GUIDELINES FOR IMPLEMENTING RISK-BASED ASSET MANAGEMENT PROGRAM TO EFFECTIVELY MANAGE DETERIORATION OF AGING DRINKING WATER PIPELINES, VALVES AND HYDRANTS

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ABSTRACT

There is an unprecedented need to manage our deteriorating water infrastructure systems effectively to mitigate the enormous consequences of their premature failure such as loss of service, money, time, damage to other infrastructure, and damage to property. Most of the water utilities understand this need and are implementing asset management approaches and technologies to increase the overall service life of their assets. However, to indeed achieve sustainable water infrastructure systems, there is a requirement to implement a risk-based asset management program which provides a more comprehensive approach to manage these aging assets. A risk-based asset management program assesses and manages the risk of failure associated with the water infrastructure assets and helps water utilities in prioritizing their assets for renewal. This program identifies the critical assets for renewal and saves the money and time invested in the renewal of "not so critical" assets.

This research incorporates an extensive literature and practice review on risk-based asset management of pipes, valves, and hydrants. The risk-based asset management consist of the following four major components: (1) understanding the deterioration modes and mechanisms, (2) implementing risk assessment and management approaches, (3) implementing condition assessment approaches and technologies, and (4) implementing asset renewal approaches and technologies. This research aims to provide enhanced guidelines based on the EPA 10 step asset management program which will help water utilities in developing a risk-based asset management program as well as in improving their existing asset management program.

This research combines the in-depth knowledge gained through a state-of-the-art literature review and practice review. The practice review is conducted to capture the real-world application of the risk-based asset management through interviews with the water utilities across the united states. This research has also compiled the knowledge gained by already published case studies to provide a more comprehensive overview of the current practices and trend in the risk-based asset management of drinking water pipelines, valves, and hydrants.

This organization of this thesis is as follows:

Chapter 1: Introduction and Background- This chapter presents the overall introduction to the current state of water infrastructure assets and why there is a need to implement a risk-based

asset management program. The scope and objectives of this research are also explained in this chapter. Along with this, a comprehensive background regarding the different types of pipelines, risk-based asset management, and its focus areas is provided.

Chapter 2: Research Methodology- This chapter presents the overall research methodology implemented for this research.

Chapter 3: Literature Review- This chapter covers an extensive literature review for understanding the deterioration modes and mechanisms, risk assessment and management approach, condition assessment approaches and technologies, and asset renewal approaches and technologies for drinking water pipelines, valves, and hydrants. The synthesis and critical analysis of various journals, conference proceedings and reports from reputed academic publications are provided in this chapter.

Chapter 4: Practice Review- This chapter covers the synthesis and critical analysis of the particular case studies which were either already published or are written specifically for this research. The latter case studies were developed by collecting documents from the water utilities from across the USA on risk-based asset management of drinking water pipelines valves and hydrants.

Chapter 5: Key Findings and Major Gaps- This chapter provides an overview of the "key findings" and the "major gaps" observed during this research through an extensive literature and practice review.

Chapter 6: Proposed Guidelines for Risk-Based Asset Management- This chapter provides Guidelines for the risk-based asset management of drinking water pipelines, valves, and hydrants as a system. These guidelines are an enhancement of the EPA 10 step asset management process and are formulated to provide a more comprehensive approach to managing deteriorating assets.

Chapter 7: Conclusion and Recommendations- This chapter concludes and analyzes the significant findings of this research. This chapter also provides recommendations formulated with an aim to aid water utilities, and future researchers drive the pipeline, valves, and hydrants risk-based asset management industry forward.

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GENERAL AUDIENCE ABSTRACT

America's drinking water infrastructure is deteriorating and there is an unprecedented need to manage our deteriorating water infrastructure systems effectively to mitigate the enormous impacts of their premature failure such as loss of service, money, time, damage to other infrastructure, and damage to property. In order to achieve sustainable water infrastructure systems, there is a requirement to implement a risk-based asset management program which is a comprehensive approach to manage these aging assets. A risk-based asset management program assesses and manages the risk of failure associated with the water infrastructure assets and helps water utilities in prioritizing their assets for renewal. This program identifies the critical assets for renewal and saves the money and time invested in the renewal of "not so critical" assets.

This research aims to provide enhanced guidelines based on the EPA 10 step asset management program which will help water utilities in developing a risk-based asset management program as well as in improving their existing asset management program. This research combines the in-depth knowledge gained through a state-of-the-art literature review and practice review. The practice review is conducted to capture the real-world application of the risk-based asset management through interviews with the water utilities across the united states. This research has also compiled the knowledge gained by already published case studies to provide a more comprehensive overview of the current practices and trend in the risk-based asset management of drinking water pipelines, valves, and hydrants.

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CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 INTRODUCTION

American Society of Civil Engineer (ASCE) 2017 infrastructure report card is out, and America's Drinking Water Infrastructure has again scored a near failing grade of D (ASCE 2017). The water infrastructure in America is aging poorly that time and again results in catastrophic events which impact the society, economy, and the environment. ASCE has also provided an estimate of $1 trillion investment in drinking water infrastructure to maintain and expand the demand over the next 25 years (ASCE 2017). Further, it is estimated that approximately 6 billion gallons of treated water is lost every day due to leaking pipes (ASCE 2017). All of this indicates that there is an unprecedented need to manage our drinking water infrastructure assets proactively to prevent these early failures and to save the enormous amounts of money and time invested in the reactive management of these assets.

A proactive approach for water infrastructure asset management requires the water utilities to pre-plan their renewal strategies based on the periodic condition and risk assessments. An efficient method for the proactive management of these assets is a "risk-based asset management program" which helps in identifying the critical assets for renewal and prevents the wastage of money and time in the renewal of "not so critical" assets.

A risk-based asset management program can serve as a practical solution to sustain and improve the performance of water infrastructure assets due to its capabilities of assessing the risk of failure associated with an asset and developing renewal strategies to prevent the failures proactively. Before developing a risk-based asset management program, it is imperative to understand the following: (1) what a risk-based asset management program is with its benefits, and; (2) what are the different types of water infrastructure assets which can have a risk-based asset management program.

According to Environment Protection Agency (EPA), "Asset management is the practice of managing infrastructure assets in such a way to minimize the total cost of owning and operating these assets while delivering the desired levels of service" (EPA 2017). In, simple words, an asset management program aims to enhance the overall service life of an asset by conducting cost-effective repairs, rehabilitation, or replacements throughout its life whenever deemed required by the condition and risk assessments. A risk-based asset management program is a more comprehensive form of asset management which focusses on assessing and managing the risk of failure associated with drinking water infrastructure and has the following focus areas or components:

- Understanding the asset deterioration modes and mechanisms
- Implementing risk assessment and management approaches
- Conducting periodic condition assessments
- Implementing asset renewal approaches and technologies

The following are the benefits of a risk-based asset management program,

As per the knowledge and understanding gained in the "CEE-5080- Infrastructure Asset Management" class at Virginia Tech by Dr. Sunil Sinha and extensive literature and practice review, the following benefits of a risk-based asset management program are realized,

1. A risk-based asset management program can enhance the overall service life of assets by providing required maintenance throughout their life.
2. The overall cost of owning and operating the asset reduces by implementing a risk-based asset management program as it decreases the extra cost incurred due to the premature failure of deteriorating assets.
3. It simplifies the overall process of developing budgets and saves a considerable amount of time by prioritizing the renewal of the assets in the most critical condition.

Further, the water infrastructure is comprised of various vertical as well as horizontal infrastructure systems such as water treatment plants, storage tanks, pumps, wells, reservoirs, pipelines, valves, and hydrants. However, this research concentrates on the risk-based asset management of horizontal water infrastructures systems such as drinking water pipelines, valves, and hydrants.

In summary, my research aims to improve the understanding and provide an insight into the approaches and technologies of a risk-based asset management program. The main components of the risk-based asset management program, namely, deterioration modes and mechanisms, risk assessment and management approach, condition assessment approaches and technologies, and asset renewal approaches and technologies are analyzed in detail through a state-of-the-art literature and practice review. An enhancement to the EPA 10-step asset management guidelines is also provided based on the knowledge gained through the literature and practice review. The aim is to aid water utilities in formulating a risk-based asset management program that caters to drinking water pipelines, valves, and hydrants equally and enhances the overall performance of these assets as a system.

1.2 BACKGROUND

The drinking water pipeline system consists of pipelines, valves, and hydrants. There are several types of pipelines based on their material such as cast iron, ductile iron, PCCP, asbestos cement, steel, reinforced concrete, and plastic pipelines. All these pipelines have different failure modes and mechanisms and generally require different condition and risk assessment methodologies.

According to ASCE 2017 infrastructure report card (ASCE 2017), there are one million miles of drinking water pipelines across the unites states. These pipelines vary in sizes and can be categorized into three broad categories, namely, small, medium, and large diameter pipelines.

It is a known fact that the drinking water infrastructure in the united states is aging and the continuous near-failing grades allotted in the ASCE infrastructure report card prove it. A possible solution to prevent the deterioration and improve the service life of these assets is by formulating and implementing a risk-based asset management program.

The four primary components/focus areas of a risk-based asset management program are shown in Figure 1.

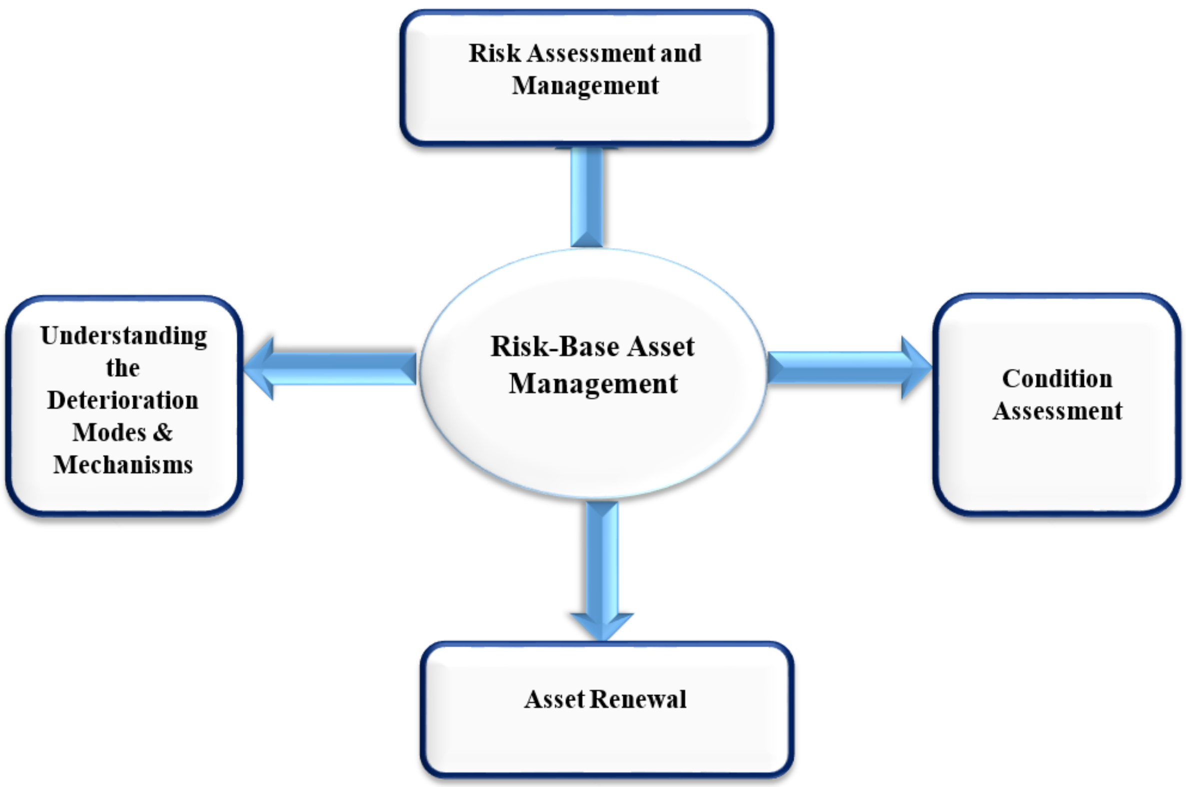

Figure 1- Components/Focus Areas of a Risk-Based Asset Management Program

As can be seen in Figure 1, the four focus areas of a risk-based asset management program are: (1) understanding the deterioration modes and mechanisms (2) risk assessment and management (3) condition assessment and (4) asset renewal, i.e., repair/rehabilitation/replacement.

It is essential to understand the importance of all the four components in order to formulate an efficient risk-based asset management program.

1.2.1 Deterioration Modes and Mechanisms

It is necessary to understand the actual modes and mechanisms of failure of an asset in order to select the most suitable management strategies. The different types of water infrastructure assets fail differently and it is essential to formulate the risk-based asset management strategies according to the probable failure mechanisms of different assets. A metallic pipelines fails majorly due to corrosion while a cement-based pipeline fails due to the aggressiveness of the water towards the pipeline material. These two pipeline have different mechanisms of failure and thus their condition assessment, risk assessment and renewal approaches should also be different as per their individual requirements. The mode and mechanism by which an asset is failing should be understood and taken into consideration while formulating its management strategies.

1.2.2 Risk Assessment and Management

The process of quantifying the risk of failure associated with an asset is the most crucial step of a risk-based asset management program. In order to understand the risk of failure, the two main components of risk, i.e., the probability of failure and the consequence of failure should be calculated. One of the major consideration while deciding the criticality of assets for renewal is their risk since by knowing the risk associated with all the assets, considerable amount of capital and time can be saved in the renewal of “not so critical” or “less risky” assets. It is equally important to devise methodologies to mitigate the risk once assessed.

1.2.3 Condition Assessment Approaches and Technologies

The current condition of an asset can be understood by implementing condition assessment approaches and technologies. It is important to understand the current condition of an asset before selecting the renewal strategy. The condition of an asset is one of the primary criteria to decide whether to repair, rehabilitate or replace an asset. The assets that are severely deteriorated are replaced while the assets that are structurally sound and only require minor repairs are repaired using coatings, and linings.

1.2.4 Asset Renewal Approaches and Technologies

The final step of a risk-based asset management program is the asset renewal. This involves the repair, rehabilitation or replacement based on the extent of deterioration of an asset. The water infrastructure assets that are not critically deteriorated are repaired using coatings and linings while the assets that are deemed unsuitable for use due to excessive deterioration are replaced using replacement methodologies.

Figure 2 shows the criteria for selection of a renewal methodology based on the extent of deterioration,

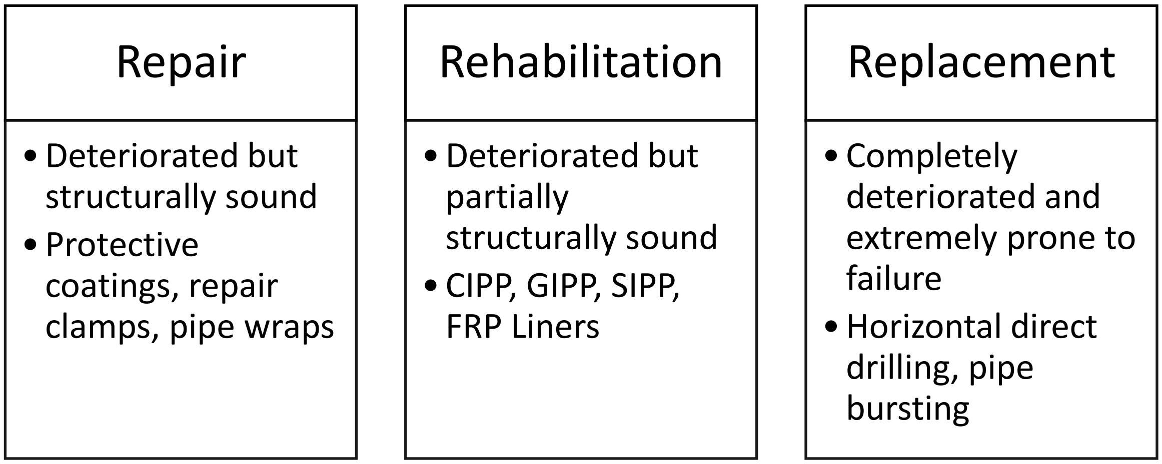

Figure 2- Selection of the Renewal Methodology based on the condition of the Pipeline

It is essential to understand that an effective risk-based asset management program consists of all the four focus areas. It is a comprehensive process, and to attain enhanced service life of the assets, all the four focus areas of this research should be understood and implemented by the water utilities. My thesis will look into the current state of knowledge and implementation existing in the industry regarding the approaches and technologies of risk-based asset management for drinking water pipelines, valves, and hydrants by an extensive literature and practice review.

1.3 **SCOPE**

The scope of the work for this research is as follows,

- Synthesis and analysis of the existing literature on the four focus areas of a risk-based asset management program for drinking water pipelines, valves, and hydrants by reviewing journals, conference proceedings, and reports from USA, Australia, and Canada.
- Synthesis and analysis of real-world case studies developed through a comprehensive practice review with water utilities from across the USA aimed at information collection regarding their understanding of deterioration modes and mechanisms, risk assessment and management approaches, condition assessment approaches and technologies, and asset renewal approaches and technologies.
- Synthesis and analysis of already published case studies on the four focus areas to obtain a broader insight of the real-world asset management practices.
- Provide enhancement of the EPA 10-step asset management guidelines based on the knowledge gained from the literature and practice review.

- Development of an understanding of the approaches and technologies for risk-based asset management.

1.4 OBJECTIVE

The two primary goals of this research are to enhance the knowledge regarding the risk-based asset management as well as to provide insight about the current approaches and technologies implemented by water utilities for the risk-based asset management of drinking water pipelines, valves, and hydrants.

To achieve the research goals, this report will meet the following five key objectives through a state-of-the-art literature and practice review:

- Analysis of the deterioration modes and mechanism from literature review, real-world practice review and published case studies
- Analysis of the risk assessment and management approaches from literature review, real-world practice review and published case studies
- Analysis of the condition assessment approaches and technologies from literature review, real-world practice review and published case studies
- Analysis of the asset renewal approaches and technologies for cost-effective renewal from literature review, real-world practice review and published case studies
- Provide enhancement to the EPA 10-step asset management guidelines for developing a risk-based asset management plan based on the knowledge gained through the literature and practice review.

CHAPTER 2

RESEARCH METHODOLOGY

Initially, a comprehensive literature review was conducted to understand the extent of knowledge existing in the industry regarding the four main focus areas of a risk-asset management program, namely, deterioration modes and mechanisms, risk assessment and management approach, condition assessment approaches and technologies, and asset renewal approaches and technologies. A significant number of online databases were searched such as ASCE database, Engineering Village, Water RF database, AWWA database, and ISI web of science to acquire academic publications from significant engineering and science publishers.

The literature review in this research was conducted in two stages: (1) Quantitative Stage and (2) Qualitative Stage.

The quantitative (first) stage consisted of searching the keywords (deterioration modes and mechanisms, risk assessment, risk management, condition assessment, and asset renewal,) in the online engineering databases to attain a numerical overview of topic areas related literature published. Country of origin, publication year, and vocabulary was recorded on each database search. The second stage comprised of selecting the most relevant journals, conference proceedings, and reports to provide a critical review of the current state of the topic areas.

Secondly, a screening-level questionnaire was developed to select water utilities for case study development (Appendix B). A set of questions about the requirements of the research were assembled in the screening-level questionnaire to understand whether the water utility qualifies for the research criteria for case study development. The utilities were screened via the screening level questionnaire based on the fact that whether or not they have an asset management program distinctly considering all or any of the four focus areas of a risk-based asset management program.

Based on the responses of the screening-level questionnaire, additional documents, such as reports, technical memorandums, and case studies created by the utilities in the course of project execution were obtained to understand the overall asset management practices and to develop case studies.

Finally, case studies were developed to address the successful condition assessment approaches and technologies, asset renewal approaches and technologies, risk assessment and management approach implemented by the water utilities. The goal was to understand the implementation of the approaches and technologies discussed in the literature into the real world as well as to present the technologies that have been proven successful by the water utilities.

Along with this, a comprehensive practice review with existing case studies was conducted to attain a broader overview of the implementation of various risk assessment and management approaches, condition assessment approaches and technologies, and asset renewal approaches and technologies by water utilities for pipelines, valves, and hydrants.

The overall methodology for this research is shown in Figure 3.

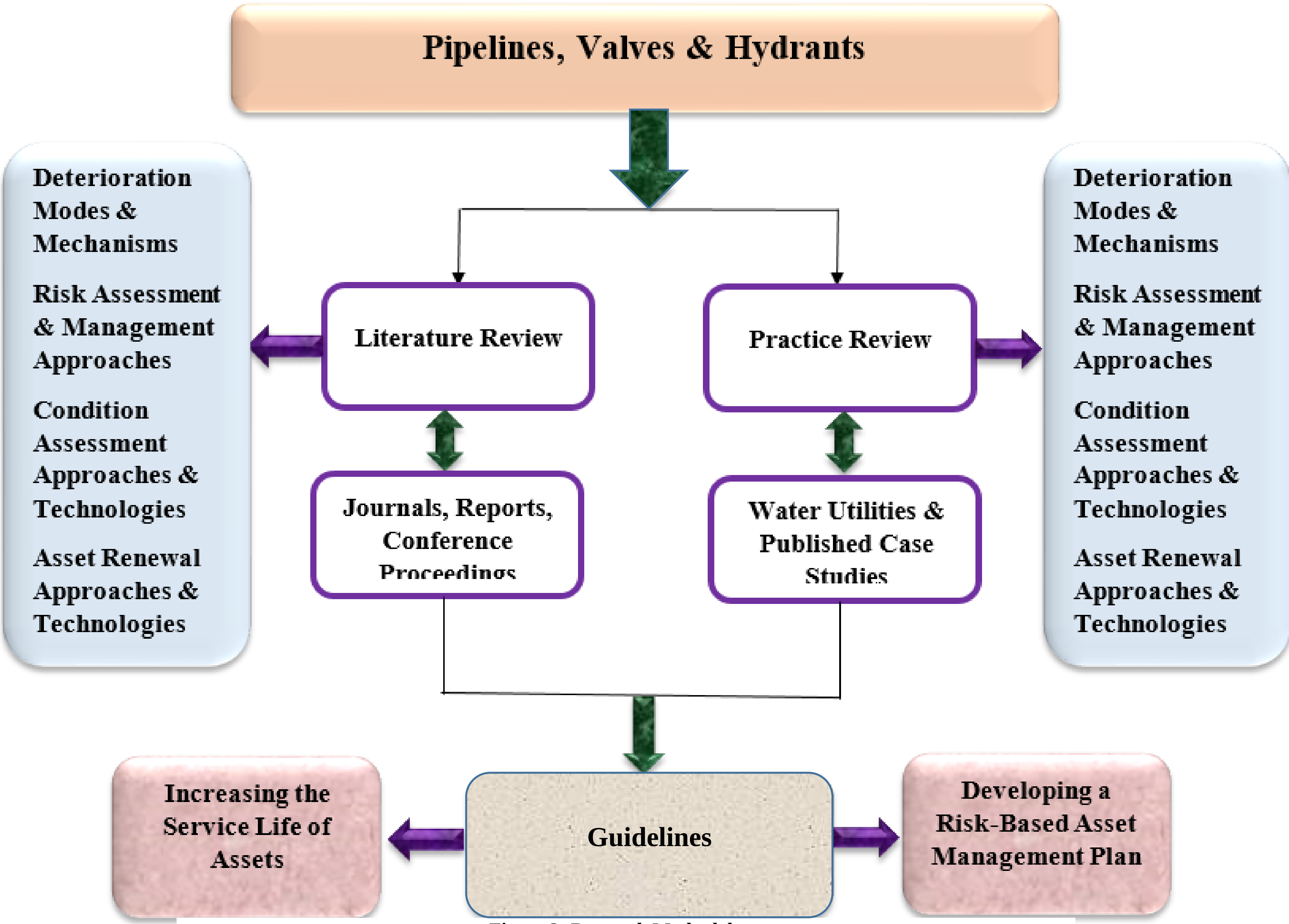

Figure 3- Research Methodology

CHAPTER 3

LITERATURE REVIEW

3.1 Introduction

This chapter provides a synthesis and analysis of the various journals, conference proceedings, and reports reviewed on the four focus areas of a risk-based asset management program for the drinking water pipelines, valves, and hydrants. The four focus areas of a risk-based asset management program are as follows,

Focus Area 1: Deterioration Modes and Mechanisms

Focus Area 2: Risk Assessment and Management Approaches

Focus Area 3: Condition Assessment Approaches and Technologies

Focus Area 4: Asset Renewal Approaches and Technologies

3.2 Asset Type 1: Pipelines

The synthesis and critical review of the literature found for the above-mentioned focus areas for drinking water pipelines are as follows:

3.2.1 Deterioration Modes and Mechanisms

An extensive literature review has provided an in-depth knowledge regarding the various deterioration modes and mechanism of drinking water pipelines. As found in the literature review, the deterioration modes and mechanism for different types of pipelines such as cast iron pipelines, ductile iron pipelines, PCCP, PVC, steel pipelines, and asbestos-cement pipelines are also different due to the difference in size, loading, and material properties.

The most prominent modes of failure for small diameter cast iron pipelines are circumferential failures and bell splitting while for large diameter cast iron pipelines it is longitudinal cracking and bell shearing. The cause of circumferential failures in small diameter cast iron pipelines is lower moment of inertia which causes longitudinal bending failures while in large diameter pipelines, high moment of inertia and high water pressure leads to longitudinal cracking and bell shearing. Bell splitting occurs due to the difference in the thermal coefficient of expansion of the pipeline and the joint material. The other common mode of failure for cast iron pipelines is blowout holes which occurs when corrosion has reduced the strength of the pipe wall in a local area to a point where a pressure surge causes the wall to rupture (Dickinson et al. 2014; Makar et al. 2000).

Some other modes of failures identified for cast iron and ductile iron pipelines include burst failure, joint failure, gasket failure and structural socket failures. The mechanisms for such failures include corrosion, ground movements, gasket degradation, and improper installation (Reed et al. 2006; Dingus et al. 2002).

The essential failure mechanisms for cast iron pipelines can be divided into four categories, namely, corrosion, manufacturing flaws, excessive forces, and human errors (Makar et al. 2000). However, the most dominant failure mechanism for metallic pipelines is electrochemical corrosion with the damage occurring in the form of corrosion pits. The conditions that promote electro-chemical corrosion include aggressive soil conditions such as moisture content, chemical and microbiological content, and electrical resistivity (Kleiner et al. 2005). The other types of corrosion causing the failure of metallic pipelines are uniform corrosion, galvanic corrosion, localized corrosion, and concentration cell corrosion (Snoeyink and Wagner 1996).

The dominant mode of failure for PCCP is the crack formation in the external mortar coating followed by subsequent delamination exposing the pipeline to the harsh exterior environment. The principal mechanism of failure for PCCP is the corrosion of pre-stressing wires resulting from the lower pH level of the surrounding soil which results in the deterioration of the pipelines (Kleiner et al. 2005). The other reasons of deterioration for PCCP include degradation due to high chloride environment, poor quality of mortar coating, poor quality of reinforcing wires, the presence of corrosive soils, inadequate thrust restraint, and construction damage.

The primary mode of failure for cement-based pipelines is cement material leaching (Spencer et al. 2015; Kleiner et al. 2005). The mechanisms which cause this type of failure are aggressiveness of water towards the cementitious material of the pipeline. These include carbonic aggressiveness as well as alkali granulate reactions and attack by ions such as magnesium and sulfate present in the water (Leroy et al. 1996). Expansive by-products can form between the cement medium and the aggregates. The increase in the volume of these by-products over those initially present causes weakening of the material. Finally, degradation takes place if the total inorganic carbon (TIC) content is too low to form precipitates within the cement matrix (Leroy et al. 1996).

Further, the PVC pipeline’s significant modes of failure are a joint failure and gasket failure. The principal mechanism of this type of failure is ground movement. Followed by these, structural socket failure is another common mode of failure for PVC pipelines. Additionally, for steel pipelines as well, gasket failure and joint failure are the two most common types of failure modes. However, the mechanisms of failure for gasket failure in steel pipelines are ground movement and gasket degradation in equal proportions (Reed et al. 2006).

It should also be noted that the mechanisms of failure for drinking water pipelines are governed by many factors including internal factors such as pipe diameter, material, age, pressure and external factors such as soil type, traffic loading, seasonal temperature change (Sinha et al. 2013). The factors influencing the pipeline failure can also be categorized into static, dynamic, and operational factors. The static factors include pipe properties, diameter, wall thickness, soil properties, and installation practices which do not change over the time. The dynamic factors are those which change over time such as age, the temperature of soil and water, bedding conditions and dynamic loadings. While the operational factors include replacement methods, protection methods, and water pressure which depends upon the efficiency and quality of operational methodology (Kleiner and Rajani 2001).

3.2.2 Risk Assessment and Management Approaches

As found in the literature review, the risk is defined as the product of likelihood/probability of failure(LoF) and consequence of failure (CoF). Likelihood of failure indicates the likelihood of an asset failure during a specified period. The consequence of Failure (CoF) includes both direct and indirect costs. Direct cost contains repairs, legal fees, and fine, while indirect cost comprises image loss, social impacts, and environmental damage costs (Sinha and Shaoqing 2013).

There are various approaches to calculate the probability/likelihood of failure as found in the literature review. These approaches include statistical models, deterministic models, probabilistic models, other advanced mathematical models as well as assessing the probability of failure based on the data known about the pipeline such as age, soil conditions, and environmental conditions (Sinha and Shaoqing 2013).

Statistical models such as Markov-chain statistical models can be employed to model stochastic processes, which focus on the probabilities as to how the process will evolve in the future depending on the present state of the process and independent of past events. Further, Bayesian-based statistical models which combine engineering knowledge with the data at hand to predict the breakage rate distribution can also be employed for calculating the probability of failure (Sinha and Shaoqing 2013).

Apart from this, deterministic models use linear or non-linear equations to predict the failure of an asset. These models are utilized in the situations where the relationship between the various components is known (Sinha and Shaoqing 2013). Other models that can be used for the calculation of the probability of failure include:

(1) A Weibull curve using historical failure data related to age, material type, coating and lining condition, and the environment that can predict the remaining useful life of a pipeline (Sinha and Shaoqing 2013);
(2) Physical models based on structural and finite element analysis and utilizing data such as pipe dimensions, loadings, and boundary conditions can be employed to determine the structural condition of the pipeline (Sinha and Shaoqing 2013).
(3) Monte-Carlo simulation can be used to determine the failure probability of a pipeline in future. It is of two types, direct simulation of a naturally random system and the addition of artificial randomness to a system and subsequent simulation of the new system (Sinha and Shaoqing 2013).

(4) Advanced mathematical models such as artificial neural networks (ANN), fuzzy logic models, and heuristic models can also be used to determine the remaining life of assets (Sinha and Shaoqing 2013).

The likelihood of failure can also be calculated based on the age, the number of previous breaks, and service conditions of the pipeline. A pipe risk-screening tool (PRST) can be utilized which manages the data on the inventory of pipe-at-risk and secondly prioritizes the renewal of pipelines based on the likelihood and consequence of failure. The tool uses a weighted average combination of the likelihood indices for age, breaks, and service to compute the overall probability of failure index. The consequence of failure can be calculated by providing scores for location, pipe size and cost of repair on a numeric scale by experts (Grigg et al. 2013).

Along with the models discussed earlier, a Microsoft-excel spreadsheet-based risk assessment tool which performs structural analysis on the pipelines by creating risk curves based on condition assessment findings can be applied to determine the risk of failure. To develop risk curves for water pipelines, the pipe structural condition, which is determined by the number of wire breaks in PCCP is compared with the pipeline structural capacity with the consideration of external and internal loads. The assessment tool categorizes the pipeline condition into the various risk of failure categories such as very-high-risk, high risk, moderate risk, and low risk (Rajah et al. 2014).

The methodologies found in the literature review for the risk management of drinking water pipelines include failure mode and effect analysis (FMEA) technique which detects the potential failure modes by calculation of risk priority degree index (Mirghafouri and Kousha 2015). A Nessie Model is also suggested which creates a financial model representing the annual capital investment needed to replace buried infrastructure in future years as well as employs electromagnetic condition assessment technologies for understanding the condition and risk of failure of pipelines (Leighton and Smith 2014). Finally, implementation of a risk management framework is also found in the literature review which consists of the following five steps: (1) establishing context, (2) identifying risks, (3) evaluating risks, (4) assessing risk treatment options, and (5) treating the risks (Raucher et al. 2017).

Earlier in 2002, Deb et al. (2002) also suggested a risk management strategy to improve the performance and reduce the risk of failure associated with pipelines. This strategy consists of the following: (1) identification of goals, (2) selection of best practice, (3) identification of performance measures, (4) definition of terms, (5) identification of data needs, (6) collection of data, and (7) analysis of data (Deb et al. 2002).

3.2.3 Condition Assessment Approaches and Technologies

There are various condition assessment approaches and technologies found for drinking water pipelines in the literature review. The condition assessment technologies mentioned in the literature for drinking water pipelines include:

(1) Visual and camera inspections

(2) Acoustic based methods

(3) Laser-based methods

(4) Electrical and electromagnetic based methods

(5) Flow-based methods

(6) Physical force based methods

(7) Temperature based methods

(8) Other advanced methods such as coupon sampling, and tracer gas technique (Sinha et al. 2013).

The different visual and camera methods include above- ground inspection, excavation for visual inspection, man entry for visual inspection, handheld digital cameras, CCTV cameras, digital scanners or optical scanners (Sinha et al. 2013; Matthews et al. 2015). The internal condition assessment of metallic pipelines (cast iron and ductile iron) using CCTV cameras is conducted for understanding the condition of protective linings and the locations of internal corrosion. Along with this, visual external condition assessment is performed to determine the state of the coating, the presence of trapped moisture, remaining wall thickness, and pit-depth measurement (Cleveland et al. 2013). Visual methods are also implemented for condition assessment of PCCP pipelines (Zarghamee et al. 2012; Kleiner et al. 2005).

Acoustic methodologies such as rod sounding can be used for condition assessment of PCCP pipelines. Rod sounding involves sounding of the internal of the pipe with a light hammer to look for hollow sounds which indicate loss of pre-stress and advanced state of distress in PCCP pipes (Zarghamee et al. 2012). Ultrasound is also an acoustic-based condition assessment method which includes methodologies like ultrasonic wall thickness measurement through the ultrasonic testing device and long-range guided ultrasonic wave methodology to determine the average wall thickness of a pipeline (Sinha et al. 2013; Dingus et al. 2002; Matthews et al. 2015). For small diameter cast iron and ductile iron pipelines, acoustic technologies such as discrete ultrasonic, guided waves ultrasonic, acoustic emission monitoring, acoustic propagation velocity measurement, and acoustic leak detection/hydrophones can be used (Dickinson et al. 2014).

Laser profiling is a standard laser-based method for condition assessment which produces continuous lines of light along the internal lining of the pipeline and generates the 2D shape of the pipe (Sinha et al. 2013).

Other common condition assessment technologies for drinking water pipelines are electrical and electromagnetic based methods such as eddy current method, remote field technologies, ground penetrating radar, and magnetic flux leakage (Sinha et al. 2013; Matthews et al. 2015; Rajani et al. 2000; Dingus et al. 2002; Dickinson et al. 2014). Electromagnetic condition assessment approaches such as remote field technology, broadband electromagnetic technologies, and magnetic flux leakage are utilized for the condition assessment of small diameter cast iron and ductile iron pipelines (Dickinson et al. 2014).

Flow-based methods can also be used for condition assessment of pipelines which include flow meters that measure the pipe flow depth, volume and velocity to determine the condition of the pipeline (Sinha et al. 2013). Along with this, physical force based methods for condition assessment include transient pressure testing and probing (Sinha et al. 2013; Dingus et al. 2002).

The temperature-based methods include infrared technologies where infrared radiations travel from colder to warmer surfaces and if there is a discontinuity in the wall thickness of the pipeline the infrared camera shows uneven heating (Sinha et al. 2013; Dingus et al. 2002). Finally, some advanced methods for condition assessment of drinking water pipelines are coupon sampling and tracer gas technique. Coupon sampling involves the use of tapping equipment to remove a "coupon" which is a piece of the pipe wall and is then tested to determine the condition of the coupon. The state of the whole pipeline is determined by extrapolating the results of the coupon testing for the entire length of the pipe. On the other hand, tracer gas technique involves insertion of a water-soluble gas into a pipeline segment (Sinha et al. 2013).

Another advanced condition assessment technology for drinking water pipelines is smart pipes where the entire length of the pipeline is equipped with an array of sensors which provide complete monitoring of the pipe condition and performance. Another technology is the augmented reality which blends the real-time, real-world video footage and computer-generated graphics and provides an advanced human-computer interface which facilitates data manipulation and enhanced visualization of the defects in pipes (Zheng and Kleiner 2012).

It is also important to note that the condition assessment technologies for drinking water pipelines such as magnetic flux leakage (MFL), remote field technology (RFT), ultra-sonic technology (UT), electromagnetic acoustic technology (EMAT), laser-based methods, and camera-based methods are classified as non-destructive technologies. These technologies allow the condition assessment of the pipelines without service disruption (Russel 2014).

Other condition assessment technologies for cast iron and ductile iron pipelines are a field-based LPR probe, fractography, and metallography.

A filed-based Linear Polarization Resistance (LPR) probe can effectively access the corrosion rate of ferrous pipes (cast iron and ductile iron). It is an indirect method of assessing the corrosion rate on a given ferrous pipe as compared to the excavation of the pipeline and direct measurement of pit depth and corrosion loss. The accumulated LPR data is input to proprietary Weibull-based algorithms that predict corrosion loss, pit depth distribution, and pit penetration of a pipeline (Flounders and Lindemuth 2015). Macroscopic analysis or fractography for cast iron pipelines involves the observations of the two mating faces of the fracture with the naked eye or with low magnification optical instrument. The two significant fracture features surface which is essential to examine at the macroscopic levels are orientation and topographical appearance

(Rajani and Kleiner 2013). Metallography or microscopic analysis or microfractography for cast iron pipelines involves identification of features that cannot be resolved by the naked eye. Examination at the microscopic level can distinguish fine-scale processes and thus lead to the affirmation of fracture mechanisms possibly identified at the macroscopic level (Kleiner and Rajani 2013; Brooks and Choudhury 1993).

The condition assessment technologies for reinforced concrete pipelines include soil resistivity survey, pipeline electrical continuity survey, and pipe-to-soil potential measurements (Buonadonna 2016). For PVC pipelines, technologies such as visual inspections, electro-scanning, acoustic monitoring, ultrasonic testing, and condition assessment based on soil properties can be conducted. Use of tracer gas and ground-penetrating- radar to detect leaks in plastic service lines is also found (Martel and Klewicki 2016).

Along with condition assessment technologies, condition assessment approaches can also be applied to understand the current condition of drinking water pipelines. These approaches include;

(1) Deterministic models
(2) Probabilistic models
(3) Artificial neural networks
(4) Fuzzy expert systems

The deterministic models predict the breakage pattern of the pipelines utilizing two or three parameters based on the pipe age and breakage history. The two types of deterministic models are time exponential models and time linear models. Probabilistic models are also of two kinds, namely, probabilistic multi-variate and probabilistic single-variate models (Kleiner and Rajani 2001). When the relationship between the components is specific, deterministic models are used while probabilistic models calculate the probability of a failure event occurring and require condition data and historical asset information (Clair and Sinha 2012).

Artificial neural network models are used to model the failure of an asset and comprised of interconnected neurons that work together to provide a result. Fuzzy-logic models are used when the data or information regarding an asset is inexact or has uncertainty. These models have an expert-rule based system that can imitate the human thinking and decision-making process (Clair and Sinha 2012). Finally, Fuzzy expert systems are knowledge-based systems utilizing the understanding of humans for problem-solving (Fares and Zayed 2010).

3.2.4 Asset Renewal Approaches and Technologies

The renewal of drinking water pipelines includes repair, rehabilitation, and replacement of pipes.

The repair technologies are used when the defect is not that severe and when the deterioration is contained to a small section. The various repair technologies for potable water pipelines are divided into three categories 1) pipe joint and leak seal 2) pipe point repairs and 3) pipe coatings (Sinha et al. 2014). Pipe joint and leak seals include internal sleeves and grouting. Among these, the most common type of repair technology for sealing joints is mechanical sleeves which can withstand high internal pressure (Sinha et al. 2014).

Pipe point repair methods consist of (1) internal repair methods which include internal pipe wraps, internal sleeves, and grouting, and (2) excavate and repair which include external repair clamps, external pipe wrap, and partial replacement (Sinha et al. 2014).

Pipe coatings are also used in practice as a pipeline repair technology and include cementitious, polymer-based, epoxy, urethane, polyurethane, polyurea, and hybrid polymer coatings (Sinha et al. 2014). Cement mortar lining, epoxy lining, calcite lining, and metallic phosphate lining provide a smooth protective non-structural coating to the interior surface of the pipe that restores the hydraulic capacity of the water main (Deb et al. 2002). It is to be noted that epoxy lining has two significant advantages over cement mortar lining. Because epoxy has a faster curing time, the main can be returned to service in 8-9 hours versus a minimum of 24 hours for cement mortar lining. Furthermore, the lining thickness for epoxy as practiced in the industry is only 0.04 inches. (1mm) regardless of the pipe size, which minimizes the impact of diameter reduction on smaller pipes. The thinner lining also means that less material is used, thus possibly lowering application costs (Urie et al. 1990).

When the pipeline is structurally strong enough to support the renewal technology partially, rehabilitation technologies are utilized. Rehabilitation improves the capacity and age of the deteriorated pipe to an extent. Rehabilitation technologies also restore the structural integrity of the pipeline system. A tremendous benefit of rehabilitation efforts is that the life expectancy of the pipeline is extended by 40-50 years. Pipe rehabilitation technologies can be broken into six major technology classes: 1) CIPP liners, 2) GIPP liners, 3) SIPP liners, 4) Sliplining, 5) Modified Sliplining, and 6) FRP Liners (Sinha et al. 2014; Grigg 2004; Ellison et al. 2015).

CIPP liners consist of fiber-reinforced hose liners, woven hose liners, glass reinforced liners, carbon reinforced liners, and polyester liners (Sinha et al. 2014). SIPP liners can be further sub-divided into cementitious, polymer-based, epoxy, urethane, polyurethane, polyurea, and hybrid polymer coatings (Sinha et al. 2014). Sliplining is also of two types which are continuous and segmental. Additionally, modified sliplining consist of deformed HDPE, radical reduction, and expand in place PVC (Sinha et al. 2014).

For rehabilitation of PCCP, application of fiber reinforced polymer (FRP), including glass fiber (GFRP) and carbon fiber (CFRP) composites, prove out to be a useful methodology. The installation of FRP structural liner inside the pipe includes many operations, such as preparation of the pipe substrate, and fiber saturation. The most critical among all the operations is the preparation of pipe substrate to ensure sufficient bond of the FRP liner material (Gipsov and Fisk 2014).

Rehabilitation technologies can also be divided into structural and non-structural rehabilitation technology categories depending upon the application of the technology in rehabilitating the structural integrity of the pipeline (Matthews et al. 2013).

Rehabilitation of small diameter cast and ductile iron pipelines can be achieved by adopting non-structural, semi-structural, or fully-structural renovation linings (Marlow et al. 2013). Non-structural lining techniques involve applying a thin layer of cement mortar or polymeric resin to the cleaned inner surface of a water pipe (Marlow et al. 2013). While, semi-structural techniques generally involve the installation of a thin lining that achieves a tight fit to the pipe wall, thereby forming a structural composite with the existing pipe. The semi-structural liner can be thin PE or PVC pipe, woven hose liner with epoxy or glass fiber reinforced flexible felt tube impregnated with epoxy (Marlow et al. 2013). Fully-structural linings are capable of sustaining the maximum allowable operating pressure of the system independent of the original pipe, but they still incorporate the existing pipe fabric as support and are thus considered renovation techniques. The primary example is cured-in-place-pipe (CIPP) lining (Marlow et al. 2013).

Finally, replacement technologies are used if the existing host pipe is no longer structurally sound enough to support repair or rehabilitation efforts or if the current host pipe is severely deteriorated or collapsed. Replacement technologies renew the life expectancy of the pipeline rather than just extending it. The pipe replacement technologies can be broken into two major technology classes: 1) in-line replacement methods and 2) off-line replacement methods (Sinha et al. 2014; Grigg 2004; Ellison et al. 2015).

In-line pipe replacement technologies are the technologies which retain the original alignment of the pipelines. The in-line replacement technologies include pipe bursting, exhume and replace, pipe splitting, and pipe cutting. Out of these, the most common type of replacement technique for in-line pipe replacement is pipe bursting. However, pipe bursting results in ground vibration which increases the risk of damage to surrounding utilities and aboveground structures. One of the benefits of pipe bursting is that it allows the installation of a new pipeline in the same location as the old pipeline (Sinha et al. 2014).

Off-line pipe replacement methodologies are those which do not retain the original alignment of the pipelines and these technologies include horizontal earth boring, pilot tube guided boring, horizontal directional drilling (HDD), abandon and replace, pipe jacking and utility tunneling, hand mining, micro-tunneling, auger boring, and pipe ramming. The benefits of HDD methodology include the installing pipelines beneath obstructions and at environmentally sensitive areas (Sinha et al. 2014).

Replacement technologies can also be divided into two groups, namely, trench and trenchless replacement technologies. Conventional trenched replacement is an ‘open cut’ operation whereby the existing pipe is uncovered to allow necessary work to be undertaken. On the other hand, a range of trenchless technologies are developed to address some of the disadvantages associated with conducting trenched replacement (Marlow et al. 2013).

Further, corrosion control in metallic drinking water pipelines can be executed by the application of cathodic protection, corrosion inhibitors, and protective coatings. In cathodic protection method, the corrosion is not stopped but redirected to a predetermined sacrificial anode and to mitigate the external corrosion at the cathode (pipeline). Concrete or mortar covering is a commonly used corrosion inhibitor. Finally, there are some coatings available in the market for protecting the pipelines from corrosion (Romer et al. in 2004).

Along with implementing pipeline renewal methodologies, it is also essential to understand the pipeline renewal prioritization methodologies.

To prioritize the renewal of drinking water pipelines, a performance-based approach can be adopted that identify the failure prone pipes. In this approach, pipes with less than three break records are analyzed using the Multi-Criteria Decision Analysis (MCDA) while the pipes with at least three break records are analyzed using the Non-Homogenous Poisson Process (NHPP). These methodologies are implemented to calculate the probability of failure, expected number of failures and time to next failure (Rogers and Grigg 2006).

Along with this, KANEW and LEYP models can be used to predict the future failure and rehabilitation needs of drinking water pipelines (Kropp et al. 2009). KANEW model incorporates cohort survival models to determine the future rehabilitation needs. Cohorts are asset types with different aging behavior. Age-specific renewal rates are calculated from service life density and survival functions. The aging functions can be obtained from either the historical rehabilitation data or the expert advice. The aging functions used in this model are derived from Herz Distribution developed for the aging infrastructure while LEYP Model is used to determine the failure rates of a pipeline. This model is based on the mathematical concept of counting process (Kropp et al. 2009).

3.3 Asset Type 2: Valves and Hydrants

The synthesis and critical review of the literature found for the above-mentioned four focus areas for valves and hydrants are as follows:

3.3.1 Deterioration Modes and Mechanisms

It is observed in the literature review that the valves do not generally fail due to the corrosion of the body but from corrosion of internal components, deterioration of seals and build-up of deposits (Marlow and Beale 2012). The other failure types for valves are operational changes, mechanical damage, and equipment failure. Operational changes include increased operating pressure, split/cracked bodies, and joint failure. Mechanical damages are collapses due to increased internal and external loads, silt blockages, poor valve design, seismic activity, temperature change, tuberculation, coating failure, cavitation, ground and embankment movement, support failure, pressure surge, and vibration (Marlow and Beale 2012). Finally, equipment failure examples include operating electrical actuators with excessive force, failure of the hydraulic motor, operating a valve hand wheel or spindle in the incorrect manner (Marlow and Beale 2012).

3.3.2 Risk Assessment and Management Approaches

Some of the risk management approaches found in the literature review for management of valves include the following: (1) the valves should not be buried under excessive fill, (2) should be set near intersecting streets or fire hydrants to facilitate location in the future, and should have marker stakes set on cross-country lines, (3) a valve box should be placed above the valve so that the valve is accessible through operating keys, (4) heavy valves should be supported, and (5) records prepared by the installing crew should be stored and well maintained (Franklin 1982).

Along with this, an approach for risk assessment of valves is risk-based valve maintenance and management strategy which defines risk as a product of failure probability and failure consequence. The probability side of the risk generally depends on the environmental conditions, operational and maintenance practices, the asset's inherent design, capacity-load relationships, human factors. On the other hand, various environmental, socio-political and economic factors influence the consequence of the failure of an appurtenance (Marlow and Beale 2012).

As mentioned in the literature, it is also imperative to choose the right valve, consideration of AWWA standards for purchasing valves, proper storage at site, adequate installation procedure including thorough inspection of the valve, checking if the valve is in closed position or not before installation to prevent the possibility of damage to the seating surface, and proper documentation regarding the valve type, location, size in order to mitigate risk efficiently (Hoff 1996).

Further, a maintenance strategy for fire hydrants includes policies prohibiting unauthorized use of fire hydrants, hydrants should be checked by visual inspection for external damage, all nozzle caps should be removed and screw threads should be greased, valve operation should be tested, barrel drainage should be inspected, stem nuts should be oiled and the hydrant should be repainted if necessary (Marlow and Beale 2012). A competent management plan for fire hydrants also requires that the governing parties understand and support the proposal, selection of a team of consultants to provide a comprehensive scope, keeping goals realistic, achievable and beneficial, and defining responsibilities of the staff clearly (Culbertson 2010).

Another approach for management of appurtenances is by following a management practice which includes maintenance of a proper inventory of valves and hydrants, regular condition assessment, documenting asset maintenance records, prioritizing, scheduling and tracking maintenance procedures and their outcomes, as well as planning and budgeting (Martin and Ries 2015).

Another management strategy for inspections of valves include checks that are carried out periodically to monitor and record how assets are performing, preventive maintenance that ensures that systems or components will act as per their expectations for their entire service life, repairs that are required when defects occur and unplanned intervention is needed, rehabilitation that replaces one major component of a system when it fails at the end of its service life, capital renewal that replaces a system because of economic, obsolescence, modernization or compatibility issues (Marlow and Beale 2012).

3.3.3 Condition Assessment Approaches and Technologies

The first stage of a condition assessment procedure for hydrants, isolation valves, air valves and automatic control valves is to identify which appurtenance needs to be inspected. The second step includes the locating of the appurtenance. The third step includes inspection of the appurtenance to collect data regarding the condition and other relevant operation regarding the operation and associated risk with the appurtenance. The fourth and the last step is an analysis of the result obtained from the condition assessment and the decision making regarding repair/rehabilitation/replacement of an asset (Marlow and Beale 2012).

The various condition assessment technologies for valves and hydrants are acoustic devices, CCTV, remote visual inspection, ultrasonic testing, radiography, eddy current inspection, and transient wave analysis (Marlow and Beale 2012). Along with this, a valve exerciser is also utilized for condition assessment of valves (Khadka 2014).

Further, the condition assessment technologies for hydrants include physical inspection which involves above and below ground inspection as well as wet and pressure tests, fire flow tests, flushing programs that check visible and audible leaks, proper operation of the valve, water pressure, turbidity, color, Ph, and chlorine level of water. Air scouring which involves isolating a section of water main between an entry point and an exit point. The valve upstream is opened slightly allowing the passage of a controlled amount of water into the isolated section producing slugs of water. Compressed air makes these slugs of water to swirl through the pipe while cleaning it in the process (Mchugh 2003).

3.3.4 Asset Renewal Approaches and Technologies

The various types of protective coatings for valves renewal include baked epoxy- powdered spray; coal tar epoxy-catalytic; urethane-polyurethane; polyester-catalytic; vinyl-solvent type, lacquers; and wax (Houston 1972).

3.4 Summary of Literature Review

The following paragraphs provide a summary of the findings made during the extensive literature review of drinking water pipelines, valves, and hydrants.

Asset Type 1: Drinking Water Pipelines

The literature review conducted for drinking water pipelines has provided an opinion that there is a considerable knowledge existing in the industry regarding the risk-based asset management of drinking water pipelines. There are several efficient condition and risk assessment approaches and technologies found in the literature for different types of pipes. Although the risk assessment approaches are found extensively in the literature, there is limited coverage of risk management practices. It is also observed in the literature review that while condition assessment technologies are extensively covered, there is less coverage of condition assessment approaches. Further, there is a relatively large body of existing knowledge on modes of failure for drinking water pipelines, specifically metallic pipelines, but there is limited literature available providing a comprehensive overview of deterioration mechanism about why precisely the pipes fail. Finally, it has been realized from the literature review that limited literature exists on renewal prioritization tools/models as compared to renewal technologies application for drinking water pipelines.

Asset Type 2: Valves and Hydrants

It is realized by the literature review that there is considerably less literature published on the risk-based asset management of valves and hydrants as compared to drinking water pipelines. However, some well-developed risk management and condition assessment approaches and technologies are found in the literature for valves and hydrants. The condition assessment technologies such as acoustic devices, CCTV, remote visual inspection, ultrasonic testing, radiography, eddy current inspection, and transient wave analysis are found in this research.

CHAPTER 4

PRACTICE REVIEW

4.1 Introduction

This chapter discusses the selective case studies which were either already published or are written specifically for this research by collecting documents and information from the water utilities across the USA on understanding of the deterioration modes and mechanisms, risk assessment and management approaches, condition assessment approaches and technologies, and asset renewal approaches and technologies for drinking water pipelines valves and hydrants. There were approximately 125 case studies reviewed/written for this research out of which the most comprehensive and informative case studies syntheses are presented in this chapter. However, the summary of the practice review section provided at the end of this chapter presents results of critical analysis of all the 125 case studies written/reviewed for this research.

This chapter aims to present the leading and successful risk-based asset management approaches and technologies implemented by the real-world water utilities to manage their aging water infrastructure. Another goal of the practice review is to identify and understand the extent of implementation of the innovative approaches and technologies mentioned in literature in the real world.

4.2 Asset Type 1: Pipelines

The following are the most relevant and informative case studies synthesis on the deterioration modes and mechanisms, risk assessment and management approaches, condition assessment and management approaches, and asset renewal approaches and technologies for drinking water pipelines.

4.2.1 Deterioration Modes and Mechanisms

The utility practices are broken down by the deterioration mode and mechanisms and are further explained below:

Joint Leaks:

One of the case studies discussed the failure modes and mechanisms for large diameter cast and ductile iron pipelines by analysis of Louisville Water Company's inventory data. The most prominent failure mode observed for cast iron pipelines was joint leaks which are defined as the failure of the joint material. It was also mentioned in this case study that failures of cast iron pipes in the form of longitudinal splits occur more frequently in larger diameter pipes (12" and larger) than circumferential failures while bell splits and corrosion hole failures are very limited (Rajani and Kleiner 2013).

4.2.2 Risk Assessment and Management Approaches

The utility practices are broken down by the risk assessment and management approaches and are further explained below:

The probability of Failure and Consequence of Failure

Water Utility A formulated a risk-assessment program to optimize their decision-making process and to efficiently determine the most cost-effective, and long-term asset renewal method for large diameter water mains. The overall risk analysis and management program at the water utility A consists of the following steps: (1) data gap analysis (2) development of prediction models for probability of failure calculation (3) probability of failure calculation and normalization of scores on a scale from 1 to 10 (4) selection of consequence of failure factors and their weights based on expert opinions (5) calculation of consequence of failure and normalization of scores on a scale from 1 to 10 and (6) calculation of risk scores of all the pipelines.

For calculating the probability of failure, a predictive model based on the machine-learning algorithms is utilized by water utility A. This model constructs a relationship between the various model factors such as necessary pipe information, climate data, soil data and the actual pipe failure in the past in order to predict the failure probability in the future. This prediction model is a combination of three different types of algorithms: linear aggression, decision tree, and Bayesian statistics.

Linear regression consists of finding the best-fitting linear relationship between the probability of failure and the factors. A decision tree is a learning method of splitting a data set into branch-like segments. Bayesian statistics involves a direct correlation between pipe failures with each factor. In the final predictive model, all the three algorithms are combined to build a Bayesian network. Further, the consequence of failure associated with a large diameter transmission main was calculated as the product of the weighted average score of all the consequence of failure factors and their respective categories. The risk of failure associated with a pipeline is calculated as a product of the normalized probability of failure and consequence of failure. This calculated risk is then categorized into low, medium-low, medium, medium-high, and high risk.

Another case study discussed the risk assessment methodology implemented at the city of Annapolis. The risk assessment methodology utilized the EPA 5- step process to develop a risk assessment plan which comprised of the following questions: (1) what is the current state of the assets (2) what is the required level of service (3) which assets are critical (4) what are the best O&M and CIP strategies (5) what is the best funding strategy. A desktop condition assessment was conducted based on the data collected through work orders and inventory regarding asset age, and material. A condition score ranging from 1 to 5 was assigned to each asset using the parameters of age, material, performance, soil corrosivity, and average life expectancy where score 1 indicates good condition while score 5 means the poor condition. The likelihood of failure was calculated based on the condition score converting to a scale from 1 to 10. The triple-bottom-line consideration was utilized for determining the consequence of failure which consists of social, economic, and environmental impacts. The consequence of failure was scored on a scale ranging from 0 to 5 where 0 is no impact while 5 is a significant impact. The consequence of failure score was calculated by adding the consequence of failure scores for each of the six criteria and converting it to a scale from 0 to 30. The business risk exposure is calculated by multiplying the likelihood and consequence of failure scores (Stillman and Jones 2017).

Risk Matrix

One of the case studies discussed water utility B's asset management program for its horizontal as well as the vertical water infrastructure assets. The asset management program comprised of the condition and the risk assessment approaches implemented at water utility B. Risk at water utility B was calculated as the product of probability and consequence of failure. The probability of failure was calculated by the data that was known for the pipeline such as age, soil conditions, historical accounts, inspection findings, condition assessment data. The consequence of failure was calculated by scoring the entire pipeline according to the differing potential effect of failure including impacts such as property damage, utility damage, loss of service, and loss of redundancy. The probability and consequence of failure for assets were depicted in a risk matrix with the probability of failure on one axis and the consequence of failure on another axis.

Another case study discussed the risk analysis methodology implemented at San Diego County Water Authority (SDCWA) where the risk of failure of PCCP was represented on a risk matrix ranking the risk on a scale from 0 to 100. The Probability of failure was calculated by considering asset age, visual condition, non-destructive testing condition assessment (NDT), monitoring activities, wire breaks, design features, construction practices, modes of operation, maintenance procedure, and external environmental factors. The consequence of failure was calculated by considering the loss of functionality, limits to water supply, damage to property, the risk to other assets, the risk to buried utilities, system redundancy, and function. The risk matrix is used to prioritize the assets for repair, rehabilitation, or replacement based on the location of the asset on the risk matrix. The prioritization for renewal was given to the assets in the highest probability and consequence of failure zones in the risk matrix (Stillman and Jones 2017).

Risk Assessment and Business Risk Exposure Calculation

One case study discussed the water utility D's Asset Management Plan (AMP) for the entire District's Transmission Mains Subsystem. In order to attain an agreed standard of service and reduce the risk for the Transmission Mains Subsystem, the AMP was developed at the water utility D. The overall purpose of the asset management plan at utility D was to ascertain that the transmission mains subsystem assets are operated and maintained in a sustainable, cost-effective and responsible manner. The AMP provided an analysis of the risks to the transmission mains, condition assessment, the likelihood of failure and consequence of failure.

The likelihood of failure at water utility D was determined by providing scores on a scale from 1 to 5 (where one is least while five is the highest) to the various probabilities/scenarios and subsequently weighing each probability to determine the overall probability of failure (POF) score. The various probabilities and likelihoods included adjacent pipe with damage score, high-pressure area score, pressure ratio score, proximity to failure score, and proximity to previous damage score.

Along with this, the typical approach to evaluating the consequence of failure factors was by the triple bottom line approach in GIS which considers social, economic, and environmental impacts of asset failure. The consequence of failure factors such as accessibility, damage to the environment, damage to property, damage to utilities, disruption to traffic, disruption to the railroad, human safety, and level of service were considered. These factors were provided a score on a scale from 1 to 5 where 1 represented no consequence while 5 represented a very high consequence of failure.

Finally, the risk of failure was calculated by the following formula,

Total Risk = Probability of Failure (POF) * Consequence of Failure (COF)

The overall risk of failure was represented in a risk matrix which placed a pipe into low or high-risk zones on the matrix based on the probability and consequence of failure scores.

Another case study discussed the asset management plan at Washington Suburban Sanitary Commission (WSSC). The risk of failure at WSSC was assessed based on the business risk exposure (BRE) principle. Apart from this, the business risk exposure was also utilized to monitor assets, identify needs, prioritize projects, optimize capital investments, and to assess the level of risk exposure to WSSC at sub-system, system, network, and enterprise level. Business risk exposure at WSSC was calculated as the product of the probability of failure (POF), the consequence of failure (COF), and the mitigation factor (MF). WSSC decided the likelihood of failure criteria based on the age and the condition of assets. The triple-bottom-line (TBL) approach was utilized to calculate the COF which assesses the social, economic, and environmental impacts due to an asset failure. Finally, the mitigation factor measures the degree to which the COF of an asset is decreased through mitigation activities (Stillman and Jones 2017).

Risk Management

One of the case studies discussed the condition and risk assessments undertaken in response to a catastrophic steel trunk main failure at Water Corporation, Australia. The condition assessment approach implemented by the utility involved routine CCTV inspections to check the integrity of the cement mortar lining and signs of steel corrosion. Based on the condition and risk assessment results some risk management strategies were suggested. These strategies include the relocation of the entire length to the replacement of fittings, installation of cathodic protection, remediation of any interference from or to adjacent infrastructure, and replacement of joints and the monitoring of leakage (Marlow et al. 2007).

4.2.3 Condition Assessment Approaches and Technologies

The utility practices are broken down by the condition assessment approaches and technologies and are further explained below:

Condition Assessment Technologies: P-Wave Tool, Remote-Filed Eddy Current Technology (RFET)

Romer et al. (2004) and Thuruthy et al. (2013) discussed the applicability of a P-Wave, a non-destructive electromagnetic inspection tool, to detect the damaged and broken prestressing wires in PCCP in case studies for Metropolitan Water District, California and Aurora Water respectively (Romer et al. 2004; Thuruthy et al. 2013). The P-Wave tool generates waveforms that are in response to broken wires in a PCCP when traversed through the entire length of the pipeline.

The results of the p-wave tool inspections were shown and explained in the form of graphs displaying anomalies and broken wires. The critique regarding the performance and accuracy of the results obtained from the P-Wave tool is also provided in this case study (Romer et al. 2004).

The second case study discussed the evaluation of a 54-inch prestressed cast concrete pipe raw water transmission main at Aurora Water using visual and sounding inspections as well as electromagnetic inspection of the pipeline using Pure Technologies' P-Wave technology (Thuruthy et al. 2013).

Condition Assessment Technologies: Leak Detection

One of the case studies discussed the acoustic leak detection methodology (MLOG) coupled with daily data transmission using a fixed-network automatic meter reading (AMR) system implemented at American Water to determine the condition of buried pipelines conclusively. The advantages of this acoustic leak detection methodology coupled with daily data transmission using a fixed-network automatic meter reading (AMR) included early identification of leaks which facilitated repair efforts before the leak could become a break and limited consequence of failure (Kirmeyer et al. 2008).

Thuruthy et al. (2013) also discussed the leak detection by use of tethered, in-line acoustic technology at Philadelphia Water Department's (PWD) for the detection of leaks in large diameter water cast iron and ductile iron transmission pipelines (Thuruthy et al. 2013).

One of the case studies discussed the application of Smartball PWA Technology for leak detection in mortar lined cast iron pipelines at Louisville Water Company. As per this case study, the Smartball PWA technology can successfully locate bell and spigot joints leaks in cast iron pipelines. The Smartball PWA tool can effectively obtain the hoop stiffness of the pipes using laser scanning. The laser scanning capabilities of the Smartball PWA tool aids in identifying the areas of more severe damage in a pipe. However, it was found in this case study that the technology couldn't detect the individual pits (Dickinson et al. 2014).

Condition Assessment Technology: Transient Pressure Monitoring, Electromagnetic Inspections, and Finite Element Analysis

The technologies implemented by water utility E to conduct condition assessment on its 72 and 66-Inch PCCP were transient pressure monitoring, a SmartBall leak and air pocket detection survey, a PipeDiver electromagnetic inspection, and structural evaluations using American Water Works Association (AWWA) C301 and AWWA C304 design standards as well as structural modeling of the pipeline, using three-dimensional, nonlinear finite element analysis.

A Telog Instruments Inc. (Telog) LPR-3li Pressure Impulse Recorder was utilized to conduct the transient pressure monitoring to record the variations in the internal pressure due to hydraulic pressure transients generated in the pipeline. Further, Pure Technologies' PipeDriver electromagnetic inspection tool was also employed to conduct an electromagnetic inspection to understand the current condition of the pre-stressing wires of the PCCP. A SmartBall leak and air pocket detection survey utilized acoustic-based technologies to detect anomalies due to breaks and defects in the pipeline. SmartBall Receivers recognized the time taken to receive ultrasonic pulses emitted by the SmartBall tool which was positioned inside the pipe. Finally, three types of structural analysis were also conducted on the pipe, namely, structural evaluations using "Cubic Parabola Design Method" of American Water Works Association (AWWA) C301 design standards, AWWA C304 design standards, and nonlinear finite element analysis. Finally, performance curves based on the finite element analysis (FEA) of the PCCP pipelines were compared with the electromagnetic inspection results to categorize the structural condition of the pipe into one of the following broad categories: (1) Micro-Cracking (2) Visible Cracking (3) Yield (4) Strength.

Condition Assessment Technologies: Echologics Hydrophones, Remote Operated Camera, Leak rate Calculator

One of the case studies discussed the condition assessment approach at water utility F for their steel cylindrical concrete pipelines (SCCP). This case study explained the leak test conducted for the steel cylindrical concrete pipelines (SCCP) using Echologics Hydrophones. These hydrophones were set up on the section of the 36-inch SCCP pipeline which was installed in 1979. Based on a comprehensive leak investigation and visual examination of this pipeline, the asset management team concluded that the pipeline under consideration was in poor condition and actively leaking. The leak investigation approach included an internal inspection with a remotely operated camera, a leak excavation and repair, and finally a calculation of the rate of leaking by a leak rate calculator.

Condition Assessment Approaches: Advanced Mathematical Models, Weibull Analysis, Fuzzy Models

One of the case study focused on the condition assessment methodology implemented for 96" diameter PCCP transmission mains by San Diego County Water Authority as well as for 96" and 114" PCCP at Arizona Public Service Company. The fuzzy condition models were used to interpret the data collected from inspection techniques such as hammer tapping, (pulse echo) (HT) to detect concrete core condition, and remote field eddy current (RFEC/TC) to identify the number of wire breaks. The discrepancies between the condition assessment data collected through the inspection techniques mentioned above and the condition ratings calculated by using the fuzzy models were also addressed in this case study. The probable causes for these discrepancies were lack of synchronization between the two non-commensurate inspection techniques, reporting and reliability, added information, inherent vagueness of the inspection technique, observational inconsistencies due to different operators, a significant change in the operating/environmental conditions in or around the pipe, or limitation within the interpretation of the distress indicators (Kleiner et al. 2005).

4.2.4 Asset Renewal Approaches and Technologies

The utility practices are broken down by the asset renewal approaches and technologies and are further explained below:

Renewal Technology: Cathodic Protection

One of the case studies focused on the Main Replacement and Rehabilitation Program (MRRP) at Louisville Water Company (LWC) which concentrated on the water mains laid before 1932 to reduce complaints, reduce maintenance, improve pressure and hydraulic capacity, and improve fire flow. The renewal efforts at LWC were driven by circumferential breaks, split pipe breaks, hole breaks, and joint leaks failures caused due to corrosion. A sacrificial anode cathodic protection program was developed, and pilot studies using lead wires and a light bulb were conducted. The plan was intended to address 1000 miles of pipes in a 20-year period (Romer et al. 2004).

Another case study focused on the assessments of condition and risk undertaken in response to a catastrophic steel trunk main failure at Water Corporation, Australia. The condition assessment approach implemented by the utility involved routine CCTV inspections to check the integrity of the cement mortar lining and signs of steel corrosion. Further, to better understand the failure modes and mechanisms and to identify any sections of pipe where a similar failure mode could occur, a detailed forensic condition assessment of the trunk failure was also conducted by the utility. The investigations were designed to improve knowledge of the likelihood of failure so that the risk of the main failing could be better managed. Based on the condition and risk assessment results, some renewal strategies were suggested such as the installation of cathodic protection, remediation of any interference from or to adjacent infrastructure, and replacement of fittings and the monitoring of leakage (Marlow et al. 2007).

Renewal technology: Linings

One of the case studies discussed the rehabilitation and replacement program implemented at the Washington Suburban Sanitary Commission (WSSC) for renewal of its 315,640 service connections in Montgomery Suburban and Prince Georges counties in the Washington, DC, area (Deb et al. 1990). As mentioned in this case study, the rehabilitation and replacement program for water mains at WSSC entailed cleaning and lining of the pipes with cement mortar linings. The primary goal to undertake this initiative was to increase the flow capacity of the mains in the densely populated areas (Deb et al. 1990). The following factors were considered while prioritizing mains for rehabilitation: population density, fire flow protection, the frequency of discolored water complaints, the age of the main, and the rate of main breaks. Moreover, priority was given to mains that served areas with higher density land use. The relationship between the central and surrounding unlined pipes was also considered (Deb et al. 1990).

Marlow et al. (2013) in one of the case study also discussed the rehabilitation options for cast iron and ductile iron pipelines implemented at an American water utility which included CIPP, epoxy, cathodic protection, and cement mortar lining (Marlow et al. 2013).

Renewal technology: Open cut replacement, pipe bursting, horizontal directional drilling

A number of case studies are published on the replacement technologies such as open cut replacement, pipe bursting, and horizontal directional drilling. One of the case studies discussed the renewal approaches and technologies implemented by an Australian Water Utility. The various replacement approaches discussed in this cases study were an open-cut replacement, sliplining, close-fit lining with a structural pipe, exhume and relay, and pipe-bursting (Marlow et al. 2013).

Another case study discussed the use of horizontal directional drilling (HDD) technology in piping replacement operations when the pipe needs to be installed under a water body or highway. This case study documents a project undertaken by the City of Jenks, Oklahoma Public Works Department to replace a continually failing section of water piping that was located in a troublesome section of a creek in the Tulsa, Oklahoma area (Welling et al. 2013).

Renewal Technology: Corrosion Control

One of the case studies discussed the Tucson Water Department's (TWD) system which developed a steady-state corrosion scale over an extended period. The re-equilibration of the corrosion scale in galvanized steel pipe in the TWD distribution was a function of changes in the historical water quality, higher turbulence and scour generated by a new flow regime, and alterations in the microbiological activity associated with the scale. The corrosion control strategies adopted by TWD included the addition of zinc orthophosphate corrosion inhibitor and pH adjustment with sodium hydroxide. One of the crucial lessons of the Tucson experience was that the duration and intensity of the corrosion problem would likely be limited when the identified corrosion control strategy is consistently applied (Reiber et al. 1997).

4.3 Asset Type 2: Valves and Hydrants

The following are the most relevant and informative case studies on the deterioration modes and mechanisms, risk assessment and management approach, condition assessment and management approaches, and asset renewal approaches and technologies for valves and hydrants.

4.3.1 Deterioration Modes and Mechanisms

There is a requirement to research to identify the deterioration modes and mechanisms observed by the water utilities for their valves and hydrants as no case study/material is found in this focus area.

4.3.2 Risk Assessment and Management Approaches

The utility practices are broken down by the risk assessment and management approaches and are further explained below:

Risk Assessment: Fire Flow Testing

One of the case studies discussed the Water Utility J's Fire Hydrant Inspection, Repair, Maintenance, and Upgrade Program. This program ensured that all the public fire hydrants in the District were inspected, repaired and maintained to provide adequate flow levels to all locations in the District. The Fire Flow Testing Procedure was adopted by Water Utility J to determine the flow pressure with an aim to identify the condition of the distribution system. This case study also discussed the water utility J's initiative to color code the hydrants after the fire flow tests were conducted to depict the expected fire flow during normal operation as per NFPA 291 standards.

Risk Assessment: Condition Scoring and Risk Analysis

One of the case studies discussed the valve condition scoring and risk analysis methodology implemented at the water utility K. The "total condition score" calculation for the valves was based on the physical condition and performance condition. Along with this, the count of consequence of failure (COF) rating for valves was conducted considering the triple-bottom-line approach. Water utility K also calculated the redundancy scores for assets to indicate the amount of risk reduction achieved through a risk mitigation measure. Finally, there was a risk analysis methodology implemented at utility K comprising of the consideration of redundancy, consequence of failure and maximum condition score. The overall risk of failure at utility K was represented on a risk matrix to facilitate better decision making for both capital and operation and maintenance programs.

4.3.3 Condition Assessment Approaches and Technologies

The utility practices are broken down by the condition assessment approaches and technologies and are further explained below:

Condition Assessment Approach: Condition rating Index

One of the case studies discussed the management strategy adopted by a USA water utility for its hydrants. The utility's asset management plan stated that hydrant condition could be determined or affected by the following: age, style, make and model, quality of drainage at installation, frequency of use and repair, time since last maintenance, damage caused by drivers, contractors or utility staff, encroachment by trees, plants or debris, site development or changes, and operating and testing procedures. For asset management planning, the utility estimated condition based on characteristics (age, style, make and model), and state of the asset (operability, parts availability, and potential to cause damage if operated). The condition rating index prepared by the utility categorized an asset into five categories, namely, very good, good, fair, poor, and very poor (Marlow and Beale 2012).

4.3.4 Asset Renewal Approaches and Technologies

There is a requirement to research to identify the asset renewal approaches and technologies implemented by the water utilities for their valves and hydrants as no case study is found in this focus area.

4.4 Summary of Practice Review

The following paragraphs provide a summary of the findings made during the extensive practice review of drinking water pipelines, valves, and hydrants.

Asset Type 1: Drinking Water Pipelines

The extensive practice review conducted for drinking water pipelines managed to find only one deterioration mode for pipes which is joint leaks. Not much information could be collected from the water utilities in the real world practice review regarding the deterioration modes and mechanism observed for drinking water pipelines. It indicates a comparatively lesser understanding and documentation of the failure modes and mechanisms in the real world by water utilities. In the analysis of already published case studies as well, only one case study was found which specifically talked about joint leaks due to the failure of the joint material as a significant cause of failure for the cast and ductile iron pipelines. This finding confirms the finding made in the literature review which asserted that joint leaks are one of the major causes of failure for drinking water pipelines

A number of risk assessment approaches were found in the practice review. It is realized from the literature review that the most common and widely adopted risk assessment methodology by the water utilities in the real-world is the calculation of the risk by the following formula,

Risk=Probability/Likelihood of Failure x Consequence of Failure

Various case studies discussed this methodology which shows that the water utilities implement the risk assessment approaches mentioned in the literature for their water infrastructure assets. Along with this, the other common methodologies found in the literature were also widely discussed in the practice review such as risk matrixes, business risk exposure calculations, and implementation of smart condition assessment technologies for risk assessment. Figure 4 shows some of the most widely accepted and implemented risk assessment approaches by water utilities as found in the practice review.

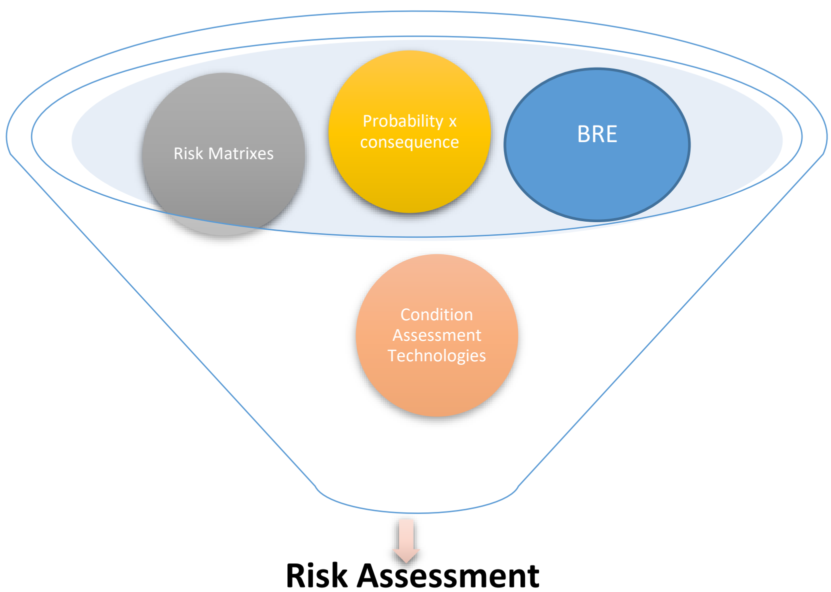

Figure 4 -Most Common Risk Assessment Approaches in Practice Review

Different methodologies implemented by the water utilities to calculate the probability and consequence of failure was also found in the practice review. Some of the most common approaches for the calculation of probability of failure as found in the practice review are predictive models based on the machine-learning algorithms; age, soil conditions, historical accounts, inspection findings, condition assessment data consideration; by providing scores on a scale (example 1 to 5 or 1 to 10) to the various probabilities/scenarios and subsequently weighing each probability to determine the overall probability. Similarly, multiple methodologies were also found in the practice review for calculating the consequence of failure. These methodologies include the selection of consequence of failure factors and their weights based on expert opinions and normalization of scores on a scale, and triple-bottom line consideration. The practice review has provided an opinion that water utilities are sincere for assessing and managing the risk of failure associated with their water infrastructure assets and are implementing efficient risk assessment and management approaches discussed in the literature review.

There were also several case studies found/written in the practice review for condition assessment approaches and technologies for drinking water pipelines. It is realized from the practice review that water utilities conduct a periodic condition assessment of their drinking water pipelines and are sincere about understanding the current condition of their pipes to formulate proactive renewal strategies. However, it is also realized from the practice review that water utilities (covered in this research) pay more attention to PCCP, cast iron, and ductile iron pipelines as compared to other pipelines. The pie chart shown in Figure 5 shows an approximate estimate of the distribution of condition assessment efforts by water utilities for different types of pipelines as per the practice review conducted for this research.

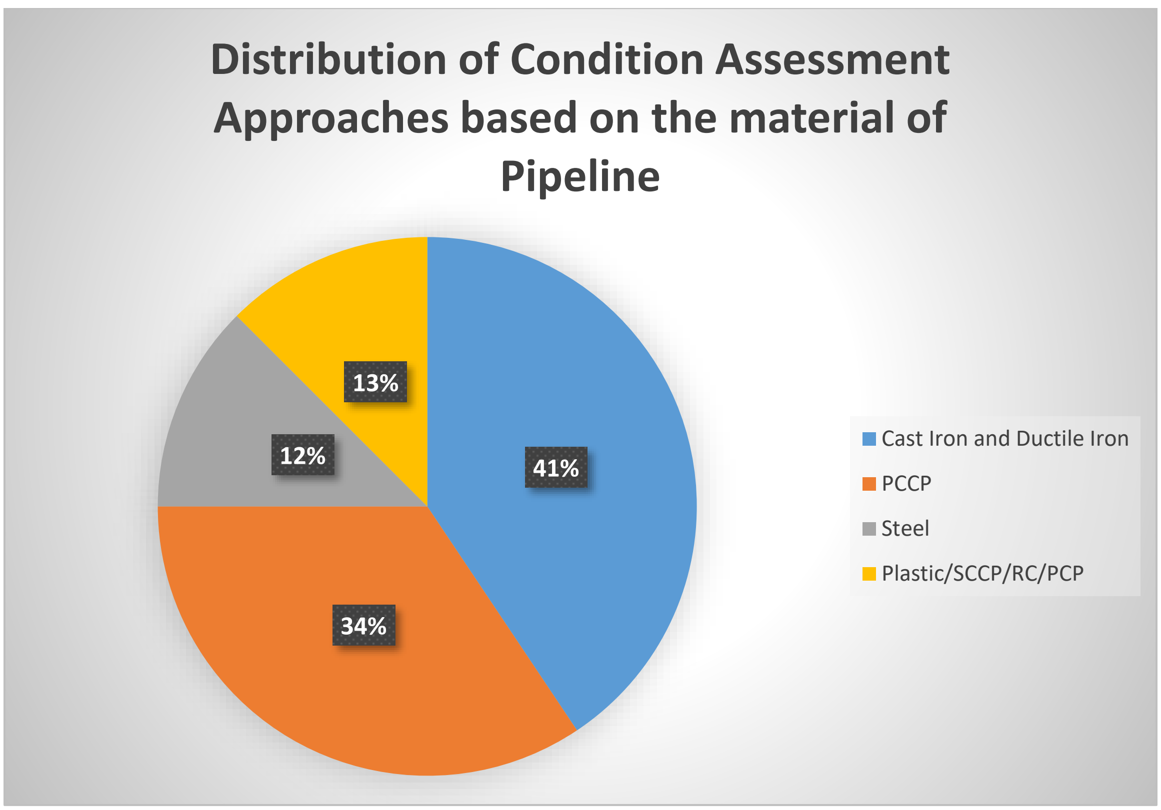

Figure 5- Distribution of Condition Assessment Efforts based on the Material of the Pipelines as per the Practice Review

Various condition assessment technologies are found in the practice review for the condition assessment of drinking water pipelines. These technologies include visual and camera methods, acoustic-based methods, ultrasonic testing methods, laser-based methods, electric and electromagnetic based methods, and electromagnetic acoustic technology (EMAT), magnetic flux leakage (MFL), and remote field technology (RFT). It is also realized from the practice review that the water utilities pay more attention to the application of condition assessment technologies compared to approaches such as advanced statistical and mathematical models, Weibull analysis, fuzzy condition models, finite element analysis, and condition rating indexes. The pie chart shown in Figure 6 shows an approximate distribution between the application of condition assessment technologies vs. condition assessment approaches by water utilities as per the practice review conducted for this research.

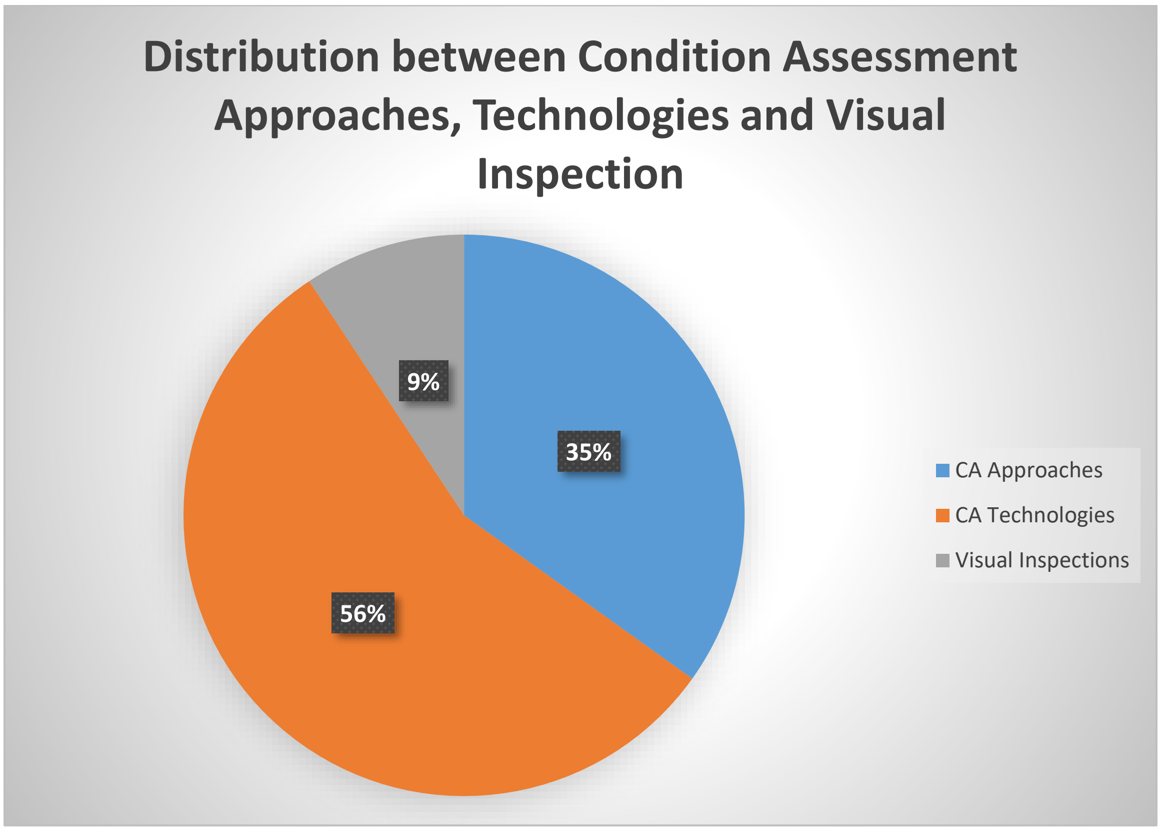

Figure 6- Distribution of Condition Assessment Approaches, Technologies and Visual Inspection as per the Practice Review

Finally, a number of asset renewal technologies were found in the practice review for drinking water pipelines. However, the practice review has provided an opinion that most of the renewal methodologies implemented by the water utilities are for cast iron and ductile iron pipelines. The pie chart in Figure 7 shows an approximate estimate of the distribution of asset renewal efforts by water utilities for different types of pipes as per the practice review conducted for this research.

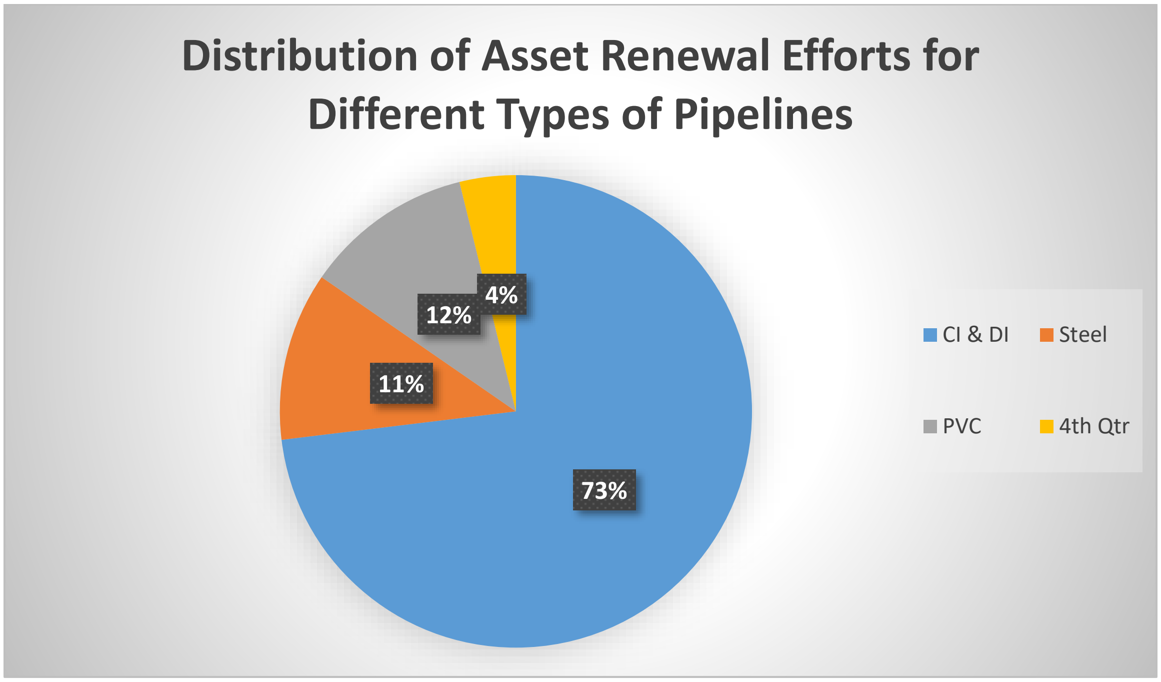

Figure 7- Distribution of Asset Renewal Efforts for Different Types of Pipelines as per the Practice Review

Along with this, the pie chart shown in Figure 8 shows the most common asset renewal technologies implemented by water utilities as found in the practice review conducted for this research. According to the Figure 8, the most common renewal approaches adopted by water utilities are pipe bursting, linings, and open-cut replacements. However, this is to be noted that the decision to repair, rehabilitate, or replace a pipeline depends upon the condition and risk of the individual pipes.

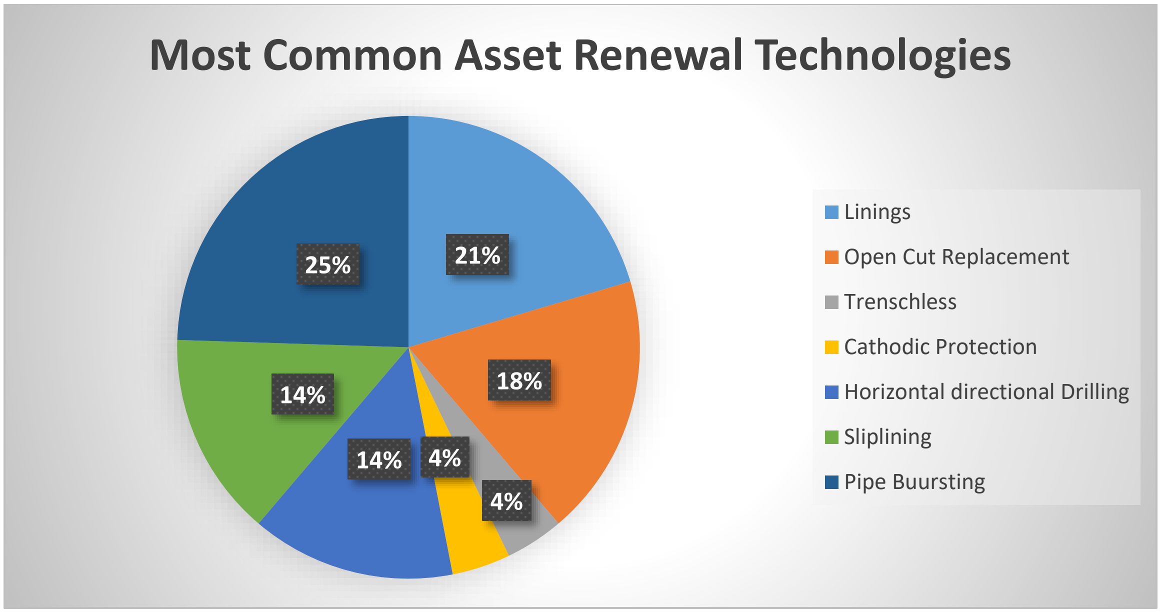

Figure 8- Most Common Asset Renewal Technologies as found in the Practice Review

Asset Type 2: Valves and Hydrants

It is observed from the practice review conducted for valves and hydrants that there is comparatively less implementation of the risk-based asset management approaches and technologies for valves and hydrants than pipelines in the real world. This matches with the findings from the literature review which also showed relatively less knowledge regarding the risk-based asset management of valves and hydrants as compared to pipelines.

The risk assessment and management approach for valves and hydrants as seen in the practice review include fire flow testing, and condition score calculation based on the physical condition and performance condition. The condition assessment technologies for valves and hydrants implemented by the water utilities include condition rating indexes and visual inspections.

The information gathered by the practice review for valves and hydrants suggest that more attention is given to the risk-based asset management of drinking water pipelines as compared to valves and hydrants.

CHAPTER 5

KEY FINDINGS AND MAJOR GAPS

5.1 Introduction

This chapter provides an overview of the "key findings" and the "major gaps" observed during this research through an extensive literature and practice review for the understanding of the risk-based asset management of drinking water pipelines, valves, and hydrants.

5.2 Asset Type 1: Pipelines

The following are the key findings and significant gaps for drinking water pipelines,

5.2.1 Key Findings

The following are the key findings observed in this research through an extensive literature and practice review for drinking water pipelines as per each focus areas.

5.2.1.1 Deterioration Modes and Mechanisms

- Major deterioration modes for small diameter cast iron pipelines are circumferential cracks and bell splitting.
- Significant modes of deterioration for large diameter cast iron pipelines are longitudinal cracking and bell shearing.
- Circumferential cracks in small diameter cast iron pipelines are caused due to longitudinal bending forces while longitudinal cracks in large diameter cast iron pipelines are caused due to high water pressure and moment of inertia.
- The other conventional modes of failure for cast iron pipelines are blowout holes, joint leaks, gasket failure, structural socket failures and spiral cracking.
- The mechanisms for failure of cast iron pipelines can be divided into four categories, namely, corrosion, manufacturing flaws, excessive forces, and human errors with electrochemical corrosion as the most prominent mechanism of failure.
- The dominant mechanism of failure for PCCP pipelines is the corrosion of the pre-stressing wires.
- The major mechanism of failure for cement-based pipelines is aggressiveness of water towards the cementitious material of the pipe such as sulfate attacks and alkali granulate reactions.
- The PVC pipeline's significant modes of failure are a joint failure and gasket failure

Table 1 provides a summary of all the primary deterioration modes and mechanisms observed for the different types of drinking water pipelines.

Table 1- Summary of Major Deterioration Modes and Mechanisms for Drinking Water Pipelines

S.NO	TYPE OF PIPELINE	DETERIORATION MODES/MECHANISM
1	Small Diameter Cast Iron Pipeline	❖ Deterioration Mode: Circumferential cracks, Bell splitting ❖ Deterioration Mechanism: Longitudinal bending forces
2	Large Diameter Cast Iron Pipelines	❖ Deterioration Mode: Longitudinal cracks, Bell shearing ❖ Deterioration Mechanisms: High water pressure
3	Metallic Pipelines (Cast Iron & Ductile Iron)	❖ Deterioration Modes: Joint leaks, Blowout holes, Gasket failure, Structural socket failures ❖ Deterioration Mechanisms: Corrosion, Excessive stresses, Human errors, Manufacturing flaws
4	PCCP	❖ Deterioration Mechanisms: Corrosion of pre-stressing wires
5	Cement-Based Pipelines	❖ Deterioration Mechanisms: Aggressiveness of water towards cement material like sulfate attack and alkali granulate reactions
6	PVC	❖ Deterioration Modes: Joint Failure, Gasket Failure

5.2.1.2 Risk Assessment and Management Approaches

- The risk of failure is calculated as the product of probability/likelihood of failure and consequence of failure.
- The most common approach to represent the risk of failure of drinking water pipelines in a “risk matrix” demonstrating the pipes in different risk zones on a graph with a probability of failure on one axis and consequence of failure on another axis.
- The probability of failure can be calculated using predictive models, statistical models, deterministic models, probabilistic models, other advanced mathematical models.
- The probability of failure can also be calculated by the data that is known for the pipeline such as age, soil conditions, historical accounts, inspection findings, condition assessment data.

- The consequence of failure can be calculated as the product of the weighted average score of all the consequence of failure factors (provided by experts) and their respective categories.
- Another standard approach for calculating the consequence of the failure of a pipeline is by the triple-bottom-line approach. This approach considers the economic, social, and environmental consequences of a pipeline failure.
- Risk management by routine CCTV inspections to check the integrity of drinking water pipelines is found in this research.

5.2.1.3 Condition Assessment Approaches and Technologies

- Most common condition assessment technologies for drinking water pipelines include visual and camera inspections, acoustic-based methods, laser-based methods, electrical and electromagnetic based methods, flow-based methods, physical force-based methods, and temperature based methods.
- Some innovative technologies such as smart pipes, augmented reality and intelligent pigs can also be used for the condition assessment of drinking water pipelines.
- The internal condition assessment of metallic pipelines (cast iron and ductile iron) is conducted using CCTV cameras to understand the condition of protective linings and the locations of internal corrosion.
- For small diameter cast iron and ductile iron pipelines, acoustic technologies such as discrete ultrasonic, guided waves ultrasonic, acoustic emission monitoring, acoustic propagation velocity measurement, and acoustic leak detection/hydrophones can be implemented.
- Electromagnetic condition assessment approaches such as remote field technology, broadband electromagnetic technologies, and magnetic flux leakage are utilized for the condition assessment of small diameter cast iron and ductile iron pipelines.
- Other condition assessment technologies for cast iron and ductile iron drinking water pipelines are a field-based LPR probe, fractography, and metallography.
- Visual methods are implemented for condition assessment of PCCP pipelines while the most commonly used acoustic technology for condition assessment of PCCP is rod sounding.
- For condition assessment of PCCP, transient pressure monitoring can also be implemented.
- Condition assessment technologies for reinforced concrete pipelines include soil resistivity survey, pipeline electrical continuity, and pipe-to-soil potential measurements.
- For PVC pipelines, technologies such as visual inspections, electro-scanning, acoustic monitoring, ultrasonic testing, and condition assessment based on soil properties can be conducted.
- Use of tracer gas and ground-penetrating- radar to detect leaks in plastic service lines is also found in this research.

- Pipe deterioration, failure, and condition prediction models such as deterministic models, probabilistic models, statistical models, artificial neural network models, fuzzy logic models and heuristic models can be applied for condition assessment of pipelines.
- For Steel Cylindrical Concrete Pipelines (SCCP), condition assessment approach can include an internal inspection with a remotely operated camera, a leak excavation, and repair, and finally a calculation of the rate of leaking by a leak rate calculator.
- For steel pipelines, routine CCTV inspections to check the integrity of the cement mortar lining and signs of steel corrosion is found in this research.

Table 2 provides a summary of all the standard and useful condition assessment technologies implemented for drinking water pipelines.

Table 2- Summary of Condition Assessment Technologies for Drinking Water Pipelines

S.NO	TYPE OF PIPELINE	CA TECHNOLOGY/APPROACH
1	Pipelines (General)	❖ Visual and camera methods, acoustic-based methods, electromagnetic and electric based methods, laser-based methods, flow-based methods, physical force-based methods, and temperature based methods ❖ Smart pipes, augmented reality and intelligent pigs ❖ Condition Assessment Approaches: Deterministic models, probabilistic models, statistical models, artificial neural network models, fuzzy logic models and heuristic models
2	Cast Iron Pipelines	❖ Visual Technologies: CCTV cameras ❖ Acoustic Technologies: Discrete ultrasonic, guided waves ultrasonic, acoustic emission monitoring, acoustic propagation velocity measurement, and acoustic leak detection/hydrophones ❖ Electromagnetic Technologies: Remote field technology, broadband electromagnetic technologies, and magnetic flux leakage ❖ Other Technologies: A field-based LPR probe, fractography, and metallography
3	Ductile Iron Pipelines	❖ Visual Technologies: CCTV cameras ❖ Acoustic Technologies: Discrete ultrasonic, guided waves ultrasonic, acoustic emission monitoring, acoustic propagation velocity measurement, and acoustic leak detection/hydrophones

		❖ Electromagnetic Technologies: Remote field technology, broadband electromagnetic technologies, and magnetic flux leakage ❖ Other Technologies: A field-based LPR probe, fractography, and metallography
4	PCCP	❖ Visual methods ❖ Acoustic Technology: Rod Sounding ❖ Electromagnetic Technology: P-wave electromagnetic inspection tool and remote field transformer coupling (RFTC) methodology ❖ Pressure-Based Methods: Transient pressure monitoring
5	Reinforced Concrete	❖ Soil resistivity survey, pipeline electrical continuity, and pipe-to-soil potential measurements
6	Steel Pipelines	❖ Visual Inspections: CCTV inspections ❖ Electromagnetic Technology: Magnetic Flux Leakage Inspections
7	PVC	❖ Visual inspections, electro-scanning, acoustic monitoring, ultrasonic testing, and condition assessment based on soil properties
8	Plastic	❖ Leak detection: Tracer gas and ground-penetrating-radar
9	SCCP	Remote operated camera inspections, a leak excavation, and repair, and finally a calculation of the rate of leaking by a leak rate calculator

5.2.1.4 Asset Renewal Approaches and Technologies

- Renewal consists of repair, rehabilitation, and replacement of a drinking water pipeline.
- When the deterioration is concentrated in a small region of the pipeline and the structural integrity of the pipe is not disturbed, repair technologies are implemented. Rehabilitation is undertaken when the pipe is structurally sound enough to partially support the renewal while a replacement is undertaken when the pipe is severely deteriorated and not structurally sound to support the renewal.
- The various repair technologies for potable water pipelines can be divided into three categories 1) pipe joint and leak seal 2) pipe point repairs and 3) pipe coatings.
- Repair technologies that are widely discussed in the literature and implemented by the water utilities include protective coatings, internal sleeves, repair clamps, and wraps.

- As per the practice review, the most commonly used repair technology is protective coatings.
- Further, the recommended approach for steel pipelines repair is by applying an internal, non-structural coating to prevent corrosion from degrading the steel material.
- The various rehabilitation technologies for drinking water pipelines are spray-in-place pipe liners (SIPP), cured-in-place pipe liners (CIPP), grout-in-place pipe liners (GIPP), sliplining, and FRP liners.
- As per the practice review, sliplining is found to be widely implemented by the water utilities.
- For rehabilitation of PCCP, application of fiber reinforced polymer (FRP), including glass fiber (GFRP) and carbon fiber (CFRP) composites can be utilized.
- Rehabilitation of small diameter cast and ductile iron pipelines can be achieved by adopting non-structural, semi-structural, or fully-structural renovation linings.
- For cast iron and ductile iron pipelines, a sacrificial anode cathodic protection approach can be applied for corrosion protection of the pipes.
- For unlined cast iron pipelines, cleaning followed by application of cement-mortar lining is another rehabilitation methodology.
- Corrosion control in steel pipelines can be achieved by the addition of zinc orthophosphate corrosion inhibitor and pH adjustment with concentrated sodium hydroxide.
- The use of sliplining technology and fusible PVC to replace a section of aged and deteriorating steel potable water main is a replacement approach for steel pipelines.
- The commonly used replacement technologies for drinking water pipelines are pipe bursting, horizontal directional drilling, and pipe pulling.
- As per the practice review, pipe bursting is the most commonly utilized replacement technology.

Table 3 provides a summary of all the conventional and efficient asset renewal approaches and technologies implemented for drinking water pipelines.

Table 3- Summary of Asset Renewal Approaches and Technologies for Drinking Water Pipelines

S.NO	TYPE OF PIPELINE	RENEWAL APPROACHES AND TECHNOLOGIES
1	Pipelines (General)	❖ Repair: Protective coatings, internal sleeves, wraps, and repair clamps ❖ Rehabilitation: CIPP liners, SIPP liners, FRP liners, GIPP liners ❖ Replacement: Pipe bursting, horizontal directional drilling (HDD), and pipe pulling
2	Cast Iron Pipelines	❖ Repair: Epoxy coatings ❖ Rehabilitation: CIPP, and Cement mortar linings

		❖ Corrosion Control: Cathodic Protection
3	Ductile Iron Pipelines	❖ Rehabilitation- Polyethylene (PE) wraps ❖ Replacement- Static pipe bursting technology with high-density polyethylene (HDPE) piping ❖ Corrosion Control: Cathodic protection
4	PVC	❖ Replacement- Pipe bursting with fusible polyvinyl chloride (FPVC); pipe-pulling (or pull-through)
5	Steel	❖ Corrosion Control- Addition of zinc orthophosphate corrosion inhibitor and pH adjustment with sodium hydroxide; Application of an internal, non-structural coating to prevent corrosion from degrading the steel material ❖ Replacement- Use of sliplining technology and fusible PVC; pipe-pulling (or pull-through) replacement technique

5.2.2 Major Gaps

The following are the significant gaps observed for drinking water pipelines through an in-depth literature and practice review. These gaps are needed to be addressed to attain a comprehensive and efficient risk-based asset management program for drinking water pipelines.

- There is a relatively large body of knowledge on modes of failure, but there is limited knowledge available on deterioration mechanism for pipelines.
- There is a requirement to formulate effective risk management approaches for drinking water pipelines. It is observed through the literature and practice review that the concentration while conducting risk-based asset management for drinking water pipelines is laid on the risk assessment and not on risk management.
- Most of the risk assessment approaches and technologies are for the metallic pipelines (cast iron, ductile iron, steel) and PCCP. Less risk assessment approaches and technologies are found for non-metallic pipes.
- A considerable number of condition assessment technologies are found for PCCP pipelines followed by the cast iron, and ductile iron pipelines. Less discussion on condition assessment for other pipe material such as asbestos-cement, and PVC is found.
- The application of condition assessment technologies is more for all types of pipelines compared to condition assessment approaches such as statistical models, prediction models, ANN models, fuzzy-logic models, condition rating index, and condition rating matrix, as found in this research.

- Most of the renewal approaches and technologies found in the literature and practice review are for the cast and ductile iron pipelines. For other material pipelines, limited renewal (repair, rehabilitation, and replacement) methodologies are found.

5.3 Asset Type 2: Valves and Hydrants

The following are the key findings and significant gaps for valves and hydrants.

5.3.1 Key Findings

The following are the key findings observed in this research through an extensive literature and practice review for valves and hydrants as per each focus areas.

5.3.1.1 Deterioration Modes and Mechanisms

- Significant modes of failure for valves include joint fracture, joint cracks, valve collapse, valve jamming, coating failures, and support failure.
- The other failure types for valves are operational changes, mechanical damage, and equipment failure.
- Corrosion of internal components of valves is found as a significant deterioration mechanism for valves and hydrants along with deterioration of seals and build-up of deposits.
- The other primary failure mechanisms for valves include high-pressure surges, internal and external loads, accumulation of sediments, seismic activities, poor valve design, water temperatures, and tuberculation.
- One of the most common failure modes for hydrants is coating failure due to corrosion.
- The primary mechanisms of failure for hydrants include temperature change and corrosion.

5.3.1.2 Risk Assessment and Management Approaches

- For pressure reducing valves (PRV), the risk of failure can be maintained by including installation of new automatic air release valves near PRV, installation of additional pressure relief valves upstream and downstream of the new PRV, SCADA alarm settings for upstream pressure, downstream pressure and flow.
- In order to improve the overall service life of valves, proper installation of the valves should be conducted, valves should not be buried under excessive fill, valves should be set near intersecting streets or fire hydrant, valves should have marker stakes set on cross-country lines, valve box should be placed above the valve, heavy valves should be supported, and records prepared by the installing crew should be stored and well maintained.
- Choosing the right valve, purchasing, and specification according to AWWA standards, following proper storage regimes, thorough inspection of the valves, as well as maintaining and updating maintenance records is also essential for adequate maintenance of valves.

- In order to assure effective asset management of fire hydrants, hydrants should be checked by visual inspection for external damage, all nozzle caps should be removed and screw threads should be greased, valve operation should be checked, barrel drainage should be inspected, stem nuts should be oiled and the hydrant should be repainted if necessary.
- Keeping an updated inventory of valves and hydrants, regular condition assessment, documenting asset management records, and proper planning and budgeting also play an essential role to manage the risk of failure of these assets.

5.3.1.3 Condition Assessment Approaches and Technologies

- A condition rating index categorizing the condition of valves into five categories namely, very good, good, fair, poor, and very poor based on characteristics (age, style, make and model), and state of the asset (operability, parts availability, and potential to cause damage if operated) can be utilized for condition assessment of valves.
- The condition assessment data collection for valves can be conducted through handheld computers and assignment of condition grading using a photographic library.
- Condition assessment technologies for valves and hydrants are acoustic devices, CCTV, remote visual inspections, ultrasonic testing, radiography, eddy current inspection, and transient wave analysis.
- Valve exercising is also a useful condition assessment technology for valves and hydrants.
- Physical inspection, fire flow tests, flushing programs, and air scouring can also be utilized for condition assessment of valves and hydrants.

5.3.1.4 Asset Renewal Approaches and Technologies

- Protective coatings can be applied for the protection of valves and hydrants from corrosion.
- Cathodic protection can also be implemented for the protection of valves and hydrants from corrosion.

5.3.2 Major Gaps

The following are the significant gaps observed for valves and hydrants through an in-depth literature and practice review. These gaps are needed to be addressed to attain a comprehensive and efficient risk-based asset management program for valves and hydrants.

- There is a limited discussion on the calculation of risk for valves and hydrants based on the probability and consequence of failure in the literature and practice review.
- The focus is more on the risk management of valves and hydrants in the literature and practice as compared to the risk assessment approaches.
- There is a deficit of implementation of advanced mathematical and statistical models for the condition assessment of water main appurtenance.

- There is a limited understanding and implementation of renewal methodologies for valves and hydrants other than protective coatings and cathodic protection.

CHAPTER 6

PROPOSED GUIDELINES FOR RISK-BASED ASSET MANAGEMENT OF DRINKING WATER PIPELINES, VALVES, AND HYDRANTS

6.1 Introduction

This chapter aims to provide an enhancement to the Environment Protection Agency (EPA) 10–step guidelines for asset management of water infrastructure systems. The four focus areas of a risk-based asset management program, namely, understanding of the deterioration modes and mechanisms, risk assessment and management approach, condition assessment approaches and technologies, and asset renewal approaches and technologies are systematically plugged into the EPA 10-step asset management guidelines to provide a more comprehensive approach for risk-based asset management. Benefits, challenges, and suggested technologies for each step of the risk-based asset management process are also presented to provide a better understanding of the entire process. The proposed guidelines in this chapter provide an efficient asset management plan that manages an asset in totality by advising the asset managers to understand the modes and mechanisms of failure, calculating the risk of failure, formulating methodologies to manage the risk, understanding the current condition, and to develop renewal prioritization strategies.

6.2 Environmental Protection Agency (EPA) 10-Step Asset Management Guidelines

The Environment Protection Agency (EPA) published a 10-step asset management plan for proactive maintenance of drinking water infrastructure assets. Figure 9 shows the 10-step asset management plan by Environment Protection Agency (EPA).

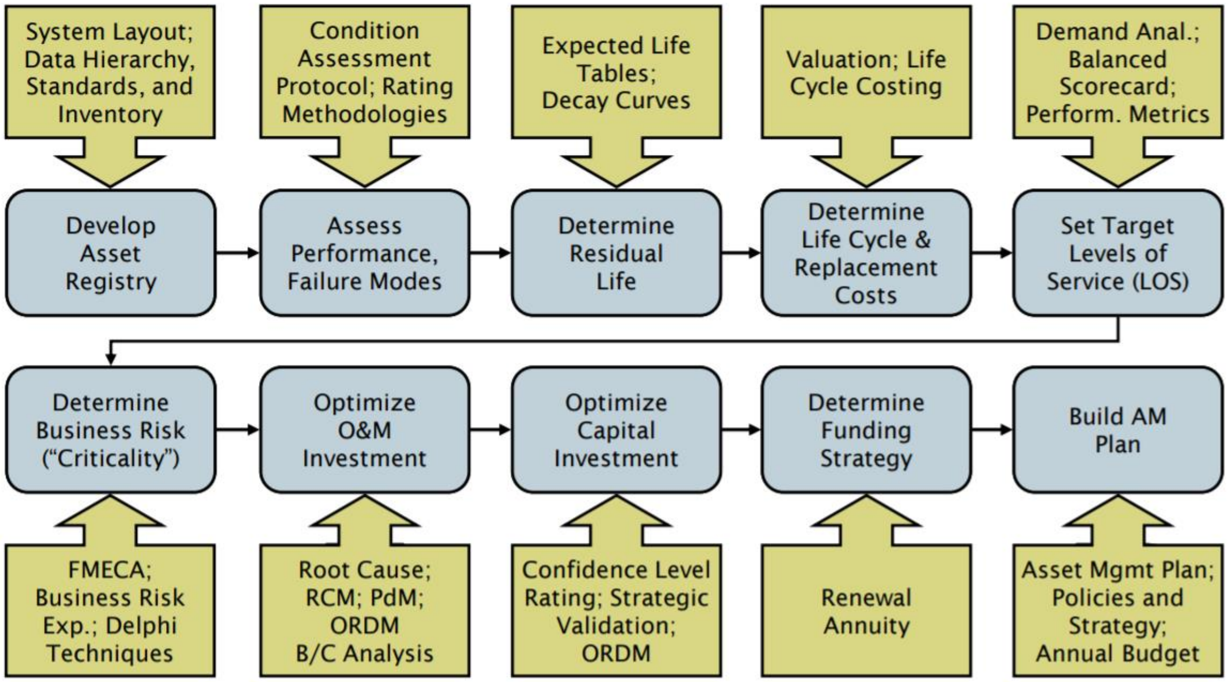

Figure 9- EPA 10-Step Process for Asset Management Plan (EPA)

This EPA 10-step process provides a basic framework for conducting asset management for water infrastructure assets. The proposed guidelines in this thesis are an enhancement of the EPA 10-step asset management process and provide a more comprehensive understanding regarding the steps of the asset management plan, their corresponding tasks, along with their benefits and challenges.

Further, approaches and technologies are also suggested for conducting each step of the asset management program based on the knowledge gained from the literature and practice review. The overall aim of these proposed guidelines is to integrate the four focus areas of a risk-based asset management program into the EPA 10-step asset management plan to provide a better risk-based approach for drinking water pipelines, valves, and hydrants asset management.

6.3 Proposed Guidelines for Risk-Based Asset Management of Drinking Water Pipelines, Valves and Hydrants

The following proposed guidelines provided in Table 4 can be followed to improve the overall service life of drinking water pipelines, valves, and hydrants and mitigate the risk of failure.

Table 4- Proposed Guidelines for Risk-Based Asset Management of Drinking Water Pipelines, Valves, and Hydrants

STEP NUMBER	TASK	BENEFIT	CHALLENGE	SUGGESTED APPROACH/TECHNOLOGY
Step 1: Develop pipeline, valves, and hydrant asset registry	Developing an understanding of the various pipes, valves, and hydrants and their characteristics	Aid in formulating the risk-based asset management strategy and budget due to in-depth knowledge regarding the features and quantities of the assets	Efficient management of a significant amount of data collected, implementation of CMMS by smaller utilities	Computerized maintenance management system (CMMS), SCADA systems
Step 2: Obtain an understanding of the deterioration modes	Develop a knowledge base for all the failure modes observed for the different material of pipelines, valves, and hydrants	Aid in formulating the deterioration and failure prevention strategy	An accurate understanding of the deterioration modes for different types of assets	Most common deterioration modes include circumferential cracks, bell splitting, longitudinal cracking, bell shearing, blowout holes, joint leaks, gasket failure, structural socket failures, valve collapse, valve jamming
Step 3: Obtain the understanding of the failure mechanisms	Develop a knowledge base for the actual cause or mechanism in which a pipeline, valve, or a hydrant fails	Enhanced knowledge regarding the behavior of the pipe, valves, and hydrants; more advanced analysis can be conducted	Identifying the most precise failure mechanism; Identifying technologies and approaches for understanding failure mechanism	Most common deterioration mechanisms include corrosion, excessive stresses, manufacturing flaws, design flaws, construction flaws
Step 4: Assess the condition and performan	Condition assessment of pipelines to understand the current state of	Understanding of the current condition helps in prioritizing assets for renewal; Aid in the selection of	Identifying the most cost-effective condition assessment	CCTV cameras, acoustic leak detection/hydrophones, remote field technology, magnetic flux leakage,

ce of the pipeline	the asset with minimum service disruption and maintaining the level of service	repair/rehabilitation/replacement based on the condition of the pipeline	technology, Identifying pipeline specific condition assessment technologies	transient pressure monitoring, soil resistivity survey, smart pipes, augmented reality, intelligent pigs, deterministic models, probabilistic models, statistical models, artificial neural network models, fuzzy logic models, valve exercising fire flow tests, and air scouring
Step 5: Assess the risk of failure associated with the pipeline, valves, and hydrants	Calculation of the risk of failure based on the probability and consequence of failure	Identification of the high-risk pipes along with the socio, economic, and environmental impacts of the failure	Determining the environmental costs, customer impacts, and socioeconomic costs	The probability of Failure: Using a predictive model, using the data that is known for the pipeline such as age, soil conditions, historical accounts, inspection findings The consequence of Failure: Triple bottom line approach (TBL)
Step 6: Formulate risk management strategies	Formulating risk management approaches to prevent the risk of failure	The service life of pipelines, valves, and hydrants increase; Capital and time in reactive maintenance is saved	Formulating asset specific risk management approaches	Routine CCTV inspections to check the integrity of drinking water pipelines
Step 7: Develop Renewal Prioritization Strategy	Formulation of the strategy to prioritize the renewal of pipelines	Capital and time is saved on the renewal of less critical pipes; More attention on the most critical pipelines	Identification of the key factors to define a pipeline criticality	Multi-Criteria Decision Analysis (MCDA), Non-Homogenous Poisson Process (NHPP)
Step 8: Repair/	Application of repair/rehabilit	Enhanced service life; improved performance	Identifying cost-effective	Repair: Protective coatings, Internal

Rehabilitation/ Replacement	ation or replacement approaches and technologies to the deteriorating pipelines	of the asset; mitigation in the risk of failure; minimum disruption in service; customer satisfaction	renewal approaches and technologies, Selection of the most appropriate renewal technology	Sleeves, Wraps, Repair Clamps Rehabilitation: CIPP liners, SIPP liners, GIPP liners Replacement: Pipe bursting, horizontal directional drilling, pipe pulling
Step 9: Evaluate the pipeline asset management plan for improvement	Determining the efficiency of the asset management plan through feedback and performance monitoring at every step	Overall quality and effectiveness of the asset management plan increases by continuous feedback and monitoring	Determining standards for acceptable/poor /good asset management plan	Feedback forms, performance analysis, and monitoring
Step 10: Build a database to support advanced asset management	Collection of condition assessment, risk assessment, data to aid advanced risk analysis	Enhanced understanding of the pipeline performance parameters for risk management, Enhanced knowledge of the high-risk pipelines	Expertise required for data collection and management	Geographic Information Systems (GIS)

6.4 Summary

The proposed guidelines provided in this chapter are an enhancement of the EPA 10-step asset management plan. The proposed guidelines integrate the four main components of a risk-based asset management plan, namely deterioration modes and mechanisms, risk assessment and management approaches, condition assessment approaches and technologies, and asset renewal approaches and technologies into the EPA 10-step asset management plan. These proposed guidelines are aimed to aid water utilities to improve their asset management program for pipelines, valves, and hydrants as a system. These guidelines are formulated based on the extensive literature and practice review conducted in this research and are suggested to be implemented to enhance the overall service life of the drinking water pipelines, valves, and hydrants. Though it is recommended to follow every step mentioned in the guidelines for efficient risk-based asset management of drinking water infrastructure, however water utilities can incorporate some or all the steps out of the 10-steps according to their budget and capabilities.

CHAPTER 7

CONCLUSION AND RECOMMENDATION

This thesis provides a comprehensive synthesis and analysis of the knowledge gained through an extensive literature and practice review regarding the risk-based asset management of drinking water pipelines, valves, and hydrants. Along with this, a number of innovative approaches and technologies are identified and discussed in this thesis which are either mentioned in the literature review or are implemented by water utilities and covered in the practice review. This thesis provides an overview of the current state of knowledge and implementation existing in the industry regarding the understanding of deterioration modes and mechanisms, condition assessment approaches and technologies, risk assessment and management approaches, and asset renewal approaches and technologies for pipelines, valves, and hydrants.

It is realized from this research that even though there is considerable understanding existing in the industry regarding the risk-based asset management of drinking water pipelines, there still a long way to go for valves and hydrants to reach the same level of expertise and application of risk-based asset management approaches and technologies. There is a requirement to consider the drinking water pipelines, valves, and hydrants as a system and providing equal importance and priority to all these assets to attain an efficient water infrastructure system.

7.1 Asset Type 1: Pipelines

A considerable amount of literature and practice is found for the risk-based asset management of drinking water pipelines. Both in the literature and practice review, a number of approaches and technologies for risk assessment, risk management, condition assessment, and asset renewal are discussed which can be implemented by water utilities to conduct risk-based asset management of pipelines. The common deterioration mode for metallic pipelines in the literature and practice review is joint failure due to either degradation of the joint material or ground movements. In almost all the literature and case studies, the risk is calculated as the product of probability/likelihood of failure and consequence of failure. Several methodologies for calculating the probability and consequence of failure are found in the literature and practice review, however, the most widely implemented approach for calculation of probability of failure is using the known data about the pipeline such as age, historical data, soil conditions while the most widely accepted methodology for calculating the consequence of failure is by the triple-bottom-line approach. Several condition assessment technologies are also found in the literature and practice review. The electromagnetic inspections, acoustic-based condition assessment, and CCTV cameras are very common in the condition assessment of pipelines. Finally, protective coatings, CIPP liners, and pipe bursting are the most commonly found repair, rehabilitation, and replacement methodologies for drinking water pipelines.

7.2 Asset Type 2: Valves and Hydrants

There is comparatively lesser knowledge and implementation of risk-based asset management of valves and hydrants than pipelines. The most common mode of failure for valves is joint fracture while for hydrants it is coating failure. The major mechanism of failure for both valves and hydrants is corrosion. It is found in the literature and practice review that mostly risk management approaches developed at the water utility level are implemented by water utilities such as: (1) valves should not be buried under excessive fill, (2) valves should be set near intersecting streets or fire hydrant, (3) valve box should be placed above the valve, (4) heavy valves should be supported, (5) hydrants should be checked by visual inspection for external damage. As far as the risk assessment of valves and hydrants is concerned, lesser discussion on calculating the risk of failure as the product of probability and consequence of failure is found as compared to pipelines. The most common condition assessment approach found in this research for valves is valve exercising and for hydrants is fire flow tests. Condition rating indexes are also widely used by the water utilities for condition assessment of valves and hydrants. Finally, as found in the literature and practice review, the renewal efforts for valves and hydrants are mostly concentrated towards corrosion protection using protective coatings and cathodic protection.

7.3 Recommendations for Practice and Future Research Work

This section will provide separate recommendations for water utilities and researchers based on observations from literature and practice that would help drive the pipeline, valves, and hydrants risk-based asset management industry forward. The following recommendations are provided based on the understanding gained from the literature and practice review.

7.3.1 Recommendations for Water Utilities (Practice)

The following are the recommendations provided for water utilities to help them make their infrastructure systems sustainable:

- The greatest need for making the water infrastructure systems sustainable is by implementing a comprehensive risk-based asset management program that focuses on the management of drinking water pipelines, valves, and hydrants equally.
- To genuinely obtain an efficient water infrastructure system, pipelines, valves, and hydrants should be considered as a system, and each of the assets should be given equal importance while conducting and assigning budgets for asset management.
- As corrosion is found as the most prominent mechanism of deterioration for pipelines, valves, and hydrants, water utilities should regularly implement protective coatings and cathodic protection on their metallic water infrastructure assets to protect them from corrosion.
- The most prominent and successful approach for calculating the risk is as the product of probability and consequence of failure and can be implemented by water utilities. It is also important for water utilities to perform the triple-bottom-line consideration while

calculating the consequence of failure as it takes into account the social, economic, and environmental impacts of asset failure.

- Water utilities should conduct a periodic condition assessment of all types of pipelines in their network. A Magnetic flux leakage, remote field eddy current, CCTV cameras, and hydrophones are the most widely used condition assessment technologies as found in the literature and practice review and can be implemented for successful condition assessment of these assets.
- There are also many modeling approaches like deterministic models, statistical models, probabilistic models, fuzzy logic models, and neural network models that can be utilized to predict the condition of the assets.
- Coatings, CIPP liners, and pipe bursting are the most common repair, rehabilitation, and replacement technologies found in the literature and practice review. There are several examples found in the practice review where water utilities successfully implemented these technologies and obtained favorable results. Water utilities can apply these technologies for repair, rehabilitation, and replacement of their drinking water pipelines.

7.3.2 Recommendations for Future Research Work

The following are the recommendations provided for research work to fill the existing gaps in knowledge:

- More understanding of the deterioration mechanism for all types of pipelines, valves, and hydrants is required. By developing more enhanced knowledge regarding why the assets fail, better methodologies to prevent these failures can be formed.
- Risk management approaches for drinking water pipelines should be formulated as mostly risk assessment approaches are found in the literature and practice review. It is not prudent to directly conduct renewal after risk assessment. It is also essential to implement risk management approaches to prevent the risk from occurring in the future.
- Research should be done to identify more repair, rehabilitation and replacement technologies for valves and hydrants other than coatings and cathodic protection.

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APPENDIX A

QUANTITATIVE ANALYSIS OF LITERATURE REVIEW

The Table 5 and Table 6 provide a comprehensive overview of the journals, reports, and conference proceedings reviewed for pipelines as well as the valves and hydrants.

Table 5- Quantitative Analysis of Literature for Pipelines

S.NO	TITLE	CATEGORY	YEAR	FOCUS AREA
1	Potential Techniques for the Assessment of Joints in Water Distribution Pipelines	Report	2006	Focus Area 1, Focus Area 3
2	Non-Destructive Condition Assessment for Small Diameter Cast and Ductile Iron Pipe	Report	2014	Focus Area 1, Focus Area 3
3	Nondestructive, Noninvasive Assessment of Underground Pipelines	Report	2002	Focus Area 1, Focus Area 3
4	Condition Assessment of Drinking Water Pipelines	Report	2013	Focus Area 1 and Focus Area 3
5	Comprehensive Review of Structural Deterioration of Water Mains: Physical Models	Journal	2001	Focus Area 1
6	Selecting Techniques for the Rehabilitation of Small Diameter Cast Iron Pipes	Report	2013	Focus Area 1 and Focus Area 4
7	Internal Corrosion of Water Distribution Systems: Principles of Corrosion of Water Distribution Systems	Report	1996	Focus Area 1
8	Internal Corrosion of Water Distribution Systems: Cement-Based Materials	Report	1996	Focus Area 1
9	Development of an Effective Management Strategy for Asbestos-Cement Pipes	Report	2015	Focus Area 1

10	External Corrosion and Corrosion Control of Buried Water Mains	Report	2004	Focus Area 1 and Focus Area 4 and Focus Area 2
11	Risk Management of Large-Diameter Water Transmission Mains	Report	2005	Focus Area 1, Focus Area 2 and Focus Area 3
12	Failure of Prestressed Concrete Cylinder Pipe	Report	2008	Focus Area 1 and Focus Area 2
13	CFRP Renewal of Prestressed Concrete Cylinder Pipe	Report	2013	Focus Area 1
14	Management Practice of Drinking Water Pipelines	Report	2013	Focus Area 2
15	Development of a Risk Assessment Tool for Managing PCCP Assets with Broken Wires	Conference Proceeding	2014	Focus Area 2
16	Risk-Based Condition Assessment and Rehabilitation Planning In Colorado Springs	Conference Proceeding	2014	Focus Area 2
17	Risk Assessment of Water Transmission Pipelines with Fuzzy FMEA-AHP Approach	Journal	2015	Focus Area 2
18	Water Distribution System Risk Tool for Investment Planning	Report	2013	Focus Area 2
19	A tale of two utilities: how Portland Water (Oregon) and WaterOne (Kansas) justify and apply condition assessment for pipe risk management	Conference Proceeding	2014	Focus Area 2
20	Managing Infrastructure Risk: The Consequence of Failure for Buried Assets	Report	2017	Focus Area 2
21	Decision Support System for Distribution System Piping Renewal	Report	2002	Focus Area 2 and Focus Area 4

22	Capital Funding Imperatives: Best Practices for Capital Improvement Programs	Report	2016	Focus Area 2
23	An Accelerometer-Based Real-Time Monitoring and Leak Detection System for Pressurized Water Pipelines	Conference Proceedings	2016	Focus Area 3
24	Acoustic Signal Processing for Pipe Condition Assessment". Water Research Foundation	Report	2014	Focus Area 3
25	Condition Assessment of a Wood Stave Intake, a Hand Dug Tunnel and Concrete Cylinder Pipelines	Conference Proceedings	2016	Focus Area 3
26	Drinking Water Pipelines Defect Coding System	Conference Proceedings	2015	Focus Area 3
27	State of the art review of inspection technologies for condition assessment of water pipes	Journal	2012	Focus Area 3
28	Strategic Condition Assessment of the Water Distribution Network in Abu Dhabi	Conference Proceedings	2013	Focus Area 3
29	What in-line technologies work best for condition assessment of pipelines, and why	Conference P2roceedings	2014	Focus Area 3
30	Best Practices Manual for Pre-Stressed Concrete Pipe Condition Assessment: What Works? What Doesn't? What's Next?	Report	2012	Focus Area 3
31	Condition Assessment of Large Diameter Iron Pipes	Report	2014	Focus Area 3

32	Improved Management of Water Infrastructure Assets Using Non-Invasive Acoustics to Help Determine Rehabilitation Strategy	Report	2015	Focus Area 3
33	Assessing pipe failure rate and mechanical reliability of water distribution networks using data-driven modeling	Journal	2009	Focus Area 3
34	Comprehensive Review of Structural Deterioration of Water Mains: Statistical Models	Journal	2001	Focus Area 3
35	Comprehensive Review of Structural Deterioration of Water Mains: Physical Models	Journal	2001	Focus Area 3
36	Investigation of Grey Cast Iron Water Mains to Develop a Methodology for Estimating Service Life	Report	2000	Focus Area 3
37	State-of-the-technology review on water pipe condition, deterioration, and failure rate prediction models	Journal	2012	Focus Area 3
38	Safety, Reliability and Risk Analysis: Theory, Methods, and Applications	Book	2009	Focus Area 3
39	Hierarchical Fuzzy Expert System for Risk of Failure of Water Mains	Journal	2010	Focus Area 3
40	State of the Science: Plastic Pipe	Report	2016	Focus Area 3
41	Water Main Evaluation for Rehabilitation/Replacement	Report	1985	Focus Area 3
42	Development and Testing of a Linear Polarization Resistance Corrosion Rate Probe for Ductile Iron Pipe	Report	2015	Focus Area 3

43	Condition Assessment Strategies and Protocols for Water and Wastewater Utility Assets	Report	2007	Focus Area 3
44	Fracture Failure of Large Diameter Cast Iron Water Mains	Report	2013	Focus Area 3
45	Metallurgical Failure Analysis	Book	1993	Focus Area 3
46	Dynamic Influences on the Deterioration Rates of Individual Water Mains	Report	2010	Focus Area 3
47	Renewal Engineering for Drinking Water Pipelines	Report	2014	Focus Area 4
48	PCCP Rehabilitation with Fiber Reinforced Polymer Composite – Confirming Installation Conditions	Conference Proceeding	2014	Focus Area 4
49	Current and Emerging Water Main Renewal Technologies	Journal	2013	Focus Area 4
50	The Application of LEYP Failure Forecast Model at the Strategic Asset Management Planning Level	Conference Proceeding	2009	Focus Area 4
51	Failure Assessment Model to Prioritize Pipe Replacement in Water Utility Asset Management	Conference Proceeding	2006	Focus Area 4
52	Main Breaks: State of the Science	Report	2015	Focus Area 4, Focus Area 3
53	Assessment and Renewal of Water Distribution Systems	Report	2004	Focus Area 4
54	The Assess-and-Fix Approach: Using Non-Destructive Evaluations to Help Select Pipe Renewal Methods	Report	2015	Focus Area 4

55	Assessment of Existing and Developing Water Main Rehabilitation Practices	Report	1990	Focus Area 4
56	Performance and Life-Span of Polyethylene Wrap Materials for Ductile Iron Pipes	Report	2010	Focus Area 4

Table 6- Quantitative Analysis of Literature for Valves and Hydrants

S.NO	TITLE	CATEGORY	YEAR	FOCUS AREA
1	Condition Assessment of Appurtenance: A Water Sector Perspective	Journal	2012	Focus Area 1 and Focus Area 3
2	Condition Assessment of Water Main Appurtenances	Report	2012	Focus Area 1, Focus Area 2 and Focus Area 3
3	Maintaining Distribution Systems Valves and Hydrants	Journal	1982	Focus Area 2
4	Lessons Learned: Maintain Fire Hydrants Today to Prevent Problems Tomorrow	Journal	2010	Focus Area 2
5	Maintain Valves and Hydrants for an Optimized Distribution System	Journal	2015	Focus Area 2
6	Distribution Valves: Selection, Installation, and Maintenance	Journal	1996	Focus Area 2
7	Valve Condition Assessment using New Technology	Conference Proceedings	2014	Focus Area 3

8	The Importance and Benefits of Valve and Hydrants Management	Journal	2003	Focus Area 3
9	Protective Coatings for Valve Interiors	Journal	1972	Focus Area 4

APPENDIX B

The following questionnaire was prepared to select the water utilities for this research. The questionnaire was sent to the water utilities to collect information regarding the approaches and technologies implemented by water utilities for risk-based asset management of drinking water pipelines, valves, and hydrants. Based on the responses received from the water utilities, selected water utilities were contacted, and documents were solicited required for developing case studies.

Case Study Compilation on Applying Risk Management Principles and Innovative Technologies to Effectively Manage Deteriorating Drinking Water Infrastructure Systems (WRF-RFP #4666) - Screening Level Questionnaire

Please complete the following questionnaire:

Utility Name and Location: ____________________

Population Served and Characteristics: ____________________

Do you have an Asset Management Plan? YES ☐ NO ☐

Drinking Water Infrastructure Systems	Treatment Plants	Storage Tanks	Water Pumps	Water Wells	Pipelines,Hydrants & Valves
Step 1: Efforts that involve risk management and/or technology (check all that apply):					
Step 2: Self-assess your efforts/practices in each area using the following scoring: (1 = little/none, 2 = partially developed/in-progress, 3 = well developed/entrenched)					
Knowledge & Understanding of Asset Deterioration Modes/Mechanisms					
Risk Assessment Practices and Management Approaches/Strategies					
Inspection and Asset Condition Assessment Practices and Methodologies					
Renewal Engineering (Repair, Rehab, Replace) Practices and Methodologies					
Costs, Financing and/or Economic Analysis for Asset Maintenance and/or Renewal					

What practice(s) are you proud of: ____________________

Where would you like to improve: ____________________

Please provide any other relevant information: ____________________