UNIVERSITY OF TORONTO

BRIDGING THEORIA AND PRAXIS:
PERFORMANCE ASSESSMENTS OF WATER
TRANSMISSION AND DISTRIBUTION SYSTEMS

BY

GEORGE L. ILLASZEWICZ

A THESIS
SUBMITTED TO THE FACULTY OF
APPLIED SCIENCE AND ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF MASTER OF APPLIED SCIENCE

© GEORGE L. ILLASZEWICZ

DEPARTMENT OF CIVIL ENGINEERING

TORONTO, ON
COPYRIGHT 2009
Bridging Theoria and Praxis: Performance Assessments of Water Transmission and Distribution Systems

George L. Illaszewicz

Master of Applied Science in Civil and Environmental Engineering
Department of Civil Engineering
University of Toronto

Copyright 2009

Abstract

This thesis is broken into two parts. The first part, Chapters 1 - 7, focuses on work completed performing partial performance assessments in two case studies: the region of Peel in the Greater Toronto Area, and Tláhuac, Mexico. In both, pressure transients were monitored using high-speed sensors. The second part, Chapters 8 - 10, proposes a framework for performance assessments of water transmission and distribution systems, primarily applicable to analysis and operation yet useful in (re)design or additional design work as well. The framework is a synthesis of concepts ranging from fuzzy engineering to psychology and human factors, and will be of particular interest to larger, more sophisticated water utilities who may have a general understanding of their systems but lack specific insights in its operation and operational effectiveness. Careful consideration is given to not only the type of information and possible information fusion, but also details of necessary software and hardware, including possibilities for the system architecture.
Acknowledgements

I would like to humbly confess that the completion of this Master’s degree and thesis was a simple endeavor, and I did it without any significant challenges or effort whatsoever… however, that would be a lie and thus I cannot. It turns out that it’s harder to convince your conscience to accept such falsehoods than one might think.

Trust me: I tried.

In truth, this thesis marks a significant milestone [1 pg. 158] on my journey to understanding. I began this degree with a feeling of incompleteness about my knowledge and education from undergrad. I finish it, feeling even more incomplete. This, I have come to realize, is not a criticism of the system but rather a compliment towards it, and even an indication of my personal growth. They say the more you learn, the more you learn you don’t know. But despite having not yet found the peace of mind I sought, my intellectual fulfillment, I fully believe that these past two years have been worth every second. Though I may feel more incomplete, I know I will leave with a deeper understanding of the world, of the theories and science behind my practice, of the people and technologies, of the philosophies, and of myself. While I owe a great debt of gratitude to those who helped me along this path, for today I hope it will suffice that I simply place it here in words.

There are many to whom I am indebted within the academic world, but I would be remiss if I did not thank four professors in particular. Professor K.D. Pressnail, who not only
supervised my undergraduate thesis and even agreed to act as a reference for my grad school application after that, has been a huge support throughout both my undergraduate and graduate studies. Professor E.C. Bentz has also had a great impact on me. His energetic teaching style has aided in my understanding of difficult concepts, and conversations we’ve had from the random to the abstract have been everything from entertaining to enlightening. Not least of all, however, he agreed to act as my other reference for my Masters application. I also owe a great debt of gratitude to Professors T.E. El-Diraby and B.W. Karney. To Professor Karney I owe thanks not only for agreeing to co-supervise me, providing me with direction and imparting me with a great deal of information and knowledge, but also for suggesting this field of risks and interdependencies and referring me to Professor El-Diraby. I owe as many thanks to Professor El-Diraby, who agreed to both co-supervise AND fund me (which, as a starving grad student, is a matter of no small importance.) Professor El-Diraby has helped me find my direction and supported my efforts throughout, and I’m glad that at the very least I was able to entertain him with my Northern background and “outlandish” Macintosh affiliations. I would like to extend a generic “thank you” to my colleagues as well, though there are far too many that have impacted and enriched my personal, professional, and academic lives to thank everyone individually.

I am also grateful for my friends and family outside the academic world. They have supported my endeavors with all the faith and patience that one could hope for, and then some in excess! Since I have never been the best for timing, there are two people in particular in my family that I wish to address that I regret having not done so earlier.
Though they may never have realized it, and now will never get the chance to know, both were and continue to be huge role models inspirations to me. My Babcia and Dziadzio were both impressive individuals, extremely smart and focused. I sincerely hope that I can live a life even half as full as theirs were, and am able to have even a fraction of the impact upon the world as they did.

Of my friends, I would like to make special mention of my girlfriend. She has helped me summon the energy to jump past this last hurdle, and given me immense support and motivation. Her faith in me has pushed me past points where I might simply have given up and quit on my own. She even claims that this thesis is much better than the abomination I make it out to be! She really is a sweetie... naïve, perhaps, but a sweetie nonetheless.

Finally, in my B.A.Sc. thesis acknowledgements I arrogantly proclaimed that anybody who I had accidentally omitted would be remembered and identified here in my next thesis. To that end I would also like to thank you, future reader, and in fact every stranger I have never met or may never meet. While I may not know you, your impact on my life has been no less for it… and so, from the bottom of my heart, I thank you too.
Table of Contents

Abstract ............................................................................................................................... ii
Acknowledgements ........................................................................................................ iii
Table of Contents ............................................................................................................. vi
List of Appendices .......................................................................................................... xi
List of Tables ................................................................................................................... xii
List of Figures .................................................................................................................. xiii
List of Equations ............................................................................................................. xiv
Nomenclature .................................................................................................................. xv

Chapter 1: Thesis .............................................................................................................. 1
  1.1 Goal ......................................................................................................................... 3
  1.2 Significance .............................................................................................................. 4
  1.3 Approach ................................................................................................................ 5
  1.4 Structure ................................................................................................................ 6

Chapter 2: Literature Review ............................................................................................ 10

Chapter 3: Data Collection ............................................................................................... 34
  3.1 Generic Process for Asset Management ................................................................. 35
  3.2 Methods of Data Collection .................................................................................... 36
    3.2.1 Manual Collection ........................................................................................... 36
    3.2.2 Automated Collection ................................................................................... 37
    3.2.3 Simulation/Modeling ..................................................................................... 37
  3.3 Summary ................................................................................................................ 38

Chapter 4: Professional Context and Case Studies .......................................................... 39
  4.1 Scope ....................................................................................................................... 40
  4.2 Case Study 1: Region of Peel, Greater Toronto Area, Ontario, Canada ................. 42
  4.3 Case Study 2: Tláhuac, Mexico City, Mexico ......................................................... 43
  4.4 Summary ................................................................................................................ 45

Chapter 5: Preliminary Results and Statistics .................................................................. 46
  5.1 Limitations of Present Work ................................................................................... 47
  5.2 Statistical Analyses ............................................................................................... 47
5.3 Case Studies
5.3.1 Peel Region
5.3.2 Tláhuac
5.4 Summary

Chapter 6: Discussion
6.1 Evaluation of Results
6.2 Lessons Learnt
6.2.1 Peel Region Case Study
6.2.2 Tláhuac Case Study
6.3 Summary

Chapter 7: Conclusions and Recommendations
7.1 Lifeblood of Society
7.2 Summary and Opportunities for Future Work

Chapter 8: Performance Boundaries
8.1 Introduction
8.2 Stakeholder Analysis
8.3 System Components
8.3.1 Raw Water Source
8.3.2 Raw Water Storage
8.3.3 Raw Water Treatment
8.3.4 Treated Water Storage
8.3.5 Piping – General
8.3.6 Piping – In-plant Piping
8.3.7 Piping – Transmission Lines
8.3.8 Piping – Distribution Lines
8.3.9 Piping – Services
8.3.10 Valves and Appurtenances
8.3.11 Pumps
8.4 System Utility and Requirements
8.4.1 Water Quality
8.4.2 System Capacity
11.4.4 Multi-Attribute Utility Theory (MAUT) Analysis ........................................ 147
11.4.5 Simple Multi Attribute Rating Technique (SMART)................................. 147
11.5 Aids for the Decision Process ....................................................................... 148
  11.5.1 Stakeholder Analysis .............................................................................. 148
  11.5.2 Defining a Problem ............................................................................... 153
  11.5.3 Determining Goals and Requirements .................................................... 155
  11.5.4 Determining Alternatives ...................................................................... 156
  11.5.5 Choosing Criteria .................................................................................. 156
  11.5.6 Sensitivity Analyses .............................................................................. 157
  11.6 Summary ..................................................................................................... 158
Chapter 12: References ...................................................................................... 159
List of Appendices

APPENDIX A: Appendix Index ................................................................. A
APPENDIX B: Maps of Peel Region Installations ........................................ B
APPENDIX C: Maps of Mexico City Installations ..................................... C
APPENDIX D: Images and Pictures ......................................................... D
APPENDIX E: TP-1 Methodologies and Procedures ................................. E
List of Tables

Table 1: Monitored Parameters in the Paris Water Distribution System ....................... 24
Table 2: Basic Technological Tools and their Applications ........................................ 26
Table 3: Peel Region Sensor Installation Details ......................................................... 43
Table 4: Tláhuac Sensor Installation Details ............................................................... 44
Table 5: Number of Unique Transient Events vs. Separation Criteria ......................... 49
Table 6: Causes and Problems of Intermittent Supply ................................................. 59
Table 7: Indicators of Water Quality ........................................................................... 80
Table 8: Monitoring Methods for Water Quality Indicators ........................................ 81
Table 9: Parameters for Real-Time Observation ......................................................... 86
Table 10: Categories of Monitored Parameters ............................................................ 97
Table 11: Measurement Scales ..................................................................................... 101
Table 12: Sensor Technologies and Discernable Parameters ...................................... 124
Table 13: Example of Normalized Criteria Weights for the AHP ............................... 146
List of Figures

Figure 1: System and Interdependencies Map ................................................................. 2
Figure 2: Generic Performance Assessment Process .......................................................... 35
Figure 3: Infrastructure Lifecycle ..................................................................................... 41
Figure 4: Number of Events vs. Separation Definition for Permanent Installations ....... 50
Figure 5: Number of Events vs. Separation Definition for Temporary Installations ...... 51
Figure 6: Number of Events vs. Separation Definition for Temporary Installations ...... 51
Figure 7: Interior Sensor Installation .............................................................................. 55
Figure 8: Outdoor Sensor Security .................................................................................. 55
Figure 9: Impacts of Environment ................................................................................... 87
Figure 10: Scorecard Metric Categories ......................................................................... 96
Figure 11: Polygon Visualization ................................................................................... 104
Figure 12: Histogram Visualization (1) .......................................................................... 106
Figure 13: Histogram Visualization (2) .......................................................................... 107
Figure 14: Non-Fuzzy and Fuzzy Scaling ....................................................................... 111
Figure 15: Wickens Model of Human Information Processing ..................................... 115
Figure 16: Architecture Formats .................................................................................... 122
Figure 17: Adoption of Innovations .............................................................................. 130
Figure 18: Rational Decision Making Process ................................................................. 135
Figure 19: Pooled Interdependence ................................................................................ 140
Figure 20: Sequential Interdependence .......................................................................... 141
Figure 21: Reciprocal Interdependence ........................................................................ 141
Figure 22: Failure Modes ............................................................................................... 142
Figure 23: Stakeholder Classification Model ................................................................. 148
Figure 24: Stakeholder Analysis Chart .......................................................................... 151
Figure 25: Stakeholder Analysis Matrix ....................................................................... 151
List of Equations

Eq. 2.1: Reliability ................................................................. 21
Eq. 2.2: Reliability in the Water Industry ................................ 21
Eq. 2.3: Simplified Reliability in the Water Industry ................ 21
Eq. 5.1: Annuity to Present Value .......................................... 144
Eq. 5.2: Growing Annuity to Present Value ............................. 145
Eq. 5.3: Future Value to Present Value .................................... 145
## Nomenclature

- **A**  – Area
- **A**  – Annuity value
- **AHP**  – Analytic Hierarchy Process
- **APWA**  – American Public Works Association
- **ASCE**  – American Society of Civil Engineers
- **AV**  – Air Valve
- **B**  – Baseline pressure record (TP1 System)
- **BCR**  – Benefit Cost Ratio
- **C**  – Hazen Williams Roughness Coefficient
- **CAD**  – Computer-Aided Design
- **CBA**  – Cost Benefit Analysis
- **CEA**  – Cost Effectiveness Analysis
- **CIS**  – Customer Information System
- **.csv**  – Comma-separated values format
- **CV**  – Check Valve
- **D**  – Diameter
- **DBP**  – Disinfection Byproduct
- **DO**  – Dissolved Oxygen
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>E.P.A.</td>
<td>Environmental Protection Agency (United States)</td>
</tr>
<tr>
<td>FT</td>
<td>Hydraulic Redundancy</td>
</tr>
<tr>
<td>FV</td>
<td>Future Value</td>
</tr>
<tr>
<td>g</td>
<td>growth rate (annuity)</td>
</tr>
<tr>
<td>GDBM</td>
<td>Georeferenced Data Base Manager</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>GWh</td>
<td>Gigawatt Hours ($10^9$ watt hours)</td>
</tr>
<tr>
<td>GWT</td>
<td>Groundwater Table</td>
</tr>
<tr>
<td>HAA</td>
<td>Haloacetic Acid</td>
</tr>
<tr>
<td>HOCl</td>
<td>Hypochlorous Acid</td>
</tr>
<tr>
<td>i</td>
<td>Interest rate</td>
</tr>
<tr>
<td>ICA</td>
<td>Instrumentation, Control and Automation systems</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>J</td>
<td></td>
</tr>
<tr>
<td>KBS</td>
<td>Knowledge Based Systems</td>
</tr>
<tr>
<td>kPa</td>
<td>Kilopascals</td>
</tr>
</tbody>
</table>
• L – Length
• LAN – Local Area Network
• LLPS – Low Lift Pump Station
• LZ – Reliability

• M – Number of Links
• MAUT – Multi-Attribute Utility Theory
• .mdb – Microsoft Database file format
• MPa – Megapascals

• n – Number of periods
• ND – “Not Supplied” Demand (m$^3$/day)
• NH$_4$ – Ammonium
• NPV – Net Present Value

• O&M – Operation & Maintenance

• pH – the base 10 logarithm of the inverse activity of hydrogen ions
• p(i, …) – Probability of link(s) (i, …) not being in service
• POF – Probability Of Failure (/day)
• POS – Period Out of Service (/day)
• PRV – Pressure-Reducing Valve
• psi – Pounds per Square Inch
• PV – Present Value
• PVB – Present Value of Benefits
• PVC – Present Value of Costs

• Q – Flow rate
• QDE – Quantitatively Directed Exploration

• R – Hydraulic Reliability
• RBE – Reliability-Based Exploration
• RSL – Remaining Service Life

• SAGAT – Situation Awareness Global Assessment Technique
• SART – Situation Awareness Rating Technique
• SCADA – Supervisory Control And Data Acquisition
• SMART – Simple Multi Attribute Rating Technique
• ST – Start of Transient event record (TP1 System)

• T – Sum of nodal demands;
• T – Transient record (TP1 System)
• TD – Maximum daily demand (m$^3$/day)
• THM – Trihalomethane
• T(i, …) – Total flow when link(s) (i, …) are not in service
• TOC – Total Organic Carbon
• TQM – Total Quality Management
• TRCA – Toronto and Region Conservation Authority

• U

• V

• WAN – Wide Area Network
• WDS – Water Distribution System(s)
• WHO – World Health Organization
• WTP – Water Treatment Plant

• X

• Y

• Z
Chapter 1:
Thesis

“We haven’t got the money,
so we’ve got to think!”

Ernest Rutherford
(1871-1937)
Figure 1: System and Interdependencies Map
1.1 Goal

Merriam-Webster defines performance as “the fulfillment of a claim, promise, or request” [2]. To clarify what this means in terms of water supply and distribution systems, the system must be examined from the perspective multiple stakeholders, including that of the client/consumer, that of regulating bodies, that of those responsible for regular operations and maintenance, and that of the utility owners. Each stakeholder has different objectives and requirements for the system. The holistic conceptualization of performance addresses the whole gamut of these issues.

The purpose of this thesis is to examine the implementation of transient pressure monitoring performance in water transmission and distribution systems, such as that portrayed in Figure 1. The significance of this is discussed in detail in Section 1.2, but in short, performance assessments aid in ensuring the operation and maintenance of the system is effective in meeting pre-defined objectives. It should be noted, however, that while this methodology and approach has been designed largely for water supply and distribution systems, many of these concepts and approaches could be expanded and remodeled for transmission and distribution systems of other fluids or waste collection/transmission systems like sewers. In later chapters, a conceptualization of issues related to assessing the overall performance of water supply and distribution systems are also cursorily presented as an effort to expand the reader’s perspective of the potential impact of this work.
1.2 Significance

The present approach for many water systems is too often to construct any required infrastructure and then forget about it until it breaks. Once it breaks (assuming the operators even notice that it broke) the decision may be made to repair the damage – or, the decision to continue using the system as it is may be made if the system still works well enough. Naturally, the loss of product and operational inefficiencies results in an economic\(^1\) loss throughout the period of operation. In addition, operating the system in a damaged state results in a loss of operational efficiency and efficacy.

This era has experienced massive environmental challenges that threaten to destroy (or, at least, to redefine) our way of life. Economic turmoil has thrown our financing methods upside down and forced owners and operators to reassess priorities. Social, cultural, and religious conflicts and confrontations (perhaps a less biased way to refer to such concepts as terrorism) have forced reexamination of the security of existing lines, equipment, and facilities. Infrastructure interdependencies, not only between infrastructure of the same type (i.e., connections between water distribution systems in neighboring regions) but also between categories of infrastructure (i.e., water/wastewater, transportation, power) only increase the complication of problems encountered today. With the magnitude of these and other challenges, it is clear why infrastructure owners, operators, and investors have begun pushing effective asset management practices.

\(^1\) Note: The term “economic” has been used here as an explicitly separate concept from “financial.” In many cases, losses may not be simply monetary in nature. “Economic loss” is inclusive of potential concurrent social, cultural, or environmental damages.
The rate at which current technological knowledge and abilities are advancing promises us the ability to better understand our infrastructure. SCADA systems are commonly used in controlling processes, but not fully used beyond the confines of treatment plants. With a greater understanding of the systems we rely upon, the more effectively we can operate and maintain them. This thesis seeks to develop a means to accurately and consistently assess the performance of water supply and distribution systems, expressing the desires of each stakeholder group and permitting both macro- and microscopic levels of examination of the system to assist in the identification of present and potential future problems, effective mitigation or avoidance strategizing, and general decision-making.

1.3 Approach

In *Water, Wastewater, and Stormwater Infrastructure Management* [3], it is suggested that a unified metric for assessing system performance is unfeasible for water distribution systems. Instead, a scorecard approach is recommended to assess infrastructure integrity. ASCE has developed a scorecard for all categories of America’s infrastructure (giving Drinking Water a D- for 2009, indicating between poor and failing [4]), but the idea of a scorecard expressly meant for water supply and distribution infrastructure is expanded and developed within this thesis. The primary goal of this work is to examine the implementation and some of the impacts of employing transient pressure sensors in system performance assessments. The scorecard developed afterwards (Chapters 8 to 10) is intended to be a high level conceptual view of implementing this in a larger, more holistic performance assessment framework that accurately represents everything from non-functional systems and system components to ideal perfect systems providing an
excellent product. Further, it was sought to design this framework with principles of human factors engineering and information processing models in mind, to simplify application in decision-making and minimize demands imposed on users. As the concept behind the scorecard is the capability to capture and display near real-time information, it has been labeled “dynamic” to represent the ever-changing nature. Further, since complete comprehensive information is rarely available, it seeks to merge this near real-time information with modeling approaches designed to fill in the gaps in data.

1.4 Structure

The structure of this thesis is intended to follow the experience of implementing a pressure transient monitoring network for a partial (structural or hydraulic efficiency) system performance assessment. Further a logical (though conceptual) path through the development and presentation of a dynamic scorecard for rating infrastructure performance is taken in later chapters. Additionally, the implementation of a dynamic scorecard using present day (2009) technologies is discussed and examples from existing systems are used to highlight various aspects of the approach. The general contents of each chapter are outlined below.

The current chapter introduces the overall goal of the thesis. It provides a general overview of the reasoning behind and impact of this thesis. The approach adopted is outlined, and the structure of the document is summarized.
Chapter 2 provides a brief review of literature relevant to the thesis. The areas of performance assessments and asset management are enormous, and thus it is impossible to acknowledge every contributor in full. The literature review, however, is meant to be both indicative of the present understanding of the area and representative of the issues to be dealt with in a holistic performance assessment, prior to examining those experienced in implementing a partial performance assessment based on pressure transient monitoring.

Chapter 3, Data Collection, discusses issues related to the approach selected for collecting data pertinent for a performance assessment. Specifically, it identifies issues directly related to selecting sensors over (for example) manual approaches to data collection. The purpose of this chapter is to introduce the reader to the reasons behind the pressure transient monitoring employed herein.

The fourth chapter is entitled “Chapter 4: Background and Introduction”. Chapter 4 summarizes the purpose of the thesis again before delving into the description of two case studies that are referenced herein. A brief description of the location and system setup, experimental goals, and hardware employed is provided for each.

In the following chapter, “Chapter 5: Preliminary Results and Statistics,” is primarily focused on analyzing data derived from the case studies. While this is of limited immediate use, the subsequent chapter “Chapter 6: Discussion of Results” extrapolates
issues to the larger perspective and also discusses how this analysis can apply to the overall scorecard approach.

Chapter 7 concludes and summarizes the findings of the case studies. It summarizes the work performed to this point, before delving into yet more opportunities for further work. Finally, it identifies the potential a more holistic framework for performance assessment holds (and some of the limitations) to effectively lead to the second speculative half of this document.

The next chapter is entitled “Chapter 8: Performance Boundaries.” The goal of this chapter is to discuss what may be boundaries set when examining the performance of the infrastructure more holistically. It begins by establishing the scope, identifying which infrastructure components are explicitly included within this analysis and which are omitted. Discussion then continues about the elements that will ultimately shape the scorecard. It should be noted that the discussion in these later chapters focuses on the technical aspects of performance, considering utility and government policies as largely extraneous factors despite their significant impact on the ultimate system performance.

The ninth chapter, “Chapter 9: Dynamic Scorecard,” discusses concepts related to the choice of this method for performance assessment, and the construction of a scorecard on a theoretical level. It discusses various forms of data, classifications of measurement scales, and how information can be effectively presented. It then elaborates the concept
of data fusion and examines possible application of this scorecard within decision-making processes.

Chapter 10 discusses the technological implementation of such a dynamic scorecard approach. It tackles the issue by dividing it into two areas, software and hardware. In both, general concepts are discussed in depth rather than to identifying specific software packages due to the dynamic nature of the industry and the staggering rate of advances and changes. With hardware, discussion is broken into computer or data processing hardware and remote sensing equipment. Lastly, barriers to implementation are discussed and possible solutions posed.

The last chapter, a decision-making primer, introduces the concept of a rational decision-making process. It runs through the basic process, and discusses related issues such as interdependencies and several decision-making tools. Finally, supporting information is given to assist a decision-maker in effectively completing several steps of the process. The goal of this chapter is to ensure that the reader understands that the previously discussed concepts must operate within a practical decision-making context to have any real impact.
Chapter 2: Literature Review

“Writing is the only profession where no one considers you ridiculous if you earn no money.”

Jules Renard
(1864-1910)
The purpose of this chapter is to provide an overview of existing research relevant to the present work, providing a birds-eye view of some concepts related to the idea of performance assessments. After exploring the importance of water distribution systems (WDS) and justifying the need for performance assessments, it identifies and examines two “main” methods for these assessments. Further, it goes on to examine research in decision-making that omits the concept of performance entirely. After this, current practices in asset management reporting and use of Instrumentation, Control, and Automation (ICA) systems in WDS are briefly surveyed. A discussion of corresponding software and data management needs follows. The chapter then inspects opportunities for implementing GIS methodologies, as well as possibilities for integrating data between separate utilities. Finally, the concepts of scorecards and the presentation of information are looked into and the need for establishing performance assessments within a decision-making context is elucidated. Subsequent chapters will then focus on efforts made in monitoring pressure transients in water distribution systems, work specifically aligned with scope of this thesis, before again jumping to the larger picture view and discussing the opportunities this works for performance assessments in general and what other concepts may still need to be addressed.

Piped water systems have been in use as early as two millennia before the Common Era to supply people with water [5]. Significant progress has been made in society since then, and the demand for water continually grows. Improvements in fire prevention and suppression resulting from deaths and damage from fire disasters made it inevitable that water distribution systems would be enlisted to assist. Indeed, many of the early water
distribution systems in North America were constructed for the purpose of fighting fires and only later adapted to serve commercial and residential needs [6]. The advent of insurance companies underwriting cities for fire protection soon brought regimented rules for system pressures into effect. Additionally, with the advancement of medicine and an increased understanding of the importance of clean water to human health and the impact of waterborne diseases, the demand has shifted to be inclusive of a standard of quality. It is not surprising then that the three general functional requirements of drinking water systems identified by Smith et al. were quality, flow, and pressure [7].

The importance of water in supporting life and society can hardly be argued. For example, the UN Department of Economic and Social Affairs Division for Sustainable Development gives their objective, in Chapter 18 of Agenda 21 [8], as “to make certain that adequate supplies of water of good quality are maintained for the entire population of this planet, while preserving the hydrological, biological and chemical functions of ecosystems, adapting human activities within the capacity limits of nature and combating vectors of water-related diseases.” Water suppliers, regardless of location or ownership, have more refined views for water utilities. For example, the Region of Peel in the Greater Toronto Area indicates that their mandate is to “plan and provide safe, secure and reliable road, water, wastewater and waste management services which meet the needs and expectations of the residents and businesses of Peel while respecting the environment” [9]. Similarly, the Massachusetts Water Resources Authority declares their mission to be “to provide reliable, cost-effective, high-quality water and sewer services that protect public health, promote environmental stewardship, maintain customer
confidence, and support a prosperous economy” [10]. Even privatized water companies
display the same goals for their operations. An example of this is Severn Trent Water,
who states in their Strategic Direction Statement that their goals for the next 25 years are
to provide a continuous supply of quality water at the lowest cost possible while
minimizing their carbon footprint and ensuring they have a sustainable impact on the
environment [11], a goal that is noble but not achievable without investment in
performance assessments and, with population and consumption increases, likely entirely
unsustainable in the long term. The theme remains clearly consistent however: a reliable
source of clean water must be available, and made so in an economically and
environmentally conscious way. Here, performance assessments of infrastructure can
play a significant role. Performance has been defined as “the carrying out of a task or
fulfillment of some promise or claim,” and thus for water supply and distribution
infrastructure, it refers to the delivery of quality water at least cost and in an
environmentally friendly manner [12]. Obviously then, performance assessments act as a
confirmation of the degree to which the infrastructure meets its requirements, as well as
providing opportunity to examine where gaps in performance exist and how
improvements may be made.

Concepts such as Total Quality Management (TQM) have been proposed as effective
means of operating water utilities, where an organization makes constant, gradual
improvements to every aspect of its products and services. Hoekstra et al. describe the
application of TQM in the water supply industry in The Netherlands [13]. They first
describe the concept and background theory and present the Deming circle. As a frame of
reference for the water sector, they adopt the ISO 9001 Standard. The authors then
discuss reasons TQM was introduced in The Netherlands, including external
considerations such as public image or environmental aspects and internal considerations
such as preventing failures or job satisfaction. They then break a water supply company
into a system view and walk through the elements of the system, discussing
organizational factors, policies, and challenges. The discussion remains at a high level
and does not delve into the specifics of identifying or classifying asset performance
levels, however there are significant areas in which such processes could be successfully
and effectively employed.

Risk management is another area where performance assessments can be critical.
Duckworth and Clarson (1998) assert that, despite views of water as a low-risk industry,
“risk management is one of the most significant challenges facing water industry
management today” [14]. The authors describe the stages that Severn Trent Water took to
develop their approach to risk management: benchmarking, development of a risk
management blueprint, and pilot testing. The risk management process developed is also
introduced. They suggest that the key stages in the process are determining the strategic
criticality of a site or system, decomposition of each site into processes as applicable, and
detailed activity risk assessments for each process. Throughout both the development of
the risk assessment methodologies and in the risk assessments themselves, there exist
many opportunities for performance assessments to play a role. In benchmarking,
performance assessments can provide consistent means to rate and compare
infrastructures. In the risk assessment process itself, performance assessments – and in
particular, the change in assessments over time – can provide insight into risks that could otherwise be overlooked. Similarly, Vreeburg et al. (1994) discuss concepts of reliability in water supply systems and describe effect categories of failures, calamities, and disasters [15]. They define failures as local incidents that are repaired within 24 hours, calamities as disruptions to main elements of the system that last longer than 24 hours, and disasters as failures of multiple main elements occurring simultaneously. They also present a flowchart for calculation of reliability based on modeling the system. Here again, an accurate performance assessment can be used either to confirm model calibration or to provide more in-depth understanding of the actual system behavior.

Cardoso et al. [16] identify two “main” methods for assessing performance of water and wastewater infrastructure: systems of performance indicators, and technical performance via simulation. They suggest that performance indicators are “a management tool applicable to the overall activity of the undertaking” and that technical performance assessments are simply “related to the engineering or technical aspects of management,” and proceed to briefly discuss both. Their discussion on technical performance assessments is primarily focused on a “Performance Assessment System (PAS).” This system, developed by Coelho in a 1996 Ph.D. thesis and loosely described in subsequent articles [17; 18; 16], is based on the concept of establishing utility functions for the modeled parameter. This function, ranging from 0 to 4 for poor performance and perfect performance, respectively, describes the desired performance of a component on a continuum. By employing weighted averages to aggregate the performance of several parameters, an overall score is attained. This final performance value can be then plotted
against either time or load factors. Two items are of particular note here. First, their efforts are focused on the easily quantifiable parameters, namely hydraulics (pressure and variation, velocity, and energy consumption), water quality (chlorine residuals and travel time), and reliability of supply in terms of supply path redundancy. Second, the approach is focused solely on results attained from simulations.

The vast majority of sources discussing simulation, however, describe models developed for single parameters of a water distribution system. Smith et al. [19], for instance, describe one method of modeling chlorine residuals. They discuss setting chlorine residual targets, model calibration, and modeling using a first-order rate equation that describes the decrease in residual as a function of residence time. Likewise, Wu et al. [20] describe a dynamic water quality model. They again use chlorine residuals as the modeled parameter and base the model on mass balance relations within water pipes, taking into account both advection transport as well as reaction kinetics. Here, a slightly more complicated transport equation is described, and again a first-order rate equation is used to model decay. Kerneïs et al. [21] describe a more comprehensive model for water quality, covering both suspended particle transport and total bacterial count using a logistic function based on water residence time instead of chlorine residuals. They describe steps in the calibration of the model, and discuss the potential for such hydraulic models on determining “risky” zones.

Models for other parameters have also been described in varying levels of detail. For instance, Madiec et al. describe a model developed for predicting pipe break failures
using statistical tools on historical data [22]. This model is solely concerned with the probability of pipe breaks as a determinant for repairs and rehabilitation of the modeled system, and is dependent upon a significant amount of historical data. Al-Barqawi and Zayed describe a similar model in the article *Condition Rating Model for Underground Infrastructure Sustainable Water Mains* [23], where an artificial neural network is employed to model the condition of a water network in Edmonton, Canada, and forecast breakages. First, Al-Barqawi and Zayed described factors that contribute to pipe deterioration, categorized as either “static, dynamic, and operational” (as cited in [24]), or “physical, environmental, and operational” (as cited in [25]). An artificial neural network was then employed to determine the degree various parameters contributed to actual pipe condition in a network in Edmonton, Canada, though several main factors were omitted from the model (i.e., pipe age, type, diameter, and soil properties), resulting in uncertainty of universal validity of their results despite the case study showing excellent accuracy. However, a rating scale between 0 and 10 has been developed based on a questionnaire distributed to various municipal experts and consultants throughout the United States and Canada that remains valid and useful regardless of the model results.

Yet more forms of modeling have been described. For instance, in another article, Walski et al. [26] present an experimental study to develop a model of leakage in water distribution systems based upon network pressures. They assert that pressure control can be used to reduce water leakage, describe two methods that have been proposed for models of leakage (fitting coefficients or using the orifice equation) and describe an experimental approach they adopt for assessing the orifice approach. Finally, they discuss
applying the orifice equation in modeling leaks in real-world scenarios. Bessey, in The economics of leakage control in the UK: theory and practice [27], describes processes for valuating leakage. The author defines the optimum level of leakage as the amount of leakage where the cost to control further leakage equals the cost of the leaking water. Water is valuated according to one of three possible levels: the first assumes constant or linear relationships between demand and operating costs, the second adds the complication of changes to fixed operating accounts and impact of investments, and the third includes changes in future demand. This type of a process could theoretically be combined with that presented by Walski et al. to develop a cost-based model for pressure control. Similarly, the number of models available, the variety of parameters simulated, and the number of methods for simulation goes on.

The other “main” method described by Cardoso et al. is systems of performance indicators. This is where the majority of articles and books on performance assessments seem to focus their efforts. In the book Infrastructure Management: Design, Construction, Maintenance, Rehabilitation, Renovation, Hudson et al. [28, pg. 62] acknowledge the multitude of factors contributing to deterioration of assets in their assertion that:

The condition deterioration of a water supply and distribution system is primarily dependent on the material of the main pipeline network, joints, subsurface moisture and soil, demand on the system […], infiltration of ground water, blockage to flow, and environmental effects on service life.
However, they appear to be more supportive of a performance indicator approach to performance assessments, further stating that:

[...] from the user’s and from the owner agency’s point of view, number of breaks per year, number of failures per 1000 km, and leakage of water per year are the most important performance indicators.

In the article *Water distribution system performance indicators* [29], a general outline of performance indices is given. This includes factors ranging from adequacy, dependability, efficiency, and quality of service, to structural and hydraulic performance. Similarly, Hirner and Mayr present a variety of performance indices in tables segregated according to their functional area [30]. In contrast, the article *Measuring water distribution system performance* [31] focuses on performing a network water balance to develop related performance indices. Indices presented there include the percent of distributed water that reaches metered users, leakage volume per unit pipe length, and consumption per unit pipe length. *Development of a framework for the assessment of operation and maintenance (O&M) performance of urban water supply and sanitation* [32], after identifying the significant links between water supply systems and other sectors of the economy and overall social well being, suggests that O&M factors were frequently the reasons for noncompliance with quality regulations. They discuss auditing the O&M functions, and using performance indicators as a means of assessment. They subsequently present three tables of O&M related indices in the appendix to their article.

Audits and random sampling play a significant role in both the performance indices presented as well as calibration of models. Sampling for quality is typically prescribed by
regulating authorities, and details can be found in documents produced by these agencies. An example of the sampling regimes can be found in the article *Sampling for determination of the drinking water quality in Göteborg’s distribution system* [33], where they describe three types of sampling undertaken by Göteborg: standard inspection and operative inspection to meet regulatory requirements, and inspections following customer complaints. The article *Directing Sampling based on Uncertainty Analysis* [34] describes a method for using statistical results from modeling to determine the best locations for taking samples. Further, the Quantitatively Directed Exploration (QDE) approach they describe can be used to determine the best parameter(s) to sample when dealing with multi-parametric models. Similarly, an approach akin to the “reliability-based exploration” described by Graettinger and Dowding [35] can be used to determine when parameters monitored and locations selected are sufficient.

There are others who espouse the use of risk-based methodologies for decision-making, largely ignoring assessment of infrastructure performance. For instance, in *Prioritizing capital improvement projects to mitigate risks*, Nagel and Elenbaas describe an approach to decision-making with respect to projects that employs Monte Carlo simulations in combination with net present value tornado diagrams and probability distributions [36]. Their approach hinges on evaluations of infrastructure condition and failure probabilities as a means to identify projects. They also indicate that rehabilitation, repair, and replacement needs should weigh into the decision-making process, which suggests even these authors have a place for performance assessments, but overall their process is
reliant on financial risk assessments. Survival curves are employed, in conjunction with 
the component’s functional life, to determine failure probabilities.

The quantification of concepts such as risk and reliability pose an interesting problem for 
a potential performance assessment methodology. In *A quantitative method to determine 
reliability of water supply systems* [15], Vreeburg et al. suggest that reliability (LZ) can 
be calculated by the equation:

\[
LZ = 1 - \frac{\text{frequency} \cdot \text{duration} \cdot \text{effect}}{\text{original demand}}
\]  
……………………………\hspace{1cm} (Eq. 2.1)

In an article focusing on the application of risk management in The Netherlands [37], 
Vreeburg et al. redefine this equation for reliability to be applicable directly to the water 
industry:

\[
R = \left[ 1 - \frac{(\text{POF} \cdot \text{POS} \cdot \text{ND})}{\text{TD}} \right] \cdot 100\% 
\]  
……………………………………\hspace{1cm} (Eq. 2.2)

\[
R = \left[ 1 - \frac{\text{ND}}{\text{TD}} \right] \cdot 100\% 
\]  
……………………………………………………\hspace{1cm} (Eq. 2.3)

Where:

\[
\begin{align*}
R &= \text{reliability (% of maximum daily demand);} \\
\text{POF} &= \text{probability of failure/day;} \\
\text{POS} &= \text{period out of service/day;}
\end{align*}
\]
**ND** = “not supplied” demand (m$^3$/d);
**TD** = maximum daily demand (m$^3$/d);

Equation 2.3 is a simplification of Equation 2.2, where it is assumed that any element can and will fail at any time. Obviously, it is also assumed that the duration of any failure will be less than 24 hours. One problem with such equations is that they are focused solely on the quantity of water delivered; requirements such as pressure are entirely ignored. The quality of the water can be taken into consideration, however, if ND includes water of questionable quality.

In their article on Asset Management Planning [38], Matichich et al. present an AWWA Research Foundation study design and key findings related to asset management reporting, where 11 utilities were selected to represent the spectrum of geography, size, and infrastructure age. They suggest an asset management approach to decision-making, and describe three levels of asset management: basic, high-end, and strategic. At a basic level of asset management, traditional valuation and service life concepts are employed to guide decision-making. This level focuses on assets by component, and aggregates these scores for an overall system evaluation. High-end asset management is described as the application of key performance measures in the assessment of individual and grouped assets to direct this process. Similarly, an overall system evaluation can be produced from combining components. They combine value-weighted asset performance scores to rate larger system components, and combine those to develop an overall system rating. The strategic level of asset management incorporates both basic and high-end levels, as well as additional strategic factors such as economic issues. All this information is then...
combined to display, for instance, projected capital costs. Matichich et al. then present figures depicting the “overall value” and “level of data management challenge” for these three approaches, as rated by the utilities. Not surprisingly, the higher valued approaches were considered more challenging in terms of managing all the data required.

Active monitoring of systems plays only a minor role in most models and performance indices. Even with asset management, it is reported that “traditionally the drinking water industry has had difficulty developing information that can be used to objectively rate infrastructure condition and potential R[replacement]&R[enewal] expenditures” [38, pp. 81-82]. The article On line quality control in distribution networks [39], however, describes an extensive system employed by the city of Paris for monitoring the quality and condition of their water distribution systems. Starting in 1992, 5400 binary data and 600 analogical sensors for flow, pressure, and quality parameters have been monitored 24 hours a day by ten operators\(^1\). The location of the majority of the water mains facilitates implementation of this extensive sensor network. A map is also provided, showing 96 main flow meters, and 64 main pressure sensors. They assert that “[o]n line quality cannot be obtained without precise knowledge of the whole network.” Information from these sensors is read every 15 seconds. Additionally, these sensors employ pre-analyses that detect and classify malfunctions, and have configurable alarms to aid with operations. Specialized squads are responsible for maintaining the sensors. They indicate, however, that their sensors are less sensitive than consumers’ palates. This presents an

\(^1\) This information is valid as of 1994, the date of publication for the article. Modifications may have occurred since, or the project canceled. The point is being used as an example of possible monitoring conditions.
inherent flaw in their monitoring regime, and is a factor that must be considered to ensure propriety in any monitoring system design. Quality is measured on the rivers by four monitoring stations, inside the treatment plants at various stages of treatment, at groundwater collection locations, in the reservoirs, at the chlorination point, and at sensitive locations in the distribution network. Table 1, adapted from the article, displays the parameters monitored at each location.

<table>
<thead>
<tr>
<th>Location</th>
<th>Parameters Monitored</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitoring Station</td>
<td>Temperature, pH, TOC, DO, NH₄, Hydrocarbons, Pesticides, Heavy Metals, Conductivity, Turbidity</td>
</tr>
<tr>
<td>Treatment Plant</td>
<td>pH, Turbidity, Chlorine, Flow, Pressure, Opening angle</td>
</tr>
<tr>
<td>Springs (Groundwater)</td>
<td>Turbidity, Nitrates, Chlorine, Flow</td>
</tr>
<tr>
<td>Reservoir</td>
<td>Chlorine, Pressure</td>
</tr>
<tr>
<td>Chlorination Point</td>
<td>Chlorine, Flow</td>
</tr>
<tr>
<td>Distribution Network</td>
<td>Chlorine, Flow, Pressure, Opening angle</td>
</tr>
</tbody>
</table>

Finally, the article deconstructs the yearly complaints received by the utilities, and shows that a minimal number of complaints are registered for faults on the utility’s end.

In Water quality in distribution: National Report Romania, Rojanschi argues that “no distribution network can be controlled from the point of view of the water quality by means of sensors mounted in specific sections” [40]. Cubillo suggests however, in Use of ICA for water treatment and water quality monitoring: International Report [41], that
Instrumentation, Control and Automation systems (ICA) can be used to monitor and control parameters in raw water, along the treatment process, and through the distribution system. The author identifies technical characteristics of instrumentation, as well as technologies used to monitor different parameters, and provides a brief discussion of the application of SCADA and information systems. Similarly, in *The integral management of quality control in a public water supply through automatic control stations: a future perspective* [42], Matia et al. assert that ICA is “the most suitable method” for guaranteeing safe water supplies.

A multitude of sensors and methods for sensing have been proposed, developed, or are in development for monitoring parameters directly or indirectly. Nguyen and Montiel, for instance, describe a chlorine sensor for detecting chlorine in the HOCl form at the end of their article [39, pg 299] that employs a Clark cell setup and provides an expected life of greater than six months with no maintenance or recalibration. Additionally, this sensor apparatus only requires replacement of the electrode. Another example of a sensor system is the electronic tongue for water quality, as described by Lindquist and Wide [43].

Apparent from these articles is that appropriate software and methodologies are necessary to efficiently implement any of these approaches to asset management or condition/performance assessments. Matichich et al. describe the necessity of software for data management, identifying databases and Geographic Information Systems (GIS) as holding potential [38]. Cubillo presents a version of the following table, Table 2, identifying basic technological tools and their potential applications [44]:

25
### Table 2: Basic Technological Tools and their Applications

<table>
<thead>
<tr>
<th>Tools</th>
<th>Network Model</th>
<th>Communication Network</th>
<th>KBS†</th>
<th>SCADA</th>
<th>Forecast Models</th>
<th>CAD</th>
<th>CIS‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customer service systems</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operations systems</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Works management systems</td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asset preventative maintenance systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leakage &amp; efficiency systems</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planning &amp; design systems</td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Georeferenced Data Base Manager (GIS).
† Knowledge Based Systems.
‡ Customer Information System – Billing.

Other individuals and articles describe software applications in other areas of operating and managing water networks. For example, D.J Glasbrook (1994) describes a UK water utility’s application of GIS in water mains rehabilitation planning [45]. Glasbrook suggests that water companies generally collect data on pipes, appurtenances, and operational and organizational records. The author describes the process that Wessex Water uses to plan rehabilitation: firstly, the region is divided into zones where each zone has approximately equivalent potential for problems. It is suggested that water quality provides a good means for establishing zones. These zones are used as basic planning units. Secondly, zones are prioritized based on the severity of problems. Lastly, rehabilitation requirements and location of each zone are examined at a detailed level. To execute these steps, data collected in GIS includes not only physical parameters of the water mains, but also customer complaints (and details of the complaints), water quality
information, burst/failure information, repair information, and useful operational information. Therefore, GIS is perceived merely as a source of data.

A later article by Shamsi describes another use of GIS in the water industry [46]. The author discusses employing dynamic GIS web pages for interaction with the public, in particular for emergency preparation and response situations. While the focus is on public relations, this concept can easily be extended to remote access for operators and utility personnel. Indeed, Mahon presents a case study of exactly this [47], a system for mobile operators employed by North West Water (United Utilities) in the UK. The mobile computing system provides operators with information they may require to perform their functions, via a “Field Centre Communication system”, such as GIS, customer contact info, work management info, operations control and monitoring, network modeling, and CAD. Ultimately, the method provides increased productivity, reduces administrative support, and increases the accuracy and availability of information.

A third application of GIS, though not specifically related to the water or wastewater industries, can be seen in the TimeMap Project [48]. The goal of this project is to develop interactive maps that are temporally dynamic. In *The TimeMap Project: Developing Time-Based GIS Display for Cultural Data* [49], Johnson and Wilson describe the project in more detail. The knowledge they describe possessing at “irregularly spaced intervals, together with generalized knowledge about trends and changes” can be viewed as analogous to many sampling-based and consumer-based sources of information in the water industry. The authors also suggest a setup employing distributed data sets on
remote servers that in the context of water utilities would enable access to information for mobile operators. Similarly, Ng et al. describe a time-sensitive GIS application for retrieving and displaying hydrodynamic and water quality information for the Pearl River estuary [50]. The idea of temporally and geographically referenced information pushes the concept of GIS to a fourth dimension that could prove to be extremely useful in assessing infrastructure performance. A tangentially related application of this concept can be seen in the article Development of a GIS model for assessing groundwater pollution from small scale petrol spills [51], where groundwater contamination is modeled using a temporal GIS. This portrays an application that could be of direct importance when assessing water distribution system performance, particularly in cases where known sources of pollution exist alongside the network and supply is intermittent. In such situations, contamination of the distributed water is far more likely.

A significant comment of note in many articles is the idea of integration [47; 52; 53]. This concept is not only considered in terms of integration between software, but also in terms of integration of data between separate utilities. Fernández, for instance, discusses integration of information sources related to customer care, distribution efficiency, and planning and design within the water industry [52]. Aebischer, on the other hand, describes the challenges and benefits from integration of cadastral information from multiple underground utilities in Berne [53].

Scorecards have been employed by many organizations and businesses in assessing performances. A common example of this is the balanced scorecard developed by Kaplan
and Norton for tracking important elements in a company’s strategy [54]. When it comes to civil infrastructure, the American Society of Civil Engineers (ASCE) has adopted a scorecard method for rating the infrastructure in the United States, due in part to the familiarity people hold with the concept of report cards. The American Public Works Association (APWA) has developed a similar report card. Price argues against the subjective nature of the approach and the lack of predefined goals and requirements, but applauds the initiative nonetheless [55]. Variations to the scorecard approach have been suggested. For instance, Bobillo et al. discuss a variation meant to capture semantics of underlying knowledge, as well as permit handling of imprecision or vagueness [56].

Regardless of the minutiae of the method however, a regimented performance assessment process for each component of the scorecard is one way to address the concerns raised by Price. Further, developing a scorecard for water supply and distribution systems will permit identification of areas in greatest need of improvement. To aggregate scores, however, an appropriate weighting structure must be established. Yuan and Chiu suggest that Genetic Algorithms be utilized rather than subjective reasoning to determine weights when employing a balanced scorecard [57]. This approach requires a degree of data processing that may be excessive in many cases. Accordingly, it may be more efficient to simply use subjective reasoning in conjunction with tools such as sensitivity analyses for quick and dirty applications.

As previously mentioned, however, it may also prove beneficial to keep the infrastructure scorecard “grades” segregated to aid in synthesis of additional information, emergent
features and other insights, as well as to avoid combining incompatible measurement scales. This then engenders the question of how the information should be presented. Drews and Westenskow have conducted a literature review and analysis of data displays in anesthesia [58]; however, in many ways the situation can be seen as somewhat analogous to the situation prospective decision makers will face. The authors assert that the development of successful information displays is possible if the task domain and constraints are studied. The analogy between a surgical patient and a water supply and distribution system can be thus described: whereas in anesthesiology, a patient is monitored for changes in four “fundamental processes” (respiration, metabolism, circulation, and anesthetic depth), a water network should be monitored in terms of its own “fundamental processes” such as quality, capacity, pressure, and structural integrity. Further, just as Drews and Westenskow indicate that “displays that are designed to be cognitive aids should help anesthesiologists in making rapid detection and diagnosis and administering treatment,” the same is true for decision-makers operating on water systems. Drews and Westenskow affirm (as cited in [59]) that displays containing separate elements for each variable are more supportive when single variables are monitored, whereas object displays are more effective when integration of variables is desirable. They also indicate that graphical representation promotes visual recognition of patterns and aids in experience-based decision-making. In their survey of literature, Drews and Westenskow identify several studies that have determined that graphical display formats result in faster detection and greater accuracy than numeric formats, and that object displays result in yet faster detection and diagnostic times [60; 61; 62]. One warning that Drews and Westenskow provide, however, is that polygonal object displays
representing variables of different scales may result in significant changes in some variables being less perceptible than a significant change in others. This indicates that careful consideration must be given to the scale and behavior of each represented variable in order to assure no undue biases are developed. Finally, the authors discuss the organization of variables in graphic displays. By placing related parameters in proximity to each other, failing components may be identified more quickly.

In *Detecting Transient Changes in Dynamic Displays: The More You Look, the Less You See*, Boot et al. perform a study of dynamically changing cluttered displays to examine the detectability of changes [63]. The authors investigate the effect of not only abruptly appearing objects (onsets) and color changes, but also visual scanning method on accuracy of detection, number of false alarms, and response time. Overall, it was found that onsets were detected more frequently and reliably than color changes, and passive observation techniques (i.e., focusing on a point and using one’s periphery to detect changes) were more effective than active scanning techniques. Further, it was shown that more effective scanning methods could be taught. They warned, however, that while this was true for the study performed, tasks should be analyzed to confirm whether or not these results hold true for the real-world situations. This information is notable when designing a data display for the network performance information. Significant changes in parameters can be highlighted more effectively by employing a mix of not only changing colors and shapes, but also abrupt changes in elements present. This study also suggests that to promote detection of important events, optimal scanning techniques can be taught to decision-makers employing the system.
To be of any use, the concept of performance assessments must be examined within the context of a decision-making framework. The history of decisions making is wide and varied, from the early philosophers’ questions on ethics to modern debates on instantaneous decisions rather than drawn-out rational decision-making processes [64]. To reach good, valid decisions that are externally auditable, a formalized, transparent and rational decision-making process must be adopted. The “disciplined decision-making process,” also often referred to as the “rational decision-making process,” is described in a Guidebook to Decision-Making Methods developed for the United States Department of Energy [65]. They outline eight steps: define the problem, determine requirements, establish goals, identify alternatives, develop criteria, select a decision-making tool, apply the tool, and check the answer. Further, they present several decision analysis techniques. Performance assessments can prove crucial in many of these steps, particularly the first four steps, and a pivotal component of many of the analysis techniques.

This literature survey identifies not only a clear need for performance assessment techniques for water distribution infrastructure, but also a clear opportunity for a technique that bridges the gaps between modeling and actively monitoring. A scorecard approach promises to permit identification of failing components, while simultaneously offering the ability to aggregate individual asset scores to reach overall system ratings. From analogous studies, the graphical presentation of the scorecard results shows potential to increase the ability of decision-makers to develop comprehensive views and understanding. Finally, by incorporating temporally sensitive GIS technologies, the system can be viewed in terms of dynamic behavior, and emergent features may be
extractable from asset and system performance. The next chapter will examine the 
method of data collection, specifically illuminating reasons behind the selection of 
automatic sensors for certain types of data. The subsequent chapter, Chapter 4, will then 
briefly discuss the thesis scope again, and introduce two case studies employed herein to 
both as the basis for the concepts discussed and lessons learnt through their 
implementation.
Chapter 3: Data Collection

“It is a capital mistake to theorize before one has data.”
Sir Arthur Conan Doyle
(1859-1930)
3.1 Generic Process for Asset Management

In *Measuring and Improving Infrastructure Performance*, a generic process for performance assessments has been presented [12, pg. 48]. This process is shown in Figure 2, and it can be seen that performance assessments are one significant portion of this overall process. During many of these stages however, it is crucial that sufficient accurate data be collected. This chapter discusses some of the possible approaches for gathering required data, and some of their pros and cons.

![Figure 2: Generic Performance Assessment Process](image)

In the second half of this thesis, a framework largely analogous to this generic process is developed for performance assessments in water transmission and distribution systems.
While local values and goals of decision-making still play significant roles in the use of this dynamic scorecard approach to performance assessments however, the goal here is to develop a system with flexibility for a wide range of possible applications. That is to say, the framework is not explicitly bound to a specific decision-making tool or concept, permitting broad applications beyond those initially envisioned.

3.2 Methods of Data Collection

The methods of data collection may vary widely, depending on the type of information sought. Some such examples include manual/discrete sampling or surveys, automated data collection through sensors, or simulation. Each method differs in its cost, implementation strategy, and ultimate effectiveness and accuracy. The next three subsections briefly discuss these approaches.

3.2.1 Manual Collection

Methods for manual collection include discrete sampling (for instance, measuring chemicals at specific locations at designated time intervals), surveys, visual inspections, or incident reports. These methods may collect either quantitative or qualitative data from a potentially large pool of sources as well as information that may otherwise be difficult to gather, but in many cases the data may be contaminated by biases or otherwise inadvertently skewed. Further, data collected through these approaches is typically after the fact. That is to say, decisions based on information derived from data collected manually are largely reactive to preexisting conditions, and in many cases are inclined to address symptoms of a problem rather than the problem itself.
3.2.2 Automated Collection

Automated data collection employs sensors to continually sample and measure preordained parameters. The two case studies this thesis focuses on, for example, utilized high-speed pressure sensors with a specialized data recording system that works to capture pressure transient behaviors. Data collection through automated methods permits near real-time understanding of a system’s behavior and permits quick response to problems that may arise. Further, it can promote proactive control of a system through insights gained from historical trends and forecasted demands. Despite these benefits, there remain significant challenges including (but not limited to) lack of training with the equipment, few existing models built specifically to incorporate acquired data, or difficulties in keeping the sensors calibrated. Further discussion on experience gained and lessons learnt in utilizing pressure transient sensors can be found in Chapters 5 through 7.

3.2.3 Simulation/Modeling

Modeling can be used to assess the expected performance of new or planned transmission/distribution systems, modifications and upgrades. Sensors or manual data collection can be used to gather information for the calibration of models, but in certain cases (such as brand new systems) this may not be necessary. The information from fieldwork performed during the two case studies was used primarily to calibrate transient performance models. In addition to this, however, modeling can be used to determine other important information about these systems, such as the hydraulic importance of pipes [66]. This topic is further discussed in Section 8.3.5.
3.3 Summary

This chapter presents a very cursory discussion on different approaches to collecting data. It begins by presenting the generic process for asset management, one possible goal for performing performance assessments, which justifies the need to gather data. Three approaches to data collection are then discussed: manual, automatic, and simulation. Some pros and cons are presented for each approach, and the possible use of the first two approaches in calibrating models is also mentioned. Knowing the benefits and drawbacks to adopting an automated data collection method, the next chapter introduces the main scope of this thesis and presents two case studies that highlight some of the important issues and lessons learnt in utilizing transient pressure sensors for partial performance assessments.
Chapter 4: Professional Context and Case Studies

“Against the dark background of this contemporary civilization of well-being, even the arts tend to mingle, to lose their identity.”

Eugenio Montale
(1896–1981)
4.1 Scope

The goal of this research is primarily to examine issues arising from the application of pressure transient sensors for partial system performance assessments. The first half of the thesis focuses on examining two pressure transient studies and associated lessons learnt, with the second half expanding that to holistic performance assessments of water supply and distribution systems that bridge the gap between generic performance indicators and network simulations. Due to time limitations, this is latter portion is developed primarily at a conceptual level. Many of the metrics developed in Chapters 8, 9 and 10 bear similarity to what may be experienced in the majority of fluid transmission and distribution systems, consequently this work can be extended to apply to many similar infrastructure systems. Due to the breadth of the information required to completely rate a system or system component on the scorecard system developed, minimal situations exist where the information was accessible. Subsequently, contrived situations are utilized to elucidate the concepts. Further, a discussion on the impacts and drawbacks to incomplete information is provided in related sections.

As previously indicated, this thesis focuses on water transmission and distribution systems. Typical components of these systems are outlined in Chapter 8, where the boundaries of a more holistic performance assessment are discussed, and a generic system map can be seen in Figure 1. In general, the condition and performance of structures encapsulating system components (such as treatment facilities) have been omitted from this work. It has not been assumed that their operation provides a level of quality throughout their lifetime that the needs of the encapsulated system are met
however. The dynamic scorecard has been developed, in part, to permit identification of where interdependent systems have failed in their requirements and theoretically may be expanded or modified to be inclusive of these components as well.

Figure 3 below depicts a lifecycle that infrastructure may follow. While concepts of most phases are briefly addressed, the focus of this thesis is on the operation phase since the case studies examined are entirely within regular system operation. Information gathered here on system performance assists in both the continued operation, as well as in decisions for future upgrades, expansions, or maintenance.

Two case studies have been selected to illustrate the issues associated with employing pressure transient monitoring as a partial performance assessment. General background information for these case studies is outlined in the subsequent sections. Lessons learnt
from this project work may also be expanded to other monitoring schemes, and a
discussion of this concept is provided in Chapter 7.

4.2 Case Study 1: Region of Peel, Greater Toronto Area, Ontario, Canada

Starting in September 2007, a number of permanent and temporary transient pressure
sensor systems were installed at various locations throughout the Region of Peel of the
Greater Toronto Area. The purpose of these installations was three-fold:

1) Calibrate a transient pressure model of the system;

2) Ascertain the magnitude and impact of transient pressures in the distribution
system studied, in order to determine appropriate levels of protection and
recommendations for proper operational procedures; and

3) Experiment, trouble-shoot, and promote the new technologies found in the TP-1
Transient Pressure Monitoring System.

Two permanent sensors have been installed at locations in the Lakeview Water Treatment
Plant, and another in the Hanlan pumping station. The control box for each of these
sensors has been connected to a DSL-2540B ADSL2+ router/modem device to permit
wireless and Internet communication. In addition to the three permanent sensors, four
sensors were temporarily installed at a total of seven other locations within the system.
Table 3 displays the sensor installation locations as well as the installation and removal
dates. Maps for the locations are provided in Appendix B, with sensors identified
according to the codes given in Table 3.
### Table 3: Peel Region Sensor Installation Details

<table>
<thead>
<tr>
<th>Location</th>
<th>Code</th>
<th>Type</th>
<th>Sensor ID</th>
<th>Installation</th>
<th>Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lakeview Treatment Plant, Zone 1</td>
<td>Z1</td>
<td>Permanent</td>
<td>5801</td>
<td>Sept 01 2007</td>
<td>-</td>
</tr>
<tr>
<td>Lakeview Treatment Plant, Zone 2</td>
<td>Z2</td>
<td>Permanent</td>
<td>59</td>
<td>Sept 02 2007</td>
<td>-</td>
</tr>
<tr>
<td>Hanlan Low Lift Pump Station (LLPS)</td>
<td>H</td>
<td>Permanent</td>
<td>6401</td>
<td>July 03 2008</td>
<td>-</td>
</tr>
<tr>
<td>Lorne Park LLPS</td>
<td>LP</td>
<td>Permanent</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Streetsville LLPS</td>
<td>SV</td>
<td>Temporary</td>
<td>3</td>
<td>July 04 2008</td>
<td>July 29 2008</td>
</tr>
<tr>
<td>MV900 Chamber 8</td>
<td>MV900</td>
<td>Temporary</td>
<td>6501</td>
<td>July 09 2008</td>
<td>July 29 2008</td>
</tr>
<tr>
<td>HG1500 Chamber 11</td>
<td>HG1500</td>
<td>Temporary</td>
<td>5501</td>
<td>July 09 2008</td>
<td>July 29 2008</td>
</tr>
<tr>
<td>BS1500 Chamber 8</td>
<td>BS1500</td>
<td>Temporary</td>
<td>66</td>
<td>July 09 2008</td>
<td>Sept 03 2008</td>
</tr>
<tr>
<td>ST1500 Chamber 9</td>
<td>ST1500</td>
<td>Temporary</td>
<td>6501</td>
<td>July 29 2008</td>
<td>Sept 03 2008</td>
</tr>
<tr>
<td>Silverthorne LLPS</td>
<td>ST</td>
<td>Temporary</td>
<td>5501</td>
<td>July 29 2008</td>
<td>Sept 03 2008</td>
</tr>
<tr>
<td>Beckett Sproule LLPS</td>
<td>BS</td>
<td>Temporary</td>
<td>3</td>
<td>July 29 2008</td>
<td>Sept 03 2008</td>
</tr>
</tbody>
</table>

A permanent sensor is to be installed at the new Lorne Park water treatment plant and pumping station being constructed within Jack Darling Park, with an expected completion date of early 2010. This sensor is to be in location during operation both prior to and post construction of additional surge protection in the vicinity, and will hopefully provide valuable insight into the actual impact of these measures.

4.3 Case Study 2: Tláhuac, Mexico City, Mexico

Between November 03, 2008 and December 09, 2008, temporary transient pressure monitoring sensors were placed at various locations along a water transmission line running from groundwater pumping stations to a reservoir and water treatment plant in
Tláhuac, Mexico City. The purpose of this project was to analyze the system to determine the impact of transient pressures (if any), as part of a larger project assessing the overall system efficiency. Table 4 displays the dates when sensors were installed for each location. Maps detailing the supply lines and specific sensor locations are provided in Appendix C.

<table>
<thead>
<tr>
<th>Location</th>
<th>Code</th>
<th>Sensor ID</th>
<th>Installation</th>
<th>Removal</th>
<th>Days Installed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tláhuac Line, Station 1</td>
<td>T1</td>
<td>8401</td>
<td>Nov 03 2008</td>
<td>Dec 05 2008</td>
<td>32</td>
</tr>
<tr>
<td>Tláhuac Line, Station 6</td>
<td>T6</td>
<td>8201</td>
<td>Nov 03 2008</td>
<td>Dec 09 2008</td>
<td>36</td>
</tr>
<tr>
<td>Tláhuac Line, Station 14</td>
<td>T14</td>
<td>8101</td>
<td>Nov 03 2008</td>
<td>Dec 09 2008</td>
<td>36</td>
</tr>
<tr>
<td>Main Pipeline, (3 + 138)</td>
<td>NT1</td>
<td>8401</td>
<td>Dec 05 2008</td>
<td>Dec 09 2008</td>
<td>4</td>
</tr>
<tr>
<td>Main Pipeline, (6 + 800)</td>
<td>NT2</td>
<td>0</td>
<td>Dec 08 2008</td>
<td>Dec 09 2008</td>
<td>2</td>
</tr>
<tr>
<td>Santa Catarina Line, Station 4</td>
<td>SC4</td>
<td>8301</td>
<td>Nov 03 2008</td>
<td>Dec 09 2008</td>
<td>36</td>
</tr>
<tr>
<td>Mixquic Line, Station 6</td>
<td>M6</td>
<td>6501</td>
<td>Nov 03 2008</td>
<td>Nov 21 2008</td>
<td>18</td>
</tr>
<tr>
<td>Mixquic Line, Station 13</td>
<td>M13</td>
<td>6401/6601</td>
<td>Nov 03 2008</td>
<td>Dec 09 2008</td>
<td>36</td>
</tr>
</tbody>
</table>

This system presented several new elements that had not previously been experienced with the case study in the Greater Toronto Area. First, the water source was no longer an open water body but rather groundwater. In this case the system was also a transmission rather than a distribution system. Additionally, all pump stations were open to the environment. Lastly, the surrounding social and cultural conditions led to a greater concern over theft or vandalism than held within the Greater Toronto Area installations.
4.4 Summary

This chapter briefly identified the purpose of this thesis and its scope in order to provide some context for the subsequent description of the two case studies that will be used herein. The first case study, located in the Region of Peel of the Greater Toronto Area, employed three permanent sensors (with an additional one currently en route and pending installation) and four additional sensors temporarily installed at seven different sites. The second case study, Tláhuac in Mexico City, utilized six sensors temporarily installed at various locations along a water transmission system. The following chapter presents some of the preliminary results from these case studies.
Chapter 5: Preliminary Results and Statistics

“However beautiful the strategy, you should occasionally look at the results.”

Winston Churchill
(1874-1965)
5.1 Limitations of Present Work

The project work undertaken for this thesis was focused entirely on monitoring transient pressure waves using the TP-1 sensor system. This imposes several limitations to the depth possible in the analysis of results. First, using one sensor system precludes the possibility of a comparison of performance and a full understanding of data accuracy. It is presumed that such an analysis was performed prior to the start of this work, however, and that the TP-1 system was found to provide accurate data with sufficiently minimal sampling errors and biases. Next, the focus on pressure prevents understanding of the performance of other sensors. A similar analysis as (what is assumed) was done for the TP-1 system should be performed for each sensor system. Further, no effort can be made to develop appropriate data fusion techniques since only one data source is available. Finally, the nature of the TP-1 sensor data recording algorithms presents unique challenges in performing meaningful statistical analyses. This issue is further discussed in Section 5.2.

5.2 Statistical Analyses

Statistical analysis of TP-1 results to establish normal distribution would not be meaningful to due the inconsistent sampling rates employed by to reduce file size. While a minimal file size is important, it introduces an automatic bias to the data. This precludes useful application of, for instance, probability distribution functions without significant preparatory work. The use of such statistics bears potential for calibrating sensor settings though, so further investigation in this area is warranted. The examination of project results herein is limited to the propriety of the software’s recognition of transient events.
5.3 Case Studies

5.3.1 Peel Region

The sensor apparatus and software used to monitor transient pressures did occasionally mislabel or identify flow conditions, primarily due to limitations in the statistical processing. From the initial work performed in the Peel Region distribution system, the issue of defining unique transient events came into question. This is of particular importance when it comes to automating processing of large quantities of data.

Examination of the raw data lead to the definition of unique transient events according the number of “baseline” recordings (B) separating each “start of transient” recording (ST) and “transient” recording (T). Table 5 presents the number of unique transient events identified using automated database processing methods, according to the number of B-type event recordings separating the T-type and ST-type data records (or separation criteria).
**Table 5: Number of Unique Transient Events vs. Separation Criteria**

<table>
<thead>
<tr>
<th>Location</th>
<th>Unique Transient Events vs. Separation Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NONE</td>
</tr>
<tr>
<td>Lakeview Treatment Plant, Zone 1</td>
<td>92249</td>
</tr>
<tr>
<td>Lakeview Treatment Plant, Zone 2</td>
<td>96279</td>
</tr>
<tr>
<td>Hanlan Low Lift Pump Station (LLPS)</td>
<td>861676</td>
</tr>
<tr>
<td></td>
<td>885620</td>
</tr>
<tr>
<td>Streetsville LLPS</td>
<td>-</td>
</tr>
<tr>
<td>MV900 Chamber 8</td>
<td>164105</td>
</tr>
<tr>
<td>HG1500 Chamber 11</td>
<td>37261</td>
</tr>
<tr>
<td>BS1500 Chamber 8</td>
<td>15074</td>
</tr>
<tr>
<td>ST1500 Chamber 9</td>
<td>657753</td>
</tr>
<tr>
<td></td>
<td>936173</td>
</tr>
<tr>
<td></td>
<td>31748</td>
</tr>
<tr>
<td></td>
<td>100691</td>
</tr>
<tr>
<td>Silverthorne LLPS</td>
<td>109740</td>
</tr>
<tr>
<td></td>
<td>578278</td>
</tr>
<tr>
<td>Beckett Sproule LLPS</td>
<td>45926</td>
</tr>
<tr>
<td></td>
<td>68657</td>
</tr>
</tbody>
</table>

* This is the default setting that was employed

The records for Lakeview Zone 1 and 2 are between February 22, 2009 and March 9, 2009. The data at nine locations are each assessed twice, once for the period ending at approximately August 8, 2008 and again for the period ending at approximately September 8, 2008. It should be noted that adjusting transient event definitions with no context of events leads to the loss of potentially important sensitivity that allows near-simultaneous events to be identified. Contrary to that, however, this method aids in the identification of significant transient-free durations.
The above graph, Figure 4, displays the number of unique transient events identified for the permanent sensor installations using the corresponding separation definition on a log-log scale. Similarly, Figure 5 and Figure 6 show this for the temporary sensor installations. In all these graphs, “A” and “B” represent cases where a particular sensor was analyzed twice, using earlier and later data files. This second analysis was performed to get an understanding of the significance associated with an increasing number of records.
Figure 5: Number of Events vs. Separation Definition for Temporary Installations

Figure 6: Number of Events vs. Separation Definition for Temporary Installations
5.3.2 Tláhuac

The Tláhuac project employed entirely temporary sensor installations, largely used for model calibration. The resulting pressure histograms were correlated with tests and events that occurred during the sensors’ residency. Here, sensor settings were decided largely based on experience rather than analytics. A repeat analysis of their validity has been omitted.

5.4 Summary

This chapter has focused on results obtained during the Region of Peel and Tláhuac case studies. Since only one sensor type was utilized, no effort could be made into data fusion techniques. Further, due to the nature of the sensors employed, no statistical analysis could justifiably be performed. The significant issue examined herein was sensor calibration exclusive to the TP-1 sensors. Specifically, the effectiveness of the automated identification of pressure transients was examined. Discussion of these results, their wider implications, and lessons learnt is made in Chapter 6.
Chapter 6: Discussion

“Anyone who in discussion relies upon authority uses, not his understanding, but rather his memory.”

Leonardo Da Vinci
(1452-1519)
6.1 Evaluation of Results

Due to the inconsistent sampling rate, statistical data is largely unavailable for analysis. Despite this, the differences between appropriate and inappropriate sensor settings are evident from the graphs in the previous chapter. For instance, Lakeview 1 in Figure 4, ST1500 and MV900 in Figure 5, and both Beckett Sproule and HG1500 in Figure 6 show the number of transient recordings remaining on at a similar magnitude despite adjusting the database separation criteria. In contrast, Hanlan in Figure 4 illustrates vast changes in the number of transient events as the separation criteria are changed. This lends no comfort to the sensor’s settings or ability to differentiate unique transient events. It should be noted, however, that this method for assessing setting propriety may not be valid for pipelines highly susceptible to pressure transients. It is conceivable that similar approaches could be adopted for other types of sensors, but there has been no opportunity to test this hypothesis in the present work.

6.2 Lessons Learnt

6.2.1 Peel Region Case Study

The Peel Region case study was the first pressure transient study performed during the process of this thesis. As this project involved significant portions of fieldwork and office work, significant lessons were learnt in each area. In terms of fieldwork, the major challenges faced were experienced in relation to sensor installation (physical and hydraulic challenges), calibration and inspections, and clock synchronization. When it came to office work (or analysis), the challenges were in terms of defining pressure
transient events, handling the large quantity of data, and coaxing user-unfriendly software to cooperate and function.

Figure 7: Interior Sensor Installation  Figure 8: Outdoor Sensor Security

Figure 7 and Figure 8 show a sensor installed indoors and security for one installed outdoors, respectively. In indoor locations, locations are relatively accessible and no additional security is required. Finding suitable locations outdoors to install sensors was a considerable challenge, and additional security required to house data storage devices protected from the elements and tampering/theft. Often manholes were flooded or located in hard-to-access locations such as the centre of an intersection. If a location was accessible, it was then never a guarantee that a working tap was available. This experience conveys several key points for consideration when planning and implementing a system for continual remote performance assessments:
The ideal location should be accessible to permit sensor maintenance when required;

Manholes prone to flooding pose the risk of inadvertent contamination through the sensor connections. Extreme care should be taken to prevent this;

Equipment located in flood-prone locations should be waterproof and/or protected from the environment; and

The use of rotating temporary sensor installations may require initial efforts to ensure locations are properly tapped.

Sensor calibration and inspection was another noteworthy problem area faced during fieldwork. Even when the procedure for calibration was followed perfectly, the sensors were known to drift over time and become un-calibrated. This is an issue that all sensors will face, and therefore a scheduled maintenance routine needs to be established. Further, software glitches would occasionally arbitrarily turn off sensor recording. This resulted in large gaps of missing information, and often the loss of useful data corresponding to known events. To address that software needs to be carefully designed and programmed, and should be thoroughly tested to remove all bugs before widespread implementation.

The last significant issue faced in the fieldwork was clock synchronization. Over time, just as the calibration would drift, the sensor time would become unsynchronized. Later versions of the TP-1 system come with GPS clock synchronization, but even those require a direct, uninterrupted line-of-sight with satellites to function. For sensors located indoors or underground, regular resynchronization is required to employ a constant
timeline for all sensors in the asset management network. Identification of an automated method for this resynchronization would be highly advantageous.

In the office work, the definition of transients also posed a challenge. The method by which the TP-1 system records data is suggestive that types of pressure (e.g., normal versus transient) would be easily identified. However, this was not necessarily the case. As can be seen from the discussions in Sections 5.3 and 6.1, neither the automated method for defining transients implemented by the sensor data recording algorithms nor those used in the database for data analysis always perform acceptably. Indeed, it is clear that the sensor’s algorithms routinely misidentify pressure classification. This difficulty can likely be extended to other software, if intelligent sampling frequency adjustments are used to classify parameter properties and adjust data recording rates appropriately. The question, however, is whether these classifications are necessarily useful. By simply converting parameter readings into unitless performance ratings and allowing access to the detailed data behind the scenes if required (e.g., if a specific cause for a problem is being sought), this concern may not play a significant role in the overall framework.

Despite the strategic data recording rate adjustments, large quantities of data were still generated. This results in the next stumbling block experienced: processing and analyzing. Ultimately, a database was developed to automate the data processing and analysis efforts – though to date, no consensus has been reached on certain issues (e.g., transient definition propriety). If back-end data is to be accessible and useful for
designers and decision-makers, parameter-specific toolboxes need be developed and tested.

Finally, the last “office work” issue was related to software problems. The TP-1 sensor system came with a software package for accessing the sensors and sensor data, viewing the data, and exporting it to other formats such as the comma-separated value (.csv) and Microsoft Database (.mdb) formats. Unfortunately, nearly each sensor was shipped with a different version of the software and only worked with that version of the software. Further, file types that were recognized by one version of the software were invisible to the newer (or older) software packages. This lack of recognition for legacy formats resulted in endless frustrations and, as in the case of Lorne Park LLPS in Table 5, prevented access to the data such that analyses could be performed. This significant failure on the part of the software developers represents an issue that developers and implementers of this framework need be aware, in that reliance on vendor software may make things temporarily easier but more difficult in the long run, and any software developed should be standardized such that legacy files remain useful for as long as necessary.

6.2.2 Tláhuac Case Study

The Tláhuac case study offers some particularly useful lessons for establishing a dynamic performance assessment system. First and most notably, the idea of propriety arises. The Tláhuac system withdraws water from a depleting aquifer, and therefore its useful life is very limited unless current practices are changed. Sustainability obviously was not
considered and could be discussed here, but the concept of sustainability is largely outside of the scope of the present work. What should be considered, however, is the impropriety of implementing a permanent system for performance assessment in an impermanent water transmission system. In other words, the framework developed in this thesis is not universally applicable. Careful consideration should be given to the remaining service life of the utility prior to deciding to implement. It may turn out that the cost of doing discrete sampling to confirm performance is more justifiable than that of installing a sensor system.

<table>
<thead>
<tr>
<th>Causes</th>
<th>Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Insufficient availability of sources of water.</td>
<td>(a) Pollution of water supply from intrusion into empty pipes of water from surrounding environment.</td>
</tr>
<tr>
<td>(b) Poor condition of the distribution system resulting in enormous losses.</td>
<td>(b) Increased wastage. Consumers will often leave taps open since the water is only received for a short time.</td>
</tr>
<tr>
<td>(c) Lack of funds for increasing the capacity of the water source and providing improved maintenance for the distribution system.</td>
<td>(c) Tendency to throw away stored water to replace with fresh water whenever it arrives.</td>
</tr>
<tr>
<td>(d) Inconsistent or unreliable power supply.</td>
<td>(d) Risk of contamination in storage.</td>
</tr>
<tr>
<td></td>
<td>(e) Consumer dissatisfaction.</td>
</tr>
</tbody>
</table>

The second item of note from the Tláhuac study is the nature of a system with intermittent supplies. The previous table (Table 6), derived from the article “Technologies to improve efficiency in distribution system with intermittent supplies,” presents some of the causes of intermittent supply and potential problems. [67]. In the case of Tláhuac, power failures are often responsible for shutting down parts or all of the
transmission system. For Tláhuac, the main problem, intrusion of contaminated water, was largely offset by the fact that the water was not potable to begin with.

In systems with intermittent supply, the effectiveness of various sensors is highly uncertain. Just as typical leak detection methods such as the minimum night flow method are ineffective due to the extremely low pressures [67, pg. 578], other sensors may suffer similar difficulties. An approach similar to the Tanker methodology outlined by Kumar [67, pg. 578] may be possible and still justifiable using only temporary sensor installations in isolated zones for sustainable systems suffering intermittent supply.

The third lesson learnt was that pre-test meetings were highly effective to reduce confusion and improved results drastically. This likely was a result of the communication barriers between the native English speakers, who spoke only English, and the native Spanish speakers who spoke only Spanish. Taking the time to clear any miscommunications or ambiguous tasks prior to commencement of the tests led to significantly smoother operations. This concept can be expanded, however, to address native speakers of English who function in different vocational areas. Despite speaking the same language, we don’t necessarily speak the same language. Preliminary meetings to determine all the requirements of various stakeholders and clear misunderstandings can prove invaluable.

Despite the success of the pre-test meetings, the next lesson learnt from this case study arose from the wide range in data collected manually during various system tests undertaken. Though the instructions were clearly delivered prior to the initiation of tests,
some confusion still ensued. To avoid this, and to ensure complete and consistent information collection, explicit forms for each participant to complete should have been developed. This concept can again be extended to the idea of the performance assessment framework developed herein.

Observing system response to operational changes provided another important lesson: the value of imperfections. Despite failed AVs and PRVs, system imperfections would protect the system from being damaged by these forces and release them in unanticipated ways. Occasionally, one valve type would even function as a different valve type (i.e., an ARV would act as a PRV). The US EPA describes a similar concept in terms of pipe materials. “Although the centrifugal casting process improved pipe strength and minimized casting imperfections [compared to pit cast], the reduction in wall thickness coupled with the lack of exterior corrosion protection has resulted in a failure rate in the industry that is higher than the older pit cast iron pipe” [68, pp. 2-3]. The point that can be taken from this is that perfection should not be sought, as it may result in an inferior system. Therefore, an idea of what constitutes over-performance is just as important as an understanding of minimum performance requirements.

Much of the information gathered was to eventually be applied to the calibration of a system model. The development of the models is where the next lesson was learnt: accurate and consistent maps are vital. The maps provided to build the model from were often outdated, lacking in information, or presented different and contradictory datum levels. Employing a GIS-based approach to the performance assessments, and
emphasizing the ability to make revisions to the database on location, should reduce the likelihood of inaccurate or missing basic data.

When it came time to present the results, the client requested a non-standard unit for pressure. Due to the nature of the TP-1 software, this conversion was not possible. Additional software packages would have been necessary to manipulate the data into the desired form. This introduces the next lesson learnt: software that incorporates a method by which to convert data into desired scales, even if it isn’t a standard unit, adds flexibility to the locales that employ the software and thus increases the rate of adoption.

The last lesson learnt in this case study is that counting down backwards in foreign languages is hard. This is only a personal observation, however, and can’t really be expanded to larger issues. It just needed to be said.

6.3 Summary
Chapter 6 analyzed results provided in Chapter 5. It then delved into lessons learnt during the Peel Region and Tláhuac case studies. Both the case studies’ results and lessons learnt are largely applicable to the wider issue of performance assessments, particularly in a framework such as the dynamic scorecard that will be described in Chapters 8 through 10. Limited statistical information was derivable from the TP-1 sensor installations, however, and no information was available to evaluate the usefulness of data gained in decision-making processes. Accordingly, there remains significant further work to be done in ascertaining and quantifying the true utility of these real-time approaches.
Therefore the next chapter, Chapter 7, focuses on the perceived value opportunity associated with a performance assessment process derived from inclusive approaches to information management such as the dynamic scorecard developed in Chapters 8 to 10 herein.
Chapter 7: Conclusions and Recommendations

“We are not certain, we are never certain. If we were we could reach some conclusions, and we could, at last, make others take us seriously.”

Albert Camus
(1913–1960)
7.1 *Lifeblood of Society*

Water is the lifeblood of society; without it our modern standards of living would not be possible. We gather it, treat it to a desirable quality standard… and then largely forget about it. It is pumped into the ground, through kilometers of unmonitored pipes that are slowly aging and falling apart, and we assume it will work. Until it doesn’t. Then, if something breaks, we try to fix it after the fact. If we notice that it’s broken. To continue with the analogy between pipelines and the human body, it is the equivalent of assuming that once we’re born we have no further use for doctors and ignoring the possibility of developing cardiovascular disease regardless of what we do to our bodies. Then we go to the doctor when we have a massive heart attack. The concept proposed herein, however, can be considered analogous to ensuring a patient’s vitals are monitored 24 hours a day for the rest of their lives. Obviously not all patients are built the same, nor are all water transmission and distribution systems. In many cases, it is sufficient to perform scheduled “checkups” to ensure everything is working acceptably well. In some cases however, especially where many lives or large investments depend upon the system operation, constant monitoring may be justifiable.

7.2 *Summary and Opportunities for Future Work*

In chapter 1, the significance and methodology of this thesis was outlined. Chapter 2 provided a literature review of the larger picture of performance assessments and examined a wide range of correlated issues. With Chapter 3, the concept of data collection was inspected and various methods were outlined. Most notably, the idea of automated data collection through sensors and the utility of this were presented. Chapter
4 outlined two case studies, the results of which were presented and then discussed in Chapters 5 and 6 respectively. The purpose of this chapter is to be a reminder of the material covered and establish the practical background that will be extended to a more holistic performance assessment framework.

The second half of this thesis presents a concept for dynamically monitoring/assessing system performance. Chapter 8 establishes the boundaries for the hypothesized performance assessment, identifying key components of a water distribution/transmission system. Chapter 9 discusses the actual scorecard, and the presentation of information. Chapter 10 discusses the implementation of a performance assessment system. Sufficient data was unavailable to assess many of the implications of this, though it is hypothesized that the improved investment efficiency and the potential for use as an early warning system will more than pay off the implementation costs, nor were the qualities that identify a suitable system for real-time monitoring clearly established. Other opportunities for further research are highlighted throughout this document. This area does have considerable potential but is still very young in its conception. Much needs to be done, and a more structured approach applied to the concept, before it can be applied with any guarantee for success.
Chapter 8: Performance Boundaries

“Le secret d’ennuyer est celui de tout dire.”

Voltaire
(1694-1778)
8.1 Introduction

The importance of asset management has been clearly delineated in the literature review (Chapter 2), but to reiterate, it is of vital importance to know that infrastructure is adequately performing the functions set out for it. For example, the U.S. EPA state in their paper entitled *Deteriorating Buried Infrastructure Management Challenges and Strategies* [68, pg. 1-2] that:

The rate of deterioration of a water system is not a function of material age but rather the cumulative effect of the external forces acting on it. During a recent water system valuation, 70+-year-old unlined cast iron main was found to be in excellent condition with negligible internal or external corrosion. Based on the field observations, there is no reason to believe that these mains will not provide another 70+ years of satisfactory service. Conversely, in another system, cast iron mains less than 50 years old are experiencing excessive and rapidly increasing break rates and severe corrosion activity. [...] Therefore, broad based decision factors regarding infrastructure replacement, whether based on age, pipe size, pipe material, linings, etc. will not result in an effective use of limited capital resources. Better information and decision making is needed.

The purpose of this chapter is to identify components of the system under consideration for a larger performance assessment, and illustrate requirements and goals for that component’s functionality in order to more ably obtain better information and subsequently make better decisions. A simplified illustration of the system extent can be seen in Figure 1. Further, akin to the desires outlined in the Queensland Government’s *Building Asset Performance Framework*, the ultimate goal of the final performance assessment framework is to be comprehensive of not only functional and financial
aspects but of social and environmental considerations as well [69]. Reflection on these issues is therefore also included herein. It should be reiterated that the following chapters, Chapter 8 through 10, are largely speculative extrapolations of the work discussed in Chapters 4 through 7.

8.2 Stakeholder Analysis

A stakeholder can be defined as any person or entity that can be impacted by or cause an impact on corporate decisions and actions. There are an equally large number of stakeholders for consideration as there are entities that depend upon the function of water supply and distribution systems. While this subsection does not describe all stakeholders relevant to these systems, it identifies several that should be acknowledged and represented. Further, while it does not delve in depth into any particular stakeholder’s interests, some of the more important issues are elucidated.

From the vantage point of a performance assessment, three main groups of stakeholders should be considered: employees/operators, management/decision-makers, and customers/end-users. These three groups of stakeholders not only have an impact in what decisions are made, but also how a system is operated and utilized, and subsequently how it performs. Collecting information from and about these stakeholders that may be useful for assessing system performance also poses significant challenges.

Useful information about employees and operators are simplest to track. This information can range from repair time for pipe bursts to training. Most importantly however, in order
to provide a quality product and service, employees/operators must possess the required competencies. According to a Ministry of the Environment Guide [70]:

- Personnel must have the appropriate education, training, skills and experience to be competent at their jobs;
- All employees whose work affects quality must receive the appropriate training;
- Employees must be aware as to how their work impacts quality; and
- Procedures must be in place to ensure competent employees cover the drinking water system at all times.

In addition to possessing the required competencies, sufficient personnel who possess these competencies must be available for their duties. A personnel management system may be employed to ensure all required competencies are available and training currency is maintained. The possibility exists for incorporating these factors into the performance assessment framework proposed in this thesis, however the details have largely been omitted as they are beyond the scope of this performance assessment framework.

With respect to customers or users, little information can be easily collected. Often at best, areal generalizations may be made on user type and demand patterns. This type of information is not only important during the design phase but, with certain modern advanced metering, there is potential for incorporating real-time and historical demands into a utility’s information system. In addition, records should be kept regarding customer complaints. The current work will examine some of these details cursorily, however the details are considered largely outside the scope of work.
8.3 System Components

8.3.1 Raw Water Source

This thesis focuses on water as the transmitted and distributed product. For other fluids, additional efforts must be made in areas such as ensuring the pipe materials are appropriate for the internal environment/product (see section 8.5.) Even with just focusing on water there is a wide range of conditions to be considered, many stemming from the water source. Depending on the source, different information may be required to effectively assess the overall drinking water system. An example of pertinent information can be found in Table 4.1 of the World Health Organization (WHO) Guidelines for Drinking Water Quality [71, pg 54]. In addition to possible contaminants, there are other factors that require consideration when examining the source of water. Recently, the concept of source security has become an increasingly popular subject in North America. Source security is beyond the scope of this thesis. Older concerns include the reliability of the source, as well as sustainability. Reliability is further discussed in Subsection 8.3.8 and Section 8.9, though for the purpose of this thesis source reliability is considered to be a component of the system design phase. Sustainability itself is an extensive subject, and while touched on cursorily (e.g., with respect to the Tláhuac case study), it is also largely beyond the scope of this work.

8.3.2 Raw Water Storage

In situations where demand may exceed source supply availability, raw water may be stored such that supply is consistent even during times of high demand and low availability. As discussed in Section 4.1, the condition of storage structures has been
omitted from this work. Accordingly, raw water storage will not explicitly fall within the scope of this thesis, except insofar as it participates in the water transmission system. Since this storage occurs prior to treatment of the water to potable standards and the actual treatment processes are considered beyond the scope of the scorecard conceptualized herein, quality of the stored water is also neglected.

### 8.3.3 Raw Water Treatment

Prior to distribution or delivery to users, the raw water typically must be treated. According to an international report on water quality in distribution systems, “water quality control throughout the world is based on three models: Drinking-water quality guidelines (WHO); Directive 80/778/EEC¹ (EU); Drinking Water Safety Act and associated regulations² (USEPA)” [72, pg. 92]. They note, however, that this statement can’t necessarily be applied to the entire world as intended because of “lack of data for Asian, African and Latin American countries” [72, pg. 89]. Treatment may include any number of processes to remove these contaminants that would otherwise pose health threats to consumers. As indicated previously, for the purpose of this thesis the treatment process is considered external to the system performance and therefore out of scope for the framework suggested herein. It has been assumed, however, that while treatment is out of scope, the distributed product has been effectively treated prior to distribution.

---

² Also referred to as the Safe Drinking Water Act, or SDWA.
8.3.4 Treated Water Storage

To reduce cyclic loads on treatment facilities, treated water is often stored. This enables a Water Treatment Plant (WTP) to treat water at a constant rate without concern for fluctuations in demand. Additionally, the WTP may be designed for a lower capacity than would otherwise be necessary to meet the peak daily demand. Treated water storage is again outside the scope of the present work, though the assumption is made that consideration of concepts such as structural capacity, lifetime performance, and even water circulation have been adequately dealt with during the design phase.

8.3.5 Piping – General

Though the associated concerns may be related to the stage of the infrastructure lifecycle (see Figure 3), piping remains a significant issue considered within this thesis. In design, appropriate pipe materials should be selected to encourage a long and effective lifespan. During construction, materials must be treated with adequate care to prevent premature damage to the system. During regular operations, the manner in which the system is run and demands imposed impact the future usefulness of the system, as well as what maintenance or upgrades are necessary. Finally, at the end of the lifecycle, decisions made throughout impact the actions necessary to decommission a line or component of the system.

Decisions made during design have arguably the largest impact on ultimate performance of a pipe. Accordingly, a logical systemized approach to handle issues such as material selection is advisable. De Rosa and McBride provide an example of this, and outline a
six-step process for selecting pipe materials [73]. First, a definition of the application must be established. At this step, the limitations of use for various pipe materials must also be ascertained. Next, a consistent set of rules for selection should be established based on technical considerations. Material options should then be justified based on these rules, as well as current/future operating conditions, training, installation equipment, and other relevant factors. Next, a cost comparison should be made for the available alternatives. The preferred materials usage strategy can then be defined. Lastly, the strategy should be implemented and monitored. This approach can be visualized as largely analogous to the decision-making process described in Chapter 11 (see Figure 18). In other words, while a formalized approach can be established, it may be sufficient to prove that a systematic and contemplative decision process was followed.

Determining the hydraulic importance of a pipe is not only important in its regular operation and maintenance, but may also be significant in determining where to best position sensors for the purposes of assessing performance. Additionally, an indication of the relative hydraulic importance of pipes can permit simpler and faster identification of critical lines when examining overall system performance. Izquierdo et al. describe one such method for determining the relative importance of pipes within a distribution system based on a fuzzy steady state model analyzing pipe sensitivity [66]. Alternately, a simplified approach such as that suggested by Arulraj and Rao may be adopted, where the proposed index is simply the ratio of the flow rate multiplied by pipe length with the Hazen Williams roughness coefficient multiplied by the diameter (QL/CD) [74]. It may make some sense to normalize such an index by dividing by the maximum flow rate.
8.3.6 Piping – In-plant Piping

In-plant piping includes all piping in the interior of a treatment or processing plant. Specific consideration of piping used strictly for internal processes is omitted from the scope of this thesis. This infrastructure should be included within the facility management processes. Piping that can be considered a component of the transmission or distribution system, however, is within scope and in many cases has been utilized in the Peel Region case study.

8.3.7 Piping – Transmission Lines

Transmission lines run from a source location to a destination location without interruption. In other words, a transmission line has no extraneous demands imposed on it between the origin and destination. Transmission lines are considered within the scope of the present work, with the Tláhuac case study being entirely composed of these lines.

8.3.8 Piping – Distribution Lines

There are three common configurations for distribution lines: grid, loop, and tree. Rough depictions of these configurations can be seen in Figure 1. Population densities can vary widely as well. Uniform density infers that the population density is equal at all points through the system, whereas mono-centric and polycentric indicate a system that has a higher population density at one or more locations, respectively.

The form of a water distribution system (which is in many cases largely dictated by the population distribution) can have a significant impact on the amount of energy required
for its operation. This quantity of energy is not insignificant; in their assessment of urban form on energy use in looped water distribution networks [75], Filion indicates (as cited in [76]) that in 1998 approximately 1.5% of Toronto’s total electricity consumption (386 GWh/year) was devoted to pumping and water distribution. As expected, they report that the minimum annual per capita energy usage results from mono-centric pipe arrangements, particularly those that offer the shortest pipe distance from source to destination and offer most redundancy. Similarly, the maximum per capita energy usage was reported in situations where the population is uniformly distributed (e.g., suburbia), or long pipe paths were required to service demands. The concept of the impact of urban form on energy use is particularly important when assessing the performance of the water distribution system in terms of energy efficiency.

If a utility is infrequently measuring energy consumed in distributing water, changes in energy consumption may be incorrectly attributed to deteriorating pipe conditions rather than system expansions or changes due to the incremental nature of cities. A minimum-entropy approach to selecting the layout could be employed in design to minimize energy use, but urban form is typically determined by transportation and land-use planning policies. Subsequently, the details of energy use are largely omitted from examination herein despite being a significant factor related to the environmentally friendly and cost effective operation of the utility.

Reliability refers to the likelihood that a component or the system as a whole will perform as intended and/or required. While a system’s reliability is intrinsically tied to its
urban form, one method for increasing a system’s reliability is to increase the redundancy of components in the system. The drawback to this approach is an increase in cost. With increased redundancy however, when one component fails, the system can adjust its functional topology and continue operating with minimal impact to consumers.

The form of the water distribution system also greatly impacts the redundancy of the system. There are many possible ways to determine redundancy in a water distribution network. One possible definition is simply summing the number of potential paths that water has to reach its destination [75, pg. 342]. Kalungi and Tanyimboh present a more complicated model for redundancy based on a head-driven simulation and component reliability [77]. The equation they present for redundancy is a function of network reliability and probabilities of component failure (or success), calculable on both system-wide and nodal levels.

8.3.9 Piping – Services

Piping services, also considered appurtenances, permit consumer access to the product distributed. These may or may not be metered, depending on the utility and the particular user. For the purpose of this thesis, services have been omitted from the scope of study. It should be noted however, that despite their omission from this work, services still have significant potential to be a source of contamination or leakage. Maintenance or repairs to services typically falls to the property owner rather than the utility, posing an even greater challenge in preventing contamination.
8.3.10 Valves and Appurtenances

Various valves and appurtenances are typically installed at strategic locations throughout water transmission and distribution systems to assist in their operation. These may include check valves (CV) to prevent backflow of fluids, pressure-reducing valves (PRV) that prevent pressure from exceeding certain levels, and air valves (AV) which allow the escape of air trapped in high points of the line. Information from various sensors (e.g., the TP-1 pressure monitoring system) may be used to determine whether or not a valve is functioning, either by directly focusing on the valves and appurtenances or indirectly through inference. While it is assumed that a water transmission or distribution system will contain numerous valves and appurtenances, for the purpose of this thesis, explicit consideration will not be given to their performance.

8.3.11 Pumps

The type, number, and location of pumps, as well as their ability to operate at variable speeds according to system demands will have a significant impact on the energy consumption of the system. They may also affect pipe condition through velocity and cavitation effects. Despite their level of impact, pumps are largely omitted from the present work.

8.4 System Utility and Requirements

8.4.1 Water Quality

As indicated in section 8.3.3, the treatment of water to potable standards is considered outside of the scope of this work and the assumption has been made that water has been
effectively treated according to established standards prior to distribution. Further, it is assumed that the production of disinfection byproducts (DBPs) such as Haloacetic Acids (HAAs) and Trihalomethanes (THMs) has been avoided through conscientious design and operation of treatment facilities. The detection of changes in water quality, however, can be considered a significant component behind the concept of assessing system performance. Water quality can be considered a significant aspect of the performance of water transmission and distribution systems, particularly where the water is intended for human consumption.

In addition to minimizing health risks, it is important to deliver water that meets aesthetic requirements of the consumers (i.e., taste, odor, color). Unfortunately, a lot of the parameters are identified in these drinking water quality models are difficult to directly measure. Others currently have no accepted method for in-situ or real-time measurements. The U.S. E.P.A. produced a document discussing numerous water quality indicators in depth [78]. Table 7 presents a selection of those possible indicators, as well as the potential pathways for contamination, type of contamination, and whether there is an expected public health outcome. The subsequent table, Table 8, presents information related to the monitoring of indicators identified in Table 7 as described by the E.P.A. white paper.
<table>
<thead>
<tr>
<th>Indicators</th>
<th>Breaches of Integrity</th>
<th>Contamination</th>
<th>Public Health Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>External Pathway</td>
<td>Internal Pathway</td>
<td>Fecal</td>
</tr>
<tr>
<td>Total Coliforms</td>
<td>*</td>
<td>*</td>
<td>*&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>E. coli</td>
<td>*</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Thermotolerant Coliforms</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Total Bacteria Counts</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Residual Disinfectant</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Alkalinity</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Conductivity</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Adenosine Triphosphate</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Chloride</td>
<td>*</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Sanitary Survey</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Turbidity</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Loss</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Temperature</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

<sup>1</sup> – total coliforms may be a broad screen for the potential for fecal contamination since some fecal bacterial pathogens may be present when total coliforms are present.

<sup>2</sup> – potentially indicative of bacterial pathogens, but not viruses and protozoa [79]

<sup>3</sup> – not all are pathogenic
Table 8: Monitoring Methods for Water Quality Indicators

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Simple</th>
<th>Well-known</th>
<th>Inexpensive</th>
<th>Fast</th>
<th>On Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Coliforms</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E. coli</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*2</td>
<td>x</td>
</tr>
<tr>
<td>Thermotolerant Coliforms</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td>*2</td>
</tr>
<tr>
<td>Total Bacteria Counts</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual Disinfectant</td>
<td></td>
<td>*</td>
<td>*</td>
<td>*1</td>
<td>*</td>
</tr>
<tr>
<td>pH</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Alkalinity</td>
<td></td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Conductivity</td>
<td></td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Adenosine Triphosphate</td>
<td>*3</td>
<td></td>
<td></td>
<td></td>
<td>*3</td>
</tr>
<tr>
<td>Iron</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloride</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Sanitary Survey</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Turbidity</td>
<td></td>
<td>*</td>
<td></td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Water Loss</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Temperature</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*1</td>
<td>*</td>
</tr>
<tr>
<td>Pressure</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

1 – immediate  
2 – 24-48 hours  
3 – developed for food industry, applicability with water uncertain

* – as per E.P.A. white paper [78]  
x – as per additional sources (general internet search)
Simple sensors exist to detect physical and chemical parameters such as residual disinfectant, pH, alkalinity, conductivity, turbidity, flow and pressure [80]. For example, Helbling and VanBriesen describe the implementation of chlorine sensors in a laboratory-scale distribution system to detect biological contamination (E. coli) [81]. Microbial parameters, often considered far more important than chemical or physical properties of the water due to their potential immediate health effects, largely lack methods for rapid, direct and/or in-situ detection. Berkeley Labs have developed a simple sensor for detecting the presence of E. coli based on an inexpensive color-changing membrane [82], but applying this would involve the replacement of sensors after any contact with the bacteria. Still, other portable methods require disposable reagents. The food industry, for example, has developed fast and reliable methods for testing for ATP using bioluminescence assays. Cho and Yoon examined the application of bioluminescence assays in evaluating disinfection performance, indicating that only the method of culturing to amplify bacteria concentrations was suitable for disinfection studies [83]. Their dismissal of the membrane filtration approach for amplification was based entirely on the inconvenience of handling “large” quantities of water (several liters for 5-7 sampling repetitions) yet ignores the improved timeliness. Contrarily, Delahaye et al. describe effective use of bioluminescence after membrane filtration in assessing the Paris distribution system [84]. Other case studies of bioluminescence using amplification by membrane filtration applied in simplified water distribution settings to quickly locate bacterial can be found on the website of the kit provider LuminUltra [85]. In general, biological contaminants can only be inferred indirectly or tested based on discrete sampling procedures.
The exact biological and chemical contaminants to be sampled for during discrete sampling are largely dependent upon the water source, quality requirements and treatment procedures. The frequency and locations are, in turn, dependent upon the location and number of users, their consumption patterns, and the overall layout of the system. Each model for water quality has developed recommendations for these sampling procedures. Additional sampling may be undertaken according to other regulations, reported incidents, after system renovations, or to reduce statistical uncertainties.

Due to the vast number of potential contaminants and the cost and availability (or lack thereof) of corresponding sensors, constant and/or real-time monitoring makes sense only for broad indicator parameters. In their guidelines for drinking-water quality, the WHO suggests that the essential water quality parameters to be monitored are *E. coli* (or thermotolerant coliforms as a substitute), and residual chlorine. They recommend that these parameters be augmented by also monitoring pH and turbidity [71, pg. 82]. The data summarized in Table 7 and Table 8 support these choices of parameters, with the exception that *E. coli* and other biological contamination may be left to indirect monitoring through remaining levels of residual disinfectants. Additional parameters may warrant consideration according to the specific system, though discrete sampling is likely still sufficient barring extraordinary circumstances.

8.4.2 System Capacity

As far as practical, water transmission and distribution systems must be designed to meet the demands of the users. In addition to certain levels of quality, users often also expect
certain standards to be maintained with regards to pressure and flow rate. In many cases, these are dictated by requirements for fire control according to regulations and/or relevant fire insurance underwriters.

Flow rate and velocity are related by the simple equation \( Q = AV \), where \( Q \) is the flow rate (volume per second), \( A \) is the area, and \( V \) is the velocity (distance per second). The quantity of water provided by the system must be sufficient to meet both user demands and be capable of handling additional fire flow demands, typically proven through simulations based on factored combinations of these demands. Fire demands are often the decisive factor in sizing pipes. In addition, it is possible to design a system sized according to an estimated optimal cost considering both capital costs for material and construction as well as pumping energy [86, Section 8.9]. For the purposes of the present work, it is assumed that all these considerations have been taken into account during the design phase and all the pipes have all been appropriately sized considering not only present demands but also predicted growth and diurnal and seasonal variations in demand.

Though ensuring provision of a sufficient quantity of water is important, the system must also be checked against a maximum permissible velocity. Excessive velocities in pipes can result in pipe scouring, and may accentuate problems with pressure transients. Subsection 8.4.3 discusses issues related to system pressure.
8.4.3 System Pressure

Pressure is a critical issue when considering the performance of transmission and distribution systems. If the pressure becomes too great, the structural capacity of pipes may be exceeded and they will burst. The maximum permissible pressure is dictated by the pipe strength. If the pressure is too low, air or water from the surrounding groundwater may enter the system. This intruding water may introduce chemical or biological contaminants to the system. The intrusion of air, on the other hand, could result in pipe bursts in poorly designed or maintained systems. Low pressures may also result in customer complaints, and negative pressures may even collapse pipes. The minimum permissible pressure is typically specified in local regulations, often to meet insurance stipulations. As may be illustrated by Jacobs and Strijdom in their article about the use of minimum residual pressure as a design criterion in South Africa however, these prescribed pressures are often arbitrarily selected [87].

Water systems can’t immediately respond to changes in demands or system conditions (e.g., pump settings, valve openings/closures, etc.), so the phenomenon of hydraulic transients occurs. Hydraulic (or pressure) transients are a temporary state of fluctuation in pressure that occurs between any change in the system and its new steady state flow conditions. These pressure fluctuations travel through the system at extremely high speeds (celerity) that are dependent on the pipe material. Pressure transients can cause similar problems as excessive or insufficient pressures, but may also result in cavitation if column separation occurs. The case studies identified in this thesis employed high-speed pressure transient monitoring systems to monitor pressure transients, in turn observing
maximum and minimum system pressures experienced. The purpose of this monitoring, however, was largely for model calibrations. The information gathered will have minimal direct importance to the present work, yet the lessons learnt are highly significant. Analysis and discussion of the case studies is presented in Chapters 5 and 6.

8.4.4 Utility and Requirements Conclusion

The purpose of this subsection is to summarize the main findings of Section 8.4. In the following table (Table 9), the main parameters identified with potential for real-time monitoring are presented alongside the information they provide. Discrete sampling is still recommended for additional chemical and biological parameters.

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Contaminants Detected</th>
<th>Breaches Detected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Biological</td>
<td>Chemical</td>
</tr>
<tr>
<td>Pressure</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Flow Rate</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Residual Disinfectant</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Turbidity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature(^5)</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^5\) Temperature may not seem an important parameter to measure, and in many cases it may not be. However, the corrosivity of water and the growth of viruses and bacteria are both affected by temperature. Further, in particularly cold climates, water has the potential to freeze and burst pipes.
8.5 Location and Use

8.5.1 External Environment

The external environment where the infrastructure is located has a significant impact on its longevity and health. For instance, the soil type must be taken into consideration when selecting pipe materials to minimize corrosion and deterioration of the pipe. Figure 9 displays some of the impacts that the external and internal environments have on pipes.

Through leaks in pipes and pressure fluctuations, pollution from the external environment has the potential to intrude into the drinking water system. This is of particular concern where the groundwater table (GWT) is above the apex of the pipe. Thus, it is evident that knowledge of an area’s GWT level is crucial for assessing the risk of groundwater intrusion into the system. It is worth note that certain organizations may have taken up
the goal of monitoring groundwater and can provide relevant information without requiring additional investment from the water utility. For example, the Toronto and Region Conservation Authority (TRCA) is working in partnership with the Ontario Ministry of the Environment to establish an Ontario-wide monitoring network. This network measures GWT levels hourly (posting online bi-weekly), and chemistry data 1-2 times per year [88]. No information is presently available regarding the possibility of direct access to the real-time data, but such external data sources should not be neglected.

In addition to the soil weight, dynamic traffic loads may also have to be resisted. The magnitude of these loads will be dependent upon the location and depth of the pipe. For the purpose of the present work, it is assumed that these loads have been taken into consideration in the design phase.

In addition to its direct effects on pipe performance, the external environment has a secondary effect due to its impact on people. For example, when seasons shift from winter to summer, additional demand is imposed on the system to permit watering of lawns. The changes in temperature and possible freeze/thaw behaviors of the soil will also affect pipe resilience. It is again assumed that these issues have been fully taken into consideration in the design phase.

8.5.2 Internal Environment

Just as the external environment can act to quickly degrade pipes, the internal environment also has a significant impact on pipe performance. As discussed in
Subsections 8.4.2 and 8.4.3, pressure and velocity can result in bursting or scouring the pipe. In addition to this, however, even the water characteristics can be harmful to pipe integrity. An example of this is the stabilization of alkalinity by reaching the saturation pH during the treatment process to avoid corrosion in metal pipes. Corrosion may not only weaken the pipe, but can also form byproducts within the pipe that reduce the hydraulic efficiency.

In addition to physical and chemical effects on the internal environment, biological activity can also impact pipe performance. The growth of biofilms can reduce cross sectional area in a manner similar to corrosion byproducts, but may also reduce chlorine residuals and increase the risk of contamination exceeding the system’s ability to handle it. Alternately, some biological organisms are able to avoid the secondary treatment by “hiding” in the biofilms.

8.6 Maintenance and Reliability

8.6.1 Asset Data (Age, Location, Material)

To effectively assess its performance, a thorough knowledge of what exists is required. A complete database (or, as complete as possible) should be produced that includes not only the type of item (e.g., cast iron water main, or pressure reducing valve) but also its characteristics (e.g., initial cost, structural capacity, etc.), state (e.g., open, percentage open, or closed with respect to valves), age, location, and important maintenance and operational notes. Without this information, it will be impossible to estimate reliability, risks and hazards with any degree of accuracy.
8.6.2 Asset Failure and Maintenance History

Having a record of asset maintenance and failure can aid in determining the depreciation modes (e.g., straight line, exponential, etc.) of certain materials and system components. This, combined with information on repairs (whether it was preventative or a reaction to a minor failure), will enable more accurate estimates of remaining service life for components. Alternately, it will make it easier to predict where failure may occur next.

8.7 Safety in Operation

The safe operation of water transmission and distribution infrastructure is a significant concern. Naturally, safety is both crucial to the owners and operators, but also important to the users. For the purposes of this thesis, issues relating to safety beyond those already discussed are considered out of scope. In other words, while the present work is concerned with maintaining water quality and hydraulic efficiency, it is not ambitious enough to assume prediction of abrupt pipe failure and the likelihood of injury to bystanders. It suffices to say, however, that good control reduces the probabilities of such disastrous events.

8.8 Customer Satisfaction

Customers using a product expect a certain level of service. Some of the factors they will desire have been outlined previously, in Section 8.4. While some lapses may go unnoticed, and prescribed minimum standards may be well above actual customer expectations, customers can be expected to complain if there are extreme violations in the
level of service. Accurate and complete records are essential here, as this information can often lead to identification of significant present or future problems.

Loosely tied to the issue of customer satisfaction is the payment for the service. In general, the value people will be willing to pay for a service is proportional to the quality of the service they receive. There are many options for billing, including billing by metering or billing related to property value. This thesis will not go into depth in examining these issues. Suffice it to say, however, that billing by metering holds some advantages over billing by property type when it comes to system performance assessments: water consumption and water loss is more easily quantifiable, actual pipe demands can be monitored, and changes in system response are more easily correlated to demands. These advantages are particularly convenient if the meters are electronic, since they can be more readily (and quickly) incorporated into a computerized system.

8.9 Reliability and Resilience
Reliability, specifically hydraulic and mechanical reliability, has been cursorily discussed in Chapter 2 (see equations 2.1, 2.2, and 2.3), and Chapter 8 Subsection 8.3.8. In this case, hydraulic reliability refers to how effectively water gets to a demand and mechanical reliability that considers whether a route exists to the demand. Reliability refers to more than simply the probability that sufficient quantities of water are provided however, or that probability that sections of the system are operating and available. This concept can be expanded to cover issues such as the reliability that the distributed water
remains of sufficient quality, customer satisfaction is maintained, or even that the system is operated safely.

Resilience refers to the ability of the system to return to normal conditions after being stressed, referring to large changes in demand, transient pressures, or even the temporary loss of one or more pipe sections. In this case, the measure of resilience most controllable after the system has been designed and installed is the response to failures and catastrophes. For the purpose of this thesis, resilience is considered out of scope. It should be noted, however, that information garnered from active monitoring can be effectively employed in planning to enhance resilience and emergency response. Further, an effective assessment will permit better understanding of both the critical and most vulnerable components of the system.

8.10 Sustainability

Can system operate at present desirable Levels of Service (LOS) without compromising ability of future generations to fulfill their needs. An example of an unsustainable practice can be seen in the Tláhuac case study, where the quantity of water withdrawn from their aquifer exceeds the aquifer’s recharge rate. For the purpose of the theorized performance assessment framework developed in this thesis, however, sustainability is largely considered out of scope. The present work will only address sustainability in the sense that it strives to ensure consistently (and justifiably) high performance is achieved in current and future transmission and distribution systems.
8.11 Summary

This chapter firmly established the perceived scope and boundaries for the conceptual performance assessment framework that is developed in Chapters 9 and 10. Not only technical aspects were identified, but stakeholders and operation/maintenance boundaries as well. Each aspect was examined in detail sufficient to justify its inclusion/exclusion and identify significant issues related to it, and in conjunction with the understanding of data collection methods (such as discussed in Chapter 3) the means to acquire the requisite data is more easily identifiable. With this knowledge, the earlier chapters that establish the dynamic scorecard and possible implementation (Chapters 9 and 10) are effectively placed in context. Finally, the decision-making framework presented in Chapter 11 seeks to remind the reader of the importance to place all the prior discussion within a decision-making context for it to have value.
Chapter 9: Dynamic Scorecard

“An ounce of performance is worth pounds of promises.”

Mae West
(1893–1980)
9.1 Introduction

In their framework for municipal infrastructure management, the NRC identifies a “roadmap” of six questions about assets was suggested: what do you own (and where is it), what is it worth, what is deferred, what is the condition, what is the remaining service life (RSL), and what do you fix first [89, pg. 4]. Their framework lacks in establishing specifics, however, as it is meant to be applied to all categories of infrastructure. The larger purpose of the dynamic scorecard described herein is to address all of these issues, to a degree, by presenting a real-time image of the system performance.

This chapter presents a proposed system for presenting performance information, and the concept of this “dynamic scorecard” framework for performance assessments. By employing a scorecard approach, a holistic approach is emphasized over piecemeal examination of system behavior. This accentuates interrelationships between facets of performance. Further, by incorporating the temporal dimension, unforeseen interdependencies can be drawn to the forefront.

9.2 Categories of Performance

The original Balanced Scorecard developed by Kaplan and Norton suggested four categories of performance: financial, customer, internal process, and innovation and learning [90]. Similarly, Hudson et al. assert that there are four general categories of performance indicators: service and user perception, safety and sufficiency, physical condition, and structural integrity/capacity [28, pp. 60-61]. Parameters used to measure performance in this proposed framework can be grouped together according to similar
categories: health and water quality, quantity and capacity, structural integrity, and financial. This adjustment is presented in Figure 10 below.

Figure 10: Scorecard Metric Categories

In *Measuring and Improving Infrastructure Performance*, the committee on measuring and improving infrastructure advises that performance be measured in terms of effectiveness, reliability, and cost [12]. The aforementioned categories can also be considered an expansion of their recommended measures. Heath and quality, and quantity and capacity can be considered equivalent to measures of effectiveness. Structural integrity is a measure of reliability, though the framework theorized herein suggests a measure of reliability can be established for each parameter and parameter category. Finally, the financial category of performance correlates with the idea of cost. There obviously is overlap in the categories a particular parameter may fall into, as shown in Table 10.
<table>
<thead>
<tr>
<th>Monitored Parameter</th>
<th>Health and Quality</th>
<th>Quantity and Capacity</th>
<th>Structural Integrity</th>
<th>Financial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Cost</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Energy Use</td>
<td></td>
<td>*</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Install Date</td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Flow Rate</td>
<td></td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Maintenance Data</td>
<td></td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Material and Location</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Customer Complaints</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual Disinfectant</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbidity</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrosivity Indices</td>
<td>⁶</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwater Information</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

9.3 Quality of Information

9.3.1 Availability of Data

In the publication *Measuring and Improving Infrastructure Performance*, the committee on measuring and improving infrastructure performance found that the availability (or unavailability) of data was a significant concern and limitation to effective management of systems [12, pg. 65]. This lack of data stems largely from the viewpoint that data collection is too costly or insufficiently useful and fiscally unjustifiable. They recommend that data be collected and monitored on a continuing and coordinated basis.

⁶ For example, the Ryznar or Langelier indices
such that long-term performance assessment becomes possible. The following subsections discuss the quantity and quality of available information, issues arising from those situations, and methods for handling them.

### 9.3.2 Perfect Information

The ideal case scenario would be to have entirely accurate, complete, and current information. This is obviously impossible to achieve, and likely fiscally impractical to attempt. Realistically, intelligent choices should be made regarding the number and location of sensors. Uncertainty- or reliability-based approaches similar to those described by Graettinger et al. can be employed to meet these ends [34; 35]. The following subsections deal with methods to address imperfect situations in more detail.

### 9.3.3 Incomplete or Outdated Information

Incomplete information requires support from alternative sources to provide a complete picture. To handle this problem there are tools such as simulations and extrapolation. Through simulation, educated “guesses” can be made for situations where minimal (or no) information is available. To avoid constantly running simulations, the theoretical outcomes given ranges of operating parameters can be included in a database and simply queried when required. Alternately, extrapolation may be used to estimate information between existing sensors where possible, reducing computing requirements that would be necessary for simulations.
In general, outdated information will occur more often when using discrete sampling (versus continuous). This issue poses a particular threat to accurate performance assessments if the information has been used to calibrate simulations or select their results. Moreover, outdated information can provide a false sense of security in the system performance. For each monitored parameter, the necessary frequency of sampling must be ascertained in order to avoid this issue. That said, it is still important to keep historical records as they enable benchmarking and an understanding of the rate of changes occurring in the system. Benchmarking is discussed in more detail in Section 9.7.

9.3.4 Nonexistent or Inaccurate Information

Where data does not exist, it becomes necessary to rely on simulations and/or expert judgment to estimate how the system is performing. In such situations, it is advisable to use several approximations for the upper, lower, and probable case scenarios. Further, a sensitivity analysis will provide a sense as to how important accuracy is here. Section 9.3.5 discusses subjective information from expert judgment in more detail.

The issue of inaccurate information presents another unique challenge. The first problem is discovering whether or not the information is accurate, and whether anomalies represent actual system behavior or errors. The simplest method for addressing this concern is to impose redundancy in monitoring. For example, while only one sensor was employed at each location in the case studies, a pair of sensors would permit comparison of data recovered from nearby locations. Anomalous readings would be more likely to be
visible since it is highly unlikely that two separate sensors would “fail” in an identical manner. A second, less preferable method for validating data is through manual effort. In other words, visually examining every data record for incorrect information. This method is undesirable as it may impose the personal biases of the examiner upon the system, and because it becomes incredibly inefficient in situations with a large number of sensors recording a wide variety of information.

9.3.5 Subjective Information
As previously indicated, subjective information is something to be avoided if at all possible. In other words, while expert judgment can be used to estimate system performance in the absence of concrete data, this scenario should only be considered a worst-case option. The reason for this is simple: despite all attempts to remain impartial, subjective approaches are likely to induce biases that could otherwise have been avoided. For example, dispassionate analysis may be dissuaded as the expert seeks to defend their reputation (if they had something to do with the design, for instance) or their views may be biased through social sentiments.

9.4 Measurement Scales
Stevens proposed four general scales of measurement: nominal, ordinal, interval, and ratio [91]. These scales merit identification because they dictate which values may be logically combined (fused), and what statistical tests may justifiably be run. The following table, Table 11, summarizes characteristics of the four scales [91, pg. 678].
Table 11: Measurement Scales

<table>
<thead>
<tr>
<th>Scale</th>
<th>Basic Empirical Operations</th>
<th>Mathematical Group Structure</th>
<th>Permissible Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>Determination of equality</td>
<td><em>Permutation group</em> ( x' = f(x) ) ( f(x) ) means any one-to-one substitution</td>
<td>Number of cases</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mode</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Contingency correlation</td>
</tr>
<tr>
<td>Ordinal</td>
<td>Determination of greater or less</td>
<td><em>Isotonic group</em> ( x' = f(x) ) ( f(x) ) means any monotonic increasing function</td>
<td>Median</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Percentiles</td>
</tr>
<tr>
<td>Interval</td>
<td>Determination of equality of intervals or differences</td>
<td><em>General linear group</em> ( x' = ax + b )</td>
<td>Mean</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Standard deviation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rank-order correlation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Product-moment correlation</td>
</tr>
<tr>
<td>Ratio</td>
<td>Determination of equality of ratios</td>
<td><em>Similarity group</em> ( x' = ax )</td>
<td>Coefficient of variation</td>
</tr>
</tbody>
</table>

9.5 Presentation Scale

Information should be available for presentation at different scales. This thesis suggests the adoption of a similar taxonomy as that proposed by Rinaldi et al. [92, pg. 21]. They identify a hierarchy of elements including a part, unit, subsystem, system, infrastructure, and interdependent infrastructure.

A high level could be considered anything from the system level to the level of interdependent infrastructures. At this scale, a general “feel” for the system should be communicated. Additionally, concepts from system dynamics can be used to highlight causal links. Section 9.6 discusses this in a little more depth, however it is still considered out of scope of the present work.
Medium level could be considered to include subsystems or systems. At this scale, it should become possible to begin to identify local traits and possible causes of (or solutions to) problems. Overview information may still play a role, and should still be accessible.

A low level can be considered parts or units. Here, location-specific and asset-specific data should be available. Overview information is generally inappropriate, and may distract from focusing on specific details of the components at hand.

9.6 Presentation of Information

The WHO guidelines for drinking water quality state that “[i]nformation alone does not lead to improvement. Instead, the effective management and use of the information generated by surveillance make possible the rational improvement of water supplies – where “rational” implies that available resources are used for maximum public health benefit” [71, pg. 84]. This section discusses the presentation of generated data to permit its effective use.

As indicated, an ideal presentation should promote optimum levels of situational awareness for the users. Methods such as the Situational Awareness Global Assessment Technique (SAGAT) or the Situational Awareness Rating Technique (SART) can be used to measure situational awareness when evaluating a display. Salmon et al. assess and compare these two methods. They find that only SAGAT shows statistical correlation
to certain levels of situational awareness\(^7\), though SART still may be of use since it
approaches the concept from a different viewpoint [93]. Regardless, potential designs for
the information interface should be evaluated for their impact to situational awareness
with each of the potential user groups prior to implementation. The present work simply
proposes a logical setup, given the author’s understanding of current state knowledge in
human factors research.

A system dynamics map may be employed at a high level. This additional feature permits
examination of the entire utility’s performance (i.e., extend the performance assessment
beyond the water distribution system to examine the water company performance as a
whole). Indeed, the water distribution system performance may be incorporated into the
system dynamics map. This is, however, considered well beyond the scope of this thesis.
For further information, refer to the article by Bianchi and Montemaggiore, who present a
case study of enhancing strategy design and planning through the application of a
dynamic balanced scorecard in a city water company [94]. Their work employs a system
dynamics approach merged with a balanced scorecard (as defined by Kaplan and Norton)
to simulate the overall performance of a water utility to certain actions, successfully
demonstrating the concept of unforeseen consequences.

At a high or medium level view of a system or infrastructure (the selected taxonomy for
scale is discussed in Section 9.5), a general sense of infrastructure performance should be
communicated. To this end, a polygon representation of the categories of performance

\(^7\) For additional information, refer to works by Dr. Mica R. Endsley
could prove useful. In other words, data indicators that comprise a performance category should be fused to then represent a spoke of the polygon (see Figure 11). Data fusion is discussed in more detail in Section 9.9. The benefits to adopting such an approach include a faster detection time with greater accuracy [58, pg. 66]. Further, if the maintenance of a water transmission and distribution system can be considered analogous to treatment by an anesthesiologist, it can be expected that there will be fewer errors and less “drugs” administered (i.e., maintenance dollars will be used more efficiently).

In their assessment of a similar method for anesthesiologists’ displays, Drews and Westenskow indicated that there were problems with the scaling of variables resulting in muting of some parameters that should have been more significant, as well as noise in the system distorting normal polygons [58]. These are smaller concerns when dealing with a
water transmission and distribution system. First, at a high level the polygonal displays are meant primarily to give an understanding of the behaviors and trends of larger units and subsystems and permit identification of emergent features. Secondly, to address noise in the system a tolerance can be given for the polygon. In other words, if the shape of a square is being used to represent the overall performance, an inner and outer boundary line can be provided to assist in differentiation between normal and abnormal condition.

While an overall understanding of system performance is helpful, users must also be able to drill down to the details in order to ascertain what the specific cause of a problem may be. To achieve this, histograms can be employed at medium and low scales (Figure 12 and Figure 13 are representations of this concept). When implementing such histograms, it should be noted that related variables should be placed in spatial proximity to one another [95] and effort should be made to follow other principles of good design (such as providing a common baseline) in order to avoid biases. Further, an indication of uncertainty and risk is highly advisable.
Figure 12: Histogram Visualization (1)
Figure 12 portrays what examination of a node might look like, using an entirely
impossible imaginary system. Nodes should be placed for all the significant features such
as manholes, significant changes in directions, or valves. Basic information such as cost
and material should be available, as well as simple representation of current information
provided from any available sensors and their behavior (e.g., rapid changes should be
highlighted). It should also be possible to link from here to specifications/drawings of the
feature, as well as more detailed histograms for the monitored parameters. Further, to
fully incorporate a temporal GIS system, the time of the overall map should be
adjustable. Similarly, Figure 13 depicts what might be seen from a closer examination of
a link. In this case, it also shows what a warning might look like. The use of an onset (the
exclamation mark, for instance) serves to draw attention to a critical event. On selecting
the pipe, information regarding its installation and condition is available. Historical
records of complaints and maintenance provide an understanding of the link’s life.
Similarly, statistical information about typical material condition and lifespan can be
incorporated to present a more complete understanding of the component’s condition.
Interpolation between sensors can also provide general comprehension of behavior of
parameters in intermediate links.

Finally, the display should be designed to maximize event detection. To this end, both
color changes and onset alerts (e.g., pop-ups) can be utilized. The importance of using of
onset alerts should be emphasized: Boot et al. found that onset events were better
detected than color change events in busy dynamic displays [63]. Logically it follows that
using both approaches will maximize detection, however this hypothesis should be confirmed through experimentation.

9.7 Simulations and Benchmarking

As previously mentioned, simulations can be used to compensate for incomplete or unavailable information. If sufficient data exists, a calibrated model can be developed. If no information is available, the simulation of a theoretical ideal condition or estimated present condition can still be useful – particularly for benchmarking purposes.

Benchmarking is a tool that can be used to effectively rate system degradation and rate of degradation. By incorporating the ability to benchmark into the asset management process, an understanding of the urgency of problems is communicated. There are two possible ways to do this: using simulated ideal conditions as the benchmark, or using historical data.

9.8 Inheritance

Inheritance is the idea that components (parts and units) adopt traits of the larger system. The concept of inheritance is noteworthy for two main reasons. First, inheritance through extrapolation of existing data and trends permits quantification of parameters in locations where sensors may not be located and sampling may not be possible. The drawback to this is that it runs the risk of propagation of errors. In other words, inaccurate or incorrect data may contaminate otherwise undetermined parameters. The other noteworthy aspect of inheritance is that it enables coordination of parts and units with databases containing
standardized component and material behaviors. This provides a baseline for estimation of present and future part performance and deterioration.

9.9 Data Fusion

Joshi and Sanderson list six reasons for fusing data: improving accuracy, synthesizing incomplete information through inference, improving sensor system reliability, increasing sensor system robustness, increasing inference timeliness, and reducing the processing time, computational resources, or hardware resources [96]. Further, to utilize general measures of performance as proposed in this framework, it becomes necessary to develop a method for fusing individual parameters. As an unintended benefit, a concrete strategy for normalizing parameters or removing units and dimensionality can facilitate application of these quantities in decision-making processes. This section provides an overview of data fusion and suggested methods. The subsequent section, Section 9.10, reinforces its importance in the decision-making process.

There are multiple ways that data may be fused: competitive, complimentary, cooperative, independent, temporal, and spatial [97]. Competitive fusion uses replicated sensor readings to increase accuracy by identifying noise and faulty sensor readings. Complimentary fusion employs partial overlapping information from different types of sensors to create a global picture. Cooperative fusion employs partial non-overlapping information to do the same. Independent fusion implies using unrelated information in collaboration, but separately. Temporal fusion is simply placing recordings from different time intervals together to form a sequence. Lastly, spatial fusion is the combination of
information from multiple locations to view the overall situation. Each form of fusion has its use in this framework, but the competitive, complimentary, and cooperative forms of fusion warrant further discussion.

The method recommended for data fusion in this performance assessment framework is based on fuzzy set theory. To convert a parameter into a percentage or unitless equivalent, a membership function should be established. In other words, rather than utilizing a true or false identification of whether or not a parameter is at the desired level (e.g., the average pressure) it uses a scale to judge the parameter against desired performance. Figure 14 illustrates this concept more clearly using pressure as an example. Cardosa et al. give several additional examples of this concept [16]. Techniques exist to develop these membership functions from available data; a discussion of fuzzy rule extraction can be found in the Fuzzy logic and neural network handbook [98].

![Figure 14: Non-Fuzzy and Fuzzy Scaling](image)

Statistical methods for data fusion also exist. Joshi and Sanderson, for example, present statistical inference methods based on maximum likelihood and a posteriori estimations [96]. Goodman et al. discuss other statistical issues, such as Bayesian filtering for fusing
unambiguous observations, Bayesian characterization of rules for combining ambiguous observations, and hypothesis testing [99]. For the purposes of this thesis, these concepts are considered out of scope and will not be examined closer.

9.10 Use in Decision Making

Chapter 11 presents a generic decision-making primer. In the words of the committee on measuring and improving infrastructure performance, “[t]he point of performance measurement is to help decision makers” [12]. This section addresses how the proposed asset management framework can be employed in decision making.

Performance assessments are useful additions to many of the stages in rational decision-making processes (see Figure 18). The role they can play is largely self-explanatory, though some discussion of the process is provided herein. In addition to their direct role in decision-making processes, high scales of observation from these performance assessments facilitate identification of interdependencies. If system dynamics maps have been implemented, a larger sense of utility performance is even communicable.

The first step for decision-making is to identify the problem. Here, stakeholders hold an important role. Subsection 11.4.1 of Chapter 11 discusses in detail what to consider when determining who should be involved in the process. In performance assessments, the idea of what “good” performance actually entails is still very subjective. By promoting stakeholder participation, a better understanding of the relative importance of various parameters is achieved. In terms of the performance assessment, this will primarily
influence the way data is fused (and therefore displayed at higher scales) and therefore permit future judgments that are closer aligned to stakeholder values. It is important, however, to seek to avoid introducing inappropriate biases in this process.

When employing various decision-making tools (i.e., during the valuating and ranking stage), data gathered during performance assessments can prove invaluable. In C.B.A.s and C.E.A.s, information from financial performance measures can readily be combined with measures of effectiveness. If the A.H.P. is employed, parameters normalized through membership functions or statistical techniques can easily be introduced. With tools such as M.A.U.T. and S.M.A.R.T., the membership functions can be readily converted to measures of utility.

The final stage of rational decision-making processes is implementation and monitoring. Performance assessments are essentially applied monitoring. In other words, the information that would be gathered through monitoring decisions can be placed into this framework to ascertain the resulting change(s) in performance. This understanding can then be used in later decision-making.

An example of a decision process in which asset management shines is that of strategic renovations. Varkevisser discusses a strategic pipeline renovation plan employing a GIS approach [100]. There, gathered data is entered into a basic GIS database and queries based on parameters such as component, size, material, and age were used to develop the renovation plan.
Two final items merit discussion when considering the implication and application of performance assessments in decision-making. First, the performance of public infrastructures is a highly political issue. That is to say, the public (or user) perspective largely drives both what appropriate performance is and what actions may be taken to achieve those standards. Performance assessments can facilitate educating the public and promoting acceptance of decisions. Lastly, accurate performance assessments permit coordination with other types of infrastructure (transportation, wastewater, hazardous and solid waste management, etc.). This impacts decision-making by permitting wiser operating and maintenance actions. Considering both the political nature of performance and the opportunity for coordination of utilities, it may make sense to offer wider access to some of the gathered information than just utility workers and decision-makers.

9.11 Human Information Processing

Figure 15 is adapted from a model of human information processing developed by Wickens. The proposed asset management framework is hypothesized to reduce mental workloads of decision-makers by providing a visual representation of important information, thereby demands on working memory, long-term memory, and other resources. This reduction in demands should lower time stress, psychological stress, and frustration levels. It should also enable a faster reaction time, ability to handle more difficult tasks, or additional simultaneous tasks. Further, it is expected that decision-making errors will be reduced in both quantity and magnitude. This hypothesis has yet to be verified however.
Figure 15: Wickens Model of Human Information Processing

9.12 Resilience

Bruneau et al. identify four properties defining resilience in physical and social systems: robustness, redundancy, resourcefulness, and rapidity [101]. Here they define robustness as the ability of the system to withstand demands without a loss of functionality, redundancy as the existence of alternatives and substitutes in a stressed system, resourcefulness as the ability to mobilize resources and services in emergencies, and rapidity as the speed in which disruptions may be overcome. They suggest that a system experiencing a disastrous event is characterized by abrupt changes in performance followed by gradual return to normal levels, something easily visualized and acted on based on the dynamic scorecard developed herein. Alternately, they state that resilience can be viewed as encompassing technical, organizational, social and economic

8 Adapted from *Engineering Psychology and Human Performance* [102]
dimensions. According to either perspective, by promoting prompt response times and effective resource utilization (a subject further examined in the following chapter), this framework actively improves system resilience. In turn, according to Bruneau et al., improved resilience results in fewer failures with reduced consequences and time for recovery [101, pg. 736].

9.13 Future Work

This proposed framework for asset management is still largely speculative. Vast opportunities exist for future work towards a complete system, some of which have already been identified. In terms of the conceptual level of this framework, some presently unidentified areas include the useful lifespan of historical data (to reduce computer workloads and justify archival practices), work on levels of detail, and quantification of economic and other benefits (specifically issues such as resilience). Suffice it to say, present knowledge is highly supportive of the value potential of active performance assessment systems such as this dynamic scorecard.

9.14 Summary

This chapter has established the proposed system for information presentation and concepts behind the dynamic scorecard. In Section 9.2 it defines four categories of information and shows their symmetry with other groupings of performance indicators and scorecard approaches, such as Kaplan and Norton’s Balanced Scorecard. It then discusses issues related to the quality of information, and approaches that may be taken to address these concerns. Concepts such as measurement scales and the presentation scale
are subsequently introduced to establish what forms of information may be meaningfully combined, and what information should be available at different levels of examination. The measurement scales are long established, but the ideas proposed within the section on presentation scale are largely speculative. Due to this speculative nature, means of measuring the effectiveness of information presentation are identified in Section 9.6, along with possible incarnations of presentation approaches. The tools of simulation and benchmarking, inheritance, and data fusion are discussed next. With data fusion in particular, a fuzzy set theory approach is highly recommended to permit quantification of the non-discrete nature of reality. At this point, possible applications of this framework within the aforementioned decision-making process are elucidated and implications on human processing and workload levels are considered. Finally, the impact of this scorecard on WDS resilience and some previously unidentified areas for future work are discussed. The next chapter discusses the actual implementation of such a system, including requisite hardware and software systems.
Chapter 10: Implementation

“There is nothing more difficult to take in hand, more perilous to conduct or more uncertain in its success than to take the lead in the introduction of a new order of things.”

Niccolo Machiavelli
(1469-1527)
10.1 Software

This section introduces and discusses concepts in software on a conceptual level, rather than identifying specific technologies currently in use. The reason behind this is the rampant development and evolution of software that would otherwise render a large portion of the thesis obsolete before it is published. Further, this proposed performance assessment framework has yet to be fully validated or field-tested. It is likely that presently envisioned systems would need modification to be suitable for actual implementation.

Arguably the most important technology behind this proposed framework is databases. In addition to simply storing raw data (and/or processed data), this provides tools for processing data as well as the fundamental backbone for querying information. The concept of databases is not a new one, and several approaches to implementing fuzzy databases (including object-oriented fuzzy databases) can be found in existing literature such as the textbook by Galindo et al., *Fuzzy databases: modeling, design and implementation* [103, Chapter 11].

The details of what to display has been discussed in great depth in Chapter 9, but the specifics of how to display it have been largely omitted. On top of the fuzzy database backbone, a spatial visualization method (such as GIS) is suggested. Rather than basic GIS, however, the dimension of time should be incorporated. In other words, a Geotemporal Information System is recommended. As can be seen from Table 2, this software arrangement affords the greatest range of applications for the framework.
Finally, various internet-based technologies can be employed to increase accessibility to the information, educate users and decision-makers, and encourage acceptance of decisions. An interactive website with limited access to the information can assuage public concerns during or after failures, and further their support for decisions. Cellular access combined with GPS technology can enable workers to quickly submit details on maintenance and act on pending concerns while in the field, improving access to critical information and reducing time to report new information (thus reducing the chance of errors).

10.2 Hardware

10.2.1 Computers and Data Processors

For reasons similar to those indicated in the discussion of software, specifics on suggested hardware have been omitted herein. Suffice it to say, to collect and process data into a user-friendly format, a series of data processors and computers are likely to be required. In the case of the TP-1 sensor system, preprocessing was performed on raw sensor data and only records meeting predetermined conditions were recorded. The information was then accessible through either an Internet connection to the TP-1 system, or through local Wi-Fi or Ethernet connections. The theory behind the preprocessing is that data quantities, and therefore the hard drive space required to store the data, are reduced. There are two drawbacks to this, however. The first drawback is that careful calibration of the settings is necessary to prevent the loss of potentially important information. Secondly, the manner in which these devices and their data were accessed precluded the opportunity to make (select) information widely accessible.
The method suggested for computer hardware in this framework would include a centralized server to permit user identification and broad access to information while preventing inadvertent modification of sensor settings. There is still the potential to include preprocessing in conceivably advantageous ways however. Subsection 10.2.2 discusses possible system architecture in more detail, though it should be noted that final decisions are largely system-dependent.

### 10.2.2 System Architecture

System architecture “deals with the control organization and data flow in a multisensory system, to ensure that maximum benefit is derived from the use of multiple sensors. The focus is on the system aspects such as mod-ularization, scheduling, coordination, robustness, and data communication among distributed measurement devices” [96, pg. 20]. This section seeks to highlight some of the issues faced with system architecture, though the remark should be made again that the system architecture is system dependent by nature. Therefore, no effort to design an actual architecture will be endeavored herein.

The following figure, Figure 16, illustrates three possible formats for system architecture. The symbolism of this figure is simple: circles represent sensors, triangles represent preprocessing or storage devices, and the rectangle represents a centralized server. The three formats illustrated should by no means be considered comprehensive.
Figure 16 (a) shows two variations of a linear data transmission method. The upper track is the most basic form, where each sensor communicates with the next down the line and passes collected information on. In the lower track it is shown how a preprocessing computer can be utilized to reduce file size prior to forwarding the information to the next sensor. The risk with this approach is that if a sensor midway through the chain fails, information from all of the prior sensors may be lost. If the architecture is designed to follow such an route, appropriate safeguards should be built into the system to handle any potential failures along the sensor chains and introduce a measure of robustness to the architecture.

Figure 16 (b) illustrates a case where each sensor communicates independently with the server. In the case of the second sensor, preprocessing is employed to again reduce file size. The concern with an approach like this is that in situations where many sensors have
been distributed in the field, the server may be unable to maintain a sufficient number of open ports to permit simultaneous communication with every sensor. In this situation it becomes critical to coordinate data communication schedules between the devices. It may also become necessary to have temporary data storage on-site to buffer the frequency of communication required. It should be noted, however, that on-site data storage may be desirable even if all sensors may be simultaneously communicating with the server, just to ensure data is not lost if there is a temporary break in the link.

Figure 16 (c) is an example of remote collection of data with data being forwarded to the server on a scheduled basis. The lower track also illustrates the application of hybrid methods. For one sensor, a preprocessor is used to reduce the quantity of data sent to the remote collection point. In the second case, a linear chain of sensors is used.

10.2.3 Remote Sensing Equipment

There are a vast number of sensors on the market or conceptualized, each designed to take advantage of some physical, chemical, or other property of the parameter desired to be observed. A transducer detects changes in this property, and converts it into an equivalent electrical signal. The concepts behind the operation of sensors are largely out of scope, though one can refer to Luo [104] for a detailed discussion on their operating principles. In addition to identifying various sensors based on their governing physical quantities (e.g., mechanical, acoustic, electrical, chemical, optical, and thermal), transduction principles (e.g., variation in mechanical or material parameters, direct signal generation, ionization or quantum mechanical), and electrical output impedance (e.g.,
resistive, capacitive, inductive, and resonant), he also outlines advantages and disadvantages of some sensor technologies. Table 12, adapted from Cubillo, is provided as an example of some of the present sensor technologies (as of 2000) and the parameters they may measure [41, pg. IR 8-4]. Not all technologies are sufficiently reliable however, nor are all the parameters justifiably employed. Those parameters that warrant constant monitoring, according to Cubillo, have been marked with asterisks.

<table>
<thead>
<tr>
<th>Sensor Technology</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical resistance thermometer</td>
<td>Temperature</td>
</tr>
<tr>
<td>Electrodes</td>
<td>Oxygen, Conductivity, Residual Chlorine</td>
</tr>
<tr>
<td>Diaphragm-type</td>
<td>Oxygen</td>
</tr>
<tr>
<td>Physico-chemical analyzers</td>
<td>Turbidity, Suspended Solids, Nitrogen Dioxide, Phenols, Volatile Organic Compounds, Radioactivity</td>
</tr>
<tr>
<td>Potentiometric analyzers</td>
<td>Ammonia, Fluorides, Chlorides</td>
</tr>
<tr>
<td>Colorimetric analyzers</td>
<td>Ammonia, Phosphorus, Cyanides, Nitrites, Nitrates, Chromium, Aluminum, Color, Bacteria</td>
</tr>
<tr>
<td>Double-rod electrodes</td>
<td>pH</td>
</tr>
<tr>
<td>Hot/cold oxidation systems</td>
<td>Total Organic Carbon</td>
</tr>
<tr>
<td>Polarographic analyzers</td>
<td>Residual Chlorine, Heavy Metals</td>
</tr>
<tr>
<td>Amperometric selective instruments</td>
<td>Chlorine Dioxide</td>
</tr>
<tr>
<td>Amperometric analyzers</td>
<td>Ozone</td>
</tr>
<tr>
<td>Reflection value of laser</td>
<td>Mineral Oils</td>
</tr>
<tr>
<td>Bio-sensors</td>
<td></td>
</tr>
<tr>
<td>Enzymatic and Immunological Sensors</td>
<td>Pesticides</td>
</tr>
</tbody>
</table>

* These parameters can be justifiably monitored [41, pg. IR 8-4]

Cubillo also identified some of the characteristics to consider when selecting instrumentation. These include accuracy, sensitivity, range, reliability, repeatability, size/weight, maintenance requirements, power requirements, environmental requirements, capital and maintenance costs, and life span [41]. Since the technology
behind sensors and the sensors themselves continuously evolve, discussion of the specifics here is omitted.

10.2.4 Sampling Locations and Frequencies

While discrete sampling should also be included in asset management and performance assessment efforts, the details of this have been omitted. Since such sampling is often regulated, it is recommended that those regulations be used as a starting guideline. This subsection discusses sampling locations and frequencies in regards to remote sensing equipment only.

The choice for sensor locations should not be arbitrary. The most logical way to approach the issue is to use a modeling approach, and many such approaches exist. The method of QDE, based on calculated uncertainty, has already been mentioned [34; 35]. With this method, if no permanent sensors have been installed yet, discrete sampling may be used to determine the initial sensor locations. A search on early warning systems or contamination detection in water networks will produce a vast array of literature on other approaches selecting optimum sensor locations. For example, Berry et al. recognize a variety of other methods and affiliated literature on placing sensors in water networks [105, pg. 238], such as integer programming models [106; 107], combinatorial heuristics [108; 109; 110], and general-purpose meta-heuristics [110] before selecting integer programming techniques for their sensor placement optimization due to the lower associated processing time. Each method has associated pros and cons, though the detailed analysis of these has been omitted from the present work.
The last subject that should be discussed regarding remote sensors is sampling frequency. According to Nyquist’s Sampling Theorem, a sampling rate must be at least twice the wavelength of the shortest wave of interest to provide a lossless description of the event described by the wave [111]. This theorem has been applied, for example, for measuring transient pressure waves with the TP-1 sensor system. Some measured parameters may require a higher sampling frequency than that, while more infrequent rates may suffice for other parameters. The more data recorded can also assist in statistical analyses of the system behavior. On the other hand, greater sampling rates increases the quantity of data that must be transmitted, stored, and processed. There is no “correct” answer to the appropriate sampling frequency however, and there is significant opportunity for further work in determining suitable sampling frequencies for all pertinent sensors.

10.3 Implementation

10.3.1 Comprehensive

A comprehensive implementation of a sensor network for performance assessments, including the supporting equipment and infrastructures, is not likely to happen. That said, however, considering the ideal case scenario can be used to effectively plan the implementation strategy. The previous section briefly illustrated the wide range of possible methods for selecting sensor locations, and the present work is not concerned about identifying the method that should be selected; each method has its pros and cons. The concept of applying an uncertainty-based approach [34; 35] has potential in selecting which sensors get placed first however, and warrants particular consideration.
10.3.2 Sequential

Due to budgetary restrictions, a sequential strategy is most realistic method of implementation. With a method like this, it may not be logical to begin with a central server and wide access to the information. Rather, emphasis should be made on providing a select group of people the information required. Alternately, space can be rented on pre-existing servers and traffic can be routed through ISPs. Viewed this way, the case study in the Peel region of the Greater Toronto Area could be considered the beginnings of a larger and more functional performance assessment system.

10.3.3 Sensor Permanence

A last issue to contend with in implementation is the concept of permanence. This refers not to the concept of the sensors existing when nobody is around to see them (that much can be safely assumed), but rather whether their installation is temporary or permanent. Temporary sensors can play a key role not only during the initial phases of implementation, but also after a comprehensive system has been established. First, the use of temporary sensors can assist in calibrating initial models to enable intelligent sensor location. Second, by employing sensors as temporary installations, fewer sensors can be utilized for complete network coverage while a full complement of equipment is being acquired over time. This approach, however, reduces some of the potential insight that may have been drawn from a fully monitored system and therefore should not be considered a permanent solution. Further, it requires constant manpower to not only maintain but to relocate sensors. Last, temporary sensors permit hypothesis testing where
data in a “complete” network is considered less than sufficient. It should be noted that at that point, temporary sensors also function as replacements for malfunctioning sensors.

10.4 Barriers to Implementation

Many barriers exist to implementation that must be overcome, including significant initial effort required and a perceived high cost of investment. There are two other significant challenges faced in implementing this type of “innovation” in public utilities especially: the size of the organization, as well as the nature of the “innovation” itself. These issues, and some counter arguments, are described herein.

To implement such a performance assessment framework, significant effort will be required. Hardware must be installed and maintained; software must be developed and effectively utilized. Due to the novel nature of this concept, significant testing and trouble-shooting and modification is also to be expected. No argument can be made that work will not be required, and utilities are often overworked and understaffed. The benefit, however, to implementing such a system is not only a reduction in future effort required, but also a greater efficiency in operation and maintenance of the system.

The second argument likely to come up is the notion of cost. “Sensors are expensive.” This argument can be considered an extremely shortsighted one however. With a relatively long lifespan, the cost of sensors and the other supporting infrastructure can be amortized over the life of the distribution system. It is hypothesized, however, that the savings from higher efficiency decision-making and the public education and goodwill
will more than compensate for these initial costs. Further, by adopting a sequential implementation strategy, the cost for putting the system in place can be spread over a larger time period.

In the words of E.M. Rogers, “[p]roblems of implementation are much more serious when the adopter is an organization rather than an individual. In an organizational setting, a number of individuals are usually involved in the innovation-decision process, and the implementers are often a different set of people from the decision makers. Also, the organizational structure that gives stability and continuity to an organization may be a resistant force to implementation of an innovation” [112, pg. 173]. These are not insignificant challenges to be addressed. While the possibility exists that an internal employee will rise to champion such an approach, organizational momentum argues strongly against the likelihood of that happening. In order to implement such a framework, then, it most likely will require external stimuli to push this agenda.

The nature of this “innovation” also poses a challenge for implementation. Performance assessments can be considered preventive in nature, and a “preventive innovation has a particularly slow rate of adoption because individuals have difficulties in perceiving its relative advantage. The sought-after consequence is distant in time, and so the relative advantage of a preventive innovation is a delayed reward. In contrast, an incremental (that is, non-preventive) innovation provides a desired outcome in the near future” [112, pg. 217]. At the present time, no information has been found on ways to bypass this problem – and the author is stumped. One possible solution is to implement a laboratory-
scale model of this framework and prove sufficient short-term advantages to illustrate the benefits from adopting this framework.

**Figure 17: Adoption of Innovations**

Figure 17, developed based on information presented in the book *Diffusion of Innovations*, depicts various factors influencing the rate of adoption of an innovation.

This thesis will not delve deeply into the concepts presented, suffice it to say that when seeking to progress beyond the various barriers to implementation, the framework should be presented as advantageous in as many of these facets as possible. Further, as Festinger noted, behavior change is often prompted by the goal of reducing or eliminating dissonance [113, pp. 163, 176]. To this end, it is sensible to promote this (or similar
frameworks) as a means by which to reduce or eliminate presently occurring problems. Alternately, a somewhat amoral approach could be to increase the perceived challenges associated with NOT implementing such a concept.

The rate of implementation is not constant over time. Considering the nature of the adoption of innovations, it is hypothesized that as time progresses it should grow easier and easier to successfully promote implementation. Further, as benefits to such a framework become more easily quantifiable, support for not adopting such practices should continue to dwindle.

10.5 Social Costs of Implementation

As previously mentioned, infrastructure performance is a highly politicized concept. Due to the impossibility of a global consensus on issues, it is generally accepted that all projects come with some form of a social price tag. While construction of new buildings, roads, and other infrastructure often comes with such a price tag, the belief here is that implementing an effective performance assessment system and the increased level of public awareness will provide a social net benefit.

10.6 Summary

In chapter 4, two case studies undertaken during the production of this work were introduced. The next chapter, Chapter 5, presented some preliminary results and statistics from these case studies. Chapter 6, in turn, evaluates the results and presents some significant lessons learnt during the case studies. Chapter 7 then concluded the primary
goal of this thesis before identifying some of the implications these have for larger performance assessments. The second half of this thesis, a conceptual holistic performance assessment for water transmission/distribution systems beginning at Chapter 8, was thus introduced. While Chapter 8 explores the boundaries of the problem considered in the latter half of this thesis and Chapter 9 introduces the concepts underlying the dynamic scorecard, no mention had been made on the actual implementation. This chapter discussed both hardware and software issues related to implementation, and strategies of implementation. Further, it identified barriers to implementation in order to provide methods for bypassing these obstacles. To recap, Chapters 8, 9 and 10 establish the theoretical and practical basis behind the dynamic scorecard. Chapter 11 provides a decision-making framework to place the dynamic scorecard in context.
“One day Alice came to a fork in the road and saw a Cheshire cat in a tree.
‘Which road do I take?’ she asked.
‘Where do you want to go?’ was his response.
‘I don’t know,’ Alice answered.
‘Then,’ said the cat, ‘it doesn’t matter.’”

*Lewis Carroll*  
(1832–1898)
11.1 Introduction

While this chapter could have been presented as an appendix due to the supplemental nature of its content, the author felt that it was necessary to include in the body of the present work to ensure that any reader remains cognizant of the importance of acting within the context of a goal or decision space. Accordingly, this chapter serves as a brief introduction to the concept of decision-making, and provides a framework for the performance assessment methodology to be viewed within. A rational decision making process is presented and described, and some decision making tools are identified and briefly explained. Finally, some aids to the decision making process are presented.

11.2 Rational Decision Making Process

To ensure decisions can be justified on audit, a rational decision making process must be adopted. Further, while biases and the framing of choices both play significant roles in individuals’ preference or choice of options [114; 115], the adoption of a logical process encourages the selection of the best alternative as well as acceptance of controversial decisions. Figure 18 displays a skeletonized diagram of the rational decision making process adopted by the current work. The time axis is meant to represent the time dimension of decision-making. In addition to the time taken for decisions to be made, there is consistency of in decisions over time if available information, requirements and goals, and criteria remain consistent. It also presents the potential for change as more information becomes available. There also exists the ability to abandon decisions or actions due to obsolescence (as an example); the “abandon” arrow leaving the cycle represents this. Subsections 11.2.1 to 11.2.7 describe the remaining steps in more detail.
11.2.1 Identification of a Problem

The first step of this process is the identification of a problem. At this stage, causes, assumptions, and scope should be established. Stakeholder interests should be identified here as well. The result of this step should be a concise and precise statement. Most references on decision-making recommend that the problem statement should be written in a single clear and unambiguous sentence, though the length may vary in the pursuit of clarity. In some cases, review and acceptance by external stakeholders may be necessary or advisable.
11.2.2 Determine Requirements and Goals

After clearly identifying and defining the problem, requirements and goals for the solution should be established. Requirements are compulsory outcomes or components of the solution. These act as constraints that determine conclusively whether or not a solution is feasible. Goals, on the other hand, are simply desirable yet optional results or components of the solution and may assist in comparing possible alternatives.

11.2.3 Determine Alternatives

Once the requirements and goals of the solution are determined, feasible alternatives should be developed. To examine all options, the established goals and requirements can be ignored at first and a free brainstorming process should be adopted. It should be noted that a “do nothing” option should always be considered. Once a list of alternatives is developed however, the list should be screened to ensure that all alternatives are feasible. The final, screened list of alternatives represents all feasible options for dealing with the problem.

11.2.4 Choose Decision-Making Tool

The next step is to determine the decision making tool. In some cases, multiple tools can be employed, though conflicting results may be obtained. Decision-making tools include (but are not limited to) Pros and Cons comparisons, Analytic Hierarchy Processes (AHP), Grid Analyses (GA), Cost Benefit Analyses (CBA), Multi-Attribute Utility Theory Analyses (MAUT), and Simple Multi Attribute Rating Techniques (SMART). Some of these tools are described in section 11.4.
11.2.5 Selection of Criteria

After a decision making tool is chosen, appropriate criteria for ranking the alternatives can be developed based on the previously established goals. Namely, the criteria should measure how well the goals are met by each alternative and accordingly there should be at least one criterion for each goal. The criteria can be grouped and organized to differentiate between objectives and displayed in tree structures as criteria and sub-criteria, etc. Baker et al. [65] state that “[c]riteria should be:

- Able to discriminate among the alternatives
- Complete – include all goals
- Operational – meaningful to the decision maker’s understanding of the implications of the alternatives
- Non-redundant – avoid double counting
- Few in number – to keep the problem dimensions manageable“

11.2.6 Valuate and Rank Alternatives

Next, alternatives should be valued and ranked according to the established criteria using a combination of quantitative and qualitative methods. Weighting criteria permits aggregation of factors and may simplify ranking of alternatives. Techniques such as paired comparison analysis can assist in determining appropriate weights. At this stage, uncertainty, sensitivity and risk analyses may also be employed to better ensure that the ‘best’ decision is made.
Once a decision is made, it should be checked against the criteria, goals and requirements. Additionally, assumptions made should be reexamined and uncertainties explored. This helps to ensure that the decision making tool wasn’t misapplied and no significant errors or omissions occurred during the process.

11.2.7 Implement and Monitor

Lastly, the decision should be implemented and monitored. Monitoring enables verification that the solution was implemented and is performing as desired. Additionally, it provides opportunity to discover new, unforeseen problems and benefits of the adopted solution. Problems developed by acting on previous issues may result in the need to repeat the decision making process.

11.3 Interdependencies

Decisions made can rarely be viewed entirely in isolation. Infrastructure and sectors are intrinsically connected, and changes to one system or within a sector have the potential to greatly affect others. Subsequently, it is worth noting the dependencies and interdependencies inherent in a large portion of both components directly involved or considered in the performance assessment, but also in those indirectly related or in entirely separate sectors. This provides additional challenge to the goal of performance assessments, and actions based on performance assessments, as it is undesirable to cause unforeseen damages as a result of solving a problem. Rinaldi et al. identify four types of interdependencies: physical, cyber, logical, and geographic [92].
Physical interdependencies are when the product of one infrastructure is required as an input to another. This type of interdependency infers that the product is a physical product. One example of a physical interdependency would be the electrical power required to run pump stations to enable distribution of water, which may in turn be employed for cooling or emission control in power generation infrastructure.

Cyber interdependencies, a result of computerization and automation, are where information from IT systems in one infrastructure is required as an input for another. An example of where they may arise may be found through the use of SCADA systems that, in addition to monitoring and controlling operations, send information to related infrastructure to help with their operations. In such cases, the information communication systems themselves may become interdependent.

Geographic interdependencies occur due to spatial relationships between infrastructures. Most notably, when numerous infrastructures are located in close proximity, the operation or failure of one may affect the behavior of others. An example of geographic interdependency can be found in the recent (January 15, 2009) power failure in Toronto, resulting from a burst pipe flooding a power substation [116].

Logical interdependencies are where infrastructure is interdependent for other reasons than physical, cyber, or geographic mechanisms. These interdependencies are often the result of human activities or decisions, including policy and legislation decisions.
Subsequently, this classification of interdependency can be also explained as an attempt to describe the softer, less technical relationships that exist.

Infrastructure interdependencies may occur in one of three forms: pooled, sequential, or reciprocal [117]. These relationships are depicted in Figure 19, Figure 20, and Figure 21. Additionally, interdependent infrastructures, systems, sectors, and types of interdependencies may be represented by more than one type of relationship.

![Figure 19: Pooled Interdependence](image)

Figure 19 presents an example of pooled interdependence, where the outputs from several sources are required for a desired objective. Should any one input fail, the desired objective fails. This is a common form of interdependence, as infrastructures (in the figure: A, B, and C) do not necessarily have to directly affect one another in order for their operation and behavior to directly impact quality of life. For example, if a happy life just requires clean water, good food, and relaxing music, the objective will be missed if their water becomes contaminated on the way to the tap (or if the music stops).
Figure 20 depicts a case of sequential interdependence, where the output of one infrastructure is the input for the next. A simple example of this type of interdependence is an assembly line. If the product from one stage is flawed or incomplete, the subsequent stages relying on that product are detrimentally affected. A simple example of this form of interdependence in a water distribution system is the pipeline itself. To deliver water to a location, there may be a single pipe that the water must flow through in order to reach the destination such as a service line. If that fails, it doesn’t matter how effectively the distribution system is running or how consistently the pumps at the treatment plant may be operating, the objective of providing water to the location has failed.

Figure 21: Reciprocal Interdependence
Figure 21 portrays reciprocal interdependence. Here, both the objective and the other processes or infrastructures all depend on one another for success. This type of relationship also leads to the greatest chance of failure, as any one relationship may result in the system collapsing if it is not sufficiently robust. The delivery of clean water is a WDS example of this type of interdependence. To deliver this water, the pipe infrastructure must exist, the pipe integrity must exist, a positive pressure must be maintained, and a reliable communication link must exist to promptly identify and react to failures. Failure of any of these points can result in contamination of the water, failure to respond to events, or failure of the water to be transmitted at all.

![Diagram of Interdependent System](image)

**Figure 22: Failure Modes**

When considering interdependencies it is not sufficient to simply examine relationships, however. The way in which infrastructure may fail is also a factor deserving in-depth
consideration. Figure 22 depicts the three failure modes possible with interdependent infrastructure: common cause failures, escalating failures, and cascading failures.

Common cause failures are situations where one event may cause failure in multiple infrastructures. Typically, either geographic proximity or the extent of the initiating event causes the multiple infrastructures to be affected. Failure is simultaneous for all affected infrastructure. This has been shown in Figure 22 as infrastructures B, C, D, and E failing due to some event initiated at A.

Cascading failures occur where the failure of one infrastructure results in the subsequent failure of another infrastructure. This can be seen in Figure 22 by the failure of D resulting in the failure of F, which in turn fails G and so on. The distance from the initiating event can be described by the “order” of the effect. In other words, the failure at G can be described as a third-order effect.

Escalating failures occur where the failure of one infrastructure exacerbates the failure at another infrastructure. This escalation may come in the form of heightened severity of the failure, or simply an increase to the time required to fix the problem(s). In Figure 22, the failure at N acts as an escalating failure for A.

11.4 Tools for Decision Making

11.4.1 Pros and Cons Comparison

This method for decision-making is a quick and straightforward method, but relies on what may be more subjective individual judgment. For each alternative, a list of
advantages and disadvantages is developed. Each alternative is then compared against the other, with equivalent advantages or disadvantages struck off the list until the preferred option is determined. This approach is best used where there are few alternatives, and the criteria are of approximately equal importance.

11.4.2 Cost Benefit Analysis (CBA)

A Cost Benefit Analysis (CBA) or the similar Cost Effectiveness Analysis (CEA) are methods for comparing alternatives where decisions are highly related to monetary factors, or where the effectiveness of alternatives is a function of the investments made. These approaches typically also examine options over their entire lifecycles, described as a net present value through the use of established discount rates.

To perform a CBA, a list of all foreseeable costs and benefits should be developed for the lifecycle of the alternative. All costs and benefits are converted to present value to provide a consistent basis for comparison. Equations to convert costs and benefits between time periods are readily available in sources such as Engineering Economy [118]. For example, Equation 5.1 and Equation 5.2 below may be used to convert annuities and growing (or shrinking) annuities to present values, respectively. Similarly, Equation 5.3 may be applied to determine the present value of discrete future values.

\[
PV = A \frac{(1 + i)^n - 1}{i(1 + i)^n} \]  

(Eq. 5.1)
\[ PV = \frac{A}{(i-g)} \left[ 1 - \left( \frac{1+g}{1+i} \right)^n \right] \]  \hspace{2cm} \text{(Eq. 5.2)}

\[ PV = \frac{FV}{(1+i)^n} \]  \hspace{2cm} \text{(Eq. 5.3)}

Where:

\begin{align*}
PV & = \text{present value;} \\
A & = \text{value of the annuity;} \\
FV & = \text{future value;} \\
i & = \text{interest rate (also known as “discount rate”);} \\
g & = \text{fixed rate growth rate of an annuity;} \\
n & = \text{number of years.}
\end{align*}

With the present value of costs and benefits calculated, the net present value of benefits and costs can be determined. The Present Value of Benefits (PVB) is determined by simply combining the present values of all benefits. The Present Value of Costs (PVC) can be similarly calculated. From these two numbers, the alternative’s total Net Present Value (NPV) can be calculated by subtracting the PVC from the PVB. Alternately, to perform a CEA, a Benefit Cost Ratio (BCR) can be calculated by dividing the PVB by the PVC. In decision-making, a positive NPV or BCR represents an alternative with a desirable outcome. Larger values for NPV or BCR are always preferable.
Where dealing with existing infrastructure, an incremental CBA or CEA may be performed. In these assessments, a value for the PVC and PVB should be determined for both the existing (current) infrastructure as well as the proposed final situation. The incremental PVC and PVB may be calculated by subtracting the proposed value from the current value, and an incremental NPV or BCR may be computed.

11.4.3 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a method for mathematically scoring and comparing alternatives where multiple quantitative and qualitative criteria exist. Criteria are first weighted against each other according to a nine-point scale, where a 1 represents criteria of equal importance and criteria of extreme importance or preference are given the value of 9. A geometric mean is calculated for each row by taking the appropriate root of the product of weights. A normalized weight is then calculated by dividing the geometric mean by the sum of geometric means. This can be seen in the example provided in Table 13 below.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Criterion</th>
<th>Criterion</th>
<th>Geometric Mean</th>
<th>Normalized Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1/5</td>
<td>1/2</td>
<td>$\sqrt[3]{1 \times 1/5 \times 1/2} = 0.464$</td>
<td>0.464/3.804 = 0.122</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>3</td>
<td>$\sqrt[3]{5 \times 1 \times 3} = 2.466$</td>
<td>2.466/3.804 = 0.648</td>
</tr>
<tr>
<td>2</td>
<td>1/3</td>
<td>1</td>
<td>$\sqrt[3]{2 \times 1/3 \times 1} = 0.874$</td>
<td>0.874/3.804 = 0.230</td>
</tr>
</tbody>
</table>

$SUM = 3.804$
Next, the performance of alternatives against each criterion is similarly compared to one another to develop normalized alternative scores. In other words, for the above example, each alternative would have three individual normalized scores. Then, by multiplying the normalized weight of each criterion with the corresponding normalized score of an alternative’s performance with respect to that criterion provides the alternative’s score for that criterion. The sum of all criterion scores for an alternative produces the alternative’s total score. The highest total score of the alternatives is then considered the best choice of alternatives.

11.4.4 Multi-Attribute Utility Theory (MAUT) Analysis

Multi-Attribute Utility Theory (MAUT) Analyses employ “utility functions” to transform dissimilar attributes into a common, dimensionless scale referred to as “utility.” Utility functions can be created either objectively based on available data, or subjectively based upon analyst opinions. The utility scores for each alternative are added to determine the alternative’s total score. As with the AHP method, the alternative with the highest total score is the preferred alternative.

11.4.5 Simple Multi Attribute Rating Technique (SMART)

The Simple Multi Attribute Rating Technique (SMART) is a variation of MAUT analyses. This approach simplifies the utility function where there is no significant difference between the performances of alternatives against particular criteria. In other words, rather than using a continuous scale, discrete points are used. The overall scoring
is performed similarly to the AHP or MAUT processes, with a highest total score determining the preferential alternative.

11.5 Aids for the Decision Process

11.5.1 Stakeholder Analysis

Many possible classification schemes have been proposed for identifying stakeholders. Literature such as *The Stakeholder Model Refined*, or *Toward a theory of stakeholder identification and salience: Defining the principle of who and what really counts* exemplify this concept well [119; 120]. For the purposes of this performance assessment and decision-making framework, a classification scheme of primary, secondary, and tertiary stakeholders has been adopted, modified from the model proposed by Mitchell et al. [120]. Figure 23 models the relationship between the stakeholder classifications and their attributes via a Venn diagram.

![Figure 23: Stakeholder Classification Model](image)
This model suggests that the number of three attributes an entity possesses can be employed to classify stakeholders. The first attribute, power, consists of coercive influence (physical/military resources), utilitarian influence (raw/material resources or finances), and normative influence (status or symbolic resources). The second attribute, legitimacy, answers the question of whether the entity holds a socially accepted status, and may occur on individual, organizational, or societal levels. Lastly, the attribute of urgency incorporates both time sensitivity as well as criticality.

Primary stakeholders are entities that hold all three attributes. They are entities that must be taken into consideration. Possible stakeholders in this group could include owners and operators of the infrastructure, as well as certain government and regulatory organizations. For example, in the Region of Peel, the primary stakeholders would be the regional government as represented through their Department of Public Works and provincial and federal governments as represented through their respective legislation. Certain advocacy and special interest groups may shift into designation as primary stakeholders depending on the decision(s) to be made, and the potential impact of those decision(s).

Secondary stakeholders are entities that hold any two of the aforementioned attributes. Mitchell et al. refer to these stakeholders as “expectant” as they have attained an active stance rather than a passive stance upon achieving a second attribute [120]. There are three types of secondary stakeholders identified: “dominant” stakeholders who possess power and legitimacy (group 4), “dangerous” stakeholders who possess urgency and
power (group 5), and “dependent” stakeholders who possess legitimacy and urgency (group 6). Due to their increasingly active condition, these stakeholders warrant some consideration in decision-making activities. Further information on each group can be obtained from Mitchell et al. [120]. Possible stakeholders in these groups could include users of the infrastructure (i.e., consumers) as dependent stakeholders, and even potential saboteurs or terrorists as dangerous stakeholders.

Tertiary stakeholders are entities that hold just one of the three attributes, also referred to as latent stakeholders by Mitchell et al. [120]. Three forms of tertiary stakeholders have been described: “dormant” stakeholders who possess the power attribute (group 1), “discretionary” stakeholders who possess the attribute of legitimacy (group 2), and “demanding” stakeholders who have the “urgency” attribute (group 3). More information can be found on each group from Mitchell et al. [120]. Tertiary stakeholders could include entities such as funding providers, the environment, or the media. These entities are passive and typically only require consideration based upon their potential for acquiring one or more additional attributes through their own actions or coalitions with other groups.

After identifying stakeholders and their importance to decision-makers, an appropriate strategy should be determined for each. There are several ways to go about this, including brainstorming using charts and mapping stakeholders according to their importance and degree of influence. The following two figures provide examples of these approaches.
The chart shown above (Figure 24) is an example of an organized method for brainstorming stakeholders and their attitudes and potential level of influence that is known as a stakeholder analysis. In addition to identifying stakeholders, a framework such as this encourages contemplation on their motivations and subsequently their attitude towards the decision. Further, by judging the level of their influence on the decisions, appropriate actions may be developed for managing stakeholders.

Figure 24: Stakeholder Analysis Chart

Figure 25: Stakeholder Analysis Matrix
The grid shown in Figure 25, also known as a Stakeholder Analysis Matrix or a Stakeholder Map, is a means of visualizing stakeholders. With the exception of “The Author,” “PETA,” “Greenpeace,” and “Other Terrorists,” the aforementioned example is an idea of what might be produced for a utility such as the Region of Peel Public Works. While this may not help in determining stakeholder motivations, it can assist in prioritizing actions when conflicting goals or limited resources necessitate it. In other words, stakeholder maps can act as a useful planning tool for managing stakeholders with conflicting interests.

In the article *Principles of Stakeholder Management*, the Clarkson Centre for Business Ethics identifies seven principles to which corporate managers should adhere [121] when managing stakeholders. These principles should be considered throughout any decision-making process. They can be paraphrased as follows:

- Concerns of all legitimate stakeholders should be acknowledged and monitored, and appropriately taken into account in decision making and operations;
- Open dialogue should be engaged with shareholders regarding concerns, contributions, and risks assumed through corporate involvement;
- Adopted processes and modes of behavior should be sensitive to the concerns and capabilities of each stakeholder group;
- Interdependence of efforts and rewards amongst stakeholders should be recognized and a fair distribution of benefits and burdens should be sought, taking into account respective risks and vulnerabilities;
• Cooperation with both public and private entities should be sought to ensure that risks of harm are minimized and, where unavoidable, properly compensated;
• Activities that may jeopardize inalienable human rights\(^9\) or result in patently unacceptable risks should be avoided entirely; and
• Potential conflicts between corporate stakeholders and their legal and moral obligations for the interests of other stakeholders should be acknowledged and openly addressed.

11.5.2 Defining a Problem

Tversky and Kahneman suggest that “[t]he frame that a decision-maker adopts is controlled partly by the formulation of the problem and partly by the norms, habits, and personal characteristics of the decision-maker” [115]. Accordingly, the definition of the problem and formulation of the problem statement are critical to the outcome of the decision-making process. Contemplation on the undesired/desired state(s) and the existing problem symptom(s) can act as heuristics for establishing the problem statement.

To effectively define a problem, it may also help to examine the issue from several viewpoints. One example of a series of viewpoints that could be employed is the acronym PESTLE: Political, Economic, Social or Socio-cultural, Technological, Legal or Legislative, and Environmental. Alternately (or concurrently), it may prove useful to approach the problem definition employing such frameworks as de Bono’s “thinking hat”

\(^9\) Note: while access to safe drinking water has been declared a basic human right by the UN Secretary general [122], it has not been recognized as such in a recent (2009) forum held the World Water Council [123].
methodology for decision-making [124]. Here, six “hats” are utilized to represent the perspective a decision should be examined from:

• White hat – just the facts are to be considered. Unemotional data and questions about getting more data;

• Green hat – innovative ideas. Creativity is emphasized with this hat;

• Black hat – pessimistic viewpoint. What are the negative consequences, or worst-case scenarios;

• Yellow hat – optimistic viewpoint. What are the positive consequences, or best-case scenarios;

• Red hat – gut feelings and emotions. This hat seeks to capture what individuals really feel; and

• Blue hat – metathinking. This hat is for considering processes and procedures.

To examine this in a WDS situation, one can envision a system that is experiencing problematic pressure transients. Wearing the white hat one might consider concepts such as the number of pipe breaks per year resulting from pressure surges, the length of time and cost for repairs, or the cost for possible mitigating actions or infrastructures. Under the green hat, different ideas for solutions might be examined. These could range from the simple and standard processes of installing PRV valves or chambers to “absurd” ideas such as water rationing and scheduling access times and procedures. The black hat would then let you examine these options pessimistically. Would the PRV end up costing the utility an exorbitant amount of money just to have a non-functioning pipe decoration?
Contrarily, the yellow hat looks at things optimistically. Maybe if the consumers are educated, transient magnitude may be sufficiently reduced. The red hat could tell you that people aren’t likely to be so thrilled with the concept of water rationing and scheduling. Finally, the blue hat would be dedicated to figuring out how to make things happen. What process should be followed to purchase/install this new PRV? How can we enforce procedures related to large clients’ changes in rate of demand?

Since stakeholder buy-in is necessary for many decisions, it is advisable to include representatives from at least the primary stakeholders in the problem definition. Secondary stakeholders should also be considered, especially if there is a high probability that they may become primary stakeholders further in the decision-making process. By incorporating the viewpoints of critical parties at the start of the process, arrival at an impasse is less likely later on.

11.5.3 Determining Goals and Requirements

Determination of the goals and requirements for solutions is as important to the outcome of a decision-making process as the accurate detailing of the problem. Alternatives are screened by solution requirements, so overly stringent requirements can weed out potentially excellent solutions. Alternately, insufficient requirements result in excessive numbers of options that may slow down or halt the decision-making process. Similarly, goals for the solution affect the criteria that are selected to weigh the options.
To begin, brainstorming may be employed to come up with a list of potential goals and requirements. Asking the question, “If an alternative does not meet this point, can it still otherwise be considered?” can help differentiate requirements from goals. If the answer to that question is ‘no,’ the point should be considered a requirement. Otherwise, if an alternative doesn’t meet the point but still may warrant consideration, the point should be considered a goal. This screening may be challenging in practice due to personal or professional biases, or pressures imposed from sources like the media or special interest groups. This is where tools such as the aforementioned Stakeholder Map can prove invaluable. By recognizing the importance of a stakeholder in relation to their level of influence, decisions may be more easily made about should be defined requirements versus goals.

11.5.4 Determining Alternatives

There are two main ways that alternatives can be generated: by brainstorming, and by examining goals and requirements. Brainstorming may result in inappropriate alternatives, so a screening process should be undertaken to ensure all the alternatives meet the specified requirements. Once sufficient alternatives have been generated, alternatives should be refined to the point where they are worthy of consideration and clearly feasible.

11.5.5 Choosing Criteria

The criteria chosen to measure a goal should be sufficient to fully capture how well alternatives fit the goals. Criteria may be either qualitative or quantitative, so long as it is
possible to discriminate between how effectively alternatives meet each criterion. Every
goal should be measurable by one or more criteria. If at least one measurable criterion
cannot be established for a goal, the goal should be omitted from the analysis. All criteria
developed should retain their association to the goals they are measuring.

Three steps can be followed to develop criteria: confirm all the important goals are
identified, confirm that sufficient criteria are identified to measure each goal, and check
to ensure criteria don’t greatly overlap, contradict, or rely upon each other. Examining the
pros and cons of alternatives can help brainstorming possible criteria, but has the
potential for unduly biasing the results from the decision-making process. To avoid this
bias, it is recommendable that focus remains on deriving criteria from goals.

11.5.6 Sensitivity Analyses

A sensitivity analysis can be performed on any analysis. Anywhere there is uncertainty in
valuation, performing a sensitivity analysis can provide a useful range of ratings for each
alternative. Assuming the most costly and time consuming events come to pass, and that
everything that Murphy’s Law holds (everything that can go wrong, will) will produce a
worst-case ranking for an alternative. Contrarily, making the assumptions that cost and
duration correspond with the minimum possible and there are no problems or mistakes
will result in a best-case ranking. Finally, if possible a third analysis should be performed
employing the expected duration, costs, and likelihood for complications to produce an
expected rating. This may prove to be overly time consuming however, so judgment
should guide the choice of whether to have an understanding of the range of values or if expected values will suffice.

If each alternative is rated three times, comparison will become more complicated. It is possible that while one alternative will be the preferred choice in a best-case scenario, it will not be for the worst-case or expected scenarios. Subsequently, three (or less) options should be selected and carefully compared to one another again. While the expected rating of the alternatives can be used to choose the best option, the magnitude of variation in rating should be used in conjunction with the level of confidence that the outcome will be favorable in order to perform a final risk assessment on the alternatives.

11.6 Summary

This chapter focused on providing an understanding of a rational decision-making process that may be used with performance assessments in order to provide context and value. In addition to clearly explaining each step of the process, tools for decision-making and some helpful heuristics for potentially challenging steps were provided. Previously, this thesis broke into two sections. The first half identified and analyzed two case studies in partial performance assessments. The second half explicitly defined the scope and boundaries, and theorized the design and implementation of the scorecard in Chapters 8 through 10.
Chapter 12: References

“Every man is a quotation from all his ancestors.”

Ralph Waldo Emerson
(1803-1882)


APPENDIX A: Appendix Index

Appendix A: Appendix Index
Appendix B: Maps of Peel Region Installations
Appendix C: Maps of Mexico City Installations
Appendix D: Images and Pictures
Appendix E: TP-1 Methodologies and Procedures
APPENDIX B: Maps of Peel Region Installations
APPENDIX C: Maps of Mexico City Installations
APPENDIX D: Images and Pictures

D.1 Peel Region Case Study

Sensor at Lakeview WTP

Pump Station Installation

Preparation of Outdoor Installation

Sensor through Manhole Cover

Flooded Chamber
D.2 Tláhuac Case Study

P1 Installation

P2 Installation

T1 Installation

T6 Installation

T14 Installation
D.3 Miscellaneous

- Broken AV
- Submerged AV
- Leaky PRV
- Flooded Valve Chamber
- TP-1 Kit
- Sensor Close-up
APPENDIX E: TP-1 Methodologies and Procedures

E.1 Introduction:
The purpose of this chapter is to establish basic procedures necessary when employing sensors for performance assessments, model calibration, or general asset management through examination of the Region of Peel and Tláhuac case studies. It discusses methodologies and procedures that were established (either formally or informally) for using the hardware and software employed during the case studies. Where possible, they have been generalized to be comprehensive of issues relevant to other hardware or software as well. A generalized discussion of issues associated with hardware and software can be found in Chapter 10.

E.2 TP-1 Procedures

E.2.1 Significance
The significance of pressure transients warrant discussion prior to expanding on procedures associated with the TP-1 pressure monitoring system. Pressure transients occur as a result of changes to the system. When a pump cuts out due to power failures or operational changes, a demand changes (increases or decreases), valves open or close, or other actions are performed on the system, the pressure will fluctuate. These fluctuations, or pressure transients, can result in pipes burst through pressures exceeding pipe pressure ratings, collapsed pipes due to negative pressures, or intrusion of (potentially contaminated) groundwater. Knowledge of their occurrence, magnitude, and possible causes can help in designing operational procedures and calibrating system simulations. With these calibrated models it becomes possible to design infrastructure systems meant
to prevent pressure surges or reduce the impact of these transients. The TP-1 system is designed to monitor these pressure transients.

E.2.2 Installation

The TP-1 System is separable into several components: a pressure transducer (sensor) capable of recording pressures between -14.7 psi (-101.4 kPa) vacuum and 500 psi (3.4 MPa) at a maximum rate of approximately 100 Hz, a control box that selectively records sensor readings, and a power source. There is an optional antenna that may be attached to the control box in order to increase Wi-Fi reception for remote access with a PDA, and in newer models it is possible to connect the control box to Local and Wide Area Networks (LAN and WAN) to enable remote access with a computer. Figure 7 (see Chapter 6) shows a typical installation.

The TP-1 sensor is installed anywhere along the pipe that has been tapped, ideally at the bottom of a pipe. A small series of additional piping and check valves enable installation of a manual pressure gauge for calibration, isolation of the sensor from the system, and the bleeding of air. In systems where water is not the product or hazardous fluids are present, bleeding of air may not be possible by this method.

The thread of each male fitting is wrapped with Teflon tape to ensure a watertight seal at the joint. They are tightly wrapped from outside inwards and in the same direction the attachment will be tightened, overlapping by half the thickness of the tape, until all
threads are covered. Effort is made to not extend over the end of the pipe, as this could result in pipe blockages or flow interference.

As previously indicated, the pipe tap should be located at the bottom of the pipe to minimize possible influence of air pockets on the sensor. In Effect of air pockets on pipeline surge pressure, Burrows and Qiu\textsuperscript{10} demonstrated how air pockets could have either a amplifying or suppressing effect on surge pressures experienced in pipelines. Accordingly, even minute air pockets trapped adjacent to the sensor hold great potential for providing inaccurate and misleading data records.

\textbf{E.2.3 Calibration}

Calibration of sensors is necessary on first installation, but occasional confirmation was required to ensure settings remained accurate. Power failures and battery changes often necessitated recalibration. One common issue encountered was ensuring that accurate time synchronization was maintained. Accordingly, network- or GPS-regulated systems may provide possible means of sustaining temporal accuracy.

E.2.4 Monitoring

Each control box records the pressure observed by the sensor at a rate dictated during calibration. While the device has a 23 megabyte storage capacity, different combinations of control box settings and system operations could fill this memory in anywhere between sixteen days and three years. A regular routine of downloading and clearing device memory is necessary where storage space is uncertain and consistency is required from the results. The capability to connect devices to LAN or WAN networks both physically as well as wirelessly supports and simplifies such data collection.

E.2.5 Pragmatic Concerns

Pragmatic concerns include vandalism, theft, and damage by natural forces or wildlife. Additionally, since the purpose of the TP-1 transient pressure monitoring system is to capture pressure transient events that occur during occasions such as power failures, backup power must be provided even where a “steady” source of energy is already available. In many cases, this consisted of simply a regular car battery.

In the two case studies presented in this thesis (Peel and Tláhuac), the devices were installed in manholes outside of secured buildings. In any situation where the device is installed outdoors or in areas that are potentially accessible to the public, concerns of vandalism or theft arise. To deter theft, installations outdoors in Peel were secured using locked knack boxes filled with additional dead weights (see Figure 8 in Chapter 6). All

potentially sensitive equipment was enclosed within. Further, these boxes were secured to the manhole lids to prevent relocation of the control box and possible damage to wires. In the case of sensors NT1 and NT2 for Tláhuac, all equipment was located within the manhole and significant deadweight used to prevent access.

To deter vandalism, sensor locations are carefully investigated and chosen. Routine inspections allowed both for data collection as well as examination of equipment. No vandalism was experienced during these case studies.