents remained without water for about 11 hours due to this break (Shaver, 2013). The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.5.

Figure 3.5: Water main break location along with effected routes for case study #3

The failure occurred on Chevy Chase Lake Drive leaving a 6-meter-deep crater. The large amount of water discharged caused flooding that severely damaged a lot of properties around the failure location. It has taken about six hours to isolate the failed section of the pipeline for repair in this case. An acoustic censor was installed to fix the problem in the pipe after the inspection.

Lost volume of water, outage period, and population affected due to the outage were the data inputs available from multiple sources. From the data available, cost evaluation of lost product, health costs, and supply outage and substitution expenses were calculated. Other data like properties damaged due to flooding, repair cost, and number of repair personnel at scene were reasonably deduced based on location factor and magnitude of the break.

Cost associated with the break is categorized and showed in Table 3.4.

Table 3.4: Cost of Various Failure Impacts in Case Study #3

Category	Cost
Lost Product	\$ 582,000.00
Repair and Return to Service	\$ 4,142,061.54
Travel Delay	\$ 6,318,000.00
Customer Outage & Substitution Expenses	\$ 2,610,989.00
Health Cost	\$ 667,789.25
Property Damage	\$ 7,530,000.00
TOTAL	\$ 21,850,839.79

Percentage distribution of overall impact costs for this case study is shown in Figure 3.6. From COWAMB analysis over the water main break costs, it is concluded that only 22% of the total costs are accounted as direct costs and 78% as indirect costs. Total of 21.8 million is estimated as the loss due to the water main break.

Figure 3.6: Percentage distribution of overall impact costs in case study #3

As there was a road closure for six days due to the break, travel delay solely accounted for 29% of the total loss due to the break. Due to magnitude of the break and higher repair and return to service time substitution expenses also costed 12% of the total loss, which is higher when compared to other studies.

Case study #4: Capital Heights, Maryland, 2011:

A 1372 mm PCCP pipeline was ruptured in Capital Heights, Maryland. Frozen water was observed on the roads near by an office park where this failure has occurred (WSSC, 2011). As a result, all southbound lanes of Interstate 95 for approximately two-mile long, between Ritchie Marlboro Road and Route 214, were closed for two days (Jacquelyn Martin, 2011). Consequently, it resulted in significant traffic detours and greater travel delay costs. The church, which serves about 60 families was damaged due

to the break. The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.7.

Figure 3.7: Water main break location along with effected routes for case study #4

As there was not much information available on this break most the data was deduced in the COWAMB model. Lost water volume was calculated based on the diameter, and time taken to control the flow after the break. Other significant data like outage period, number of repair personnel at scene, repair cost, customers affected due to outage, population at risk and number of properties damaged due to flooding were reasonably deduced and were used for calculating the travel delay, substitution expenses and property damage. Cost associated with the break is categorized and showed in Table 3.5.

Table 3.5: Cost of Various Failure Impacts in Case Study #4

Category	Cost
Lost Product	\$ 485,000.00
Repair and Return to Service	\$ 5,013,975.96
Travel Delay	\$ 2,646,000.00
Customer Outage & Substitution Expenses	\$ 1,462,959.00
Health Cost	\$ 486,900.07
Property Damage	\$ 5,912,500.00
TOTAL	\$ 16,007,335.03

Percentage distribution of overall impact costs for this case study is shown in Figure 3.8. From COWAMB analysis over the water main break costs, it is concluded that only 34% of the total costs are accounted as direct costs and 66% as indirect costs. Total of 16 million is estimated as the loss due to the water main break.

Figure 3.8: Percentage distribution of overall impact costs in case study #4

Since the break has occurred near the interstate repair and return to service and travel delay costs were extensive as they reported to be 31% and 17% of the overall cost respectively. Due to the presence of church and other prominent properties near to the location of the break property damage accounted for a major share of 37% of overall costs.

Case study # 5: Metro West Tunnel, Boston, Massachusetts, 2010:

A new 7-year-old 3048 mm steel pipeline broke in Metro West Tunnel, Boston, Massachusetts. The break occurred near Recreation Road by the intersection of the Massachusetts Turnpike and Route 128 (WSSC, 2011). While travel delay costs were not significant, damages inflicted on the nearby properties were very high as nearly 10 million m³ of water flooded the surroundings of the failure (Levenson, 2010). Due to the significantly higher magnitude of flooding, costs of property damage and lost product accounted for more than 50% of the overall impact cost. The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.9.

Figure 3.9: Water main break location along with effected routes for case study #5

Nearly 2 million residents of Greater Boston lost their supply of clean drinking water for a 9-hour period for nearly an estimated 1,500 commercial buildings (Henry, 2010). 8 million gallons per hour gush from huge Weston pipe. The crisis began in the morning when a 10-foot-wide pipe in Weston sprang a leak, which worsened throughout the afternoon and eventually cut off Greater Boston from the Quibbling Reservoir, where most of its water supply is stored.

Information on lost water volume, properties damaged due to flooding, customers affected due to supply outage, and outage period were available from the sources and were used in calculating impact costs due to lost product, property damage, supply outage and substitution expenses, and health risk. Significant data like operating pressure, and number of repair personnel at scene were deduced reasonably and were used for calculating travel delay and repair and return to service costs.

Cost associated with the break is categorized and showed in Table 3.6.

Table 3.6: Cost of Various Failure Impacts in Case Study #5

Category	Cost
Lost Product	\$ 33,655,000.00
Repair and Return to Service	\$ 5,052,615.38
Travel Delay	\$ -
Customer Outage & Substitution Expenses	\$ 15,731,312.00
Health Cost	\$ 7,647,171.61
Property Damage	\$ 23,187,500.00
TOTAL	\$ 85,273,598.99

Percentage distribution of overall impact costs for this case study is shown in Figure 3.10. From COWAMB analysis over the water main break costs, it is concluded that only 46% of the total costs are accounted as direct costs and 54% as indirect costs. Total of 85 million is estimated as the loss due to the water main break.

Figure 3.10: Percentage distribution of overall impact costs in case study #5

As the diameter of the pipe is large and break occurred 20-foot below the ground it was difficult to control the flow and hence the lost product cost solely accounted for 40% of the overall costs. Since there was no information on the travel delays and detours due to repairs, travel delay expenses do not have any effect on the overall costs.

Case study #6: Dundalk, Maryland, 2009:

A 1830 mm diameter PCCP pipeline was ruptured in UCLA campus, Westwood. This failure resulted in significant damage to nearby properties due to the pipeline's higher elevation (WSSC, 2011). Although there were no injuries due to this main break, 100 homes were reported to be flooded, in addition to washing away of a part of the road, damaging cars, trapping some residents in their homes (Hirsch, 2009). Due to the flooding, a section of the Broening highway was closed for two to four weeks while repair work on the road and the failed pipeline continued. Cost of property damage was significant in this case due to the high magnitude of damage caused by flooding (Hirsch, 2009). The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.11.

As there was no information on lost volume of water, it has been quantified through the diameter of the pipeline, operating pressure, and time taken by officials to control the flow. Health risks and property damage has been calculated by COWAMB model by using data inputs population at risk, properties damaged due to flooding. Other information on repair cost, and repair personnel at scene were accordingly deduced to

estimate impact costs of repair and return to service and travel delay. Cost associated with the break is categorized and showed in Table 3.7.

Figure 3.11: Water main break location along with effected routes for case study #6

Percentage distribution of overall impact costs for this case study is shown in Figure 3.12. From COWAMB analysis over the water main break costs, it is concluded that only 54% of the total costs are accounted as direct costs and 46% as indirect costs. Total of 7.2 million is estimated as the loss due to the water main break.

Table 3.7: Cost of Various Failure Impacts in Case Study #6

Category	Cost
Lost Product	\$ 353,909.84
Repair and Return to Service	\$ 3,517,757.69
Travel Delay	\$ 1,836,000.00
Customer Outage & Substitution Expenses	\$ 216,623.25
Health Cost	\$ 80,964.74
Property Damage	\$ 1,231,387.34
TOTAL	\$ 7,236,642.87

Figure 3.12: Percentage distribution of overall impact costs in case study #6

Water main break at Dundalk caused closure of Broening highway for almost four weeks, due to which repair cost and travel delay expenses accounted as major share of 49% and 25% of overall cost respectively. Next effective cost category is estimated to be property damage at 17% of overall costs, as 100 homes were flooded due to the break.

Case study #7: Denver, Colorado, 2008:

A 1676 mm PCCP pipeline was ruptured in Denver, Colorado (WSSC, 2011). This main break caused a sinkhole that is 12.2-meter-wide and 4.8-meter-deep, shutting down all northbound lanes of I-25 (McPhee, 2008). Although no injuries resulted due to this break, it has taken longer time to repair it, and therefore resulted in significant travel delay costs. The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.13.

Figure 3.13: Water main break location along with effected routes for case study #7

Due to the failure location being closer to the Interstate-25, great damage was caused to the highway which reportedly took 11 days to repair before it was reopened. Consequently, costs of travel delays and repair work were high. Lost product of 7570 m³

was reported due to the break, which also opened up a 40 by 40-foot sinkhole of 16 feet deep (Mark Belcher, 2008).

Information on lost water volume, and repair period was available and is used to estimate lost product and repair and return to service impact costs. Although information on population at risk, outage period, customers affected due to supply outage, and property damage was unavailable and these significant data was deduced reasonably based on the location and magnitude of the break. Cost associated with the break is categorized and showed in Table 3.8.

Table 3.8: Cost of Various Failure Impacts in Case Study #7

Category	Cost
Lost Product	\$ 25,600.00
Repair and Return to Service	\$ 7,289,384.62
Travel Delay	\$ 10,719,000.00
Customer Outage & Substitution Expenses	\$ 490,608.00
Health Cost	\$ 35,593.01
Property Damage	\$ 87,500.00
TOTAL	\$ 18,647,685.62

Percentage distribution of overall impact costs for this case study is shown in Figure 3.14. From COWAMB analysis over the water main break costs, it is concluded that only 39% of the total costs are accounted as direct costs and 61% as indirect costs. Total of 18 million is estimated as the loss due to the water main break.

Figure 3.14: Percentage distribution of overall impact costs in case study #7

As the break has caused closure of all northbound lanes of Interstate 25 and due to high annual average daily trips on the Interstate travel delay expenses solely accounted for 57% of the overall costs due to the break. Next extensive cost category is estimated to be repair and return to service at 39% of the overall cost.

Case study #8: Bethesda, Maryland, 2008:

A 1676 mm PCCP pipeline was ruptured in Bethesda, Maryland. Damage to nearby residential communities was prevented due to their significantly higher ground elevation relative to the failed pipeline (WSSC, 2011). It was reported that discharge from the broken main was at a rate of 34,000m³/hr and that it has taken about three hours to isolate the broken pipeline section for repair, and an additional four hours to re-pressurize the water system in the county (Lovino, 2008). As many as 18 cars were

reported to be trapped in the discharged water that was 3 to 4 feet high in some locations. Few customers also reported water discoloration for 12 to 18 hours after the break is fixed and pipeline re-commissioned into service (Lovino, 2008). Travel delay costs are estimated to be significant due to the blocking of River Road traffic. The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.15.

Figure 3.15: Water main break location along with effected routes for case study #8

Lost water volume, repair period, outage period and properties damaged due to flooding are the data inputs available in this case study. Data including repair cost, number of repair personnel on scene, customers affected due to supply outage, and population at were deduced considering the location factor, traffic flows and detour times for the closure lanes/routes. Cost associated with the break is categorized and showed in Table 3.9.

Percentage distribution of overall impact costs for this case study is shown in Figure 3.16. From COWAMB analysis over the water main break costs, it is concluded that only 40% of the total costs are accounted as direct costs and 60% as indirect costs. Total of 11 million is estimated as the loss due to the water main break.

Table 3.9: Cost of Various Failure Impacts in Case Study #8

Category	Cost
Lost Product	\$ 436,500.00
Repair and Return to Service	\$ 4,063,138.46
Travel Delay	\$ 4,293,000.00
Customer Outage & Substitution Expenses	\$ 387,459.25
Health Cost	\$ 71,937.78
Property Damage	\$ 2,126,250.00
TOTAL	\$ 11,378,285.49

Figure 3.16: Percentage distribution of overall impact costs in case study #8

Travel delay costs are significantly 38% of the overall costs due to the blockage of traffic at the River Road which has high annual average daily trips. Though there was a huge quantity of water lost due to the break, cost due to the lost product is only 4% of the overall cost as the concerned officials responded quickly in controlling the flow.

Case study #9: Fort Lauderdale, Florida, 2011:

A 762 mm steel pipeline was ruptured in UCLA campus, Westwood. Surrounding properties were significantly damaged due to the large amounts of discharged water (WSSC, 2011). This water main break caused a 7.6-meter-wide sinkhole collapsing a portion of the roadway it is buried under. Nearly 200,000 residents were reported to have been without water for more than 3 hours (Clary, 2011). Since this break occurred on a Christmas Eve, it has taken longer time and cost to fix it, for the lack of adequate work force available. The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.17.

Figure 3.17: Water main break location along with effected routes for case study #9

Lost water volume has been calculated based on the diameter of the pipe, operating pressure, and response time to control the flow. Population affected due to supply outage, outage period, and population at risk data inputs were available. Operating pressure, repair cost, number of repair personnel on scene, properties damaged due to flooding and other significant data were deduced accordingly. Cost associated with the break is categorized and showed in Table 3.10.

Table 3.10: Cost of Various Failure Impacts in Case Study #9

Category	Cost
Lost Product	\$ 129,118.31
Repair and Return to Service	\$ 2,005,480.77
Travel Delay	\$ 420,000.00
Customer Outage & Substitution Expenses	\$ 1,169,616.00
Health Cost	\$ 86,657.91
Property Damage	\$ 501,574.98
TOTAL	\$ 4,312,447.97

Percentage distribution of overall impact costs for this case study is shown in Figure 3.18. From COWAMB analysis over the water main break costs, it is concluded that only 50% of the total costs are accounted as direct costs and 50% as indirect costs. Total of 4 million is estimated as the loss due to the water main break.

Figure 3.18: Percentage distribution of overall impact costs in case study #9

As the break has occurred during the Christmas Eve there was lack of adequate work force to counter act the effects of the break. Hence repair and return to service costed 47% of the overall loss due to the break.

Case study #10: Manhattan, New York, 1998:

A 1220 mm cast iron pipeline broke in the streets of Manhattan, New York. This break occurred between 19th and 20th streets near Madison Square, resulting in the explosion of a nearby gas pipeline that created a 7.6-meter-deep and 60.9-meter-wide crater in the middle of the street (WSSC, 2011). The water main break created a 10.6-meter-wide sinkhole collapsing a portion of the 5th Avenue Street. It has also resulted in the loss of approximately 635,950m³ of water over a span of 6.5 hours (Reuters, 1998). Although no one got injured, it was reported that numerous business houses, apartments

and other nearby properties got damaged due to flooding. The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.19.

Figure 3.19: Water main break location along with effected routes for case study #10

A 25-foot deep crater created an explosion which was more than 200 feet wide in the middle of the avenue, there by damaging the cars parked in the streets of Manhattan. Several buildings in the neighborhood were evacuated because of the flames that were shot from the street two to three stories into the air. Midtown Manhattan has been affected by many other infrastructure problems, most of the problem raised in Madison Avenue and 53rd Street, the traces were detected where bricks began tumbling from the facade of an office building, after that closing the street for weeks.

Information on lost water volume, and repair period, were available and used to compute cost effects of lost product, and repair and return to service. Data inputs

including outage period, repair cost, number of repair personnel on scene, population affected due to supply outage, and population at risk were reasonably deduced. Assumptions are made considering the factors such as location, traffic volume of the affected routes, cost of living. Cost associated with the break is categorized and showed in Table 3.11.

Table 3.11: Cost of Various Failure Impacts in Case Study #10

Category	Cost
Lost Product	\$ 320,424.22
Repair and Return to Service	\$3,005,480.77
Travel Delay	\$1,800,000.00
Customer Outage & Substitution Expenses	\$1,609,938.13
Health Cost	\$ 839,250.96
Property Damage	\$1,886,708.38
TOTAL	\$9,461,802.45

Percentage distribution of overall impact costs for this case study is shown in Figure 3.20. From COWAMB analysis over the water main break costs, it is concluded that only 35% of the total costs are accounted as direct costs and 65% as indirect costs. Total of 9 million is estimated as the loss due to the water main break.

Figure 3.20: Percentage distribution of overall impact costs in case study #10

Since the break occurred in one of the busiest location in New York, loss due to repair and return to service, travel delay expenses and property damage have been significant at 32%, 19% and 20% of the overall costs respectively. Due to the evacuation measures which were taken immediately after the break the health cost were controlled at 3% of overall costs.

Case study #11: Montgomery County, Alabama, 1998:

A 2438 mm PCCP pipeline broke in the streets of Montgomery County, Alabama. Before the utility operator could isolate the failed section of the pipeline, over 264,980 m³ of water was reported to be lost from the main break, which was about the same amount of water distributed daily by the respective utility operator (WSSC, 2011). Water

flooding due to the break blocked a roadway due to which cost of travel delay was greater.

Lost water volume data input is only available information on this case study and is used in estimating the impact costs due to lost product. Outage period, repair period, repair cost, number of repair personnel on scene, population affected due to supply outage, population at risk, and properties damaged due to flooding information was deduced accordingly to calculate cost effects of travel delay, substitution expenses, health risk expenses, property damage, repair costs. Assumptions are made considering the factors such as location, traffic volume of the affected routes, cost of living. Cost associated with the break is categorized and showed in Table 3.12.

Table 3.12: Cost of Various Failure Impacts in Case Study #11

Category	Cost
Lost Product	\$ 487,500.00
Repair and Return to Service	\$ 2,547,353.85
Travel Delay	\$ 2,640,000.00
Customer Outage & Substitution Expenses	\$ 1,047,016.00
Health Cost	\$ 1,209,339.62
Property Damage	\$ 1,916,250.00
TOTAL	\$ 9,847,459.46

Percentage distribution of overall impact costs for this case study is shown in Figure 3.21. From COWAMB analysis over the water main break costs, it is concluded that only 31% of the total costs are accounted as direct costs and 69% as indirect costs. Total of 9.8 million is estimated as the loss due to the water main break.

Figure 3.21: Percentage distribution of overall impact costs in case study #11

Due to blockage of a roadway due to the break, cost associated with repair and return to service and travel delay expenses were estimated to be 26% and 27% of the overall costs respectively.

Case study #12: DeKalb County, Georgia, 2015:

A 40-year-old 914mm CIPP pipeline broke in DeKalb county in Georgia. Break has occurred between South Columbia and Parkhill Drive outside the city (Belt, 2015). All the eight schools in the Decatur school system had low pressure or no water situation caused by the break, which forced the school officials to send back kids home as bathrooms did not work. Reports say that the 914mm water main is over 40 years old and is repaired within 48 hours (Belt, 2015). The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 22.

Figure 3.22: Water main break location along with effected routes for case study #12

The main system has been pressured back up to meet the needs of the public and such that it does not pose an issue during the repair. The repairs were made to the damaged water main. These repairs are made sure for the water quality to be acceptable in that line and placed the line back in service.

Information on repair period and properties damaged due to flooding was available and are used to estimate the impact costs of repair and return to service and property damage. Data inputs including lost water volume, outage period, repair cost, number of repair personnel on scene, customers affected due to supply outage were deduced reasonably to estimate cost effects of repair and return to service and property damage are calculated using the available information. Assumptions are made considering location factor, traffic volume of the affected routes. Cost associated with the break is categorized and showed in Table 3.13.

Percentage distribution of overall impact costs for this case study is shown in Figure 3.23. From COWAMB analysis over the water main break costs, it is concluded that only 38% of the total costs are accounted as direct costs and 62% as indirect costs. Total of 3 million is estimated as the loss due to the water main break.

Table 3.13: Cost of Various Failure Impacts in Case Study #12

Category	Cost
Lost Product	\$ 108,219.10
Repair and Return to Service	\$ 1,017,538.46
Travel Delay	\$ 357,600.00
Customer Outage & Substitution Expenses	\$ 286,941.60
Health Cost	\$ 221,609.20
Property Damage	\$ 1,028,933.55
TOTAL	\$ 3,020,841.91

Figure 3.23: Percentage distribution of overall impact costs in case study #12

Since the break effected nearly eight schools in the vicinity, property damage costs have been extensively 34% of the overall costs. Repair and return to service costs of the break are also been equally effective as property damage.

Case study #13: Frankford, Philadelphia, Pennsylvania, 2013:

A 1220 mm pipeline ruptured in the Frankford, Philadelphia, Pennsylvania. Schools, hospitals and dare care centers faced disruptions due to the break which occurred in the area of Frankford and Torresdale Avenue (Abrams et al, 2013). The 1220mm water main was attached to a 1524mm pipeline, ruptured just before 9:00 a.m. and the break was under control by 11:30 a.m. which was losing water at a rate of 567811 m³ a day (Action News, 2013). The Philadelphia School District dismissed more than 30 schools due to the break and six homes were temporarily evacuated. The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.24.

Figure 3.24: Water main break location along with effected routes for case study #13

Due to the break which occurred 20 feet below the ground, several day care centers have been evacuated. Several bus routes have been detoured due to the severity of the break.

Data inputs including lost water volume, properties damaged due to break were available and are used to estimate the impact cost of lost product, property damage. Information on outage period, repair period, repair cost, number of repair personnel on scene, population affected due to supply outage, and population at risk were deduced. Cost associated with the break is categorized and showed in Table 3.14.

Table 3.14: Cost of Various Failure Impacts in Case Study #13

Category	Cost
Lost Product	\$ 42,445.43
Repair and Return to Service	\$ 1,012,276.92
Travel Delay	\$ 405,000.00
Customer Outage & Substitution Expenses	\$ 76,726.00
Health Cost	\$ 89,400.36
Property Damage	\$ 453,676.98
TOTAL	\$ 2,079,525.69

Percentage distribution of overall impact costs for this case study is shown in Figure 3.25. From COWAMB analysis over the water main break costs, it is concluded that only 51% of the total costs are accounted as direct costs and 49% as indirect costs. Total of 2 million is estimated as the loss due to the water main break.

Figure 3.25: Percentage distribution of overall impact costs in case study #13

Since the break occurred 20 feet below ground, the time taken to repair and cost invested in repairs have been significant. Cost for repair and return to service is estimated to be 49% of the overall cost. As many schools, day care centers are effected due to the break, property damage has also been effective in this case with 19% of the overall cost.

Case study #14: West Kensington, Philadelphia, Pennsylvania, 2012 :

The 1220mm water main break has happened at the intersection of Front and Tioga Streets in the city's West Kensington Section. Occurring at 7:00 a.m. break has flooded the Front Street leaving many cars under water. Six houses had to pump out water from their basements due to the break. Though break repairs were completed by the end of the day, the Water Department stated that it takes several weeks to completely fix the intersection and are also planning to replace 20 miles of the 100-year-old pipe (Beck et al., 2012). The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.26.

Figure 3.26: Water main break location along with effected routes for case study #14

Properties damaged due to flooding information was available and is used to estimate the impact cost of property damage. Lost water volume is calculated from pipe diameter, operational pressure and containment period. Other significant data inputs including outage period, repair period, repair cost, number of repair personnel on scene, customers affected due to supply outage, and population at risk were deduced to estimate impact costs of travel delay, substitution expenses, health risk expenses. Cost associated with the break is categorized and showed in Table 3.15.

Percentage distribution of overall impact costs for this case study is shown in Figure 3.27. From COWAMB analysis over the water main break costs, it is concluded that only 50% of the total costs are accounted as direct costs and 50% as indirect costs. Total of 2 million is estimated as the loss due to the water main break.

Table 3.15: Cost of Various Failure Impacts in Case Study #14

Category	Cost
Lost Product	\$ 88,071.63
Repair and Return to Service	\$ 1,008,769.23
Travel Delay	\$ 478,800.00
Customer Outage & Substitution Expenses	\$ 63,310.80
Health Cost	\$ 38,303.86
Property Damage	\$ 508,783.01
TOTAL	\$ 2,186,038.52

Figure 3.27: Percentage distribution of overall impact costs in case study #14

Since it took several weeks to completely fix the intersection of Front and Tioga Streets where the break has occurred and also several homes and infrastructure around the location of the break have been damaged due to the break, cost effects of repair and return to service, property damage and travel delay have been extensive. They are estimated to be 46%, 24% and 23% of the overall costs due to break.

Case study #15: Louisville, Kentucky, 2011:

A 1220 mm pipeline broke in Louisville, Kentucky. Around 6:00 p.m. the break was reported at Floyd and Warnock streets near University of Louisville which left several thousand homes and business without water and brought low water pressure to many other customers across a widespread area. Original estimate states that the impact of water main break was on 75,000 people without water service (Gazaway, 2011). Planned backup for all the three hospitals in the break area could not effect patients in the hospitals. Restaurant chain along Bradstown Road in the highlands were closed due to the water problems. Water pressure in the pipelines were bought back to normal around 3:00 a.m. The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.28.

Figure 3.28: Water main break location along with effected routes for case study #15

Customers due to supply outage, population at risk and properties damaged due to flooding information was available from multiple sources. Lost product is estimated

assuming the operational pressure of the main and reported response time to control the flow. Data inputs including repair period, outage period, repair cost, number of repair personnel on scene were deduced to estimate the impact costs of travel delay, substitution expenses. Cost associated with the break is categorized and showed in Table 3.16.

Table 3.16: Cost of Various Failure Impacts in Case Study #15

Category	Cost
Lost Product	\$ 280,994.15
Repair and Return to Service	\$ 754,603.85
Travel Delay	\$ 58,500.00
Customer Outage & Substitution Expenses	\$ 97,713.00
Health Cost	\$ 103,074.98
Property Damage	\$ 328,192.39
TOTAL	\$ 1,623,078.36

Percentage distribution of overall impact costs for this case study is shown in Figure 3.29. From COWAMB analysis over the water main break costs, it is concluded that only 64% of the total costs are accounted as direct costs and 36% as indirect costs. Total of 1.6 million is estimated as the loss due to the water main break.

Repair and return to service expenses and property damage due to the break are the two categories to cover the major share in the overall loss due to the break. This is due to Bradstown road is severely damaged and several homes, hospitals and restaurants are effected due to the break.

Figure 3.29: Percentage distribution of overall impact costs in case study #15

Case study #16: Old City, Pennsylvania, 2012:

A 914 mm pipeline ruptured in Old City, Pennsylvania. Break was reported around 12:30 a.m. near 3rd and Walnut streets which left more than 3785.41178 m³ onto the streets at a high rate of pressure and turned the streets into streams. No injuries were reported due to the break but low water pressure situation with a little damage to the property was reported by the residents. The break was under control within 90 minutes with the help of several utility companies. Due to the break the intersection of 3rd and Walnut streets remained close from Locust to Chestnut along 3rd, 2nd and 4th on Walnut street (Action News, 2012). The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.30.

Figure 3.30: Water main break location along with effected routes for case study #16

Lost water volume, containment period, and population at risk data was available and used to estimate impact costs of lost product, health risk. Information like repair period, outage period, repair cost, number of repair personnel on scene, and properties damaged due to flooding were deduced to estimate the impact costs of repair and return to service, substitution expenses, health risk expenses and property damage. Cost associated with the break is categorized and showed in Table 3.17.

Percentage distribution of overall impact costs for this case study is shown in Figure 3.31. From COWAMB analysis over the water main break costs, it is concluded that only 57% of the total costs are accounted as direct costs and 43% as indirect costs. Total of 1 million is estimated as the loss due to the water main break.

Table 3.17: Cost of Various Failure Impacts in Case Study #16

Category	Cost
Lost Product	\$ 71,146.82
Repair and Return to Service	\$ 504,384.62
Travel Delay	\$ 189,000.00
Customer Outage & Substitution Expenses	\$ 44,148.00
Health Cost	\$ 26,821.08
Property Damage	\$ 181,971.69
TOTAL	\$ 1,017,472.21

Figure 3.31: Percentage distribution of overall impact costs in case study #16

3rd and Walnut streets are closed from Locust to Chestnut along 3rd, 2nd and 4th on Walnut Street due to the break. This effects the costs of repair and return to service costs, travel delay and thus they cover major share in the overall costs as 50% and 19% respectively.

Case study #17: Robbinsdale, Minnesota, 2014:

A 914 mm cast iron pipeline broke in the streets of Manhattan, New York. Break has occurred at County Road 9, also known as 42nd Avenue N. which is between Hwy. 100 and W. Broadway. County Road 9 was shut down after water main break sent 2271.2 m³ of water gushing into the streets. Department crew worked on Friday to assess the damage and repair about half a mile of County Road 9 (Smith, 2014). Many complaints were reported from residents as the water main break blocked sewer lines. This massive water main break left the County Road 9 under repair for several weeks. The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.32.

Figure 3.32: Water main break location along with effected routes for case study #17

Lost water volume, repair cost information was available and is used to calculate the impact costs of lost product, repair and return to service. Data inputs including repair period, outage period, number of repair personnel on scene, population affected due to

supply outage, population at risk, and properties damaged due to flooding were deduced reasonably. Cost associated with the break is categorized and showed in Table 3.18.

Table 3.18: Cost of Various Failure Impacts in Case Study #17

Category	Cost
Lost Product	\$ 272,678.04
Repair and Return to Service	\$ 507,815.38
Travel Delay	\$ 3,104,000.00
Customer Outage & Substitution Expenses	\$ 246,120.00
Health Cost	\$ 190,960.52
Property Damage	\$ 3,108,103.64
TOTAL	\$ 7,429,677.59

Percentage distribution of overall impact costs for this case study is shown in Figure 3.33. From COWAMB analysis over the water main break costs, it is concluded that only 11% of the total costs are accounted as direct costs and 89% as indirect costs. Total of 7.4 million is estimated as the loss due to the water main break.

County Road 9 left under for repairs for several weeks due to the break which effects the indirect cost to public interims of travel delay. Closure of a road leads to detouring and lot of time is being utilized more than normal. This effect is computed interims of cost as travel delay expenses. Also due to the loss of 2271.2 m³ of water resulted in flooding and thus estimated property damage expenses is 42% of the overall loss due to the break.

Figure 3.33: Percentage distribution of overall impact costs in case study #17

Case study #18: Salt Lake City, Utah, 2014:

A 1220 mm pipeline ruptured in Salt Lake City, Utah. Estimated lost product due to the break was reported to be 9463.52946 m³ (Goodell, 2014). Break has occurred just before 9 p.m. near Foothill Drive at 1700 South which left rushing water into the streets and impacted several homes and caused substantial damage to Montessori community school and some other nearby businesses. Reports state that 18 residential properties experienced flooding along with other schools and communities (Leonard et al., 2014). All the impacted properties received assistance with damage mitigation. Break has caused the intersection at 1700 South and Foothill Drive closed through the weekend for repairs. The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.34.

Figure 3.34: Water main break location along with effected routes for case study #18

Information on lost water volume, properties damaged due to flooding, and repair period was available from multiple sources. Data inputs including outage period, repair cost, number of repair personnel on scene, population affected due to supply outage, and population at risk information was not available and are deduced accordingly. Cost associated with the break is categorized and showed in Table 3.19.

Percentage distribution of overall impact costs for this case study is shown in Figure 3.35. From COWAMB analysis over the water main break costs, it is concluded that only 49% of the total costs are accounted as direct costs and 51% as indirect costs. Total of 1 million is estimated as the loss due to the water main break.

Table 3.19: Cost of Various Failure Impacts in Case Study #18

Category	Cost
Lost Product	\$ 32,250.00
Repair and Return to Service	\$ 512,085.10
Travel Delay	\$ 153,900.00
Customer Outage & Substitution Expenses	\$ 132,577.68
Health Cost	\$ 80,563.83
Property Damage	\$ 202,500.00
TOTAL	\$ 1,113,876.60

Figure 3.35: Percentage distribution of overall impact costs in case study #18

Since the intersection at 1700 South and Foothill Drive closed for several days for repairs due to the break, the repair and return to service costs have been higher due to the increase in the number of working hours for the repair personnel. Loss due to repair accounted for 46% of the overall costs.

Case study #19: San Bruno, California, 2015:

A 1372 mm PCCP pipeline ruptured in San Bruno, California. 80-year-old water main reported a break shortly after 9:30 p.m. at the Junipero Serra County Park in San Bruno (Melendez, 2015). Estimated lost product due to the break was 56781 m³. Water coming from Crystal Springs Reservoir through the break was diverted by the department crew after 13-hour work. Drinking water for residents was kept safe by the department by allowing the system flowing (Weigel, 2015). As the break occurred inside the park, lost water entered a storm drain through an existing creek and finally leading into the bay. The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.36.

Figure 3.36: Water main break location along with effected routes for case study #19

Information on lost water volume, affected routes due to flooding and properties damaged was available. Data inputs like operational pressure of main, outage period, repair period, repair cost, number of repair personnel on scene, customers affected due to supply outage information was not available and so reasonably deduced. Cost associated with the break is categorized and showed in Table 3.20.

Percentage distribution of overall impact costs for this case study is shown in Figure 3.37. From COWAMB analysis over the water main break costs, it is concluded that only 39% of the total costs are accounted as direct costs and 61% as indirect costs. Total of 2.4 million is estimated as the loss due to the water main break.

Table 3.20: Cost of Various Failure Impacts in Case Study #19

Category	Cost
Lost Product	\$ 195,000.00
Repair and Return to Service	\$ 769,292.31
Travel Delay	\$ 151,200.00
Customer Outage & Substitution Expenses	\$ 319,814.00
Health Cost	\$ 194,592.54
Property Damage	\$ 822,000.00
TOTAL	\$ 2,451,898.85

As 56781 m³ is water is gushed into the streets due to the break, properties around the location of the break are estimated to be severely affected. Loss due to property damage is estimated to be 34% of the overall loss, which is higher than the remaining categories.

Figure 3.37: Percentage distribution of overall impact costs in case study #19

Case study #20: West Philadelphia, Pennsylvania, 2015:

A 914 mm CIP pipeline broke in the streets of West Philadelphia, Pennsylvania. Break has occurred around 4:30 a.m. on 52nd Street in West Philadelphia sending large amount of water onto the streets West Philadelphia neighbourhood. Several homes and properties were evacuated as nearly 56781m³ of lost product was gushing into the streets (Beck, 2015). Nearly 50 properties, more than a dozen vehicles, several homes and whole street left extensively damaged due to the break. Though Water Department shut off water before 7:00 a.m. could not control the property damage and injuries (Action News, 2015). The water main break location and routes effected due to flooding and traffic delays are depicted in Figure 3.38.

Figure 3.38: Water main break location along with effected routes for case study #20

Lost water volume, properties damaged due to flooding information was available from multiple sources. Information on repair period, outage period, repair cost, number of repair personnel on scene, customers affected due to supply outage were not available and these data inputs were reasonably deduced based on location factor, traffic volume and magnitude of the break. Cost associated with the break is categorized and showed in Table 3.21.

Table 3.21: Cost of Various Failure Impacts in Case Study #20

Category	Cost
Lost Product	\$ 83,081.59
Repair and Return to Service	\$ 1,010,523.08
Travel Delay	\$ 195,750.00
Customer Outage & Substitution Expenses	\$ 148,504.00
Health Cost	\$ 90,381.46
Property Damage	\$ 672,960.89
TOTAL	\$ 2,201,201.02

Percentage distribution of overall impact costs for this case study is shown in Figure 3.39. From COWAMB analysis over the water main break costs, it is concluded that only 50% of the total costs are accounted as direct costs and 50% as indirect costs. Total of 2.2 million is estimated as the loss due to the water main break.

Figure 3.39: Percentage distribution of overall impact costs in case study #20

Huge quantity of water was lost due to the break and this also effected several homes and other properties around the location of the break. Repair and return to service and property damage have been extensive due to the break, which are estimated as 46% and 30% of the overall loss respectively.

CHAPTER 4: ANALYSIS

The overall costs of 20 water main breaks estimated using COWAMB model are analyzed for useful trends. Collective significance of each cost category is evaluated and factors that lead to the observed variances among the various failure cases are identified. Estimated overall impact costs for all the investigated 20 failure case studies is presented in Table 4.1. It can be noticed that the bounds of estimated overall impact costs ranged from \$1 million in case study #16 for a 36-inch steel pipeline failure to an estimated \$83.5 million in case study #5 for a 120-inch PCCP pipeline failure. The average impact cost over the 20 case studies is estimated to be about \$12 million.

Mean percentage distribution of the estimated overall impact costs among the six cost categories can be seen in Figure 4.1. It can be noticed from Figure 4.1 that the impact cost of health risk category accounted for the least with only 5% while the cost of repairing and return to service is estimated to account for about 35% of the overall failure costs. Other categories including property damages and travel delays accounted for 22% and 21% respectively, of the overall impact costs. While it is interesting to collectively analyze the gathered data, it is eminent that the 20 water main break cases analyzed in this study had substantial variance in the data with bounds of standard deviation ranging from 3.2 to 14.2 percentage points. For example, cost accounted for lost water is estimated to be nearly 40% of the overall impact cost in case study #6 while the mean percentage over the 20 cases for the same category is merely 6%, as can be noticed from Figure 4.1. The significant deviation in this particular case study is due to the larger pipeline diameter (3050mm) and longer time taken to isolate the failed section.

Table 4.1: Impact related data for water main break cases

CASE	Month/Year	Diameter (mm)	Lost Product (m ³)	Repair Time (hr)	Operating Pressure (psi)	Overall Cost (\$ Million)
1	Sep. 2015	914	6,814	6	110	3.3
2	Jul. 2015	762	45,264.53	238	200	28.8
3	Mar. 2015	1,524	227,125	144	120	21.9
4	Jan. 2015	1,372	189,270	17	125	16
5	May 2015	3,048	10,031,341	60	150	85.3
6	Sep. 2015	1,830	138,112.77	24	110	7.2
7	Feb. 2015	1,676	7,571	264	110	18.6
8	Dec. 2015	1,676	170,344	96	118.6	11.4
9	Jun. 2015	1,066	37,597.36	10	110	4.3
10	Jan. 1998	1,220	159,596.98	10	110	9.5
11	Mar. 1996	2,438	283,906	72	115	9.8
12	Jan. 2015	914	32,256	48	150	3
13	Dec. 2015	1,220	12,553	21	115	2.1
14	Aug. 2015	1,220	25,645	12	120	2.2
15	Jul. 2015	1,220	83,100	12	140	1.6
16	Oct. 2015	914	20,717	6	110	1
17	Sep. 2015	914	80,640	504	150	7.4
18	Oct. 2015	1,220	9,464	21	130	1.1
19	Jul. 2015	1,372	56,781	24	110	2.5
20	Jun. 2015	914	24,192	12	150	2.2

Figure 4.1: Mean percentage distribution of overall costs

In general, it has been found that several parameters including pipe diameter, property damage are decisive in influencing the overall costs of large diameter water main failures, but few input parameters were highly correlated to the overall impact costs. With estimated correlation coefficient values of 0.92 and 0.91 and p-values less than 0.05 in both cases, “lost water volume” and “population affected from supply outage” respectively, are found to be highly correlated to the overall costs. Next highly correlated parameter is found to be “pipeline diameter” which resulted in having a correlation coefficient of 0.7 with p-value much less than 0.005. No other significant parameters were found to be reasonably correlated with the overall impact costs. This elevates the prominence of widening the criteria taken into consideration for evaluating failure risk as part of water utility rehabilitation planning schemes.

The other fascinating element considered in the analysis is the comparison of direct versus indirect costs of the failure impacts. Loss in the revenue due to the lost

product and cost incurred in repairing and returning the pipe to service are the cost categories that are considered as direct costs. Indirect costs include health risk expenses, property damage and travel delay time experienced due to the break. Share of direct versus indirect costs are analyzed and illustrated in Figure 4.2. Overall average share of direct costs for the 20 case studies is nearly 41%, while the indirect costs accounted for 59% of the overall impact costs. Such distribution of direct and indirect costs may not be true in each case as in some cases, the indirect costs may also be borne by water utilities. For example, if there is an extensive property damage reported due to the water main break, compensation may be provided by the water utilities. In some case due to the longer repair times of the failed pipelines, temporary service connections may be provided by water utilities using ad-hoc arrangements. Percent share of indirect costs could be lower than 59%, if such exemptions are made by the utilities. It should be noted that, due to lack of adequate data, damage claims were not included in the overall costs calculated in this study.

Figure 4.2: Percentage distribution of direct vs. indirect costs of water main breaks

Clearly, consideration of indirect costs would make a significant difference to rehabilitation planning, making it more justifiable to rehabilitate or replace pipelines before they fail. Needing to rehabilitate or replace more pipelines will require more financial capital. Given the lack of adequate funding available with public water utilities to invest in maintenance and capital improvement planning, it is debatable whether to consider the overall costs or just the costs that the utility is directly responsible for.

CHAPTER FIVE

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

Providing sustainable access to safe drinking water for public has become a challenge for water utilities. Drinking water systems in the United States have been aging and this could affect the environmental, public health, and economic gains if not attended to in a timely manner. About 240,000 water main breaks occur annually in the United States (ASCE, 2013). Consequences of these failures have been significant due to the multi-fold dependence of communities on reliable water service. Especially, the indirect costs of the failure consequences, which are endured by the society, are considerable and there is a need to assess the overall costs of these failures to appropriately inform rehabilitation planning of water infrastructures. To address this need, this study adapted a previously proposed failure cost estimating model and estimated the overall costs of 20 large diameter water main failures in the U.S.

Cost analysis of the 20 water main failures revealed that the overall impact costs ranged from \$1 million to \$85.3 million with a mean value of about \$12 million. It was found that “lost product” due to a water main break and “the number of customers that are affected due to the supply outage” are highly correlated with the overall impact costs. The share of indirect cost was found to be 59% on average over the 20 water main failures. Including indirect costs in asset management and rehabilitation planning practices will most likely allow the benefits to outweigh the costs of rehabilitation. It should however be noted that this may result in the greater number of pipelines needing

replacement, which aggravates the need for financial capital. From analyzing the overall impact costs of the 20 case studies, some recommendations are made to minimize the overall failure impact costs:

1. Maintaining less operating pressures in aged main sections.
2. Utilities with improved monitoring efficiency of network performance to recognize and detect failures as soon as they occur
3. Increase in the number of valves or placing valves to enable isolation of smaller sections of failed pipelines
4. Improving redundancy of the network to compensate the loss of a crucial asset during the time of repair
5. Preparation with temporary water supply alternatives to counteract the failure effects.
6. Attentiveness to reduce failure repair times

Due to the unavailability of sufficient data, numerous assumptions had to be made while analyzing the costs in the failure case studies. Majority of these assumptions were chosen from the suggested ranges in the GCM model and made in favor of any specific failure case or water utility. To address the shortcoming of data unavailability, a standard data collection sheet should be distributed to all the water utilities so that all relevant data is recorded in a timely manner when it is available or easy to determine. The standardized data collection will lead to a large database of overall impact costs of water main breaks which will be much more informative than the findings of this study. Nevertheless, the estimated overall impacts due to the failures may not be far from the actual values, but

could be different due to the uncertainties with some data inputs. Due to the uncertainties with some data inputs, the results of the case studies are recommended to be used with caution. Other limitation of the study is that the overall impact costs of only 20 water main breaks have been documented, while an estimated 240,000 water mains break annually in the U.S. Consequently, the findings of this study are based on a very small sample and that too not random enough to have statistical significance. It is recommended that more case studies are documented in the future to enable Meta-analysis of the impact cost for producing useful trends.

REFERENCES

- (1) Parker, R. 2014. "West Hollywood water main break gushes 9,600 gallons of water per minute," Accessed at <<http://www.latimes.com/local/lanow/la-me-ln-water-main-break-sunset-strip-20140926-story.html>>
- (2) Hailey B. Potts and Ryan Parker, Las Vegas Sun News. 2014. "Water-main break floods Hollywood's Sunset Strip," Accessed at <<http://www.lasvegassun.com/news/2014/sep/26/water-main-break-floods-hollywoods-sunset-strip/>>
- (3) Lloyd, J. 2014. "20M Gallons of Water Lost in UCLA Main Break," Accessed at <[http://www.nbclosangeles.com/news/local/Water-Main-Break-Floods-UCLA-Campus-Sunset Boulevard-Closed-269200881.html](http://www.nbclosangeles.com/news/local/Water-Main-Break-Floods-UCLA-Campus-Sunset-Boulevard-Closed-269200881.html)>
- (4) Shaver, K. 2013. "Water main bursts in Chevy Chase, Md., despite break-detection equipment," Accessed at <http://www.washingtonpost.com/local/water-main-break-shuts-down-connecticut-avenue-in-chevy-chase/2013/03/19/e703a426-907b-11e2-9abd-e4c5c9dc5e90_story.html>
- (5) Washington Suburban Sanitary Commission (WSSC). 2011. "Setback Recommendations Report," Accessed at <<http://www.wsscwater.com/file/EngAndConst/80footsetbackparts/part3.pdf>>
- (6) Jacquelyn Martin, The Washington Times. 2011. "Water main break closes Beltway in P.G. County," Accessed at <<http://www.washingtontimes.com/news/2011/jan/24/water-main-break-closes-beltway-pg-county/>>

- (7) Levenson, M. 2010. "A 'catastrophic' rupture hits region's water system," Accessed at <http://www.boston.com/news/local/massachusetts/articles/2010/05/02/a_catastrophic_rupture_hits_regions_water_system/>
- (8) Henry, D. 2010. "Ruptured Pipe Cuts Water in Boston," Accessed at <http://www.nytimes.com/2010/05/03/us/03boston.html?_r=1&>
- (9) Hirsch, A. 2009. "Cleaning Up-As Workers Pump Out The Last Of Dundalk's Flooded Homes, An Expert Warns That More Pipes Are Sure To Fail," Accessed at <http://articles.baltimoresun.com/2009-09-20/news/0909190126_1_baltimore-county-water-main-type-of-pipe>
- (10) Mark Belcher, The Denver Channel. 2008. "NB I-25 Reopens Next To Sinkhole," Accessed at <<http://www.thedenverchannel.com/news/nb-i-25-reopens-next-to-sinkhole>>
- (11) McPhee, M. 2008. "Hole lot of delays on I-25," Accessed at <http://www.denverpost.com/ci_8202776>
- (12) Lovino, J. 2008. "'Wall of Water' Traps Motorists on Maryland Road," Accessed at <<http://www.nbcwashington.com/news/archive/Large-Water-Main-Break-Reported-in-Montgomery-Co.html>>
- (13) Clary, M. 2011. "Main break on Christmas Eve makes blood pressure rise, water pressure drop," Accessed at <http://articles.sun-sentinel.com/2011-12-25/news/fl-water-main-break-20111225_1_precautionary-boil-water-notice-water-order-water-pressure>
- (14) Reuters, Los Angeles Times. 1998. "5th Avenue Water Main Break, Gas Blast Disrupt Manhattan Traffic," Accessed at <<http://articles.latimes.com/1998/jan/03/news/mn-4588>>

- (15) Belt, D. 2015. "Decatur Schools Make Decision on Friday Classes," Accessed at <<http://patch.com/georgia/decatatur/decatatur-schools-make-decision-friday-classes>>
- (16) Action News. 2013. "Massive Water Main Break Floods Frankford," Accessed at <<http://6abc.com/archive/9369654/>>
- (17) Abrams, M. and Chowdhry, S. 2013. "Large Water Main Break Floods Frankford," Accessed at <<http://philadelphia.cbslocal.com/2013/12/23/crews-responding-to-water-main-break-at-northeast-philadelphia-intersection/>>
- (18) Mike, D. and Beck, S. 2012. "48-inch Water Main Break In West Kensington," Accessed at <<http://philadelphia.cbslocal.com/2012/08/01/water-main-break-in-philadelphia/>>
- (19) Gazaway, C. 2011. "75,000 People Without Water After Large Water Main Break," Accessed at <<http://www.wave3.com/story/15062672/large-water-main-break-at-floyd-and-warnock>>
- (20) Action News. 2012. "36-inch Water Main Break In Old City," Accessed at <<http://abclocal.go.com/story?section=news/local&id=8846238>>
- (21) Smith, K. 2014. "County Road 9 Shutdown In Robbinsdale As Crews Fix Water Main Break," Accessed at <<http://www.startribune.com/county-road-9-remains-shut-down-in-robbinsdale-after-water-main-break/275803701/>>
- (22) Goodell, A. 2014. "Water Main Break Sends Estimated 2.5 Million Gallons Into Homes, A Nearby School," Accessed at <<http://fox13now.com/2014/10/10/roads-closed-due-to-water-main-break-near-1700-south-foothill-drive/>>
- (23) Leonard, W. and Joi O'Donoghue, A. 2014. "Foothill Boulevard To Partially Reopen After Pipeline Break," Accessed at <<http://www.deseretnews.com/article/865612925/Foothill-residents-crews-dig-out-flooded-homes-after-water-main-break.html>>

- (24) Melendez, L. 2015. "15 Million Gallons Of Water Lost In San Bruno Main Break," Accessed at <<http://abc7news.com/news/15-million-gallons-of-water-lost-in-san-bruno-main-break/889900/>>
- (25) Weigel, S. 2015. "Final Pipe Laid In \$4.8 Billion Seismic Upgrade: San Francisco Public Utilities Commission Replaces San Bruno Line, Is Nearing End Of Water System Improvement Program," Accessed at <<http://www.smdailyjournal.com/articles/news/2015-09-09/final-pipe-laid-in-48-billion-seismic-upgrade-san-francisco-public-utilities-commission-replaces-san-bruno-line-is-nearing-end-of-water-system-improvement-program/1776425149855.html>>
- (26) Action News. 2015. "Cleanup Work Underway After Massive Water Main Break in West Philadelphia," Accessed at <<http://6abc.com/news/cleanup-underway-after-west-phila-water-main-break/783385/>>
- (27) Beck, S. 2015. "Millions Of Gallons Of Water Flow After Water Main Break In West Philly," Accessed at <<http://www.nbcphiladelphia.com/news/local/Water-Main-Break-West-Philadelphia-Water-Department-52nd-Street-307289801.html>>
- (28) Cromwell, J., Reynolds, H. and Young, K. 2002. "Costs of Infrastructure Failures," AwwaRF and AWWA, Denver, CO, 2002.
- (29) Raymond E. Davis, Harvey H. Jordan. "The Orifice As A Means Of Measuring Flow Of Water Through Pipe", University Of Illinois Bulletin. 1918.
- (30) District of Columbia Water and Sewer Authority, "District of Columbia Water and Sewer Authority refunds \$389.1 million of public utility subordinate LEN revenue bonds, Series 2016A (tax-exempt)," 2016.
- (31) NW Financial Group LLC, Why the Bayonne water/wastewater public-private partnership succeeded, April 1, 2013.