Risk and Opportunity in Upgrading the U.S. Drinking Water Infrastructure System

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ABSTRACT**:** *This paper presents a generic risk assessment methodology to provide the drinking water infrastructure decision-maker with an objective risk assessment tool for maintaining a desired level-of-service while managing the expected capital improvement program budgetary impact. The expected capital improvement program budgetary outcome is based on the decision-maker's sensitivity to risk as represented by the system's reinvestment rate and level of scheduled maintenance activity costs. The results demonstrate that by proactively monitoring the risk of the drinking water infrastructure system level-of-service through an adequate reinvestment rate will effectively manage capital improvement program budgetary compliance. The conclusions of the paper reveal that developing a risk-avoidance position through a proactive asset management strategy can have a positive affect on the capital improvement program budget.*

INTRODUCTION

Traditional risk analysis is undertaken to improve the quality of information that the decision-maker utilizes by examining the uncertainty of decision response alternatives. The risk analysis is performed by calculating the magnitude of risk for an individual risk factor and/or cumulative risk. The cumulative risk is represented by the summation of the individual risk factors times the relative weight of the respective risk factors (Hastak and Baim, 2001). A comprehensive risk analysis should quantitatively understand the risk factors, their intermediate/final impacts on cost, and the actions to mitigate their impact (Ezell et al, 2000).

Risk assessment looks at what can go wrong as well as its likelihood and consequences. Infrastructure risk is defined as the product of the probability of system failure p(f) and associated costs of returning the system to service (Haimes, 1998; Hastak and Baim, 2001). This mathematical relationship is represented as: $R = p(f) \times C$, where R is defined as the risk of infrastructure system failure; p(f) is defined as the probability or likelihood of the system failure; and C is defined as the economic-value of returning the failed system to service. The economic-value of an infrastructure system failure is calculated as the total service expenditures in terms of equipment, material, and labor costs that are necessary to return the system to its normal operating condition.

Drinking water infrastructure system uncertainty or risk is defined as the likelihood or probability that the drinking water service fails to provide water on-demand to its customers. The water infrastructure system decision-maker either: 1) waits until critical components of the water infrastructure system fails and then expeditiously completes an emergency repair activity; or 2) schedules maintenance of critical components of the water infrastructure system prior to its failure. These are receptacle decision response alternatives that provide the decision-maker the ability to balance the expected capital improvement program (CIP) budgetary outcome on an annual basis.

The scheduled maintenance (SM) activity decision responses are the known or controllable costs that can be delayed by the decision-maker in response to their affect on the CIP budgetary outcome. However, delaying the scheduled maintenance of critical components of the water infrastructure system adversely affects the likelihood of system failure over the life of the infrastructure system. Correspondingly, as the likelihood of system failure rises, the level of the emergency repair (ER) activity increases. (Lauer, 2001) found that balancing ER activities with SM activities is the key to minimizing overall maintenance and repair (MR) costs.

The ER activity decision responses are uncertain or uncontrollable costs that are determined by the likelihood of system failure. It is the randomness in the level of the ER activity costs that create the uncertainty for the decision-maker regarding its cumulative affect on the expected CIP budgetary outcome. This situation is acerbated further by the fact that ER activity costs are paid at overtime or premium rates. These premium rates are charged for the ER activities because they require immediate attention causing increased costs for shifting, expediting, and/or providing extra personnel, materials, and equipment on a moments notice. The ER activity premium costs typically range from 1.5 to 2.0 times the SM activity costs.

This paper presents a generic risk assessment methodology for incorporating the decision-maker's sensitivity to risk into the analysis of the expected drinking water infrastructure CIP budgetary outcome. The decision-maker's sensitivity to risk is represented as the system's rate of reinvestment (RR). A risk analysis is performed utilizing three decision response alternatives that are based on desired risk-sensitivity in terms of low, medium, or high rate of reinvestment. The goal of this paper is to demonstrate an objective drinking water infrastructure risk assessment tool for maintaining a desired level-of-service r(f) while managing the expected CIP budgetary impacts. The objectives of this paper are to: 1) incorporate probability of drinking water infrastructure system failure p(f) into the CIP budgetary analysis process and 2) evaluate the affects of probability of drinking water infrastructure system failure p(f) on the expected CIP budgetary outcome.

BACKGROUND

Many professional and governmental agencies have published assessments and projections for the nation's drinking water infrastructure needs over the next 20-years. These need assessments have shown that the current drinking water infrastructure is in a state of general disrepair and substantial funding above the current levels will be required to maintain the drinking water infrastructure at acceptable levels-of-service r(f) through cost-effective capital improvement programs. To further compound the current needs dilemma the drinking water infrastructure competes for limited resources with the other critical public infrastructures for transportation, schools, wastewater, solid-waste, and energy.

The American Society of Civil Engineers (ASCE) published their *Report Card on America's Infrastructure* in March 2001(ASCE, 2001). This report gave America's infrastructures an overall grade of D+ and identified a 5-year total infrastructure investment need of $1.3 trillion. Specifically, the drinking water infrastructure consisting of approximately 54,000 community water services (CWS) will face an annual investment shortfall of $11 billion for replacement and compliance requirements. The ASCE report recommended immediately increasing the federal funding levels by an additional $5 billion per year under the Safe Drinking Water Act (SDWA). The report also recommended the creation of a water trust fund to ensure sustainable funding for the projected infrastructure needs as well as a source of associated innovative financing mechanisms to develop public/private partnerships to encourage a steady influx of new capital for technological advancement (ASCE, 2001).

The Environmental Protection Agency (EPA) completed its *1999 Drinking Water Infrastructure Needs Survey* (DWINS) in February 2001. The EPA report surveyed approximately 54,000 CWS and 21,400 not-for-profit non-community water services (NCWS) for their respective infrastructure needs (EPA, 2001). The report documented a 20-year capital investment need of $150.9 billion for public water systems that are eligible to receive funding under the State Revolving Fund (SRF) program. The report found that $31.2 billion is directly attributable to specific SDWA regulations. The report also documented that the average age of the drinking water infrastructure network is estimated to be between 50-100 years (EPA, 2001).

The continued aging or deterioration of the drinking water infrastructure network is the primary reason for the projected financial needs as documented in the Water Infrastructure Network (WIN) Coalition report entitled, "*Safe and Clean Water for the 21st Century: A Renewed National Commitment to the Water and Wastewater Infrastructure*" in April 2000 (WIN, 2000) and in its follow-up report entitled, "*Water Infrastructure NOW: Recommendations for Clean and Safe Water in the 21st Century*" in February 2001 (WIN, 2001). These reports argue for a combination of federal, non-federal, and private solutions for the resolution of the infrastructure-funding shortfall. The (WIN, 2000) report suggests that the economic and political history of general infrastructure investment has precedent for providing clean water under the Clean Water Act (CWA) and safe water under the SDWA.

The (WIN, 2001) report recommends a number of ways the federal government might take a leadership role, including research grants, water trust funds, low-interest loans, and incentives for private investment. Without a significantly enhanced federal role in financing the drinking water and wastewater infrastructure, critical investments will not occur. Failure to meet the clean and safe water investment needs of the next 20-years risks reversing the environmental, public health, and economic gains of the last three decades. Since federal government subsidy programs are down 75% from 1986 levels, local governments and ratepayers must fund approximately 90% of the clean and safe water infrastructure costs while grappling with competing needs for new schools, law enforcement, and social services (WIN, 2001).

The current financial health of the nation's CWS sector is documented by the EPA's *1995 Nation-wide Community Water System Survey* which was completed in January 1997 (EPA, 1997). The survey results revealed that the 1995 CWS sector spent $32 billion from 1986 through 1995 on capital improvement programs. On average the CWS sector's asset management activities spent approximately 20% on water quality (WQ) compliance, 30% on maintenance and repair (MR), and 50% on scheduled replacement (SR). On average the 1995

CWS sector completed MR activities on approximately 2% of their respective piping networks. In addition, the CWS sector completed SR activities on approximately 2% of their respective piping networks. The WQ compliance, MR activities, and SR improvements compete for the same water infrastructure asset management dollars.

The aging of the drinking water infrastructure system, along with increasing competitive pressures and customer demands, are forcing public water services to develop effective asset management programs such as the GASB-34 requirements for maintaining service efficiency and product reliability while meeting quality standards and containing service costs (Booth and Rogers, 2001). The public water services are looking to asset management programs to provide integrated solutions to improve the service efficiency and product reliability by balancing the MR activities as a function of the SM and ER needs (Stern and Kendall, 2001). It is generally accepted that as the drinking water infrastructure system ages the occurrence of ER activities increases due to the adverse impact of physical, chemical, and biological deterioration forces. Additionally, as the frequency of ER activities increases, the SR improvements of the aging drinking water infrastructure system become the more viable option (Silinis and Steward, 2003).

Drinking water infrastructure needs may range from ER activities for maintaining the level-of-service r(f) to SR improvements for creating new capacity for present and projected demand. The ability to pay may range from public water services with strong bases of commercial and affluent users to those with large bases of government services and low-to-moderate-income residential users. Managing the drinking water infrastructure requires decision-makers to manage the old as well as to build the new. They must know about governance, public health, engineering, operations, and politics as well as economics and finance. The drinking water infrastructure problems discussed in the public forum are only 5% technical; 95% of the focus is on finance, public acceptance, and environmental impacts. There are abundant opportunities in the drinking water infrastructure arena to take lead roles in defining issues, creating solutions, explaining to public, and leading the holistic implementation process. Communicating the critical nature of drinking water infrastructure WQ, MR, and SR budgetary activities under the CIP is paramount for the fundamental survival, public-health protection, economic development, and quality of life of America’s people (Grigg, 1999; Means, 2001).

Craun and Calderon (2001) emphasized the importance of adequately maintaining drinking water infrastructure systems. Craun and Calderon found that since 1995 drinking water distribution system deficiencies have been responsible for 45% of all waterborne disease outbreaks reported by the nation's 54,000 CWS. The water distribution system deficiencies involved chemical and microbial contamination through cross-connections, back siphonage, inadequate separation, contaminated storage facilities, water main repairs, water main construction, and meter installation (Craun and Calderon, 2001). To reduce the risk of waterborne disease outbreaks more attention needs to be placed on the preventing of contamination of the distribution system through an optimal combination of corrective, preventative, and proactive maintenance policies.

The water infrastructure system is aging, which contributes to waterborne disease outbreak and reduced level of service or system reliability r(f). Sufficient CIP funds consisting of WQ, MR, and SR budgetary components should be allocated for the routine inspection, repair, and expansion of water mains and storage facilities as well as the scheduled replacement of the older infrastructure. To reduce the potential for distribution system outbreaks and failures, water services must maintain adequate water pressures, repair leaking mains, maintain chlorine residual, adopt cross-connection programs, include inspection programs, adequately disinfect after construction work, and increase corrosion control efforts (Craun and Calderon, 2001).

Scharfenaker (2001) complements the growing body of related research by estimating the nation's projected investment need to replace buried drinking water pipes and associated appurtenances. Scharfenaker forecasts water infrastructure repair and replacement expenditures based on how such assets wear out over their expected life spans. The historic investment pattern for US water services shows: 1) local revenue financing is resulting in a steady accumulation of "invisible replacement liability" through deferred maintenance and repair decisions; 2) changes in pipe manufacturing techniques has resulted in a significant drop in life expectancy; 3) specific short-term facility upgrades concentrated on compliance with the stringent SDWA water quality standards over the last 25-years; and 4) demographic change places a severe financial strain on public water systems and has resulted in the projected "replacement gap" in many areas of the country. Scharfenaker (2001) estimates drinking water services expenditures to be approximately $250 billion over the next 30-years. Water services must develop innovative ways to close this "replacement gap" to ensure the continued delivery of safe water by transitioning from a path of repairing their pipe networks to cost-effectively replacing huge amounts of buried infrastructure that is now at the end of its life (Scharfenaker, 2001).

Scharfenaker (2001) recommends three steps to close the “replacement gap” and associated “affordability gap”: 1) developing a comprehensive local strategy to assess the condition of the infrastructure; 2) reforming state programs so that they are required to use federal funds in a timely, efficient, and effective manner; and 3) increasing federal assistance by expanding the existing SRF programs and creating new funds to stimulate research for more efficient management and technologies. Failure to accurately predict the appropriate drinking water infrastructure system reinvestment rate risks severe level-of-service r(f) deterioration adversely affecting the financial stability of the public water services.

Optimizing the financial tradeoffs between the asset management program activities for corrective, preventative, and proactive maintenance subject to minimizing the adverse impacts on the expected CIP budget outcome emphasizes the importance of water distribution system maintenance in the effectiveness of the overall system safety and reliability (Stern & Kendall, 2001 and Silinis & Steward, 2003). Many quantitative analysis methodologies utilize mathematical representations to model the complex physical, chemical, and biological deterioration processes that adversely affect the water infrastructure system reliability (Quimpo & Wu 1997; McKay et al, 1999; Guignier & Madanat, 1999; Franks, 1999; Wu et al, 2001; Stern & Kendall, 2001; and Silinis & Steward, 2003). These quantitative analysis methodologies provide objective and repeatable procedures to justify CIP budgets that effectively allocate dollars, extend asset life, and plan programs to maintain system reliability. However, they do not incorporate risk assessment into their respective quantitative analysis methodologies.

More recent quantitative analysis methodologies incorporate risk assessment and management techniques to facilitate decision analysis by highlighting tradeoffs among individual risks factors and associated mitigation cost impacts to effectively manage infrastructure assets (Kakimoto and Seneviratne; 2000; Hastak & Baim, 2001; and Ezell et al, 2001). However, the stochastic nature of the water infrastructure system deterioration processes adds considerable complexity to these quantitative analysis methodologies requiring substantial technical and modeling expertise. While the required drinking water infrastructure system investment is daunting in size, it creates an opportunity to sensitize the consumers and decision-makers of the opportunities of strategic risk management as communities differ in their drinking water infrastructure needs, ability to pay, and ability to manage risk. This paper demonstrates an objective risk assessment tool for maintaining a desired level-of-service r(f) while managing the expected CIP budgetary impacts.

The ability to manage risk by minimizing the probability of system failure p(f) may range from instituting high reinvestment strategies to no reinvestment strategies due to limited budgets.

METHODOLOGY

The discontinuation of the current state of disrepair of the drinking water infrastructure system requires the prioritization of corrective, preventative, and proactive maintenance activities within the CIP budgeting process to ensure the effective allocation of limited resources (Li and Haimes, 1992). The drinking water infrastructure system is now nearly 100 years old with at least 26% of the drinking water mains constructed of unlined cast iron and steel piping. These drinking water mains have greatly reduced carrying capacities and are rated in poor condition adversely impacting the current drinking water infrastructure system level-of-service (Kirmeyer et al, 1994).

The prioritization of corrective, preventative, and proactive maintenance activities within the CIP budgeting process is the basis for the development of the drinking water infrastructure risk assessment tool. The drinking water infrastructure risk assessment tool is characterized by three risk-sensitive decision response alternatives which are described in **Table 1**.

Table 1 The Description of the Drinking Water Infrastructure Decision Response Alternatives as a Function of the Level of the Probability of System Failure, Risk Sensitivity of the Decision-Maker, and Frequency of the Emergency Repair Activities.

Decision Responses	**p(f)**	**Risk Sensitivity**	**Emergency Repairs**
Null (Corrective)	High	Low	High
Traditional (Preventative)	Medium	Medium	Medium
Strategic (Proactive)	Low	High	Low

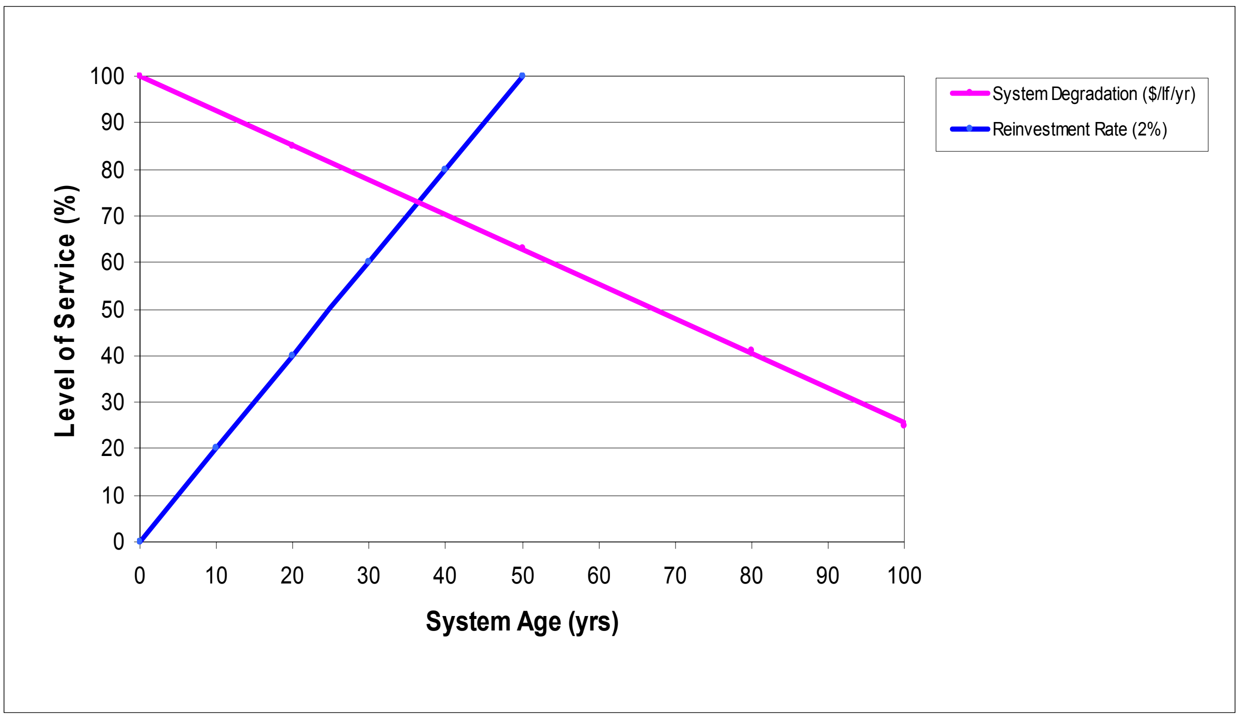
The **Null** or corrective decision response assumes that the p(f) is high and decision-maker's risk sensitivity is low because low levels of SM or preventative maintenance activities are planned to mitigate the p(f) due to infrastructure deterioration. The associated infrastructure level-of-service is adversely affected because the ER or corrective maintenance activities are performed only after the infrastructure system fails.

The **Traditional** or preventative decision response assumes that the p(f) is medium and decision-maker's risk sensitivity is medium because medium levels of SM or preventative maintenance activities are planned to mitigate the p(f) due to infrastructure deterioration. The associated infrastructure level-of-service r(f) remains stable since the level of ER or corrective maintenance activities is marginally reduced by the SM activities.

Finally, the **Strategic** or proactive decision response assumes that the p(f) is low and decision-maker's risk sensitivity is high because high levels of SM or preventative maintenance activities are planned to prohibit the p(f) due to infrastructure deterioration. The associated infrastructure level-of-service r(f) increases since the level of ER or corrective maintenance activities is substantially reduced by the SM activities.

The basic relationships for infrastructure maintenance frequency (MF) and system performance are discussed in detail by Nelson, R.E. et al (1999) in an EPA report entitled; "*Optimization of Collection System Maintenance Frequency and System Performance.*" These relationships are diagramed in **Figure 1**.

Figure 1 The Graphical Representation of the Linear Relationships between the Infrastructure System's Age (Years) and Level-of-Service (% Like-New Performance) as a Function of the System Degradation and Reinvestment Rates.



Source: Nelson, R. E., Hsiung, P. H., and Witt, A. A., *Optimization of Collection System Maintenance Frequency and System Performance*, EPA Cooperative Agreement No. CX-824902-01-0, Washington, DC, February 1999.

The Nelson, R.E. et al (1999) methodology involves the following assumptions:

1.) The average infrastructure system life expectancy is assumed to be 100 years with a salvage value of 25%. The average infrastructure system unit value is assumed to be $100 per linear foot of pipe. The rate of infrastructure degradation is assumed to be $0.75 per linear foot per year. Based on these assumptions the **rate of system degradation (SD)** is represented by the following linear relationship: **SD = $100 – ($0.75 * X)**, where the (x-axis) value is equal to the average age of the infrastructure network in years.

2.) The level-of-service r(f) or associated (y-axis) value is assumed to be the percentage of the "like new" system performance. The remaining infrastructure system value is a function of the average MF and system age. The percentage of the "like-new" system performance is assumed to represent the infrastructure's current level-of-service r(f). The infrastructure system MF is assumed to be the number of years to return the system to 100% or a "like-new" system performance level given a specific level-of-maintenance activities or RR.

3) Infrastructure system MR program is defined as ongoing ER and/or SM activities which include actions that retard or correct the deterioration of the infrastructure system. Infrastructure system maintenance levels or RR is defined as the percentage of system rehabilitated within a given time period or MF.

4) The infrastructure system reinvestment rate (RR) is assumed to be the inverse of the maintenance frequency (MF). The RR or 1/MF determines the level-of-maintenance activities or percentage of the total system rehabilitated to return the system to "like-new" condition in a given period of time. For example, a RR=2% will return the system to a "like-new" system performance condition in MF= 1/0.02 = 50 years.

Figure 1 is utilized to estimate the expected infrastructure level-of-service r(f) given the average rate of system degradation (SD) and reinvestment (RR) assumptions that are specified in the (EPA, 1997) survey. The methodology steps include: 1) drop a vertical line from the end of the 2% RR line to the corresponding point on the SD line; 2) draw a horizontal line to the level-of-service [% "like-new" system performance or r(f)] axis; and 3) note that the r(f) [y-axis] value is intersected at 65% which represents the current system level-of-service. Therefore, given the assumed rate of system degradation with a 2% reinvestment rate the overall infrastructure system level-of-service is expected to perform at 65% of the performance level of a similar "like-new" infrastructure system.

The infrastructure system level-of-service or system reliability r(f) is defined as probability that the infrastructure system operates correctly throughout a specified period of time given the system is operating at the start of the time period (Haimes, 1998). The system unreliability or probability of system failure p(f) is defined as the probability that the infrastructure system fails during a specified period of time given the system is operating at the start of the time period. The relationship between system reliability r(f) and probability of system failure p(f) is expressed as the p(f)=1-r(f). Given this relationship the level-of-service r(f) or y-axis value calculated in **Figure 1** can be expressed as the p(f) over a given 1/MF or RR. For example, given the average rate of SD in **Figure 1** with a 2% RR from the previous example, the r(f) is estimated to be 65% of the "like-new" system performance level and the p(f) within the 50-year MF period is estimated to be 35%. This means that the infrastructure system with a 2% RR is operating at a level-of-service r(f) that is 35% below the 100% system performance level. In other words, the infrastructure system has a 35% chance of failing to operate at least once throughout the associated 50-year maintenance frequency.

(Guignier and Madanat, 1999; EPA, 1997) found that the water infrastructure system CIP budgets are broken into WQ compliant activities, MR as function of the tradeoffs between SM and ER activities, and SR improvements. The MR component consists of CIP budgetary line-items that are broken down as scheduled maintenance (SM) and/or emergency repair (ER) activities. The MR activities retard and/or correct infrastructure deterioration after the system has failed. The MR activities are stochastic in nature and vary widely from one year to the next because they are based on risk factors such as infrastructure age, material, leakage, water quality, etc. The WQ and SR components consist of CIP budgetary line-items that are deterministic quality compliant and replacement improvement activities. The WQ compliant activities are set by the drinking water service permit conditions relative to the source water quality. The SR improvements functional alter the infrastructure system returning it to a "like-new" condition state. The WQ and SR component budgetary line-item amounts are deterministic in nature and these CIP budgetary amounts that are set by the decision-maker for each budgetary cycle.

The water infrastructure decision-making problem involves balancing the tradeoffs between the stochastic MR activities. The ER activities are expensive and variable relative to the cost-effective and consistent SM activities. The ER and SM activity levels are considered as receptacle corrective and preventative maintenance activities within the CIP budget. However, the ER activities are uncertain making the level of ER activities variable. Therefore, the water infrastructure decision-maker will want to answer the following question: What is the optimum level of preventative maintenance (SM) activities that will maintain the current level-of-service r(f) while minimizing adverse affects on the expected CIP budgetary outcome?

To answer this question the following conceptual water infrastructure system CIP budget assumptions were made to incorporate risk assessment in the terms of the probability of system failure p(f) into the calculation of the expected CIP budgetary outcome with in the conceptual drinking water infrastructure risk assessment tool :

1. Annual Water Quality (WQ) Compliance Budget
   SR ($/yr) = Labor + Material + Equipment aspects
   SR ($/yr) = ($/hr, $/lf, $/event) x (# hrs, # lf, # / events)
2. Annual Scheduled Replacement (SR) Improvements Budget
   SR ($/yr) = Labor + Material + Equipment aspects
   SR ($/yr) = ($/hr, $/lf, $/event) x (# hrs, # lf, # / events)
   a. Annual Scheduled Maintenance (SM) Activities
      SM ($/yr) = Labor + Material + Equipment aspects
      SM ($/yr) = ($/hr, $/lf, $/event) x (# hrs, # lf, # / events)
   b. Annual Emergency Repair (ER) Activities
      ER ($/yr) = 1.5 x SM activities
      ER ($/yr) = 1.5 x (Labor + Material + Equipment) aspects
      ER ($/yr) = 1.5 x ($/hr, $/lf, $/event) x (# hrs, # lf, # / events)
3. Average Capital Improvement Program Budget (T) with **no** risk assessment
   CIP ($/yr) = WQ+MR+SR
   CIP ($/yr) = WQ+(ER +SM)+SR, assume coefficients must sum to 1 for balanced budget
   CIP ($/yr) = (0.20)*T + (0.3)*T + (0.50)*T
4. Annual Maintenance and Repair (MR) Activities Budget
   MR ($/yr) = 0.3 (ER + SM), as constrained by MR portion of CIP Budget
   MR ($/yr) = (0.3-b)*T + (b)*T, where **b** is the SM portion of the MR component
   MR ($/yr) = [(1.5 x 0.3-b) + (b)]*T
5. Probability of system failure as a function system reliability: **p(f) = 1 – r(f)**
6. Risk of Emergency Repair Activities
   Risk ($/yr) = p(f) x C
   ER ($/yr) = p(f) x [1.5 x SM]
   ER ($/yr) = [p (f) x 1.5 x (0.3-b)]*T
7. Average Capital Improvement Program Budget (T) **with** risk assessment
   CIP ($/yr) = WQ + MR + SR
   CIP ($/yr) = WQ + (ER+SM) + SR
   CIP ($/yr) = 0.2*T +0.3* T + 0.5*T
   CIP (T) = (0.2)*T + [p (f) x 1.5 x (0.3-b)]*T + (b)*T + (0.5)*T **(1)**

The above coefficients for the conceptual water infrastructure CIP budget utilize the WQ, MR, and SR coefficients which are based on the national averages from a 1997 EPA Survey. However, these water infrastructure CIP budgetary coefficients are drinking water service-specific and would be developed on an individual drinking water service-basis. The WQ and SR coefficients are assumed to be constant asset management activities within the CIP budget. The ER and SM coefficients in the MR component are assumed to be receptacle asset management activities within the CIP budget.

The conceptual water infrastructure risk assessment tool assumes that under normal conditions the decision-maker will re-allocate funds between the ER and SM activities within the MR component of the CIP budget. The MR component funds are re-allocated based on the competing needs to maintain the current level-of-service r(f) and balance the total CIP budget. The conceptual water infrastructure risk assessment tool allows the decision-maker to set the rate of reinvestment in accordance with his/her level of risk-sensitivity (low, medium, high) and determine its impact on the expected CIP budgetary outcome.

RESULTS

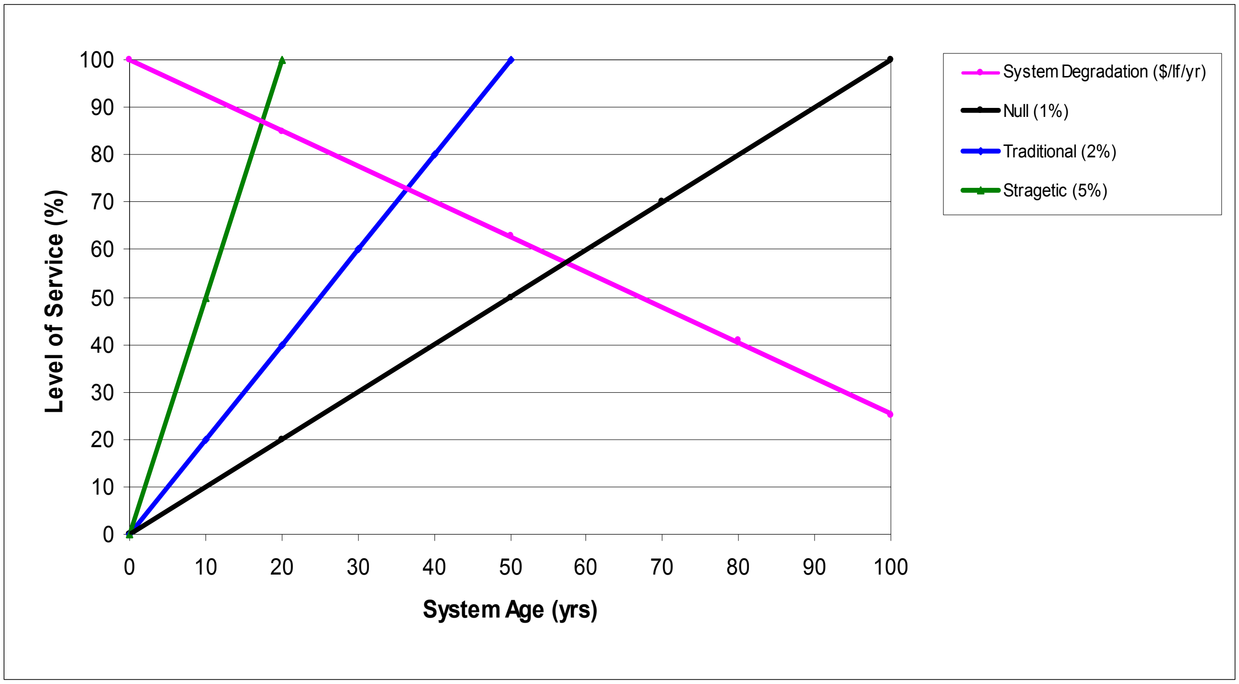
To demonstrate the utilization of the conceptual water infrastructure risk assessment tool the three water infrastructure system risk-sensitive (low, medium, high) decision response alternatives, as described in the above **Table 1**, are defined as follows:

1. **NULL** (Corrective): The decision-maker's risk-sensitivity level is low and selects a RR of 1% which equates to a system MF of 100-years. Then using **Figure 2** below, the y-axis value for the associated r(f) is equal to 25%. Therefore the system p(f) is calculated as 1-0.25 = 0.75.

2. **TRAD** (Preventative): The decision-maker's risk-sensitivity level is medium and selects a RR of 2% which equates to a system MF of 50-years. Then using **Figure 2** below, the y-axis value for the associated r(f) is equal to 65%. Therefore, the system p(f) is calculated as 1-0.65 = 0.35.

3. **STRAT** (Proactive): The decision-maker's risk-sensitivity level is high and selects a RR of 5% which equates to a system MF of 20-years. Then using **Figure 2** below, the y-axis value for the associated r(f) is 85%. Therefore, the system p(f) is calculated as 1-0.85 = 0.15.

Figure 2 The Graphical Representation of the Three Risk-Sensitive Decision Response Alternative Reinvestment Rate (%) assumptions as a Function of the System's Age (Years), Level-of-Service (% Like-New Performance), and Rate of System Degradation.



Source: Source: Nelson, R. E., Hsiung, P. H., and Witt, A. A., *Optimization of Collection System Maintenance Frequency and System Performance*, EPA Cooperative Agreement No. CX-824902-01-0, Washington, DC, February 1999.

Next, the decision-maker sets the level (b) of SM activities and calculates the associated level (0.3-b) of ER activities relative to his/her risk-sensitivity. It is assumed that the more risk-sensitive the decision-maker the higher the level of SM activities within the MR component of the CIP budget. The three water infrastructure system risk-sensitive decision response alternatives with associated levels of SM and ER activity are shown in **Table 2**.

Table 2 The Three Risk-Sensitive Decision Response Alternatives as a Function of the level of Scheduled Maintenance (b), and associated Emergency Repair (0.3-b) Activities within the Maintenance and Repair Component of the Capital Improvement Program Budget.

Decision Response Alternative	SM = b	ER = 0.30 - b
Null (Low Risk-Sensitivity)	0.10	0.20
Traditional (Medium Risk-Sensitivity)	0.20	0.10
Strategic (High Risk-Sensitivity)	0.25	0.05

The level for the SM (b) activities represents the decision-maker's ability to manage the magnitude of adverse budgetary impact by mitigating the expected level ER (0.3-b) activities within the MR component of the CIP budget. In other words, as the probability of system failure increases the level of expected ER activities increases within the MR budgetary component of the CIP Budget.

Finally, using **Equation 1**, as developed under the conceptual water infrastructure system CIP budget assumptions, the total CIP budgetary impact is calculated for each of the risk-sensitive water infrastructure system decision response alternatives:

Total CIP Budgetary Impact =>

$$\textbf{T (\$/yr)} = [p(f)*1.5*(0.3-b)]T + (b)T + 0.5T + 0.2T, \text{ given } 0.0 < b < 0.3 \qquad (1)$$

The conceptual water infrastructure risk assessment tool calculates the affects of the risk-sensitive (low, medium, and high) decision response alternatives on the expected total CIP budgetary outcome. The results of this demonstration of the conceptual water infrastructure risk assessment tool are shown in **Table 3**.

Table 3 The Demonstration Results of the Conceptual Water Infrastructure Risk Assessment Tool for Evaluating the Impact of the Three Risk-Sensitive Decision Response Alternatives on the Expected Total Capital Improvement Budget Outcome.

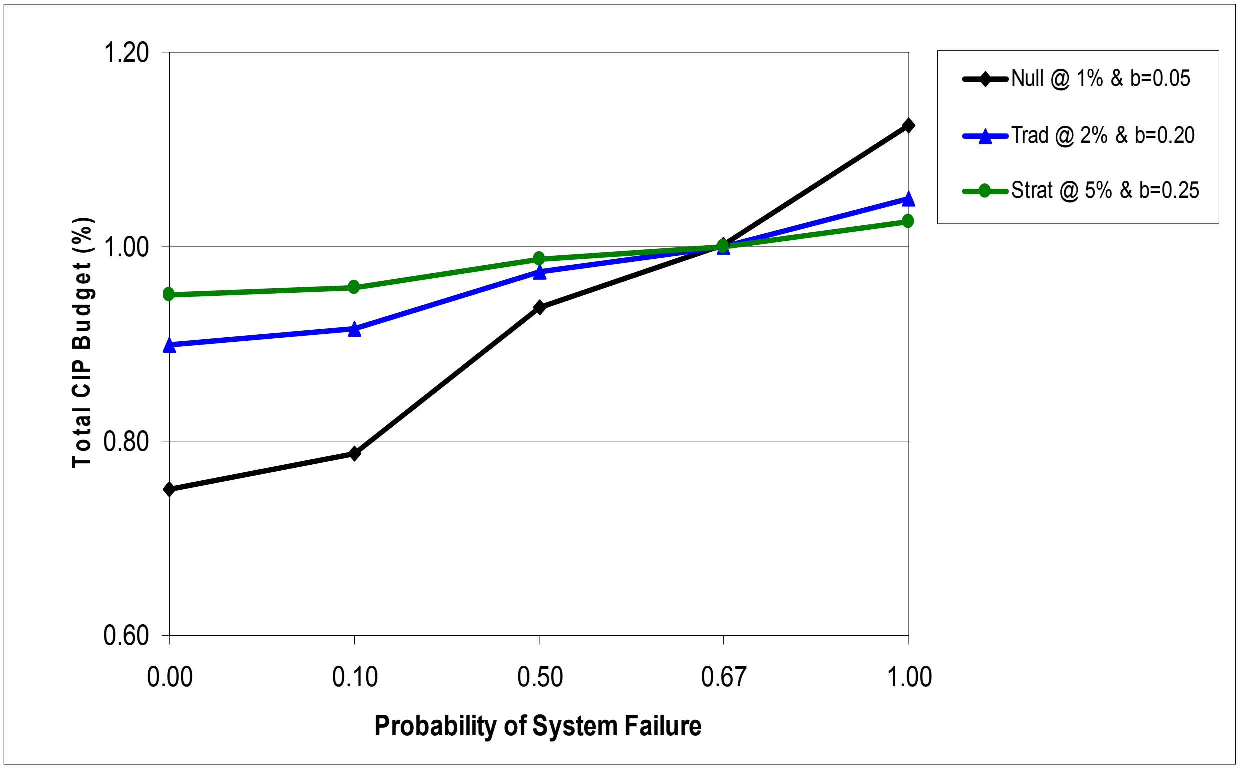
Decision Response Alternative	Rate of Reinvestment	r(f)	p(f)	SM	ER	SR	WQ	CIP Budget Impact
Null (Low Risk-Sensitivity)	1%	25%	0.75	**0.10**	**0.20**	**0.50**	**0.20**	**1.03 x T**
Traditional (Medium Risk-Sensitivity)	2%	65%	0.35	**0.20**	**0.10**	**0.50**	**0.20**	**0.95 x T**
Strategic (High Risk-Sensitivity)	5%	85%	0.15	**0.25**	**0.05**	**0.50**	**0.20**	**0.96 x T**

The results of the above demonstration reveal that the implementation of SM activities as part of the MR component can have a favorable impact on the expected total CIP budget outcome. An important result to note from **Table 3** is that under the conceptual water infrastructure risk assessment tool assumptions increasing the SM level from b=0.20 to b=0.25 imposes very little marginal impact 0.95 to 0.96 on the expected total CIP (T) budgetary outcome. This result suggests that a threshold level exists for which changes to the SM level have insignificant impact on the expected total CIP budgetary outcome. This result coincides with (Lauer, 2001) rule-of-thumb which suggests that the overall MR component costs can be minimized when the following breakdown is utilized: 2/3 of MR component costs are SM activities and 1/3 of MR component costs are ER activities within the total CIP budget.

Intuitively, the drinking water infrastructure decision-maker assumes that as the level of infrastructure reinvestment (RR) increases the level-of-service r(f) increases and the probability of system failure p(f) decreases proportionally. However, in order for the p(f) to decrease the expected level of ER activities to an acceptable level that favorably impacts the expected CIP budgetary outcome, the decision-maker must resolve to manage risk through tradeoffs between the optimal level of ER and SM activities which are financed as a proportion of the MR budgetary component. The conceptual water infrastructure risk assessment tool, which utilizes the **Figure 2** and **Equation 1** infrastructure and budgetary relationships, assumes different SM activity levels for each of the risk-sensitive decision response alternatives under constant level-of-service assumptions clearly offers the decision-maker an objective methodology to proactively mitigate the expected CIP budgetary impacts.

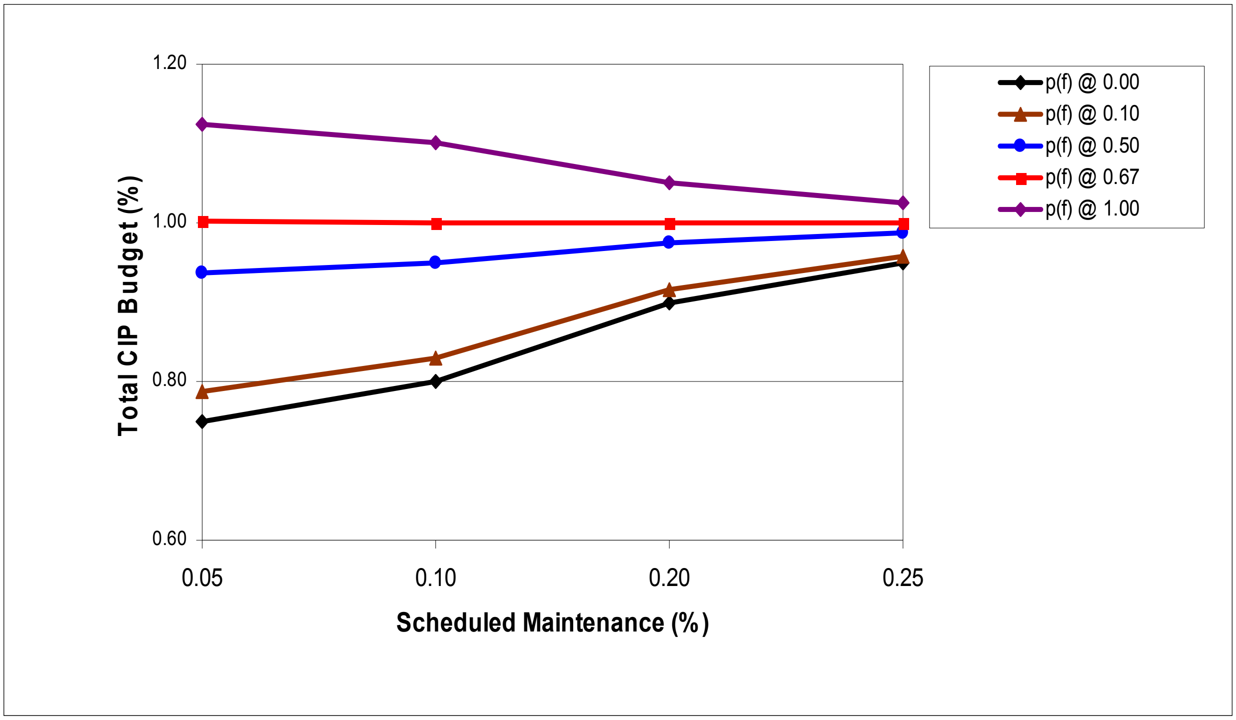
Now suppose that the risk-sensitive decision response alternative and associated level (b) of SM activities are held constant. How will the level-of-service r(f) and associated probability of system failure p(f) affect the expected total CIP budgetary outcome? This sensitivity analysis is graphically displayed in **Figure 3**. The sensitivity analysis results show that under the conceptual water infrastructure risk assessment tool assumptions, the p(f) does not negatively impact the expected total CIP budget outcome until the p(f) exceeds 0.67 indicating that a minimal level-of-service r(f) of 0.33 should be maintained at all times. This phenomenon is explained because as the p(f) approaches unity the impact of the premium rates (1.5 to 2.0) from the expected ER activity costs become more significant thereby offsetting the benefits of the risk-reduction through the SM activities.

Figure 3 The Sensitivity Analysis for the Conceptual Water Infrastructure Risk Assessment Tool showing the Impacts of the Probability of System Failure on the Total Capital Improvement Program Budget for each of the Risk-Sensitive Decision Response Alternatives.



Now suppose the level-of-service r(f) and associated probability of system failure p(f) are held constant across the risk-sensitive decision response alternatives. How will the risk-sensitive decision response alternative and associated level of SM (b %) activities affect the expected CIP budgetary outcome? This sensitivity analysis is graphically displayed in **Figure 4**. The sensitivity analysis shows under the conceptual water infrastructure risk assessment tool assumptions, the impacts for the level of SM activity costs on the expected total CIP budgetary outcome over the complete range the p(f) values as partitioned by the risk-sensitive decision response alternatives. As the level of the SM activities increase in the MR budgetary component, the overall magnitude of the expected CIP budgetary impact stabilizes over the entire p(f) range. This phenomenon occurs because the variability in the stochastic ER activity costs is mitigated by risk-reduction through the SM activities.

Figure 4 The Sensitivity Analysis for the Conceptual Water Infrastructure Risk Assessment Tool showing the impacts of the Level of Scheduled Maintenance Activities on the Total Capital Improvement Program Budget over the complete range the Probability of System Failure values for each of the Risk-Sensitive Decision Response Alternatives.



Under the conceptual water infrastructure risk assessment tool assumptions, the magnitude of the expected total CIP budgetary outcome impacts can be migrated by increasing the level of SM activities within the MR component regardless of the p(f). In the same vain, the magnitude of the expected total CIP budgetary outcome impacts can be migrated by increasing the overall water infrastructure RR regardless of the p(f). Therefore, the decision-maker may elect to take either a pay now or pay later approach to ensure that the appropriate level-of-service is maintained through an adequate reinvestment rate throughout the life of the drinking water infrastructure.

CONCLUSIONS

The purpose of the paper is to demonstrate an objective drinking water infrastructure risk assessment tool for maintaining a desired level-of-service r(f) while managing the expected total CIP budgetary impacts. The objectives of this paper are to: 1) incorporate probability of drinking water infrastructure system failure p(f) into the CIP budgetary analysis process and 2) evaluate the affects of probability of drinking water infrastructure system failure p(f) on the expected CIP budgetary outcome.

The usefulness of the conceptual water infrastructure risk assessment tool was demonstrated by defining three risk-sensitive (low, medium, high) decision response alternatives that are encountered by the typical drinking water service decision-maker. To use the conceptual water infrastructure risk assessment tool the decision-maker manages risk by selecting the RR (%) and determining the associated r(f) from **Figure 2**. Next, the associated probability of system failure is calculated as p(f)=1-r(f). Then, the decision-maker sets the level of SM activities such that ($0.0 \leq b \leq 0.3$) and calculates the associated level of the ER activities as {p(f)x[1.5x(0.3-b)]}. Finally, using **Equation 1**, the expected budgetary impact is determined as a percentage of the total capital improvement (T) budget.

The conceptual water infrastructure system CIP budgetary assumptions extends the maintenance frequency and system performance relationships developed by Nelson, R.E., et al (1999) to the drinking water infrastructure arena. The conceptual water infrastructure system CIP budgetary assumptions extends the utilization of the EPA, (1997) survey average total CIP asset management budgetary breakdown to include the probability of system failure as a risk assessment component in the decision-making process. The conceptual water infrastructure risk assessment tool validates the (Lauer, 2001) rule of thumb that the optimal breakdown of the MR component of the total CIP budget should be 2/3 SM activity costs and 1/3 ER activity costs.

This paper concludes that the drinking water infrastructure level-of-service or system reliability directly affects the probability of system failure which in turn, affects the expected amount of emergency repair activities. The decision-maker can minimize his expected total CIP budgetary impact by maintaining a minimum level-of-service or maximum probability of system failure threshold through the selection of an adequate reinvestment rate. Optimizing the associated tradeoffs between the levels of ER and SM activities within the MR budgetary component will mitigate the adverse impacts of the expected total CIP budgetary outcome. When applied to the risk-sensitive three decision response alternatives, the conceptual risk assessment tool reveals that by selecting an adequate reinvestment rate to ensure an acceptable level-of-service, the decision-maker can anticipate the expected impact on the total CIP budgetary outcome.

Every drinking water infrastructure decision-maker must meet annual budgetary constraints under their respective CIP budgets. The overall drinking water infrastructure system reinvestment rate and associated probability of system failure have a significant impact on the expected total CIP budgetary outcome through the level of scheduled maintenance activities that the decision-maker selects. Drinking water infrastructure decision-makers must use strategic risk management tools as a means to effectively allocate resources. This means developing risk-avoidance positions through the optimal breakdown of corrective, preventative, and proactive maintenance and repair activities within the context of the overall asset management program over the life of the infrastructure system.

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