Risk-based approach to manage aging urban water main infrastructure

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ABSTRACT

The growing number of challenges in how to manage aging infrastructures, while maintaining a suitable level of service, have become major problems for many municipal water utility companies. As a result, municipalities are increasingly considering the concept of risk assessment and prioritization as the first and an important step that has to be used towards effective asset-management practices. Most experts agree that the main effort has to focus on implementing risk-based asset-management practices meeting a degree of sustainability decision-making process. However, there are so many challenges to establish common practices and understand the ground for operational implementations of the concept of the risk. This paper aims to form a basic decision support model to address urgent needs of risk-based water main asset-management tools. Furthermore, efforts have been made to demonstrate how this model can be used to support decision-makers to reach sound decisions for prioritization of mitigation with more informed and sound collective judgments of peer experts. This includes addressing the existing or potential risks based on scenarios, likelihood, consequences of the outcomes, and results of the action. In conclusion, this model would benefit decision-makers in evaluating further different planning horizons and set priorities for replacement or rehabilitation maintenance programs.

Key words | asset management, consequence, likelihood, risk-based analysis, risk rating, scenarios

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INTRODUCTION: RISK-BASED ASSET MANAGEMENT

Risk-based asset management is defined as a systematic process to identify risks that may have an impact on urban infrastructures, and analyze their consequences to develop measures for prioritizing of rehabilitation or replacement (R&R) maintenance strategies (Haimes 2005, 2011; MacGillivray & Pollard 2008). According to AWWSC (2002) and AWWA & AWWARF (2001), the criteria for utility companies to prioritize their R&R plans have to be based on risk as well as social, monetary, and public issues (Gargari 2009; AWWSC 2002; AWWARF 2004; Rahman & Vanier 2004). Studies suggest that rising regulatory pressures and the global trend towards requiring financial self-sufficiency are the two factors, which lead water utility companies to consider the role of risk analysis in their asset-management practices (Su & Mays 1988; Quimpo 1996; Røstum 1997; Dalgleish & Cooper 2005;

MacGillivray *et al.* 2006). Therefore, today, risk-based asset management becomes an integrated process to identify, analyze, and finally prioritize the high-risk assets considering pipe age, failure mechanisms, installation history, water quality, hydraulics, corrosion, material, pressure, location, soil type, ground water, loads, etc. (Deb *et al.* 1998; Gargari 2009; Su & Mays 1988). However, there are still challenges related to establishing a common understanding of the concept of risk-based asset-management (RBAM) process and how to implement to the operational practices.

THE CONCEPT OF RISK

Recently, risk analysis has become a core topic receiving significant consideration in infrastructure asset-management

process (Gargari 2009). Considering the huge impact along with service disruption, loss of revenue due to water loss, regulatory compliance, public image, workforce stress, damage to property, including the reputation of water utility companies involved, there is an increasing trend towards using the concept of risk assessment as an important tool in infrastructure asset management (Christodoulou *et al.* 2009; Dalgleish & Cooper 2005; Deodatis *et al.* 2014). Water utility companies need RBAM strategies that provide the decision support tools required to perform risk assessment providing engineers and involved practitioners with a sound risk profile that defines which assets are at the greatest risk. Risk analysis process addresses three fundamental points (Bender 2002; Cheung *et al.* 2003) as follows:

(1)   What can go wrong? (An unwanted event may or may not occur or the cause of an unwanted event, which may or may not occur.)

(2)   How likely is the water main pipeline to fail? (The probability of water main pipeline failure may or may not occur or the statistical expectation value of unwanted events, which may or may not occur, which include the physical condition, hydraulic capacity, and water quality.)

(3)   What are the consequences? How severe are the consequences of pipe failure? (For example, environmental impact, loss of service, regulatory compliance, water loss, community disruption, public image, workforce stress, damage to property, loss of revenue, and service agreements.)

In analyzing risk, we are attempting to investigate how the future will turn out if we undertake a certain course of action (or inaction) (Wengström 1993a, b, c; Røstum 1997; WRc 1998). In order to address the above fundamental three questions, we can formulate a list of different scenarios (see Figure 1), which can be modeled as a function of time and a set of underlining risk matrices and the risk can be denoted as a set of $\langle \lambda_i , \omega_j , \xi_k \rangle$ (Wengström 1993a, b, c; WRc 1998).

$$R = \left\{ \langle \lambda_i , \omega_j , \xi_k \rangle \right\} \tag{1}$$

where

$$i = 1, 2, \ldots, N, j = 1, 2, \ldots, N, \text{ and } k = 1, 2, \ldots, N;$$
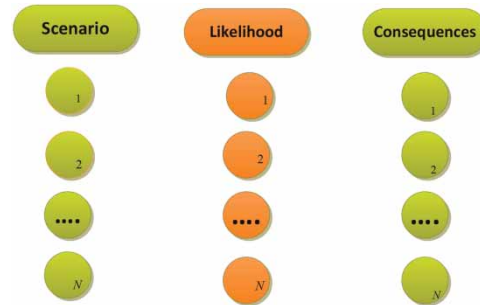

Figure 1 | Lists of scenario, likelihood, and consequences.

R is the risk which is a set of {scenario, likelihood, consequences};

λ_i is a list of outcome or scenario as $\lambda = (\lambda_1 , \lambda_2 , \ldots, \lambda_N)t$ which is a description of considered threats or hazards;

ω_i is the probability or the likelihood of an unwanted event which may or may not occur as $\omega = (\omega_1 , \omega_2 , \ldots, \omega_N)t$ which is a probability statement of the scenario; and

ξ_i is the consequence or evaluation measure of that scenario $\xi = (\xi_1 , \xi_2 , \ldots, \xi_N)t$ which is the qualitative or quantitative description or evaluation of the consequences. The consequences will typically have a multidimensional outcome.

Each risk scenario can be described by three parameters: $[\lambda_i, \omega_i, \xi_i]$, and the total risk value is given by listing all risk scenarios that include threats or hazards, events, and trends with their associated probabilities and consequences.

CAUSE OF WATER MAIN PIPE FAILURES

Deterioration of water distribution system

Several studies have been done to figure out the main factor that contributes to water main pipeline failure. Some of the identified physical, environmental, and operational components that have a huge role in water main pipeline failure include number of previous breaks, pipe material, pipe length, pipe diameter, operational conditions, design parameters, external loads, internal loads (operating and surge pressure), temperature changes, loss of bedding support, pipe properties and condition, corrosion (i.e., tuberculation), traffic load and closeness to highway, and

subway and roadway intersections (Eisenbeis 1994, 1997; Malandain et al. 1999; AWWSC 2002; Fadaee & Tabatabaei 2010). Studies show that many of the water utility companies or water agencies rarely record the above-mentioned factors, which make the process of water main failure rate analysis very difficult. Even if all this information was recorded and available for use, the analysis would still include uncertainty due to the large inherited spatial and temporal variability (Deb et al. 1998; Eisenbeis et al. 1999; Christodoulou et al. 2009, 2010). Most of the time, deterioration of water distribution systems can be made evident by one or more of the following manifestations: impaired water quality due to internal corrosion of unlined metallic components and/or poor maintenance practices; or reduced hydraulic capacity due to internal corrosion (i.e., tuberculation) of unlined metallic components; high leakage rate due to corrosion and/or deteriorating joints; and frequent breaks due to corrosion, material degradation, poor installation practices, manufacturing defects, and operating conditions (Su & Mays 1988; Grigg 2010; Mamo et al. 2013). Figure 2 shows a summary of the three main factors (physical, environmental, and operational) that contribute to water main deterioration factors.

Structural failure of water mains

Water mains pipelines typically break when the extent of corrosion or degradation is sufficient that the water main pipelines are no longer able to withstand the forces acting on them (Malandain et al. 1999; Rahman & Vanier 2004). Recent research indicates that failure often takes place in multiple stages rather than in a single episode. There are two primary reasons for a water main to break under external and internal loads (Goulter 1993; Eisenbeis 1997; Fadaee & Tabatabaei 2010; Mamo et al. 2013). The first and most common one is circumferential stress and cracking due to bending as a beam. Soil movement generates voids in pipe bedding, causing a pipe segment to act as a beam across the void and bend due to the pipe's own weight and overburden lateral soil pressure (Wengström 1993c; Rahman & Vanier 2004). This bending results in separation at joints and circumferential cracking depending on the conditions of joints or pipe material. The other main reason for structural failure is hoop stress resulting from internal pressure. Hoop stress failure will appear as longitudinal cracking and is more common among plastic pipes, which are made of more flexible materials (WRc 1998).

MODELING THE PROBABILITY OF WATER MAIN FAILURE

Several studies have shown that there are three main approaches to model the technical state of water main pipeline networks with respect to failures, and these are descriptive analysis, physical analysis, and predictive analysis (Goulter et al. 1993; Wengström 1993b; WRc 1998; Eisenbeis et al. 1999; Faber & Stewart 2003; Dalgleish & Cooper 2005; Kroger 2008). A summary of these approaches is given in Wengström (1993b). For example, the descriptive analysis organizes and summarizes the data and can be used to indicate various trends in failures and analyzing factors affecting pipe failures. Every effort to model the structural condition of a pipe network should begin with this basic analysis. Physical analysis is used to estimate the external loading, the amount of internal and external corrosion and
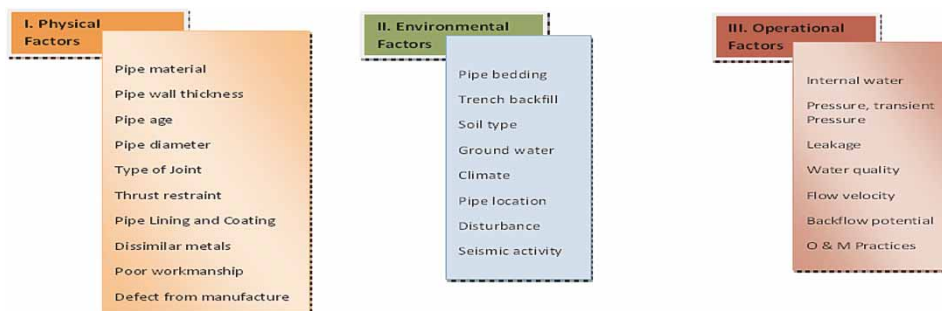

Figure 2 | Three main factors that contribute towards water main deterioration.

pipe stress to model the structural state of the water main pipe material. Predictive analysis uses statistical techniques to predict future system failures. For instance, one can use stochastic point process, which is a mathematical model for highly localized events or (failures) distributed randomly over the time axis. By 'highly localized' what is meant is that the failures occur instantaneously in time. This will, however, be an approximation of real life where a failure is considered to be a deterioration process (Wengström 1993b; Kumar & Klefsjö 1994). Moreover, the temporal development of the rate of occurrence of failures (ROCOF) in a water network over the service life can be described as the time derivative of the expected cumulative number of failures and it is expressed as follows (Goulter et al. 1993; Wengström 1993a, b):

$$v(t) = \mathrm{d}V \frac{(t)}{\mathrm{d}t} E(N(t)) \equiv \mathrm{ROCOF} \tag{2}$$

where $v(t) = E(N(t))$ denotes the mean number of failures in the interval $(0, t]$. It follows that the ROCOF may be regarded as the mean number of failures per time unit at time t. To best interpret the ROCOF, we can write

$$v(t)\mathrm{d}t = E[N(t + \mathrm{d}t)] - E[N(t)] \tag{3}$$

Expected number of failures in $(t, t + \mathrm{d}t]$, interims of probabilities, this can be written and expressed as follows:

$$v(t)\mathrm{d}t = P(\text{failures in } (t, t + \mathrm{d}t]] \tag{4}$$

For making maintenance decisions in a water network, it will be useful to know the development for the following reliability measures as a function of time for each pipe as ROCOF, the number of failures in the time interval $(0, t]$, $N(t)$, availability, and probability of new failure. The above-mentioned measures are all related, but they are used in different ways within water network management. The ROCOF is the key measure and serves as input for risk analysis and management. For a manager, the ROCOF makes known deteriorating trends in the network. The probability of failure and its consequences determine the risk of failure. When carrying out risk analysis for water supply networks, statistical models should be used

for assessing the probability of failures for different scenarios (Goulter et al. 1993; Fadaee & Tabatabaei 2010). One of the most sited references concerning pipe failure modeling is the so-called Shamir and Howard approach, a method used to determine the optimal time of replacement for water pipes (Su & Mays 1988; Wagner et al. 1988; Wengström 1993b; Malandain et al. 1999). Both existing and replaced pipes are considered in this model. Based on failure data, the number of breaks per unit length per year is forecast by

$$B(t) = B(t_0) \times \mathrm{e}^{A(t-t_0)} \tag{5}$$

where $B(t)$ denotes the break rate (breaks/year/km) in year (t) and $B(t_0)$ the initial break rate in year (t_0). A is a constant with the unit year – 1. (Shamir and Howard used the notation $N(t)$ instead of $B(t)$ for break rate. Since the term $N(t)$ is widely used for counting processes as the cumulative number of failures during $(0, t]$, $B(t)$ is substituted for $N(t)$ in this work.) After replacement, the pipe is considered 'virtually break free' within the planning horizon. Shamir and Howard combined the break forecast with economic data to find the optimum time for replacement. This break regression equation has been recommended by other authors (Walski 1987). Another fundamental element in conditional failure analysis is the hazard function. This function is known as the conditional failure rate in reliability theory, the force of mortality in demography, or simply the hazard rate. The hazard function $h(x)$ defined as the conditional probability that at time (x), the water main pipe will fail in a small time interval $(x, x + \Delta x)$, provided that it has not failed up to time (x). The hazard function is defined by

$$h(x) = \lim_{\Delta x \to 0} \frac{P[x \leq X < x + \Delta x | X \geq x]}{\Delta x} \tag{6}$$

The term $h(x)\Delta x$ can best be interpreted as the probability that the first failure occurs in $(x, x + \Delta x)$. If X is a continuous random variable, then

$$h(x) = \frac{f(x)}{s(x)} = -\partial \ln[s(x)] \tag{7}$$

where $f(x)$ is the density function. A related quantity is the cumulative hazard function $H(x)$, defined by

$$h(x) = \int_0^x h(u)\mathrm{d}u = -\ln[s(x)] \qquad (8)$$

$$s(x) = \exp[-X(x)] = \exp\left[-\int_0^x h(u)\mathrm{d}u\right] \qquad (9)$$

$s(x)$ is the probability that an individual will survive beyond time x. It is defined as $s(x) = pr(X > x)$.

The failure time distribution of pipes in a water distribution network may be investigated through the survival function $s(x)$, or the hazard function $h(x)$. In summary, the overall likelihood index of failure can be calculated as a function of age, number of breaks, and service connection using

$$H(I) = f(a, b, \#\, s, \ldots, n) \qquad (10)$$

where a is age of the pipeline segment, b is number of previous breaks or repairs, and $\#\, s$ is service condition (service condition is an indicator variable to measure threats such as traffic load, high pressure zones, corrosive soils, and other conditions that might cause the pipe to fail more quickly than the average). n is different additional factors.

WATER MAIN INFRASTRUCTURE ASSET INVENTORY/MONITORING AND CONDITION ASSESSMENT

Recent practice for investigating the condition of buried water main infrastructure is based on a two-phase approach (Eisenbeis 1997; Deb et al. 1998; Mamo et al. 2013). The first phase involves preliminary assessment including structural condition, hydraulic capacity, leakage, and water quality network wide based on data collected by every water utility company on a routine basis. The second phase involves a more detailed investigation of specific problems based on findings during the preliminary assessment (AWWSC 2002). This approach addresses both critical and non-critical water mains condition assessments. The critical water mains include those that would cause significant property, economic, and environmental damage if they break and/or are

the primary source of water supply to a large population or to customers that require high reliability (e.g., hospitals and some industries). For both critical and non-critical water mains utility, companies should monitor the condition of their water mains infrastructures to manage their failures to minimize the cost for operation and maintenance (Goulter et al. 1993; Fadaee & Tabatabaei 2010). Failure of individual water mains through high break rates or excessive leakage typically indicates the need to replace or, in some cases, to use structural liners. However, failure of individual water mains in terms of hydraulic capacity or water quality does not always require replacement since rehabilitation might be a more cost-effective solution. Therefore, RBAM process should be used to evaluate different planning horizons (short, medium, and long term) and identify, analyze, and set priorities of the high-risk assets, to meet the requirements of the different stakeholders and water utility agencies levels of standards and objectives by assigning resources and ensuring organizational success (Morris 1967; Goulter et al. 1993; Kleiner et al. 1998; Grigg 2010; Deodatis et al. 2014). Table 1 is a summary of water mains infrastructure asset inventory/monitoring and condition assessment.

DETERMINING THE RISK RATINGS FOR PRIORITIZATION OF MITIGATION

From the perspective of an urban infrastructure practitioner's point of view, risk is the potential for loss or damage to an asset (Haimes 2005, 2011; MacGillivray et al. 2006, 2007; Bradshaw 2008; MacGillivray & Pollard 2008). Each water distribution pipeline network has its own distinct characteristics, such as different operating pressure, service location, pipe sizes, material, and deterioration factors. Most of the time, risk prioritization and mitigation process are based on the greatest vulnerabilities that can be imposed by the highest risk rating in terms of water main structural damage and loss of operation. In general, risk is based on the scenario, likelihood, or probability of the hazard occurring and the consequences of the occurrence (Quimpo 1996; MacGillivray 2006; Christodoulou et al. 2009, 2010). A risk assessment analyzes the threat (probability of occurrence), asset value (consequences of the occurrence), and vulnerabilities to find out the level of risk to each water

Table 1 | Water main infrastructure asset inventory/monitoring and condition assessment

Condition assessment of water distribution systems

Problem Type	Preliminary condition Assessment	Reasons for more detailed condition Assessment	Detailed condition Assessment
		Level of service	
Structural condition	Spatial and temporal analysis of water main breaks. Compilation of soil map. Routine inspection of valves and hydrants. Routine inspection of insulation and heat tracing in northern areas	Preliminary investigations indicate: an excessive break rate; excessive leakage; inadequate hydraulic capacity; and/or impairment of water quality	Detailed analysis of break pattern rates and trends. Failure analysis. Statistical and physical models. Pipe sampling and visual inspection. Soil corrosivity and pit depth measurement. Non-destructive testing
		Cost effectiveness	
Hydraulic capacity	Low-pressure complaints. Hydrant flow tests. Rusty/colored water occurrences. Visual inspection of pipe interior. Monitoring of pressure and pumping costs	To facilitate capital planning and asset-management programs Pilot testing of new technologies to facilitate long-range planning support Opportunistic work, such as when a water main is temporarily out of service	Hazen–Williams C factor tests. Pipe roughness. Computer modeling
		Risk management	
Leakage	Water use audit. Per capita water demand. Routine leak detection survey	Risk analysis identifies critical water mains that have a high potential for significant property damage, environmental impact, or loss of service	Leak detection survey. Detailed limited area leakage. Demand assessment
Water quality	Water quality complaints. Routine sampling data. Results of flushing program	Due diligence (failure analysis of critical water main)	Detailed water quality investigation. Computer modeling

main infrastructure asset. The risk assessment provides infrastructure asset-management decision-makers and engineers with relative risk profile that defines which assets are at the highest risk or which asset needs an immediate action. There are numerous methodologies and technologies for conducting a risk assessment and assembling the results of the threat, asset value, and vulnerability assessment, and determining numeric value of risk for each asset in accordance with Equation (11). In general, by multiplying the values assigned to each of the three factors, quantification of total risk is provided (Kumar & Klefsjö 1994; Quimpo 1996; MacGillivray 2006; Marlow *et al.* 2012; Mamo *et al.* 2013), and the results of the risk rating used to help prioritize which mitigation measures should be adopted.

$$R = [\lambda_i, \omega_j, \zeta_k]$$
$$i = 1, 2, \ldots, N, j = 1, 2, \ldots, N, \text{ and}$$
$$k = 1, 2, \ldots, N$$

(11)

$$\text{Risk rating} = \text{asset value} \times \text{threat rating} \times \text{vulnerability rating}$$

(12)

DEMONSTRATION

This example demonstrates a hypothetical pipeline segment as part of the study to advance the general understanding of the proposed model, which can be used to compute values to screen buried water infrastructure pipeline segments by risk using the generally accepted risk ranking Equation (11). Five hypothetical pipeline segments have been chosen (see Table 2), with different parameters with relative importance factors. The values assigned to risk factors are for illustration purposes only. The proposed model estimates a failure likelihood value, and a failure consequences value for each water main pipeline segment by using a combination of a point system and relationships defined by the user. This includes

Table 2 | Example of hypothetical pipeline segments used to calculate relative importance factors

	Age	# Break	Service	Pipe size
Pipe 1	10	1	2	6
Pipe 2	15	2	1	8
Pipe 3	25	4	15	10
Pipe 4	40	6	8	12
Pipe 5	50	12	20	24

the likelihood of failure (meaning estimated likelihood of failure in the next few years) based on threat factors such as age, soils, number of previous breaks, service conditions, traffic load, and other causes of deterioration. The model data requirement is shown in Figure 1. All the hypothetical pipeline segments are conducted using the index method, in which a level for probability, consequences, and vulnerabilities is stated on a scale from 1 to 10, where 1 is low and 10 is very high or worst. These indices of likelihood are then combined with consequence of failure and vulnerability to give an overall risk rating using Equation (11). The overall likelihood estimate is called an index, because it is not an empirical observation of an actual likelihood but is an estimate based on a calculation. Following probability principles, the lower bound of the likelihood index is zero meaning a pipe segment might not fail in many years. The upper bound of likelihood is 1 meaning there is a 100% chance of failure.

Overall likelihood index of failure or probability of
$$\text{occurrence} = f \,(\text{age, breaks, service, and pipe size}$$
$$\ldots N \text{ factors}) \tag{13}$$

To compute the overall likelihood index, we can use a weighted average combination of likelihood indices for age, breaks, and service as follows:

$$\text{Probability of occurrence} = w1 \times H(I)(\text{age}) + w2$$
$$\times H(I)(\text{breaks}) + w3 \times H(I)(\text{service}) \tag{14}$$

The utility companies have to specify the relative importance of the normalized weights as ($w1$, $w2$, $w3$, $w4$, etc.), based on the overall water system configuration and the risk each pipeline segment poses on social, economic, and

environmental aspects, the normalized weights are computed by dividing the individual relative importance values by the sum of all the relative importance values. For example, consider different pipe segments (Table 2) with different parameters, the relative importance factors for pipe 4 (40, 6, 8, and 12) will produce normalized weights of 0.61, 0.09, 0.12, and 0.18, respectively.

The overall likelihood index of failure or probability of occurrence index calculation for the number of pipe breaks is based on national statistics of average conditions that show about 0.3 breaks per mile per year (1 mile = 1.609 km) (Wagner *et al.* 1988) (Figures 3 and 4).

For example, a pipe segment of 1,056 feet (1/5 mile; 1 foot = 0.305 metre) would have an average annual likelihood of failure of $0.3/5 = 0.06$. During a 25-year period, that pipe segment might experience 1.5 breaks (on average), which is computed as $25 \times 0.06 = 1.5$. The pipe data input contains the length of the pipe segment, the year of installation, and the number of breaks experienced. The risk equation also requires an estimate of the asset value or consequences of the occurrence, to prioritize pipe segments on the basis of risk levels. The asset value or consequences of the occurrence describe the result of failure. The consequence is normally evaluated for human safety, environmental impact, and economic loss. Therefore, the overall consequences score is computed as a weighted sum of these factors for each driver and ranked to describe the
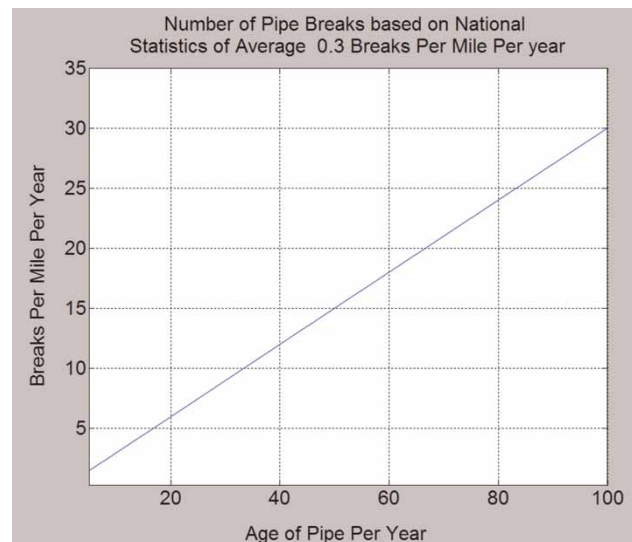
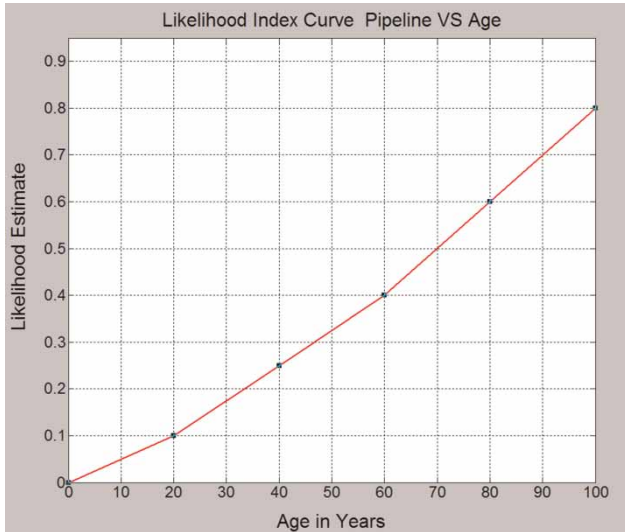**Figure 3** | Number of pipe breaks 0.3 per mile per year.

Figure 4 | Likelihood of failure curve.

severity of a consequence from 1 for minor or insignificant to 5 major or catastrophic consequences.

Overall consequences score $= w1$
$\times$ consequences (human safety) $+ w2$
$\times$ consequences (environmental) $+ w3$
$\times$ consequences (economic) $\qquad$ (15)

The final risk assessment ranking consists of the overall likelihood index of failure or probability of occurrence, overall consequence rankings, and the vulnerability rating, then comparing the result against the acceptance criteria. Figure 5 shows the detailed process. After we determine the risk factors applicable for each pipeline segment, we then assign values or numbers to
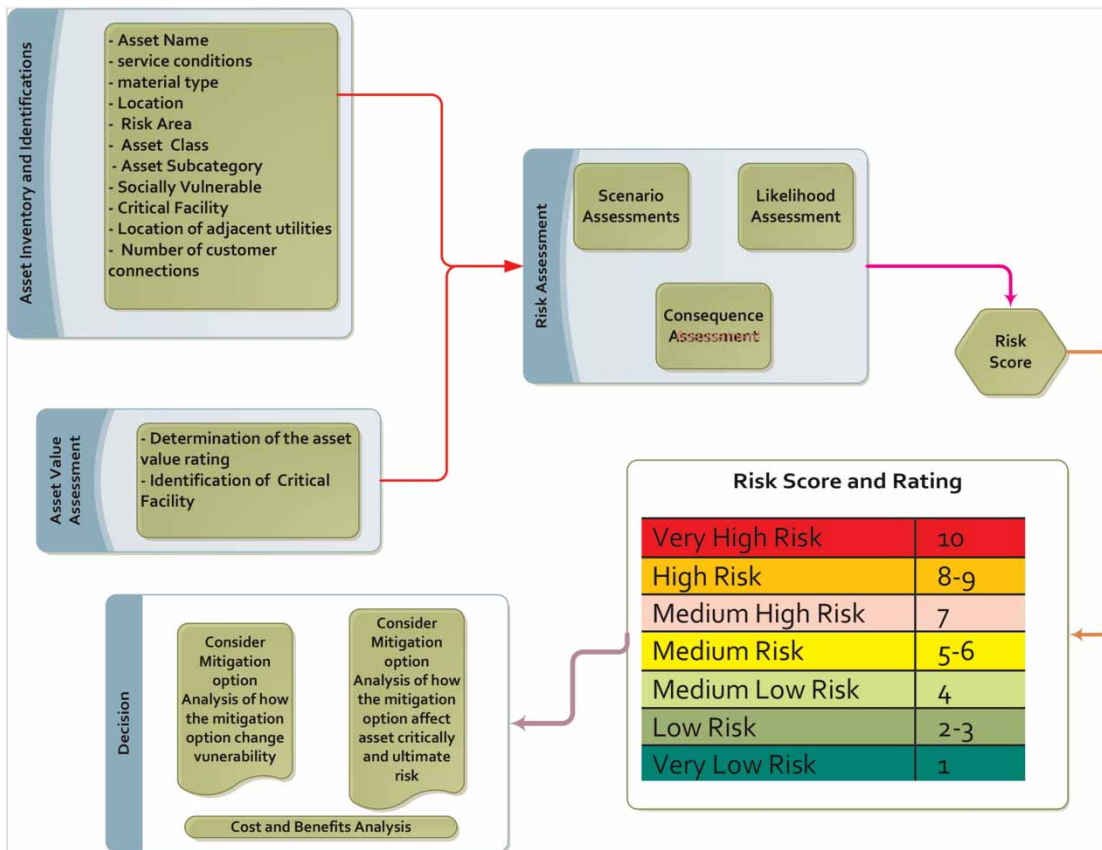

Figure 5 | Risk-based asset-management process model and data requirement.

each factor, such as, asset value (x), threat rating value (y), or vulnerability rating value (z). We can determine an overall risk classification, such as, very high risk (10), medium risk (5–6), or low risk (2–3), for the segment using the above calculations and risk score and rating scale values as 10–1 (see Figure 5). This process could enable us to classify a segment with overall risk value for any one segment when compared with other segments of a pipeline. For this example, segment pipeline 5 has the risk rating factor of 5.79 which fell between the 5 and 6 range of the risk score and rating maximum value, which is medium risk, and the remaining segments follow the same calculation of risk rating. The last part of the proposed model is to support the decision-making process by indicating what type of action needs to be considered based on the risk score and rating.

CONCLUSION

This paper discusses the concept of a RBAM process model as an important tool in municipal water utility infrastructure asset management. This paper also describes the model framework that integrates all aspects of parameters (social, economic, and environmental) that are responsible for: (1) identifying the scenario for an unwanted event that may or may not occur on critical components of water main infrastructure; (2) modeling the probability of an unwanted event that may or may not occur and how likely it is to happen (how likely the water main pipe is to fail, physical condition, hydraulic capacity, water quality, and maintenance practices); (3) identifying the consequences such as how severe the consequences of pipe failure are (environmental impact, loss of service, regulatory compliance, water loss, community disruption, public image, workforce stress, damage to property, loss of revenue, and service agreements); (4) analyzing risk for determining risk rating score and developing decision support system for prioritizing R&R maintenance and response strategies. The paper also calls attention to the necessary decision support methodologies required to perform various RBAM tasks as well as the future use of the RBAM programs for water utility companies.

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