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## Water Main Asset Management in the City of Hamilton: A Comprehensive Overview of Policies, Practices, Tools, and Technology

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### ABSTRACT:

With the Infrastructure deficit in Canada and other countries climbing along with the changing economy, there is a real need for municipalities and utility's to take a hard look at the way they view the management of their infrastructure assets. The "asset management" eras is upon us and many municipalities across Canada and internationally are recognizing the necessity to change there service delivery model, essentially re-evaluating how they do business. The effective management of municipal water distribution pipes is no exception and as such, many municipalities and utilities across the country and internationally have significantly changed their philosophical and pragmatic approach to managing their distribution systems.

The paper presents the results of 2-years of comprehensive studies into water main management practices in the City of Hamilton. The studies encompassed four main components: Water Main Criticality Model, a Water Main Performance Model, Critical Water Main Management, and the Information Management Framework.

### Introduction

There is a growing need by cities and water utilities to find better ways to prioritize their infrastructure asset maintenance, rehabilitation and replacement projects and employ infrastructure asset management techniques within their decision making. As infrastructure ages, it becomes increasingly more challenging to assign limited capital expenditures to the repair, rehabilitation or replacement of the assets. The prudent management of water mains requires a reasonable assessment of its current condition coupled with a reliable methodology to forecast future condition under different management scenarios.

It can be argued that water mains are one of the most difficult infrastructure assets to properly manage in a total asset management framework. This can be partly attributed to the difficulties associated with ascertaining a reliable measure for their physical condition. Faced with this challenge, in 2006 the City of Hamilton embarked on an ambitious series of studies geared towards the creation of a comprehensive tool set for managing water mains. In this regard, 4 main studies were conducted:



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- 1- **Water Main Criticality Model:** As the starting point for risk management, the criticality model classifies assets based on their ramifications of failure. The model encompasses economic, environmental, social and operational consequences of pipe failure. The model defines the subsequent management practices that will be used for high, low, and medium criticality pipe. For low criticality pipe, failure can be tolerated and the goal is to develop sound management policies that balance life-cycle costs with acceptable levels of service. For high criticality pipe, failure is not acceptable and hence more proactive policies driven by actual pipe condition and deterioration factors are sought.
- 2- **Water Main Performance Model:** The challenge associated with developing a performance model for water mains stems from the lack of reliable data on which to base the notion of 'pipe condition'. The performance model is developed for low criticality pipe and uses the number of breaks as a proxy for condition. By mining the break history of various pipe vintages (ductile iron, cast iron pit cast, and cast iron spun cast), a life regression model is calibrated for times between subsequent breaks. The model is subsequently used as a forward looking predictive model to forecast the expected failure times. The model was used to assist in the development of economic intervention strategies for replacement and/or rehabilitation, long-term budget forecasts of repair and rehabilitation needs in addition to aiding at the tactical level in rationalizing the coordination of capital works with sewers and road.
- 3- **Critical Water Main Management:** A unique approach for critical water mains is developed based on the proactive collection of condition information. The framework is composed of two main components: A condition assessment rationalization framework and a condition rating consolidation framework.
- 4- **Information Management Framework:** The aforementioned components all require sound and reliable information. This framework aims to standardize the way information is used to make decisions pertaining to water main assets. The framework is currently developing standard information policies and practices that include all stakeholders that interact with water main information throughout its life cycle. In addition, the framework is investigating the most optimum use of HANSEN (CMMS) to support existing and evolving business processes within the City.

### **Water Main Criticality Model**

The premise behind this model stems from the risk-based prioritization and decision-making concepts that are entrenched in the City's overall approach to asset management. The intent of this model is to answer questions such as "Which water mains will have the greatest impact to the City, should a break occur?" in order to focus resources and effort on these assets before they fail. Prior to the establishment of the criticality model there was no standard method for the creation of a Water Main Criticality Model. It remains a subjective process in which the municipality must be heavily involved with the selection of and ranking of parameters that they feel affect water main rehabilitation and replacement costs for the local area. Because of this, the parameters affecting cost of rehabilitation and replacement of water main infrastructure were selected and ranked within a joint effort between the consultant and the City of Hamilton.

Examples of criticality parameters include pipe characteristics such as material and bury depth, type of land use in which the pipe is situated, whether the pipe is connected to major water users



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or to important public health facilities such as hospitals and dialysis centers, whether the pipe is located in steep slopes or environmentally sensitive areas, etc.

The application of GIS is particularly well suited to the development of Criticality Models because of its ability to apply many of the criticality parameters to the segments representing the water main assets through spatial analysis. Because of this, the Criticality Model was developed with Intergraph GeoMedia Professional, which is the corporate GIS platform implemented by the City of Hamilton. GeoMedia Professional is well suited to the development of a Criticality Model because of its ability to perform spatial analysis as well as its ability to perform priority ranking calculations, all within a single software package. Risk elements were organized into four main categories:

- Economic – influence of the asset’s failure on monetary resources
- Operational – influence of the asset’s failure on operational ability
- Social – influence of the asset’s failure on society
- Environmental – influence of the asset’s failure on the environment

For each risk category, several risk variables were used to define the category. Figure 1 shows the risk variables that were used to define the social risk category and their relative weights.

Index Weight	Social 25%							
Category Weight	Public Disruption 60%				Visibility 40%			
Parameter Weight	Road Type 40%		No Diversion 60%		Pipe Size 75%		Land Use 25%	
Parameter Value Scoring	Value	Score	Value	Score	Value	Score	Value	Score
	OTHER	1	No	1	0-300	1	OTHER	1
	RC	5	Yes	100	300-449	5	Park	5
	RA, UC	10			450-749	10	Residential	10
	UAMI	25			750-1199	50	Comm/Indst	25
	EXPWY, HWY, UAMJ	100			1200+	100	HighDens	100

Figure 1: Risk variables for the Social Risk category

The result of the criticality model was the categorization of the city's inventory of water mains into three distinct groups:

- High criticality water mains: Water mains whose failure cannot be tolerated because failure cannot be addressed through normal operation and where a proactive approach to condition assessment and rehabilitation needs to be developed.
- Medium criticality water mains: An intermediate group between A and C where a balanced approach to management will be adopted.
- Low criticality water mains: Water mains where failure can be tolerated and a 'run to failure' approach can be employed. Intervention strategies are structured around balancing cost of service with level of service by minimizing life cycle costs (balancing repair, rehabilitation and replacement costs) and providing a minimum acceptable level of service to customers.



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The following figure highlights the spatial categorization of the criticality model. The model categorized ~10% of the network as having a high criticality, ~20% of the network as Medium criticality and ~70% as low criticality.

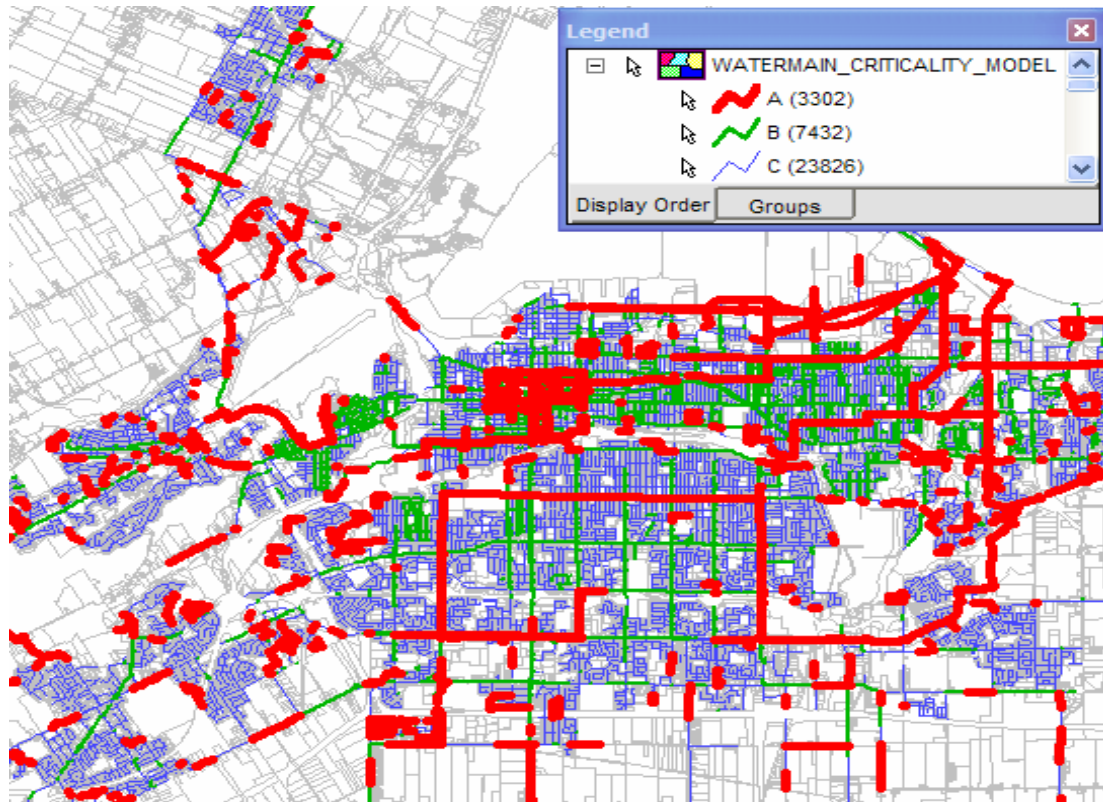


Figure 2: Results of the water main criticality model visualized in GIS

### Water Main Performance Model

The performance model is geared towards addressing the needs of low criticality water mains. The model is based on a statistical approach founded on developing mathematical models that utilize past failure history to forecast future trends and variations in breakage rates. As mentioned in the introduction to this paper, the ST-LR approach models the time between successive water main failures. The approach models each failure number (i.e. 1<sup>st</sup> failure, 2<sup>nd</sup> failure, etc...) as a separate and distinct condition state. The model uses a semi-Markov process in which each break order (e.g., 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> break, etc.) is considered a “state” in the process and the inter-break time  $t_i$  is considered the “holding time” between state  $(i-1)$  and state  $i$ . The Life Regression component of the ST – LR model uses Weibull probability distributions to model the time between failures, i.e. the time between transitions from one state to the next state in sequence.

Calibration of the State Transition – Life Regression model involves fitting Weibull distributions to times between failures for each of the state transitions; 0 to 1, 1 to 2, 2 to 3 and so on. This should be done for similar 'cohorts' of pipes based on distinct similarities in performance. In the



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case of the City of Hamilton cohorts were selected based on material type. Five distinct cohorts were modeled; 3 vintages of cast iron (spun cast), pit cast iron, and ductile iron. Other material types were in use (Hyprotec ductile and plastic) but did not have sufficient failure history to warrant a stand-alone analysis.

The concept of censored data is important to the fitting of Weibull distributions to the inter-failure time data. The most common form of censoring is right-censored data. In this case, the failure starting the inter-failure time has occurred but at the time of the last update to the data, the failure ending the inter-failure time has not occurred. All that is known for sure is that the probability of failure since the starting failure is zero and that the ending failure will occur sometime in the future. Including censors has the impact of including the effect of 'no-failures' in addition to the effect of 'failures'. Extrapolating this trend over the entire inventory has the impact of improving the overall predicted performance of the population. This can be viewed as one of the advantages of the ST-LR model compared to rate-of-failure models.

Sample results of the calibration process are shown in table 1. Results show a relatively long mean time to first failure for ductile iron pipes compared to cast iron pipes. However, for mean time to subsequent failures (especially after the 4<sup>th</sup> failure) cast iron pipes tend to outperform ductile iron. No significant differences were noticed in the performance of spun and pit cast iron pipes.

**Table 1 Sample Weibull parameters for various material types and failure occurrences**

State	Weibull Parameter	Pipe Material Type/Vintage			
		Ductile	CIPIT	CISP1	CISP3
Time to second failure	Alpha	61.25522	37.27617	37.41538	31.16957
	Beta	0.571146	0.720985	0.572962	0.624836
	MTTF	98.5903	45.91374	59.94733	44.57487
Time to fourth failure	Alpha	9.02527	11.55926	10.66693	6.648598
	Beta	0.450631	0.542016	0.673825	0.704786
	MTTF	22.30006	20.13408	14.02286	8.361831
Time to sixth failure	Alpha	8.038522	3.426698	6.747531	4.09902
	Beta	0.486966	0.726976	0.49988	0.67752
	MTTF	16.90065	4.189806	13.50105	5.358

The performance model was used to predict the following:

- 1- Long-term funding requirements for repair and replacement/rehabilitation under different level of service scenarios. Level of service was measured by number of failures experienced on a water main segment.
- 2- Using a Monte Carlo simulation to predict future failure patterns on various water main vintages, the optimum time to replace/rehabilitate was computed as a function of the ratio to repair to replacement cost. This minimum expected economic loss (MEEL) was found to be somewhat large for typical cost ratios (8-12 failures on a water main segment). This indicated that the governing criterion is more likely to be a level of service indicator set by the municipality rather than pure economics.



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In addition to the use of the model at the strategic planning level, the performance model was used to develop two important tools for water main management at the tactical/operational level.

1- Coordinated infrastructure renewal tool: This tool estimates the probability of experiencing no failures on any of a given selection of water mains in the next 'x' number of years. This application is used to determine whether or not the selected water mains should be rehabilitated or replaced during a roadway reconstruction project or whether replacement should be deferred..

2- Early replacement tool set: This tool estimates the economic loss/gain of fixing the date of the rehabilitation/replacement of a cast iron water main in comparison to rehabilitating or replacing the main in the year following when the Minimum Expected Economic Loss<sup>1</sup> (MEEL) criterion or the Minimum Acceptable Levels of Service<sup>2</sup> (MALOS) criterion is met. The tool is used to estimate the economics of advancing or deferring the date of rehabilitation/replacement of a cast iron or ductile iron water main.

The interested reader is referred to Gustafson et al (2007) for more information on the performance model.

### **Critical Water Main Management**

The approach for managing critical water mains differs considerably from that for non-critical mains. Some of these key differences include:

- Repair policy: With non-critical water mains, breaks can be tolerated and hence a run-to-end of service life approach can be accepted. Conversely, critical water mains with zero tolerance for failure, a proactive maintenance and rehabilitation policy should be sought.
- Tolerance to uncertainty: Whereas with non-critical water mains and their run to failure management approach, uncertainty in condition state can be tolerated, no such tolerance can be allowed for critical water mains. This has ramifications on:
  - The amount of information being collected. For non-critical water mains, breakage data along with basic pipe attributes (e.g. material, diameter, age, depth, etc...) are usually sufficient to drive a performance model. On the other hand, for critical water mains more detailed information pertaining to deterioration factors (e.g. detailed soil properties, potable water quality, presence of stray current, etc...) as well as observed distress indicators (e.g. cracking, pitting, joint displacement, etc....) need to be collected and properly managed.
  - The level of detail at which this information should be stored. In non-critical water mains a coarse network segmentation can be tolerated (e.g. at a street block level), whereas with critical water mains information should be tracked at a more individual pipe-segment level (e.g. using laying schedules).

<sup>1</sup> Minimum Expected Economic Loss: Number of failures where replacement is economically optimum

<sup>2</sup> Minimum Expected Level of Service: Number of breaks beyond which further failure will not be tolerated



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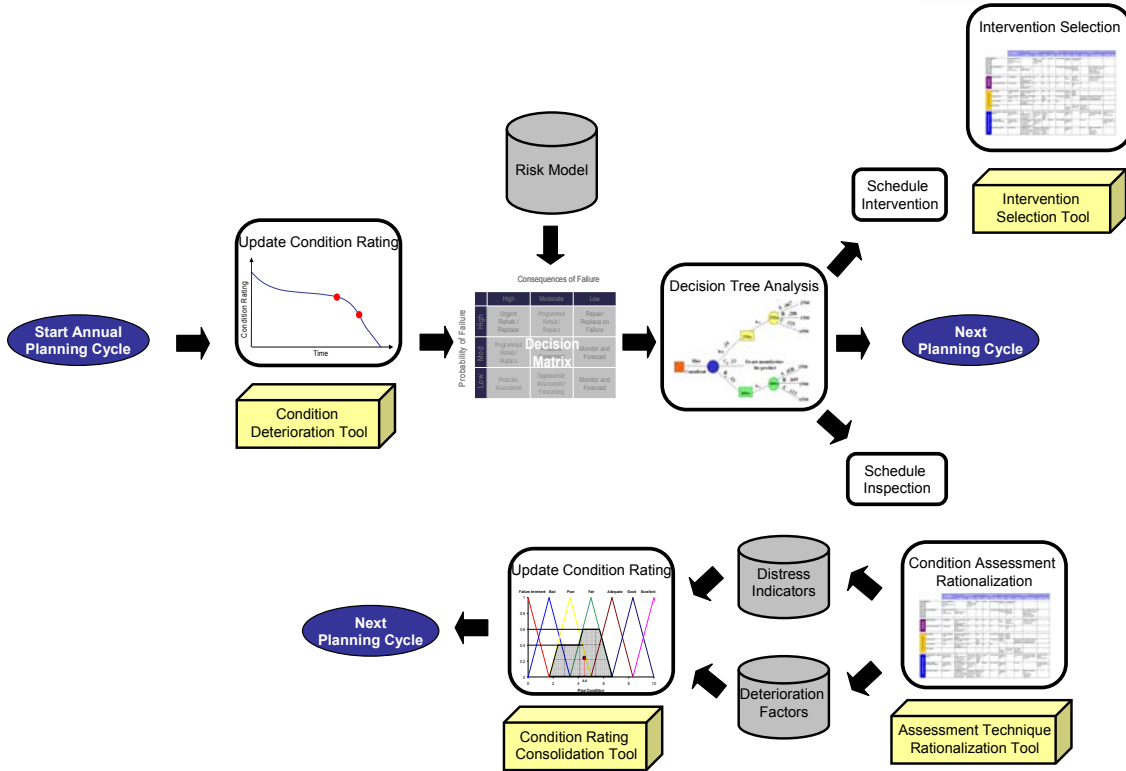


Figure 3: Overall components and cycle for critical water main management

The critical water main management framework consists of three main tool sets:

1- Assessment rationalization framework: This tool set is composed of a set of matrices that help the asset manager identify the suitability of each technique (When and Where to use?), the needs associated with each technique (constraints, costs, and impacts) and the expected outcomes of each technique (data reliability). The matrices are especially useful due to the plethora of new assessment techniques being developed as they serve as a standard framework for technique classification and evaluation. Pipe assessment technique can rely on measuring actual pipeline distress (direct assessment) or surrounding factors that will likely influence pipeline deterioration (indirect assessment). The result of using an assessment technique will either be a deterioration factor or distress indicator. Factors/indicators were classified into four cascading levels of detail as shown in table 2.



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Table 2 Listing of some common distress indicators and deterioration factors

Deterioration Factors		Distress Indicators	
Preliminary	Detailed	Preliminary	Detailed
<ul style="list-style-type: none"> <li>• Water pH</li> <li>• Pipe embedment</li> <li>• Backfill type</li> <li>• Cathodic protection</li> <li>• Soil type</li> </ul>	<ul style="list-style-type: none"> <li>• Corrosion potential</li> <li>• Soil resistivity</li> <li>• Soil pH, chlorides</li> <li>• Rate of wire breaks</li> <li>• Pressure data</li> </ul>	<ul style="list-style-type: none"> <li>• Leak detection</li> <li>• Visual inspection (test pits)</li> <li>• Pit depth measurement</li> </ul>	<ul style="list-style-type: none"> <li>• RFEC/TC</li> <li>• Ultrasonic wall thickness</li> <li>• Visual inspection</li> </ul>

2- Condition rating consolidation framework: This tool set attempts to standardize the way the results of assessment techniques are interpreted and subsequently used to drive decisions. The framework is developed for Ductile Iron and Cast Iron water mains as they compose the majority of the City's critical inventory. The framework utilizes Fuzzy Logic and the Analytical Hierarchy Process to combine condition rating results into an overall rating for the condition state as well as the expected deterioration rate of the pipe.

Fuzzy sets were selected as the tool-of-choice for the consolidation system. Fuzzy sets have been successfully used for the risk management of transmission water mains (Kleiner et al, 2005). The fuzzy sets developed in this model have been adapted from this AWWARF report. Fuzzy sets define the degree of membership of an individual to a class. For example, in Figure 3 (a), a pipe condition rating of 4 implies a 35% degree of membership to the class of 'Fair' pipe and a 65% membership to the class of 'Poor' pipe. Fuzzy membership functions were used to relate overall pipe condition to one of 7 condition states as shown in Figure 3. Similarly, 5 states were used for deterioration rates. Mapping tables were developed to relate the results of an assessment survey to one or more condition state or deterioration rate.

For example, the result of a pit measurement survey that revealed a 42% pitting depth would imply that this pipe belongs to the 'Fair' class of pipe with a degree of 40% and to the 'Poor' class with a degree of 60% (Figure 2(c)). Similarly, the results of a soil resistivity survey that indicated that soil surrounding a pipe segment had a resistivity of 800Ω would imply deterioration conditions belonging to the class of 'Rapid' with a degree of 80% and 'Moderate' with a degree of 20% (Figure 2 (d)). Pipe age and deterioration rate are subsequently combined to obtain an overall pipe condition rating (Figure 2(e)). Mapping tables were developed for 6 different distress indicators and 12 deterioration factors for ductile iron and cast iron pipe. Factors and indicators were selected such that could be feasibly obtained using condition assessment techniques.

3- Planning Cycle Decision Analysis Tool: The purpose of this tool is to equip the asset manager with a consistent methodology for decision-making during each planning cycle. Within a planning cycle, the asset manger must make one of three decisions for the critical water main inventory:

- Schedule Intervention: This action is triggered when there is enough information to reasonably conclude that risk is unmanageable and that a repair, rehabilitation or replacement is required.
- Schedule Inspection: This action is triggered when: a) the current assessment information is uncertain and possibly suggestive of deteriorated condition state, and b) The risk associated with operating the pipe segment cannot be tolerated at this level of information certainty.



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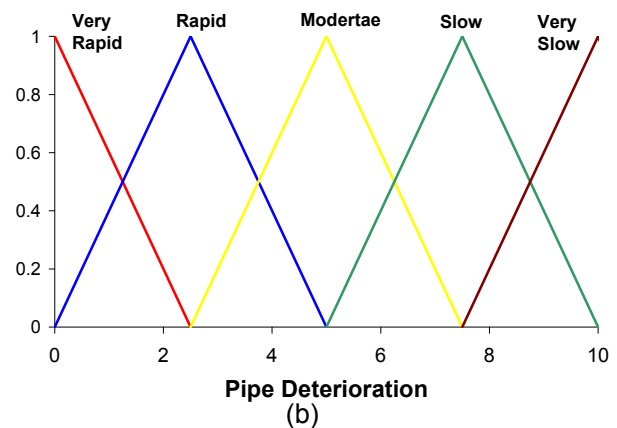
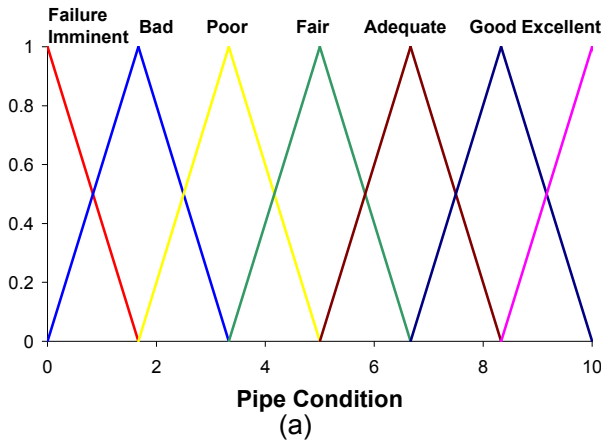
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- Revisit at next planning cycle: This action is triggered when current assessment information (and its certainty) has not exceeded the risk threshold of pipeline operation. This is equivalent to a 'do-nothing' scenario.

In order to make an informed decision, the asset manager must consider the following aspects:

- Condition State. This is analogous to the probability of failure.
- Pipeline Risk. This corresponds to the consequence of failure.
- Extent of condition/deterioration information currently available. The tool performs a trade-off between the available amount of condition/deterioration information and the risk associated with operating the pipeline.
- Level of uncertainty associated with inferring the condition state. Associated with the condition state that is inferred from the consolidation tool will be a measure of uncertainty. This factor must be considered in the decision process.

The interested reader is referred to Osman et al (2008) for more information on the critical water main management framework.



External pipe  
External pit depth (% of WT)

	Excellent	Good	Adequate	Fair	Poor	Bad	Failure Imminent
<10%	0.9	0.1	0	0	0	0	0
10% < depth < 40%	0	0.2	0.6	0.2	0	0	0
40% < depth < 60%	0	0	0	0.6	0.4	0	0
60% < depth < 80%	0	0	0	0.2	0.6	0.2	0
> 80%	0	0	0	0	0	0.5	0.5

(c)

Soil Resistivity  $\Omega$  (based on NACE)

	Very Rapid	Rapid	Moderate	Slow	Very Slow
0-500	0.9	0.1			
500-1,000		0.8	0.2		
1,000-2,000			0.5	0.5	
2,000-10,000				0.8	0.2
> 10,000					1

(d)

		Deterioration				
		Very Rapid	Rapid	Moderate	Slow	Very Slow
Age	> 70 years	Failure Imminent	Bad	Poor	Poor	Fair
	50-70 years	Bad	Poor	Poor	Fair	Adequate
	30-50 years	Bad	Poor	Fair	Adequate	Good
	10-30 years	Poor	Fair	Adequate	Good	Excellent
	< 10 years	Fair	Adequate	Good	Excellent	Excellent

(e)

Figure 3 Fuzzy membership functions and mapping tables for pipe condition and deterioration



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### **Water Main Information Management**

This study is still ongoing and aims to re-evaluate what information is collected, the way information is stored and handled throughout the lifecycle of the watermain assets. Some of ongoing work is aimed to:

- 1- Develop clearly defined business process models for some key water main processes that involve interfacing with vital asset attributes. These include recording water complaints, service outage times, routine maintenance of water fixtures, water main repairs, water main rehabilitation and incorporation of new as built information into the HANSEN database.
- 2- Evaluation of data needs outside of HANSEN: Current data repositories that exist outside of HANSEN will be identified and evaluated. Evaluation is focused on data relevance, frequency of use and update, accuracy, and relationship to actors within the organization. Examples of existing data repositories to be included in the evaluation include: As-built records, Design specifications, Soil characteristics, Laying schedules, Risk categorization (as defined in the criticality model).
- 3- Create and maintain metadata: This vital for some of the key water main attributes that are used in the decision making process (e.g. failure dates, construction dates, material type and diameter).
- 4- Completion of missing data records (or those that are known to be erroneous) through geospatial analysis, review of as-built records or opportunistic verification of by O&M personnel.
- 5- Perform a detailed review of how water main asset management decision-support applications (e.g. risk model, performance model, and developed toolsets) will eventually interface with HANSEN data repositories and other software applications that support asset management functions.
- 6- Review and possibly revise current protocols for replaced water main assets so as to link a meaningful repair history for new assets and maintain repair history of old asset for analysis purposes.
- 7- Maintain and strengthen existing data entry protocols for water main repair. Convey importance of recording accurate break histories to operations crews as it relates to making optimized decisions regarding pipe rehabilitation.

### **Conclusion**

With these tools built, the City has established the foundation for the effective management of its watermain infrastructure. Furthermore as these tools are integrated in the daily business decision process, they will be refined and improved to reflect the increasing knowledge growth within the City. They will also form the basis for clearly articulating the ramifications of decisions. This includes the need to focus resources, particularly financial on the assessment of critical infrastructure, which in many cases has not yet failed or otherwise caused operational issues. These types of studies are often expensive and don't result in new tangible assets, but rather an improved understanding of the probability of failure. As such these types of expenditures can often be challenging for Cities and utilities to get funding approval for without being able to demonstrate the non tangible benefits.



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