3-30-2006

Development of A GIS Based Infrastructure Replacement Prioritization System; A Case Study

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Development of A GIS Based Infrastructure Replacement

Prioritization System; A Case Study

by

Brian D. Pickard

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Environmental Engineering
Department of Civil and Environmental Engineering
College of Engineering
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Date of Approval:
March 30, 2006

Keywords: asset, utility, IMS, IMMS, main, rehabilitation, hydraulic, model

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DEDICATION

This project is dedicated to those before me who have built a strong foundation for this project, have willfully supported me during this project regardless of personal sacrifices, and to those having the drive to improve upon this project for the greater good.

ACKNOWLEDGEMENTS

The Tampa Water Department (TWD) has been 100% supportive of this project by providing both tangible and intangible resources. I am particularly thankful to several TWD employees have been particularly beneficial to this project including:

- Harlan Reynolds and Rory Jones who initially introduced me to the potential benefits of utilizing GIS to prioritize water infrastructure improvements. Harlan Reynolds has been particularly helpful in sharing AutoCAD techniques saving me hours of labor and preventing avoidable mistakes.
- Jeff Hough has been extremely helpful by demonstrating methods to integrate MapInfo with AutoCAD as well as demonstrating how queries are performed in the GIS environment.

The Graduate Committee for this project has provided valuable insight and recommendations without making this project unnecessarily burdensome. Dr. Levine in particular has devoted many hours towards project direction, organization and formatting. Dr. Carnahan and Dr. Levine have also greatly assisted in providing administrative guidance in obtaining final approval for this project.

Special Note to the Reader

The original document contains color that is necessary for understanding the data.

The original thesis is on file with the USF library in Tampa, Florida.

TABLE OF CONTENTS

LIST OF TABLES	iv
LIST OF FIGURES	v
NOMENCLATURE	viii
ABSTRACT	x
INTRODUCTION	1
OBJECTIVES	7
LITERATURE REVIEW	8
Infrastructure needs.....	8
Accounting challenges	9
Infrastructure failure costs	10
Water infrastructure replacement.....	11
Asset management	12
Geographic information systems (GIS)	13
Infrastructure condition databases	14
Integrated infrastructure management systems.....	15
METHODOLOGY	17
Phase 1 – Policy decisions	18
Master plan programs	18

Prioritization elements	19
Survey	21
Phase 2 – Data collection, mapping and formatting	22
Data collection	22
Construction costs	24
Phase 3 – Structured queries and database development.....	24
Structured queries	25
Database development	26
Phase 4 – Project prioritization	28
RESULTS	31
Phase 1 – Policy decisions	29
Phase 2 – Data collection, mapping and formatting	30
Data collection	32
Construction costs	42
Phase 3 – Data extraction.....	42
Structured queries	44
Database development	45
Phase 4 – Project prioritization and master planning.....	45
DISCUSSION	49
Prioritization system	49
Integrated database.....	50
Database applications.....	51

Condition indicators.....	51
Resource management	52
CONCLUSION.....	54
ENGINEERING IMPLICATIONS	56
Procedural changes	56
Improved resources to support decisions	59
ADDITIONAL RESEARCH.....	60
REFERENCES	64
BIBLIOGRAPHY	67

LIST OF TABLES

Table 1:	Comparison of four master plan programs that were developed to address particular issues related to a certain type of pipe	19
Table 2:	Summary of data for the TWD service area and the time frame of data availability.....	20
Table 3:	Matrix linking master plan programs and prioritization elements as determined by survey of TWD policy makers.....	21
Table 4:	Description of attribute data variable types used for database manipulation ..	23
Table 5:	Overlay of benefit units of each prioritization element with master plan combinations to allow for calculation of benefit to cost ratios	28
Table 6:	Results of Tampa Water Department survey to determine benefit factor values	31
Table 7:	Cost factors utilized for various nominal pipe diameters ranging from 4-36 inches	42
Table 8:	Dimensions of buffer regions for each type of prioritization element.....	44
Table 9:	Relative annual changes in water main breaks, service line breaks, pressure complaints and water quality complaints.....	47
Table 10:	Benefit unit based costs utilized in the prioritization process.....	47

LIST OF FIGURES

Figure 1:	The Tampa Water Department service area covers a 211 square mile area	1
Figure 2:	The illustrated planned infrastructure project is contained within a buffer region. The buffer region associates planned projects with the location of prioritization elements	4
Figure 3:	Area of water distribution system with a proposed hydraulic looping project. The buffer region dimensions are increased to encompass a hydrant for system flushing	5
Figure 4:	Area of water distribution system with an unlined water main causing red water complaints. The buffer region dimensions are increased to encompass the complaint locations that resulted from the unlined water main	6
Figure 5:	Design overview of research project.....	17
Figure 6:	Example of SQL script utilized to associate prioritization elements with planned projects	26
Figure 7:	Example of the “count” command in MS Access to combine databases. Note the query is written to include all planned projects in the results table	27
Figure 8:	Total Length of Rehabilitation & Replacement Projects by Type (miles)	33
Figure 9:	Relative location of various types of planned rehabilitation, replacement and improvement projects within the TWD service area	34

Figure 10: Water main break locations within the TWD service area	35
Figure 11: Service main break locations within the TWD service area	36
Figure 12: Water main flushing locations within the TWD service area	37
Figure 13: Water quality complaint locations within the TWD service area	38
Figure 14: Water pressure complaint locations within the TWD service area.....	39
Figure 15: Proposed fire hydrant locations within the TWD service area	40
Figure 16: Results of water age modeling within the TWD service area.....	41
Figure 17: Estimated construction costs for planned TWD rehabilitation, replacement and improvement projects.....	43
Figure 18: Visual representation of planned project buffer regions and prioritization elements.....	45
Figure 19: Comparison of average quantities of prioritization element occurrences amon planned rehabilitation, replacement and improvement projects	46
Figure 20: Results yield benefit to cost ratios ranging from 0.35 to 0.00. A relatively small portion of projects have benefit to cost ratios greater than 0.10.	48
Figure 21: Comparison of existing rehabilitation and replacement funding levels and the ideal funding levels as determined by the top 10% of prioritized projects determined by this project.....	53
Figure 22: Procedures are needed to continually maintain geospatial databases when customer driven projects and capital projects occur simultaneously. The process flow diagram above shows input from several functional groups are needed to accomplish this task.....	58

Figure 23: Example of inaccurate assignments of prioritization elements due to the	
use of buffer regions.	61

NOMENCLATURE

Benefit factor: A policy generated dimensionless value expressing a relative importance to a water utility.

Benefit unit: A cost associated with a future occurrence of a prioritization element. This value is determined by utilizing tangible costs in conjunction with policy decisions.

CMMS: Computerized Maintenance Management System

GIS: Geographic Information System

IMS: Infrastructure Management System

IIMS: Integrated Infrastructure Management System

LRS: Linear Referencing System

Master plan program: A group of projects expected to accomplish a specific goal having value to a water utility.

Prioritization element: A category of spatial data that can have either tangible or no tangible value to a water utility.

R&R: Rehabilitation and replacement

TWD: Tampa Water Department

**Development of A GIS Based Infrastructure Replacement
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ABSTRACT

Maintenance, repair, and replacement of transmission mains and distribution system piping is expected to cost approximately \$75 billion over the next two decades to ensure that public water systems are capable of providing the United States with safe drinking water. However, there is a significant gap between the funds available and the projected costs of infrastructure replacement or rehabilitation. Infrastructure Management Systems (IMS) have been developed to assist utilities and decision-makers in determining how to allocate resources for infrastructure. This project utilizes the Tampa Water Department (TWD) as a case study to develop a tool for prioritizing infrastructure replacement.

TWD is responsible for managing over 2,240 miles of pipeline. Building booms in the 1920s and 1950s have inadvertently resulted in a significant need to replace or rehabilitate pipelines due to the aging of the overall water supply infrastructure. To address this problem, TWD is taking the first steps in applying IMS to transmission and distribution pipelines. Currently, approximately 500 miles of water mains have been slated for replacement or rehabilitation. The TWD has a GIS that has been used to map and integrate information on main breaks, service line breaks, customer complaints and

modeled water age. Information on fire hydrant spacing and line flushing dates are also integrated into the GIS.

Following development of the GIS based infrastructure replacement prioritization system, approximately 3,000 pipe segments were identified and queries were performed to help develop cost to benefit analyses. The results were used to develop a prioritized list of potential capital projects and incorporate the time value of money and event forecasting. The GIS was also used to develop indicators of the overall infrastructure condition. From this analysis it was possible to develop an approach to categorize projects and identify the resources needed to address high priority problems associated with undersized mains, unlined cast iron mains, asbestos cement mains, and hydraulic looping projects.

As water infrastructure rehabilitation and replacement needs increase in the future, the need for adaptable methods to prioritize capital spending will also increase. This study has demonstrated the ability to prioritize long-term and short-term infrastructure projects using a GIS platform in conjunction with databases and spreadsheets.

INTRODUCTION

The Tampa Water Department (TWD) administers the City of Tampa's water utility. The service area covers an area 211 square miles in size and serves approximately 510,000 residents. The TWD service area is shown in Figure 1.

Figure 1. The Tampa Water Department service area covers a 211 square mile area.

The City of Tampa water supply system consists of supply, treatment, storage, pumping, transmission, distribution and service. Treated water is distributed to fire mains, 12,543 fire hydrants and 124,371 meters. The transmission system consists of 268 miles of pipe having a nominal diameter of 16 inches to 54 inches. The distribution system consists of more than 2,007 miles of pipe ranging in size from 2-inch to 14-inch. Pipes are made of cast iron (CI), ductile iron (DI), asbestos cement (AC), high-density polyethylene (HDPE), and polyvinyl chloride (PVC).

The Tampa Water Department recognizes the need for planning infrastructure rehabilitation, replacement and improvement. Master plans identify vulnerable portions of the service area where water system problems are most likely to occur and elucidate preventive measures to maintain service levels. These plans are used extensively for budgeting and planning purposes. This thesis is focused on four TWD master plans.

1. Undersized Main Replacement (UMR) Master Plan
2. Unlined Cast Iron Main Replacement (UCIMR) Master Plan
3. Hydraulic Looping System Master Plan
4. Asbestos Cement Main Replacement (ACMR) Master Plan

Approximately 2,900 infrastructure related projects are identified by the master plans with an approximate construction cost of \$390 million in 2006 dollars. However, only approximately \$6 million is available on an annual basis. Thus, a mechanism is

needed to prioritize rehabilitation, replacement and improvement projects based on a rational basis.

One tool that can be applied to project prioritization is Geographic Information Systems (GIS) software. Information on infrastructure condition indicators such as main breaks, service main breaks, customer complaints and water age are collected by the TWD. However, these data are not compiled in a way that allows for a comprehensive view of historical trends in infrastructure rehabilitation, replacement and improvement projects. GIS software can be used to integrate these databases into a single location thereby allowing for prioritization with a goal of providing improved service to rate payers.

The starting point is to establish prioritization elements—a category of spatial data that has tangible or no tangible value to a water utility. Buffer regions are then established surrounding planned rehabilitation, replacement and improvement projects. A buffer region is necessary because the prioritization element occurrences are not entered into GIS software at exactly the same location as the planned projects. Typically, databases containing information such as main breaks, customer complaints, and flushing locations contain addresses not coordinates. These address-based databases are linked to a database containing the coordinates for all addresses within the service area. Because the assigned coordinates for each address is not linked to the water main serving the address, the size of the buffer region is established so the occurrence of a prioritization element can be linked to a planned project. This concept is illustrated in Figure 2.

Figure 2. The illustrated planned infrastructure project is contained within a buffer region. The buffer region associates planned projects with the location of prioritization elements.

For some prioritization elements, it may be necessary to increase the buffer region dimensions. For example, it is important that the proposed region generated around a planned hydraulic looping project contains the flush point locations. However, projects intended to eliminate flushing requirements are not necessarily near hydrant locations that can be used for water main flushing. An example of increasing the buffer region dimension is shown in Figure 3.

Figure 3. Area of water distribution system with a proposed hydraulic looping project. The buffer region dimensions are increased to encompass a hydrant for system flushing.

It is also useful to increase buffer region dimensions when associating customer complaints with planned infrastructure projects. Pressure or water quality complaints can be caused by pipes located at different locations than the complaint itself. Red water, a common water quality concern related with unlined pipe, can originate on one street and flow into other locations. An example of how pipes can cause water quality issues in a larger area is shown in Figure 4.

Figure 4. Area of water distribution system with an unlined water main causing red water complaints. The buffer region dimensions are increased to encompass the complaint locations that resulted from the unlined water main.

The use of GIS and appropriate buffer regions allows for linking different information sources in a format that can allow for prioritization of rehabilitation, replacement and improvement projects. This integrated approach enables a utility to prioritize projects based on a hierarchy of factors with the ultimate result of providing improved service and rate stabilization to water customers.

OBJECTIVES

The purpose of this project is to investigate the feasibility of applying GIS to prioritize water infrastructure rehabilitation, replacement and improvement projects for the City of Tampa Water Department. There are four objectives.

1. Convert existing infrastructure replacement master plans into an electronic format incorporating attribute data to permit geospatial analysis.
2. Consolidate existing databases including main break reports, service main break reports, customer complaint logs and flushing reports into a common format that can be utilized by GIS software.
3. Perform geospatial analyses to determine a benefit to cost ratio for each planned project based on a prioritization matrix agreed upon by Tampa Water Department policy makers.
4. Prepare a combined, prioritized infrastructure replacement master plan and make appropriate budget recommendations.

LITERATURE REVIEW

Infrastructure needs

Most water utilities place most available resources on distribution system expansions as opposed to ensuring the sustainability of existing systems. Inadequate funding and few support technologies within the United States contribute to the current need to address aging water infrastructure. (Vanier, Danylo and Ville de Montreal Finance Department, 1998) This need is quantified in two reports to congress prepared by the United States Environmental Protection Agency (USEPA).

A 1997 report prepared by the USEPA includes the results of a water utility survey including 4,000 community water systems. Conducted in 1995 and 1996, the survey addresses infrastructure needs for community water systems to comply with the Safe Drinking Water Act. Although the 1997 USEPA report does not estimate replacement and rehabilitation needs, it does estimate the percentage of need related to water distribution and transmission piping is 56 percent of the total \$138.4 billion 20-year need. (USEPA, 1997) A second water utility survey conducted in 1999 by the USEPA shows the total infrastructure need is likely underestimated by the 1997 Drinking Water Infrastructure Needs Survey. The 1999 survey indicates the total existing need to comply

with the Safe Drinking Water Act, excluding rehabilitation and replacement needs is \$150.9 billion. (USEPA, 2001)

Two reports have compared current spending levels with the estimated funding required to provide a safe drinking water supply. This difference in funding levels is known as the water infrastructure funding “gap.” The Clean Water and Drinking Water Infrastructure Gap Analysis estimates an annual \$12 billion funding deficiency exists within the United States. (USEPA, 2002) Another report prepared by the Congressional Budget Office estimates the gap to be between -\$0.2 billion and \$8.3 billion annually depending on future revenue stream increases. (Congressional Budget Office, 2002)

Water customers currently receive an excellent value when compared to other utilities. Water, sewer, and solid waste charges combined cost customers less than 0.8 percent of total household expenditures. When compared to 2.4 percent and 2.1 percent for electric and telecommunication expenditures respectively, the costs of water, sewer, and solid waste are small. (Beecher, 2001)

Accounting challenges

One cause of the funding gap is due to the method water utilities account for buried infrastructure. Although water transmission and distribution systems account for approximately 80 percent of assets owned by a water utility (Grablutz and Hanneken, 2001), they are excluded from the general fund regardless if they have been purchased with general fund dollars. This is because transmission and distribution system piping is

not considered to be a means to meet debt service or obtain revenue. Because this infrastructure is not considered a general fund asset, the effect of the depreciation is often overlooked when analyzing the financial strength of water utilities. (Lemer, 1998) This method does not encourage enacting methods to assure buried water infrastructure remains a sustainable asset.

Infrastructure failure costs

“The real value of infrastructure lies, however in the services it provides, its enabling role in supporting other economic and social activities.” (Lemer, 1998) Thus the value of water main infrastructure does not equal the replacement cost and can be both tangible and non-tangible.

Efforts to prioritize infrastructure replacements and improvements are historically based on economic approaches. Recent literature suggests it is appropriate to also include non-tangible values. The Decision Support System and the Grand Central Model, developed by the American Water Works Association Research Foundation (AwwaRF) include operational, social, and other factors with non-tangible value. (Zhang, 2004)

Another AwwaRF project classifies costs as follows:

“Costs Incurred Directly by the Utility

1. Administrative and legal costs of damage settlements
2. Lost product costs
3. Public safety costs

4. Repair and return to service costs
5. Service outage mitigation costs
6. Utility emergency response costs

Routine (high incidence-low impact) Social Costs

1. Access impairment and travel delay costs
2. Customer outage and substitution costs

Low Incidence/High Impact Social Costs

1. Health damages
2. Direct damage at the point of failure
3. Waterborne illness introduced as a result of failure
4. Property damages
5. Reduced fire fighting costs”

The sum of all costs above is referred to as the Total Societal Cost. Perhaps the greatest challenge associated with incorporating non-tangible costs is assigning corresponding numerical values. This causes difficulty in generating a one size fits all model. (Hasan, 2002)

Water infrastructure replacement

Literature recommends utilities to fund maintenance and repairs at approximately 2 to 4 percent of their asset replacement value. (Vanier, Danylo, and Ville de Montreal Finance Department, 1998) Approximately \$1.74 billion is spent annually in

the United States for water infrastructure rehabilitation or replacement. Various techniques utilized include cleaning and lining, pipe lining and slip lining. (Weston, 2002) Most utilities have not yet experienced the financial effects of replacing large quantities of infrastructure. However, research indicates water infrastructure is maturing, and a new era is on the horizon known as the “Replacement Era.” (GAO and AWWA, 2001) The public will ultimately fund these replacements if the current level of service is expected to remain unchanged. (Neukrug, 2002)

Asset management

Asset management is “the process of keeping track of and deploying the public’s capital.” (Lemer, 1998) Effective asset management programs contain tools for “minimizing costly emergency repairs, making strategic funding decisions designed to keep rates low and bond ratings high, measure the efficiency and effectiveness of maintenance programs, defending and protecting cash reserves for future asset R&R expenditures and meeting new accounting and environmental regulatory standards. (Anderson and Smith, accessed 2006) One element that assists in accomplishing the above goals is project prioritization. Effectively prioritizing projects can maximize returns, stabilize rates, decrease bond interest rates and enhance communication among stakeholders. (Nagel and Elenbass, 2006) However, the quantity of buried water main infrastructure makes prioritizing projects extremely problematic. (AWWA, 2004)

AwwaRF recommends considering “the age and material of pipe, number and frequency of main breaks, reduction in hydraulic capacity, water quality problems, joint types and related joint leaks, strategic considerations such as pavement overlay programs, soil conditions and pipe depth, customers that cannot have their service interrupted, number and frequency of [fittings] and [quantity] of service connections” when prioritizing the replacement of buried water main infrastructure. (Weston, 2002)

Utilizing factors such as these can result in efficiency savings. The key to effective asset management is considering as many relevant factors as possible when making maintenance and replacement choices. (CBO, 2002)

Geographic information systems (GIS)

Considering various factors for a large number of water main infrastructure projects inherently involves vast data quantities. Managing this data is of primary importance and requires a relatively large effort to perform this task sufficiently. (Matichich, Allen and Allen, 2006)

One critical type of data management that must be accomplished to effectively prioritize water infrastructure projects is associating attribute data to a geographic location. This powerful tool is becoming increasingly popular with governmental agencies. (Lemer, 1998)

The Seattle Public Utilities utilizes GIS in a “Sewer Pipe Risk Model” to prioritize sewer infrastructure replacements (Martin, 2005) and the “PIPES” system to evaluate water pipelines. The PIPES system combines a criticality rating and a

deterioration rating to effectively manage infrastructure rehabilitation and replacement. (Lim and Pratti, 1997) The St. Louis County Water Company uses a similar method by utilizing GIS to compare a water main condition database with historical water pipeline work orders. Direct costs are calculated from the water main condition database and indirect costs are estimated to be approximately 20 to 40 percent of direct costs. (Grablutz and Hanneken, 2001)

Infrastructure condition databases

Although GIS is becoming increasingly popular, the majority of water utilities do not utilize software packages designed to facilitate decisions regarding pipe rehabilitation or replacement. (Weston, 2002) However, there currently exists many commercialized computerized maintenance management systems (CMMS). These systems are extremely capable in storing data associated with infrastructure condition, but are historically not perfect with respect to water distribution system life cycle analysis, risk analysis, and project prioritization. (Vanier, Danylo and Ville de Montreal Finance Department, 1998) Several of these packages are tailored to a specific infrastructure type, such as water distribution system infrastructure. (Lemer, 1998) The KANEW model in particular helps asset managers address the timing of infrastructure replacement on a macro-scale level. The KANEW model does not address individual pipe segments. (Grablutz and Hanneken, 2001) Asset management software and infrastructure condition databases are beginning to incorporate probabilistic failure, the time value of money and the balance

between theoretically ideal replacement times and real world budget limitations. (Nagel and Elenbass, 2006)

Integrated infrastructure management systems (IMMS)

Infrastructure Management Systems (IMS), an element of an asset management program, are currently utilized separately for each infrastructure class—e.i. water, sewer, storm water and transportation. The first IMS originated with pavement management systems (PMS) and bridge management systems (BMS). A switch in management paradigms to consider each infrastructure class collectively as part of an Integrated Infrastructure Management System (IIMS) is on the horizon. (Ferreira and Duarte, 2005) Lemer proposes IIMS due to inefficiencies associated with considering each infrastructure class independently.

“The inefficiencies are widespread and easy to see: jammed traffic on roads designed to carry only a fraction of the current demand, newly-resurfaced city streets ripped open to repair aged subsurface pipes, news media expressing outrage that traffic lanes must be closed for maintenance or that basements are flooded.” (Lemer,1998)

It is clear individual infrastructure classes are closely integrated and the overall cost to the rate paying public can be reduced by addressing each infrastructure class collectively. An IIMS can be designed to combine information from multiple platforms or establish a single platform reducing the difficulties in merging multiple data formats.

Regardless of the chosen method, an IIMS should consider each infrastructure class when facilitating asset management decisions. (Ferreira and Duarte, 2005)

METHODOLOGY

This project is organized into four phases. Phase 1 is designed to establish items of value for project prioritization. The data to support the items of value identified during Phase 1 are gathered, mapped and formatted in a geospatial format incorporating attribute data during Phase 2. During Phase 3, the geospatial data are associated with planned projects in a single database. The database created during Phase 3 is utilized in conjunction with items of value identified in Phase 1 to prioritize planned projects during Phase 4. Detailed methods for each phase are included below. The interrelationships among the four phases is illustrated in Figure 5.

Figure 5. Design overview of research project.

Phase 1 – Policy decisions

Prioritizing infrastructure rehabilitation or replacement projects inevitably involves policy decisions. Master plan programs are created to address certain issues often related to a particular type of pipe. These issues can also be called prioritization elements because the extent that each issue is present with each planned project can be used as a basis to prioritize the projects within master plan programs. This project surveys water utility policy makers to determine the importance of each prioritization element for each master plan program.

Master plan programs

The Tampa Water Department has historically categorized rehabilitation, replacement or improvement projects in four categories as defined in Table 1.

Table 1. Comparison of four master plan programs that were developed to address particular issues related to a certain type of pipe.

Master Plan Program	Definition
Undersized Main Replacement	These projects consist of the replacement of water mains having a diameter of less than 6 inches. Much of this pipe is galvanized which has decreased C-factors due to tuberculation. Water mains of these sizes are not capable of providing fire flows meeting modern standards and are considered a public health and safety concern.
Unlined Cast Iron Main Replacement	Iron and other metals can leach out of unlined pipe creating tuberculation. Excessive tuberculation is associated with red water and poor C-factors. Red water leads to customer complaints and low C-factors ultimately result in inadequate fire flow. This pipe is replaced with lined ductile iron pipe under this program. Due to metal leaching this type of pipe is also susceptible to structural failures leading to water main breaks.
Hydraulic Looping System Projects	Without flushing, dead end water mains cause increased water ages ultimately leading to customer complaints. This type of project “loops” dead end mains together to facilitate water flow and decrease water age. These projects also increase available fire flow and decrease costs associated with water main flushing.
Asbestos Cement Main Replacement	Although not considered a public safety concern from a water supply standpoint, this pipe is extremely brittle and breaks easily. Tapping this type of pipe also requires specific procedures to prevent exposure to airborne asbestos. These projects replace asbestos cement pipe eliminating maintenance and environmental concerns.

Prioritization elements

Because the age of the infrastructure and the pace of development, 2,886 projects have been identified that can be categorized as rehabilitation, replacement or improvement projects. To prioritize these projects and allocated resources, it is necessary to define specific items of value. These items of value, or *prioritization elements*, are

defined as a type of spatial data that can have tangible or intangible value to water utility rate payers. The prioritization elements that have a geospatial component available for this project are listed in Table 2.

Table 2. Summary of data for the TWD service area and the time frame of data availability.

Geospatial Component	Time Frame Available for Analysis
Water Main Breaks	FY 2001 through FY 2005
Service Main Breaks	FY 2001 through FY 2005
Approximate Water Age	FY 2004 demand allocation
Flushing logs	FY 2004 and FY 2005
Customer Pressure Complaints	FY 2001 through FY 2005
Customer Water Quality Complaints	FY 2001 through FY 2005

Undersized mains are not sized to provide fire protection. The location of additional fire hydrants necessary to meet the fire hydrant spacing requirement of the utility can be used as a prioritization element for evaluating undersized mains. The TWD policy is for fire hydrant spacing is “fire hydrants shall be no more than 450 feet apart when measured along streets or acceptable access ways. For dead-end cul-de-sacs, fire hydrants shall be placed no more than 450 feet from the rear of the farthest structure” (TWD, 2002). Currently, compliance with this standard is assessed through a tedious manual technique. Proposed new hydrant locations are divided into two categories:

those that can be installed without water main improvements and those that will need water main improvements to achieve available flows for fire protection.

Survey

Survey participants including the TWD director, deputy director, chief engineer, chief planning engineer and chief design engineer are asked to rank the importance of various prioritization elements for each type of master plan program. Each participant is instructed to assign a weighted value to each of the prioritization elements in each of the master plan programs on a percentage basis. The data is compiled to yield a prioritization matrix that can be presented to utility policy makers. The survey itself takes the form of Table 3.

Table 3. Matrix linking master plan programs and prioritization elements as determined by survey of TWD policy makers.

Master Plan Program	Percent Importance						
	Water Main Breaks	Service Main Breaks	Quantity of Proposed New Hydrants	Modeled Water Age	Quantity of Flushing Visits	Water Pressure Complaints	Water Quality Complaints
Hydraulic Looping							
Undersized Mains							
Unlined Cast Iron							
Asbestos Cement							

Phase 2 – Data collection and construction costs

Data describing planned projects and prioritization elements are collected and formatted so the various databases can be effectively utilized for a common purpose. The geospatial component of the projects and prioritization elements is then determined so GIS analysis can be performed. Construction costs are estimated for each nominal pipe diameter to aid in later analysis.

Data collection

To develop the framework for this project, it is necessary to convert master plan programs from a hardcopy format to an electronic format with geospatial components and attribute data. When converting the individual pipe segments found in each master plan program to an electronic format, it is critical that an appropriate coordinate system is used. For example, the coordinate system used by TWD is the USA NAD83, Florida State Plane, West Zone, US-foot coordinate system. Attribute data must be attached to each planned project to allow for information retrieval by personnel not utilizing GIS software. The attribute data attached as part of this project are given in Table 4.

Table 4. Description of attribute data variable types used for database manipulation.

Attribute Data	Description	Data Type
Master plan program	Type of project (undersize main, hydraulic looping, etc.)	Text String
Proposed nominal pipe diameter	Pipe diameter listed in inches	Integer
"Along" Street	Common street name parallel to the planned project.	Text String
"From" Street	Street intersecting the "Along Street" at the beginning boundary of the planned project	Text String
"To" Street	Street intersecting the "Along Street" at the ending boundary of the planned project	Text String
Associated atlas page	TWD utilizes a numbered atlas system based on a one mile grid pattern	Text String
Water age	Estimated average day time elapsed from the treatment facility to a specific location in the distribution system	Text String or Real Number
Pipe installation date (if available)	Calendar year when the pipe that is to be replaced by a planned project was installed	Integer

In each case, Autodesk Land Desktop 2006 is used to enter data and define the attribute data.

Water age is determined by running an average day extended period simulation in a hydraulic modeling software package. The simulation length should be the maximum water age expected in the system plus a large safety margin. The run time length is checked for appropriateness by comparing the water age at several simulation intervals towards the end of the simulation to assure the calculated water age values remain constant. The model links and nodes are then color coded by calculated water age at the final simulation time increment. Regions containing calculated water age increments are then created in AutoCAD and the water age increment is then associated with each planned rehabilitation, replacement or improvement project as attribute data.

Due to the relative importance of proposed new hydrants on planned undersized main projects, a fire hydrant placement master plan is created as part of this project. The proposed fire hydrant locations were divided into two broad categories. The first category is proposed fire hydrants that can be installed with no water main improvements. The second category is proposed fire hydrants installations that would require water main improvements. Proposed fire hydrant locations are determined utilizing TWD fire hydrant spacing criteria.

Construction costs

Estimated construction costs on a per foot basis are calculated for various pipe sizes to allow later calculations of estimated project costs. An estimated cost per foot is determined for each nominal pipe diameter for both grassed and paved areas. A single average cost per linear foot can then be estimated from historical utility data on the percentages of water mains being installed under street pavement or within grassed areas.

Phase 3 – Structured queries and database development

Once all data is collected and formatted into a geospatial database, GIS is utilized to extract the occurrence of each prioritization element for each planned project. Once prioritization element occurrences are linked to a planned project, the resulting databases are then combined into a master database suitable for the prioritization process.

Structured queries

Once prioritization elements and individual projects are combined into an electronic format in a common coordinate system, data can be extracted in accordance with the prioritization matrix developed in Phase 1 using a GIS software package. First, the data collected in Phase 2 are imported into MapInfo Professional keeping the coordinate systems consistent. Appropriate buffer region dimensions are then established and a reference key for each planned replacement, rehabilitation or improvement project is then added to the corresponding buffer region. Once the identifying key is generated, it is important to not change the table of planned capital projects midstream during the prioritization process. Otherwise the database will not associate prioritization elements with the correct planned capital project.

The buffer region table with the desired buffer length is then opened simultaneously with the prioritization element of interest. A Structured Query Language (SQL) script is then written to select all occurrences of a prioritization element within each of the planned capital project buffer regions. An example of how this SQL script is written in MapInfo is shown in Figure 6.

Figure 6. Example of SQL script utilized to associate prioritization elements with planned projects

Database development

The results of this query are then exported to an Access database for further analysis.

Because there may be more than one occurrence of a prioritization element within the associated buffer region for each planned capital project, it is necessary to employ the

“Count” command in Access to determine the number of prioritization element occurrences for each planned capital project. An example of an MS Access query is shown in Figure 7.

Figure 7. Example of the “count” command in MS Access to combine databases. Note the query is written to include all planned projects in the results table.

After obtaining the number of occurrences for each planned project, the identifying key is then used to generate a single table containing all planned capital projects with the corresponding number of occurrences for each prioritization element. The summary table provides input for the prioritization matrix generated in Phase 1 (See Table 3).

Phase 4 –Project prioritization

The combined database containing each prioritization element (main breaks, service main breaks, etc.) for each planned capital project is then evaluated from the perspective of projected financial benefit of proceeding with each planned capital project. The prioritization matrix developed in Phase 1 is applied to determine a cost for each occurrence of a prioritization element, or *benefit unit*. The benefit unit for each master plan program is determined based on the developed prioritization matrix and the prioritization element having the greatest tangible value. A table of benefit units is created as shown in Table 5.

Table 5. Overlay of benefit units of each prioritization element with master plan combinations to allow for calculation of benefit to cost ratios.

Master Plan Program	Cost of Prioritization Element Occurrences (Benefit Units)						
	Water Main Breaks	Service Main Breaks	Quantity of Proposed New Hydrants	Water Age	Quantity of Flushing Visits	Water Pressure Complaints	Water Quality Complaints
Hydraulic Looping	[\$ per break]	[\$ per break]	[\$ per hydrant]	[\$ per age increment]	[\$ per visit]	[\$ per complaint]	[\$ per complaint]
Undersized Mains	[\$ per break]	[\$ per break]	[\$ per hydrant]	[\$ per age increment]	[\$ per visit]	[\$ per complaint]	[\$ per complaint]
Unlined Cast Iron	[\$ per break]	[\$ per break]	[\$ per hydrant]	[\$ per age increment]	[\$ per visit]	[\$ per complaint]	[\$ per complaint]
Asbestos Cement	[\$ per break]	[\$ per break]	[\$ per hydrant]	[\$ per age increment]	[\$ per visit]	[\$ per complaint]	[\$ per complaint]

The net present value (NPV) of projected prioritization element occurrences during the next 20 year planning period is computed based on an assumed discount rate

and a projected rate in water main construction cost increases. Predicting future occurrences is accomplished by determining the average annual increase of prioritization element occurrences for all planned capital projects. The average increase is then multiplied by the number of years into the future, and added to the historical average number of occurrences for each planned capital project. If sufficient historical data are available, an individual projection can be applied to each planned capital project to compensate for errors associated with the linear extrapolation that may not accurately reflect the expected times a particular asset will fail. More rigorous models predicting pipe failure can also be incorporated into this project at this step in the prioritization process. The net present value of the benefit associated with preventing the occurrences of a prioritization element is then determined.

Equation (1) can be used as a method to determine the total benefit of each prioritization element.

$$B_y^i = k_y^x \sum_{j=0}^{n-yrs} \{NPV(BU_y^x N_y)\} \quad (1)$$

where

B_y^i = benefit of prioritization element y for project i, [=] dollars

k_y^x = benefit factor of prioritization element y in master plan program x, policy driven

BU_y^x = benefit unit for prioritization element y in master plan program x, [=] $\frac{\text{dollars}}{\text{occurrence}}$

N_y = quantity of prioritization element y occurrences during year j

Once the individual benefits of each prioritization element are calculated, a net benefit factor can be calculated for each project from Equation (2).

$$B^i = \sum_{all\ y} B_y^i \quad (2)$$

where

B^i = Net benefit of project i

Based on the estimated cost per foot, the construction cost of each planned capital project, C^i , is then estimated. Once the net benefit and construction cost for each planned improvement project are determined, a ratio can be established to prioritize projects as defined in Equation (3).

$$Prioritization\ Ratio = \frac{B^i}{C^i} \quad (3)$$

The database is then sorted by the prioritization ratio to obtain a prioritized list of planned capital projects.

RESULTS

Results for each of the four project phases are included below. Generally, the established methodology shows to be effective for prioritizing planned capital projects within the TWD service area.

Phase 1 – Policy decisions

A survey conducted among Tampa Water Department policy makers including the director, chief engineer, chief design engineer, chief planning engineer, and a planning engineer determines *benefit factors* to be applied in a cost to benefit prioritization methodology. Survey results are shown in Table 6.

Table 6. Results of Tampa Water Department survey to determine benefit factor values.

Master Plan Program	Water Main Break	Service Main Break	Quantity of Proposed New Hydrants	Modeled Water Age	Quantity of Flushing Visits	Water Pressure Complaint	Water Quality Complaint
Hydraulic Looping				10%	70%	10%	10%
Undersized Mains	30%	10%	50%			10%	
Unlined Cast Iron	50%	10%	10%			20%	10%
Asbestos Cement	80%	10%	10%				

Phase 2 – Data collection and construction costs

The specified methodology for collecting data and establishing construction costs adequately describes the steps necessary to allow for later GIS analysis. Results of the data collection and the determination of estimated capital costs are described below.

Data collection

Planned rehabilitation and replacement projects are successfully converted to a geospatial format utilizing the USA NAD83, Florida State Plane, West Zone coordinate system. This conversion involves 2,886 projects consisting of 495 miles of planned water main improvements. Attribute data including the master plan program, proposed nominal pipe diameter, street in which the project is located, beginning and ending streets defining the project boundary, reference atlas page, and the approximate water age at the project location are incorporated for each planned project. The total length of planned rehabilitation, replacement and improvement projects for each master plan category is shown in Figure 8.

Total Length of Rehabilitation & Replacement Projects by Type (miles)

Figure 8. Pie chart comparing quantity of planned TWD rehabilitation, replacement, and improvement projects (HLS = hydraulic looping system, ACMR = asbestos cement main replacement, UMR = undersized main replacement, UCIMR = unlined cast iron main replacement)

The relative locations of planned capital improvement projects are shown in Figure 9.

Figure 9. Relative location of various types of planned rehabilitation, replacement and improvement projects within the TWD service area.

Prioritization elements specified in Table 6 are also successfully compiled. This information is presented in Figures 10 through 16.

Figure 10. Water main break locations within the TWD service area.

Figure 11. Service main break locations within the TWD service area.

Figure 12. Water main flushing locations within the TWD service area.

Figure 13. Water quality complaint locations within the TWD service area.

Figure 14. Water pressure complaint locations within the TWD service area.

Figure 15. Proposed fire hydrant locations within the TWD service area. A total of 2,607 fire hydrant locations were identified that require a water main improvement. A total of 2,584 fire hydrant locations were identified that do not require a water main improvement.

Figure 16. Results of water age modeling within the TWD service area.

Construction costs

Estimated construction cost factors are obtained from the Tampa Water Department. Meter spacing is assumed to be 0.03 meters per foot and the cost of a meter set is determined to be \$1,411. Cost factors for various nominal pipe diameters utilized for this project are provided in Table 7.

Table 7. Cost factors utilized for various nominal pipe diameters ranging from 4-36 inches

Nominal Diameter (in)	Cost* (\$/ft)
4	83
6	96
8	102
12	144
16	200
20	224
24	295
30	479
36	517

*Per foot costs having a nominal diameter greater than 12" is based on a linear extrapolation.

Attribute data for each planned rehabilitation and replacement project is exported into a spreadsheet where the above cost factors are applied. The total construction cost of all planned rehabilitation or replacement projects is estimated to be \$388 million. The current construction cost of all planned rehabilitation or replacement projects by master plan program is illustrated in Figure 17.

Figure 17. Estimated construction costs for planned TWD rehabilitation, replacement and improvement projects (HLS = hydraulic looping system, ACMR = asbestos cement main replacement, UMR = undersized main replacement, UCIMR = unlined cast iron main replacement)

Phase 3 – Data extraction

The structured query presented in the methodology section is shown to be effective at linking occurrences of prioritization elements to planned capital projects. Once these queries are performed, a single database is developed to aid in prioritization.

Structured queries

Buffer region dimensions are determined based on typical lot sizes and other previously discussed factors. The buffer dimensions determined to be appropriate for this project are shown in Table 8.

Table 8. Dimensions of buffer regions for each type of prioritization element.

Prioritization Element	Buffer Region Radius Dimension (feet)
Water Main Breaks	125
Service Main Breaks	125
Proposed New Hydrants	125
Water Age	125
Flushing Visits	450
Pressure Complaints	125
Water Quality Complaints	125

Created planned project buffers with the location of prioritization element occurrences are shown in Figure 18.

Figure 18. Visual representation of planned project buffer regions and prioritization elements

Database development

Once the SQL queries are performed within MapInfo, a database containing all planned rehabilitation and replacement projects and all prioritization elements within the respective buffer region is generated by utilizing the unique identifying key. This database is used to determine average occurrences of various prioritization elements for fiscal year 2002 through fiscal year 2005. Results are summarized in Figure 19.

Prioritization Element Occurrences

Figure 19. Comparison of average quantities of prioritization element occurrences among planned rehabilitation, replacement and improvement projects

The data are further digested to yield a historical annual average increase or decrease in the occurrences of various prioritization elements. A summary of these infrastructure condition indicators is shown in Table 9.

Table 9. Relative annual changes in water main breaks, service line breaks, pressure complaints and water quality complaints

	Water Main Breaks	Service Line Breaks	Pressure Complaints	Water Quality Complaints
FY02-FY03	5%	1%	16%	-128%
FY03-FY04	24%	-29%	-23%	51%
FY04-FY05	16%	61%	7%	-199%
AVG	15%	11%	0%	-92%

These infrastructure condition indicators are used as factors to forecast prioritization element occurrences for the next 20 year period.

Phase 4 –Project prioritization and master planning

Prioritization element occurrences are converted to monetary costs based on the benefits specified in Table 6. It was assumed the total cost of a main break is \$1,500 and the cost of a water main flushing activity is \$100. The resultant costs to the Tampa Water Department based on developed benefit units are listed in Table 10.

Table 10. Benefit unit based costs utilized in the prioritization process

Program	Water Main Breaks	Service Line Breaks	Quantity of Proposed New Hydrants	Modeled Water Age	Flushing Time	Water Pressure Complaints	Water Quality Complaints
Hydraulic Looping System Improvements				\$1 each increment	\$70 / flush	\$10	\$10
Fire Protection / Undersized Main Replacement	\$450	\$150	\$750			\$150	
Water Main Rehabilitation or Replacement	\$750	\$150	\$150			\$300	\$150
Cement Main Replacement	\$1,200	\$150	\$150				

These costs are then applied to the developed database containing the historic and projected occurrences of prioritization elements. Utilizing a 3 percent cost escalation for expected costs and a 7 percent discount rate, a net present value of all costs associated with maintaining each water main planned to be rehabilitated or replaced is calculated for a 20 year planning horizon. The construction cost of each planned replacement or rehabilitation project is then combined with the net present value of expected benefits to obtain prioritization ratios. The resulting ratios vary from 0.35 to 0.00. However, the distribution of the results show a relatively small quantity of planned projects having a benefit to cost ratio greater than 0.1. Figure 20 shows the approximate benefit to cost ratio distribution.

Figure 20. Results yield benefit to cost ratios ranging from 0.35 to 0.00. A relatively small portion of projects have benefit to cost ratios greater than 0.10.

DISCUSSION

The use of GIS permits the developed prioritization system to analyze large numbers of planned capital projects to efficiently generate benefit to cost ratios. This system has several key benefits including short and long term planning, the ability to monitor the general condition of water main infrastructure and to appropriately allocate available funding resources among master plan programs.

Prioritization system

Allowing an efficient method for associating prioritization elements to planned projects, buffer zones can be utilized with reasonable accuracy when resources do not allow for the full scale implementation of a computerized maintenance management system. Although the use of GIS software and the interpretation of data requires specialized personnel, large numbers of personnel do not need to be trained on new software packages such as computerized maintenance management systems.

Integrated database

Combining rehabilitation, replacement and improvement master plans into a single geospatial database provides a means to improve access to data and increase the ease of use. The availability of this information clearinghouse has significant long-term benefits for the water utility. Some questions that can be answered using the integrated database concepts developed in this project are:

1. Which distribution system projects maximize available resources during a given budget year?
2. What is the condition of the infrastructure near a planned development and what planned infrastructure improvements should the developer be required to fund?
3. What is the 5 and 20 year plan for infrastructure rehabilitation, replacement and improvements?

The developed database can also be utilized as part of a future integrated infrastructure management system.

Database applications

Depending on the size of the area to be analyzed, answering questions regarding planned infrastructure in a specific service area section historically requires extensive soft resources and can not be reasonably performed in the time frame of a few hours due to inefficient methods of storing data. The electronic data format created by this project reduces the soft resources required to answer common questions such as what are the planned projects, when are they scheduled to be completed and how much will they cost. The resources necessary to answer these questions has been reduced by an estimated 85 percent. For example, an analysis of planned capital projects within a recent proposed development area consumed the time of a staff engineer and one engineering technician for approximately three days. Once the methods described in this project were applied to the same area, the same task could be completed in approximately 4 hours primarily by an engineering technician.

Condition indicators

Between FY2002 and FY2005 the TWD has implemented projects such as ozonation that have decreased water quality complaints near planned distribution system projects by an average of 92 percent annually. Replacing unlined cast iron water mains and installing hydraulic looping system projects are expected to continue decreasing the quantity of water quality complaints in these areas.

However, the presented analysis of water main breaks and service main breaks near planned rehabilitation, replacement and improvement projects indicate the condition of water infrastructure near these planned project locations is gradually deteriorating. Between FY2002 and FY2005, water main breaks have increased near planned project locations by 15 percent annually while service main breaks near the same locations have increased by 11 percent annually. These trends are consistent with the national issue of deteriorating utility infrastructure within the United States. It is expected utilizing the prioritization technique presented in this project will decrease the realized effects of deteriorating infrastructure by replacing the pipe segments in the worst condition first.

Resource management

Utilizing the developed prioritization technique, the distribution of benefit to cost ratios is skewed strongly left, indicating a relatively small number of projects are more favorable for implementation than others. This suggests relatively small resource expenditures can generate a relatively large amount of value when resources are efficiently utilized. Currently, the TWD chooses all projects within a neighborhood and constructs them during the relatively same time period. However, at the current funding levels, TWD is typically not able to replace or rehabilitate all planned projects within a neighborhood. Therefore, regardless if the projects are more spread out throughout the service area, it is more appropriate to select the most cost effective projects rather than pursuing a neighborhood-wide approach.

Utilizing the data obtained in this project, funds can be distributed appropriately between each master plan program. Analyzing the top 10% of planned capital projects, it is shown the current rehabilitation and replacement budget distribution can be improved. The undersized main replacement funding should be approximately four to five times that of unlined cast iron replacement funding. Figure 21 shows the existing and proposed funding levels for each master plan program.

Figure 21. Comparison of existing rehabilitation and replacement funding levels and the ideal funding levels as determined by the top 10% of prioritized projects determined by this project.

The obtained data can also be utilized to determine if utility rates are adequate to sustain existing service levels. Because the quantity of water main breaks and service line breaks presented in this project are increasing, it can be implied existing rehabilitation and replacement funding levels should be increased to sustain service levels. The necessary rate increase amount is beyond the scope of this project.

CONCLUSION

This project successfully consolidates master plan programs, main break reports, service main break reports, customer complaint logs, flushing reports, fire hydrant spacing criteria and estimated water age into a single database eliminating analysis difficulties due to inconsistent data formats. Once a consolidated database is obtained, benefit to cost ratios for 2,886 planned projects are successfully calculated based on GIS analysis. Analyzing the top 10 percent of planned capital projects allows the water utility to appropriately allocate available funding between master plan programs. Specific conclusions for each project objective are listed below.

1. Objective: Convert existing infrastructure replacement master plans into an electronic format incorporating attribute data to permit geospatial analysis.

Conclusion: Master plan programs are successfully converted into an electronic format appropriate for GIS analysis.

2. Objective: Consolidate existing databases including main break reports, service main break reports, customer complaint logs, and flushing reports into a common format that can be utilized by GIS software.

Conclusion: Databases containing listed infrastructure condition indicators are consolidated into a common format suitable for GIS analysis.

3. Objective: Perform geospatial analyses to determine a benefit to cost ratio for each planned project based on a prioritization matrix agreed upon by Tampa Water Department policy makers.

Conclusion: A prioritization matrix developed by Tampa Water Department policy makers is developed. Benefit to cost ratios for 2,886 planned capital projects are included as part of this project.

4. Objective: Prepare a combined, prioritized infrastructure replacement master plan and make appropriate budget recommendations.

Conclusion: A prioritized capital project master plan and budget recommendations are made as part of this project.

The prioritization procedure specified in this project is shown to be a viable alternative for utilities already owning licenses to GIS software and do not currently have the benefits of full-scale computerized maintenance management systems available for their use.

ENGINEERING IMPLICATIONS

Beneficial use of the prioritization strategy developed by this project depends on procedural changes to maintain necessary databases as well as the use of engineering judgment to interpret project results. Proposed procedural changes are included and the need to still use common sense judgment for individual projects is addressed below.

Procedural changes

The prioritization system developed in this project can provide a robust tool that utilities can use to modify existing procedures to maintain geospatial data in a useable, up to date format. Maintaining geospatial data requires input from personnel involved in engineering, line maintenance, information technology, customer service and records. Project planning is a dynamic process that needs to respond to ongoing occurrences of water main breaks, service line breaks, flushing activities and customer complaints. In addition, the inventory of planned projects is continually changing due to redevelopment and urban infill. The implementation of planned replacement or rehabilitation projects is often due to the need for additional capacity and reliability demanded by these redevelopment and urban infill projects, not necessarily because they were listed as a potential capital project. These different driving forces demonstrate the need to link

rehabilitation and replacement planning with infrastructure upgrades necessary for redevelopment and urban infill projects. A conceptual procedure to continually update the inventory of planned projects when capital improvement projects and customer driven projects occur simultaneously is shown in Figure 22.

Figure 22. Procedures are needed to continually maintain geospatial databases when customer driven projects and capital projects occur simultaneously. The process flow diagram above shows input from several functional groups are needed to accomplish this task.

Improved resources to support decisions

The procedures developed by this project provide a valuable resource for prioritizing planned water infrastructure projects. One should not be 100 percent replaced by the procedures developed in this project. The ready availability of this information coupled with the opportunity for scenario analysis can aid engineers and planners in making sound judgments pertaining to infrastructure projects.

ADDITIONAL RESEARCH

Although the prioritization technique presented in this project is shown to be successful, key questions remain unanswered for the Tampa Water Department and are included below as recommendations for additional research.

1. How much can implementation costs be reduced by right-sizing projects?

During this project, it became known additional work is needed on the undersized main replacement (UMR) master plan. Nearly all planned UMR projects are proposed as 8-inch diameter improvements. A large portion of these projects can be reduced in size to 6-inch diameter improvements and still comply with TWD fire flow standards.

Downsizing UMR proposed pipe sizes could potentially reduce capital expenditures by 6 percent based on the difference between 8-inch and 6-inch pipe installation costs.

Because the cost of the project is used to prioritize the projects, this should be done on a system wide basis rather than the current method of downsizing the project as it is selected for design.

2. Can buffer regions be improved increasing project accuracy?

One significant improvement that can be made to the method presented in this project is to eliminate inaccuracies associated with assigning buffer regions to associate

planned projects with prioritization element occurrences such as main breaks and customer complaints. Figure 23 illustrates one weakness that results from buffer regions.

Figure 23. Example of inaccurate assignments of prioritization elements due to the use of buffer regions.

One way to eliminate this error is to develop a full scale computerized maintenance management system for all distribution piping operated by the TWD. This system should incorporate a geospatial component so records of prioritization occurrences can be associated with the appropriate segment of piping without error. The benefit to cost

analysis utilized in this project is still effective, however the method to acquire the input data in Phase 3 would be greatly increased in accuracy.

3. What additional efficiency can be realized by developing an integrated infrastructure management system?

Opportunities exist to optimize capital expenditures by expanding the prioritization process to include other infrastructure types such as storm water, sanitary sewer, sidewalks, and pavement. The techniques developed for this project could be carried over into an integrated infrastructure management system provided the necessary interdepartmental coordination occurs.

4. What savings would result from incorporating pipe age and improved life cycle models into the prioritization process?

Pipe age can be a very good general indicator of infrastructure condition. Incorporating this into this project is currently not practical due to the difficulty in accessing historical records, however pipe installation dates should be included as attribute data associated with all pipe currently being installed to facilitate similar projects in the generations to come.

5. Can currently available techniques sufficiently prioritize transmission and grid system projects?

The TWD delivery and grid system master plan should be prioritized. One way to accomplish this task is through genetic algorithm optimization utilizing existing hydraulic models. Genetic algorithm optimization is a series of computer calculations designed to iteratively generate optimal implementation scenarios. Questions that can potentially be answered by this type of computer modeling include which projects should be selected, what size pipes should be installed and which projects should be constructed together to obtain synergistic effects. Genetic algorithm optimization may also incorporate a master plan for expanding and optimizing water storage and pumping sequences.

6. What is the Tampa Water Department infrastructure budget “Gap?”

The difference between the current rate of infrastructure reinvestment needs to be compared against the rate necessary to maintain the existing level of service. This would assist in making budget recommendations as well as justify any necessary rate increases.

7. Is pipe rehabilitation a viable option for the Tampa Water Department?

The TWD relies on pipe replacement instead of pipe rehabilitation for infrastructure projects. A study comparing the economics of the various options should be performed to further optimize the use of capital resources.

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