WEB-BASED PLATFORM FOR FORCE MAIN INFRASTRUCTURE ASSET MANAGEMENT

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ABSTRACT

Asset management of force main infrastructure entails accurate prediction of the condition of the system to operate and maintain at the lowest overall costs. In this thesis report, guidelines for asset management of force main infrastructure is provided by synthesizing the trends observed in the inspection, condition assessment and renewal engineering strategies. Furthermore, this thesis focuses on development of a centralized web-based platform for advanced asset management of force main infrastructure. The key components involved in this comprehensive asset management of the force main infrastructure are data management, model implementation and information visualization. The thesis depicts various aspects involved in developing a web-based application for utilities that store, collect and analyze the data in dissimilar methods. A risk assessment model employed by a utility to prioritize the assets for renewal is demonstrated with various utilities' data. Consequently, the model is published as geo-processing services through ESRI ArcGIS Server. A visualization tool is developed for individual utilities that interacts with the geo-processing services and renders a web-based interactive map to visualize the model results. A drupal website (www.pipeid.org) is developed to support the data collection and model dissemination process.

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Table of Contents

List of Tables

List of Figures

ACRONYMS AND ABBREVIATIONS

AC	Asbestos Cement
API	Application Program Interface
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing and Materials
AWT	Apparent Wall Thickness
AWWA	American Water Works Association
BEM	Broadband Electromagnetic
BRE	Business Risk Exposure
CCTV	Closed-circuit Television
CI	Cast Iron
CIP	Capital Improvements Program
CIPP	Cured In Place Pipe
CLP	Confidence Level Rating
CMMS	Computerized Maintenance Management System
CMOM	Capacity, Management, Operation and Maintenance
COF	Consequence of Failure
CSO	Combined Sewer Overflow
DI	Ductile Iron
DOT	Department of Transportation
EPA	Environmental Protection Agency
fPVC	Fusible Polyvinyl Chloride
FRP	Fiberglass Reinforced Pipe
FTP	File Transfer Protocol
GIS	Geographic Information System
HDPE	High Density Polyethylene
HSK	Hand Scanning Kit
LEYP	Linear Extended Yule Process
LOF	Likelihood of Failure
LOS	Level of Service
MACP	Manhole Assessment and Certification Program
MFL	Magnetic Flux Leakage
NASSCO	National Association of Sewer Service Companies
NRCS	National Resources Conservation Service
PACP	Pipeline Assessment and Certification Program
PCCP	Prestressed Concrete Cylinder Pipe
PE	Polyethylene
PIPEiD	Pipeline Infrastructure Database
PVC	Poly Vinyl Chloride
PVCO	Molecularly-oriented Polyvinyl Chloride

RCCP	Reinforced Concrete Cylinder Pipe
RCP	Reinforced Concrete Pipe
REST	Representational State Transfer
RFEC	Remote Field Eddy Current
SQL	Structured Query Language
SWIM	Sustainable Water Infrastructure Management
URL	Uniform Resource Locator
USEPA	United States Environmental Protection Agency
USDA	United States Department of Agriculture
UT	Ultrasonic Testing
UV	Ultraviolet
WATERiD	Water Infrastructure Database
WERF	Water Environment & Reuse Foundation

CHAPTER 1.0

INTRODUCTION

The wastewater collection system consists of network of pipes and pumping systems to convey the wastewater for treatment. The major components of a wastewater collection system include: gravity sewer lines, force mains, manholes, treatment plants and lift stations. According to the 2004 WERF survey, 7.5% of wastewater collection system assets are force mains. Traditionally, most utilities have relied on a reactive approach to managing their force main assets. The main reason for this approach is the difficulties associated with force main condition assessment, as it should be taken out of service for inspection which is a major limitation. Moreover, providing a by-pass service during inspection is typically very expensive.

Over the next two decades, $300 billion is estimated to be required to meet the needs of the failing wastewater infrastructure system (ASCE, 2013b). The renewal of pipelines associated with the failure comprises the largest share of the capital need. The investment needs should be met immediately; otherwise, it would jeopardize the condition of the pipes, which are approaching the end of their service life. The condition assessment of the critical pipelines requires financial resources, which affect the decision making process of repair, rehabilitation, replacement, operation and maintenance.

Understanding the definition, location and condition of the force main assets can be supported with data and information systems to make good decisions in infrastructure asset management. This involves data management of extremely large data sets which entail synthesizing, analyzing and visualizing large quantities of information. The key elements in this asset management framework are data collection, data storage and retrieval, and data analysis (Flintsch and Bryant, 2006). The level of detail of collected data depends on the hierarchical level of the decision made. When significant detailed information is collected, it is an expensive operation which involves significant amount of storage issues. Additionally, analyzing the data to retrieve meaningful and necessary information is a major challenge.

The pipeline industry is not an exception to the data management hurdles. Even before addressing the implementation of the data management process, the imminent problem that needs to be tackled is the lack of consistent data. Documenting a standard set of data for renewal, rehabilitation, replacement, maintenance and operation of the existing infrastructure is of paramount importance. Standard data collection parameters ensure that the same set of data is collected by all the utilities in the nation. To provide the required uniform national standards for force main infrastructure data, a consensus should be gained on the parameters that need to be incorporated in the database. This provides dynamic aggregation and centralized storage of force main inventory and inspection data from across the industry. Condition assessment and risk management models can leverage the standardized data to provide decision support for various asset management needs.

One critical aspect of the force main infrastructure data is the significance of the location of the asset. The actual location of the asset denoted using a geographic reference is an essential attribute of the force mains in addition to its condition and physical characteristics. Geographic Information Systems (GIS) enable users to store, analyze and visualize spatial or geographical data. Predicting the likelihood and consequence of failure of force mains involves development of models by analyzing the effect of parameters on their performance. The integration of these models to the extensive data set provides a robust decision making approach to risk evaluation, which is a function of likelihood of failure and consequence of failure (EPA, 2009b). GIS facilitates these models to incorporate the available data as input data, thereby acting as a decision support system to visualize the results (Shamsi, 2002). This research integrates the components of data management, model implementation and information visualization. Subsequently, a web-based GIS platform is developed for advanced asset management of force main infrastructure.

1.1 Research Objectives

The objectives of this research are two-fold:

- Provide guidelines for asset management of force main infrastructure
- Develop a web-based platform for advanced asset management of force main infrastructure

The key components of the research objectives are:

1.1.1 Guidelines for Asset Management of Force Mains Infrastructure

- The characteristics of the force main networks are studied and the causes of failure of various force main materials are reviewed.
- The current inspection practices and technologies associated with force mains are identified through literature and practice review.
- The existing practices regarding the condition assessment of the force mains are identified through literature and practice review.
- The renewal practices related to the renewal of force mains are reviewed and the technologies developed for repair, rehabilitation and replacement are identified.

1.1.2 Web-based Platform for Advanced Asset Management of Force Main Infrastructure

- The existing data models and standards for water and wastewater pipeline database systems were reviewed. A data model incorporating the force mains characteristics was developed based on existing wastewater data model.
- Various data collection protocols were reviewed and a data collection platform was developed through a drupal content management system. A website (www.pipeid.org) was developed to collect data from various utilities.
- The existing utility data was migrated to the data model structure by creating a personal geo-database for each utility.

- A utility model was re-created using the ArcGIS ModelBuilder platform and published using ArcGIS Server.
- A web-based platform was developed using ArcGIS API for Flex to provide access to the model to various utilities. A geo-processing tool was incorporated in the platform which enabled the user to run the model according to user preferences. Furthermore, the results of the model can be queried using the query tools embedded in the platform.
- The models were disseminated to the utilities through the website (www.pipeid.org). A utility hub page was created for individual utilities in the website. The hub page provided secure access to the standardized data and executable models.

1.2 Organization of the Report

The report is organized into 5 chapters as summarized below:

Chapter 1. *Introduction* describes the objective of the report, in addition to some background information.

Chapter 2. *Literature Review* provides an overview of the key components involved in comprehensive asset management of the force main infrastructure.

Chapter 3. *Guidelines for Asset Management of Force Mains* provides a framework for inspection, condition assessment and renewal engineering of force main infrastructure.

Chapter 4. *Web-based Platform for Advanced Asset Management of Force Main Infrastructure* discusses the critical components of a comprehensive asset management program through the web-based platform.

Chapter 5: *Conclusions and Recommendations* provides concluding remarks and recommendations to fill the gaps and limitations in the force main infrastructure asset management. In addition, the aspects to improve the web-based platform are presented.

CHAPTER 2.0

LITERATURE REVIEW

The essential aspect of asset management of the force main infrastructure involves understanding the condition and performance of the asset. This entails accurate prediction of the failure modes at various phases of life-cycle of the pipeline. The condition of the pipeline infrastructure can be assessed by analyzing the data collected throughout the service life. The relationship between the data components is a key element that determines the likelihood and consequence of failure of the pipeline (EPA 2009b). Depicting the failure of the pipeline by combining different types of information on pipe failure provides context and scope for decision making (EPA 2012). Furthermore, linking the information to the location provides spatial significance. The components involved in this kind of comprehensive asset management of the force main infrastructure are studied through literature review (Figure 2-1).

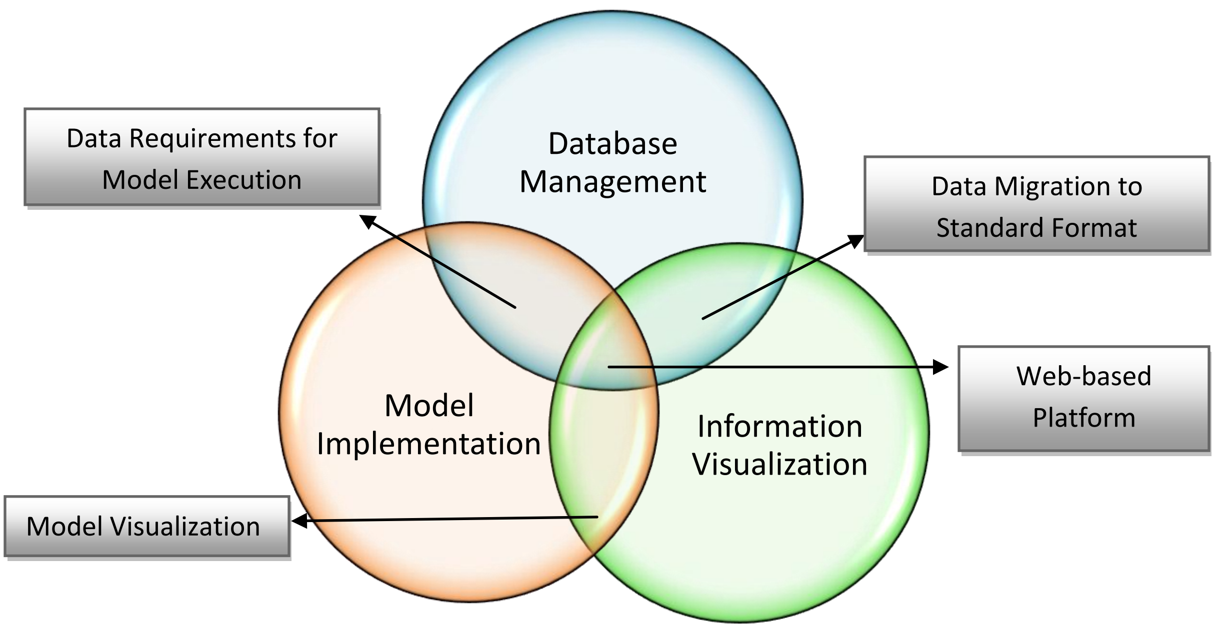

Figure 2-1. Components of Asset Management of Pipeline Infrastructure.

2.1 Database Management

Sinha et al., 2009 addresses the problem of lack of standard data model for water and wastewater systems in the nation. The utilities supporting the water and wastewater systems have employed in house data management systems which are specific to the utility. The research work defines a protocol to standardize the municipal water and wastewater pipeline infrastructure data. The transforming of the data sets to the standard structure was discussed, but the mapping of the disparate data sets to the standard data model is not presented which involves rigorous computing coding. The utilities managing the pipeline infrastructure maintain the level of service, which impose least possible cost to the public. This is accomplished by monitoring the tasks that effect the level of service. These tasks include design, maintenance, condition assessment, renewal engineering and future resource allocation (WERF 2013).

The data collected for the asset management can support the important tasks for providing a decision support system. This involves vast amount of storage and access requirements which is accomplished by employing the Computerized Maintenance Management System (CMMS). The implementation strategy of the CMMS system is the key factor that needs to be addressed at various levels of decision making process, keeping in mind the overall asset management process. Since the data is accumulated over the years it needs to be managed and collected such that it identifies the needs of the decision making process. The level of depth and detail at which the data is collected primarily depends on the hierarchical level of the decision making process (U.S.DOT, 2006).

The lack of robust database is a foremost obstacle to the water utilities to determine the failure patterns for the various ages and types of pipelines located in different regions. The failure databases are incomplete and inaccurate, and recorded in a non-uniform manner which inhibits a comparison between different utilities. Although, there is a huge amount of raw data available on the assets and the failures, key data sets are not available which make a reliable condition assessment and life prediction. There is a lack of consensus on collection and recording this key information due to the fact that the exact factors leading to the structural failure of the pipes are of multiple types and magnitudes. Gay and Sinha, 2014 discusses the importance of understanding the pipe assets and their condition, which results in accumulation of large amounts of data. The usage of GIS is recommended as it helps in prioritizing the projects by sharing the information and combining data from multiple departments.

The key challenge posed is the decision making process of the pipeline asset management, when the data is viewed in tables. The solution that is recommended by the U.S. Department of Transportation is analyzing the data set using Geographic Information System (GIS) as a data management tool as it provides geographic referencing to the data. The usage of GIS is recommended as it helps in prioritizing the projects by sharing the information and combining data from multiple departments.

2.2 Model Implementation

The models that are developed based on the data available provide assistance to the utilities in a broad range of scenarios. The modeling platform offers performance indicators which describe the overall network picture and evaluate the system at a zonal level. The models that are developed to predict the life of the pipe infrastructure require a high level of technical input (Koo and Ariaratnam, 2006). The physical mechanisms that trigger pipe failure often require data that are not instantly available and involve costs to obtain. Attaining this kind of sophisticated information is restricted to large organizations and the third parties that are promoting the model. The medium scale utilities do not have the flexibility and resources to maintain this level of detail in terms of data collection and organization. Therefore an in house condition assessment has been employed by some utilities and an internal analysis model has been developed by them to mitigate the pipe breaks. But nevertheless the utilities take a huge leap of faith in terms of the functional validity of the models.

The challenging aspect of the model developed is to determine the residual life of the pipe and accurately predict the timeline of pipe failure. Interpreting the factors responsible for residual life determination depends on the historical performance, which is an intricate and a demanding task (Pelletier et al., 2003). The economic life of an asset is another concept that was developed by the researchers to estimate the life expectancy. Statistically developed life expectancy curves are developed to determine the probability of replacement of the pipe which combines a series of normal distribution curves for different types of pipes at various periods of time (Lawless, 1982).

The major drawback associated with modeling is that they are all computer based techniques which have high data needs and require professional engineering skills. Rogers and Griggs, 2006 identifies the pipes which are prone to failure and replacing the pipes by prioritizing the pipes to develop a failure assessment model. Furthermore, the quality of the model's predictions is completely based on the available data and the need to gather better data is emphasized in the paper.

The factors responsible for designing the model are considered based on the availability of the parameters in the database. The physical, environmental and operational conditions are considered as factors in modeling a scenario to reflect the real life system (Al-Barqawi and Zayed, 2006). But a quantitative measurement of these conditions is a difficult task.

To support the models with the data, the inspection technologies produce the necessary data points for modeling. The key barriers to the inspection techniques are the physical difficulties and costs involved in gaining access to the buried pipes (Liu and Kleiner, 2012b). The external maintenance and inspection of the force main involves costs in terms of excavations, traffic control and pavement removal. Furthermore, the quality of information available through the internal and external inspections is debatable and the utilities rely on a technology based on the technology provider's proposal and cost. There is a lack of objective testing and evaluating information to compare the technologies proficiency (Liu and Kleiner, 2012a). In a nutshell, the industry currently faces the chicken and egg scenario, wherein the lack of economic incentive dissuades providers from developing innovative technologies and the lack of cost effective inspection technology is keeping the utilities away from employing the current inspection methods.

2.3 Information Visualization

The model results are published by the utilities for further analysis and the model output can be queried to provide an insight into the decision making process. Geographical Information

System (GIS) acts a visualization tool to access the model output effectively. Schroeder and Fallara, 2010 describes the need for information management from various data sources and models. The paper emphasizes the flexibility of using time-dependant data. Also, maintaining a spatial database by using GIS facilitates a better decision support system. The importance of developing a custom user interface for data editing and analysis is presented in the paper.

GIS offers a customizable platform to analyze the complex data sets as well as run the models and display results. The data and models associated with the pipeline infrastructure involve spatial reference to the attributes. GIS provides a visualization environment that enables the users to manipulate the data and models which have spatial significance (Vairavamoorthy et al., 2007).

External models can be integrated to the GIS interface which offers the models to use the GIS visualization tools to access the results. The ability of GIS to store large amounts of spatial data enables the user to analyze the pipeline infrastructure to develop a risk assessment model. Garaci and Zhang, 2009 demonstrated the tools that supported the GIS map, which is an interactive user interface. The paper presented an idea of linking the CCTV and quantitative data to the qualitative attributes through a GIS management tool

GIS acts as a powerful analysis tool for utilities by providing options to include information of a particular set of parameters in the form of a shape file to an existing model (Liu et al., 2007). The interoperability of the diverse data set helps models to connect to different databases. The flexible aspect of GIS allows users to run complex statistical analysis software and display the results graphically. The relationship between different parameters is depicted in the map document. The important feature that GIS provides is the automation of the databases for quality assurance and quality control of the data, based upon observed geospatial relationships.

The features that GIS provides in terms of visualizing the individual components of a map in the form of layers can be used to transpose various results of the model on one another. GIS offers the option of writing queries in Structured Query Language (SQL) to obtain information on the pipeline infrastructure. The non-spatial information can be joined to the attribute table of the spatial information, which helps in organizing the database. When an operation is performed on the existing dataset to analyze the dataset, it is called geo-processing (Ormsby et al., 2010). Geo-processing enables the users to streamline the dataset by grouping the features with the same attributes.

CHAPTER 3.0

GUIDELINES FOR ASSET MANAGEMENT OF FORCE MAIN INFRASTRUCTURE

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3.1 Introduction

This manuscript is developed based on the case studies developed for the WATERiD knowledgebase and is a part of the synthesis report titled Asset Management of Force Main Infrastructure. The synthesis report was developed in collaboration with Water Environment and Reuse Foundation, while the project was funded by SWIM Center at Virginia Tech.

This manuscript presents a structured approach to execute a comprehensive force main asset management program. This study encompasses the current technology and practices for inspection, condition assessment and renewal engineering of force main infrastructure. The necessary information on the inspection technologies, condition assessment practices and renewal strategies was gathered to develop the guidelines. An extensive literature review was conducted on force mains characteristics and asset management. The literature review included journal articles, conference papers, books and major reports. Simultaneously, practice review was conducted by contacting utilities for their support and participation. Data was collected from the utilities on the current asset management practices. Utilities were contacted to provide reports, technical memorandums etc., that would provide an understanding of the implementation of the inspection, condition assessment and renewal engineering practices. The information developed through literature and practice review was analyzed to ensure coverage of the inspection technologies, condition assessment practices and renewal strategies. The information from literature and practice review was then synthesized to identify the utility mindset, typical practices, trends and needs. Subsequently, case studies were developed from the information. Eventually, the information was used to develop a 10 step guidelines for asset management of force main infrastructure.

The asset management of force main infrastructure can be broadly categorized into a three step process: inspection, condition assessment and renewal engineering. Inspection of force mains would enable the utilities to understand the current state of the assets. Condition assessment would facilitate the utilities to identify the critical assets for sustained performance. Renewal engineering involves repair, replacement or rehabilitation of the high risk pipes identified through performance assessment modeling and operating condition requirements. The 10 step structured guidelines that is developed is depicted in Figure 3-1.

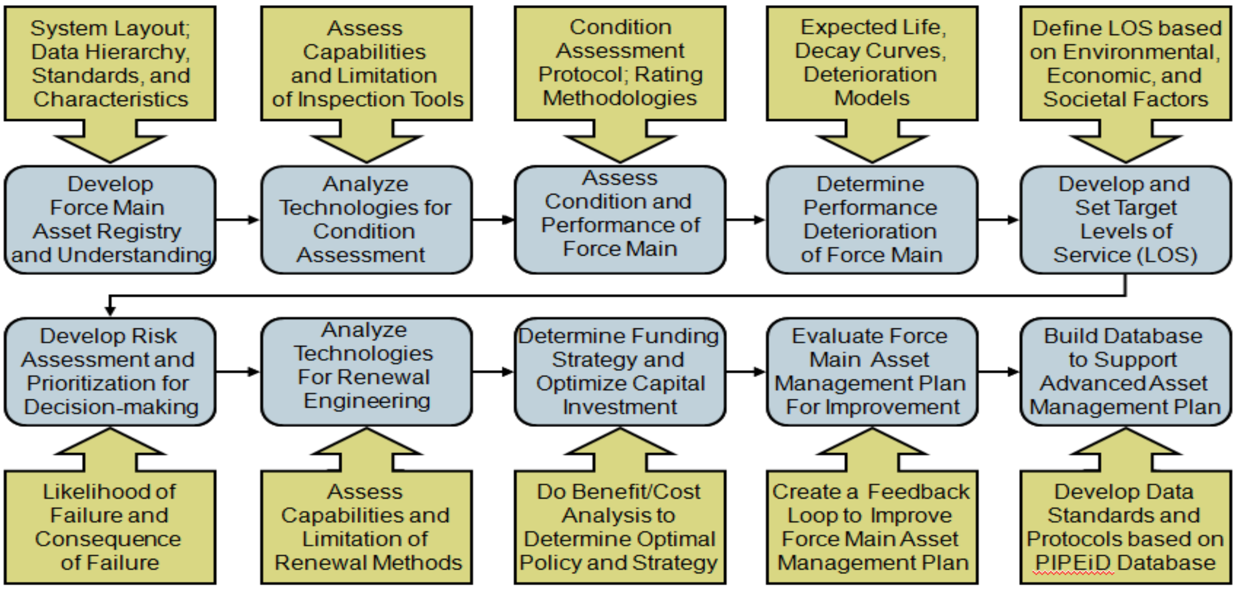

Figure 3-1. 10-Step Force Main Asset Management Program.

Table 3-1 provides the ten steps developed for the asset management of force mains and the tasks associated with individual steps. The following sub-sections provide a detailed description of the tasks associated for asset management of force main infrastructure.

Table 3-1. 10-Step Asset Management Process.

Step Number	Task	Benefit	Challenge
Step 1: Develop force main asset registry and understanding	Examining the characteristics of various pipe materials in the asset registry and identifying the material for inspection	Knowledge on trends of failure of various pipe materials	Understanding the failure modes and mechanisms, performance indicators, failure trends, operation and maintenance costs, and risk of failure
Step 2: Analyze the technologies for condition assessment	Summarize the available technologies that can quantify the condition of the specific pipe material and can collect information with minimum service disruption and maintaining the required level of service	A preliminary list of various technologies encompassing the capabilities and limitations is created, cost-effective approach can be chalked out through comparison	Diameter, wall thickness, bypass requirements, service disruption costs, limitations in inspecting through coatings and linings should be taken into consideration while selecting from the limited proven technologies

Step Number	Task	Benefit	Challenge
Step 3: Assessing condition and performance of force main	A condition rating system should be developed to assess the current condition of assets	Rating scale provides an understanding of the performance of the force mains	Developing the relationship between parameters affecting the performance
Step 4: Determine performance deterioration of force main	Performance prediction curves and deterioration models should be developed	Estimate the remaining useful life of assets	Defining the parameters affecting the deterioration, availability of the parameters in the database
Step 5: Develop and set target Levels of Service (LOS)	Define LOS based on environmental, economic and societal factors	Helps in monitoring the performance of the assets against the defined LOS goals	Identifying the performance indicators that can be used to establish a rational level of service
Step 6: Develop risk assessment and prioritization for decision making	Predicting the risk of failure of the assets based on the consequence of failure and likelihood of failure.	Identification of high risk pipes	Assessing the environmental costs, customer impacts, socioeconomic costs, etc.
Step 7: Analyze the technologies for renewal engineering	Summarize the available technologies that can renew the condition of the specific pipe material with minimum service disruption and maintaining the required level of service	A preliminary list of various technologies encompassing the capabilities and limitations is created	Technology suitable for various diameter, wall thickness, pipe length and other factors should also be taken into consideration
Step 8: Determine the funding strategy and optimize capital investment	Perform benefit/cost analysis to determine optimal policy and strategy	Minimized annual rate impacts, cost minimization and optimum use of financial resources	Requires an integrated iterative planning process
Step 9: Evaluate force main asset management plan for improvement	Determining whether the performance is met and creating a feedback loop through performance monitoring at every step	Quality assurance assessment is created through the monitoring methods at every step	Creating performance requirements and acceptable quality levels for every step
Step 10: Build database to support advanced asset management	Develop data standards and protocols based on PIPEiD database	Facilitates consistent terminology, provides better analysis of pipeline infrastructure asset management data, advance understanding of pipeline performance parameters for risk management	Significant database management expertise is required

3.2 Inspection

The failures associated with various pipe materials can be quantified by investigating the condition of the pipes through use of inspection technologies to identify the types of defects found in the system. The technologies can be selected based on the required condition assessment information. The current inspection practices and technologies employed by the utilities capture some parameters that are crucial in prioritizing force mains for renewal. Inspection techniques can be categorized into: visual inspection, structural condition assessment, leak detection, and multi-sensor platforms as identified through the literature review.

Visual Inspection

Visual inspection techniques include CCTV inspection, digital scanning and laser profiling.

- A permanent video record of the defects of pipe segments is captured through CCTV inspections.
- Digital scanning is a subset of the camera inspection technology where multiple high resolution cameras are transported through the force main using self-propelled crawlers.
- The practical applications of CCTV inspection and digital scanning include detection of defects at the downstream sections of the force mains near the discharge point where the pipeline may flow as a gravity line.
- The changes in pipe shape due to deflections and deformations can be detected through laser based pipe inspection.

Structural Condition Assessment

The structural integrity of the pipes cannot be determined through visual inspection techniques. The structural condition of the pipes can be assessed through ultrasonic wall thickness measurement and electromagnetic corrosion detection techniques.

Ultrasonic Wall Thickness

The pipe wall thickness, corrosion intensity and the presence of cracks in ferrous pipeline can be detected through in-line inspection and guided wave ultrasonic testing.

- The external remote detection of pipe structural condition is carried out through Guided Wave Ultrasonic Testing. Guided-wave method is primarily used as a screening tool which indicates an existing wall anomaly along the pipeline but does not return actual wall thickness data.
- The wall thickness and corrosion of the pipelines can be measured by in-line inspection technique, which uses a piezo-electric transducer to generate an ultrasonic pulse.
- The ultrasonic wave is stopped by the joints in DI and CI pipes and therefore is suitable only for one pipe length.

Electromagnetic Corrosion Detection

The defects in ferrous pipes are detected using electrical/electromagnetic current. The defects in the pipe wall and the wall thickness are quantified using three major techniques: Magnetic Flux Leakage (MFL), Remote Field Eddy Current (RFEC), and Broadband Electro-Magnetic (BEM).

Magnetic Flux Leakage: The pipe wall surface is magnetized and the leakages produced due to the presence of defects or metal loss in the pipe wall is measured by the MFL technique.

- The disadvantages of the MFL technique include the large amount of data that need to be analyzed to quantify the defects.
- The magnets and the Hall Effect sensors should be placed very close to the pipe wall in the MFL technique, which makes it impractical for the DI and CI pipes due to wall variations and joints. This adds significantly to the cost of inspection.

Remote Field Eddy Current: The corrosion intensity and location can be evaluated by the RFEC inspection technique. Pipes with internal linings can be scanned using the RFEC tool.

Broadband Electro-Magnetic: The wall thickness of ferrous pipe is measured through the BEM non-destructive testing technique. The advantage of employing the BEM technology is its ability to scan through coatings and linings without requiring contact with the pipe wall.

The disadvantage when scanning pipelines internally, compared to intelligent pigs, is that the process is not continuous and therefore it takes more time to survey a pipeline.

Leak Detection

The leaks in force mains are detected by analyzing the vibrations or sound generated through leak detectors. The various types of leak detectors are hand-held listening devices, leak noise correlators and in-line devices. The major acoustic leak detection monitoring techniques are free swimming leak detection and tethered leak detection.

Free Swimming Leak Detection

SmartBall™ is a free swimming leak detection product which continuously measures the acoustic signal and detects an increase in the signal when it encounters a leak. Gas pockets can also be detected through this technique.

Tethered Leak Detection

Sahara™ system is a tethered leak detection product which can detect acoustic signals indicating leaks, gas pockets or areas of turbulence within the pipeline. An advantage of the Sahara™ system is that it can be used to track the location of the pipeline from the ground surface.

Correlators

Correlators are sensors, installed at intervals along the pipeline leak points to identify the location of leaks. Currently available products include LeakFinder™ and Permalog™.

Multi-sensor Inspection

Various types of defects in the wastewater collection system can be detected by employing multiple technologies. The extensively used camera based technologies can be supplemented with other leak detection, ultrasonic testing and electromagnetic technologies to offset the drawbacks of visual inspection technologies. Multi-sensor inspection robots are available which incorporate CCTV, laser profiling etc., to identify the defects in the system. Hydromax USA, Redzone Robotics and Hibbard Inshore provide multi-sensor platforms.

Practice Review

The major technologies that were employed by the utilities in each inspection category were visual inspection, structural condition assessment and leak detection as identified through the practice review.

Firstly, the utilities conducted leak detection through acoustic inspection technique. SmartBall tool was employed by utilities to quantify the leaks and air pockets in the pipe segments. Further validation to assess the risk due to pipe wall anomalies detected through SmartBall was recommended. The acoustic information from SmartBall was not completely trustworthy unless certain factors such as build-up within the pipe were accounted for and identified in the analysis. BEM or MFL can be employed for further validation of the anomalies. In addition, Sahara Pipe Wall Assessment (PWA) tool was also employed by some utilities to detect leaks, gas pockets, bends and variation in hoop stiffness.

Secondly, the structural condition assessment of ferrous pipes is conducted through use of RFEC and BEM techniques. RFEC/TC technique was employed using PipeDiver technology to quantify and locate wire breaks in PCCP Pipes. The inspection using PipeDiver™ was estimated to take less than two hours, but the preparation, inspection, collection of equipment, and clean-up took up to three business days to complete. The plan for deploying the PipeDiver™ should involve careful calculations. It is important that adequate pressure and velocity be maintained in the pipe to enable the PipeDiver™ to move through the pipe. BEM technique using Hand Scanning Kit (HSK) was used for external inspection of ductile iron pipes. The average wall thickness of the area under the sensor's footprint was measured in the BEM technique. Therefore, the resolution of the sensor is a crucial factor that should be taken into consideration. Additionally, the BEM technique cannot determine the location of the wall thickness i.e., whether on the front or back of the wall. Major surface scratches and significant sized isolated pits were detected through the BEM technique.

The following sub-sections summarize the advantages and limitations of existing technologies for condition assessment of force mains.

3.2.1 Force Main Asset Registry and Understanding

The condition inspection program can focus on the critical force mains in the network. The critical force mains can be prioritized for inspection by analyzing the existing data pertaining to pipe material, installation year, location, diameter, depth, length etc. Additionally, pipe break and leak rates can be taken into account while prioritizing the force mains for inspection. The critical force mains identified through this preliminary data analysis can be inspected through an inspection program. The defects associated with force mains vary with pipe material. Various technologies are available to identify these defects and selection of technology depends on the pipe diameter, pipe length, pipe material, pipe location, pipe wall thickness, soil condition, areas of corrosion, type of defect etc.

3.2.2 Technologies for Condition Assessment

The technical competence and feasibility of the technology should be assessed to select the inspection method. The technology should be selected based on the required information to quantify the defects in the force mains and the required accuracy. Subsequently, the inspection can be carried out in-house or through a third party consultant. The feasibility of the technology can be addressed by considering the technology's performance based on:

- Asset location: limitations to certain force main geometry,
- Asset condition: limitations to coatings and linings
- Access requirements: whether the force main should be shut down during inspection
- Data characteristics: whether the data is time-dependent and can be validated

The failure prediction of large and small diameter pipes is an aspect that is debatable in terms of their cost effectiveness. One school of thought suggests that the total expenditure involved in inspecting the large number of small diameter pipes was more than the costs implicated in large diameter pipes. On the contrary, the counter view proposes reducing the failures of small diameter pipes, as the consequence of failure of the large number of small diameter was higher than smaller number of large diameter pipes. The fail and fix approach is employed by some utilities which proved cost efficient for the small diameter pipe condition assessment. Furthermore, the costs associated with the inspection of small diameter pipes are a significant percentage of the repair and rehabilitation cost. The internal inspection of these pipes can provide comprehensive information on the pipes condition, but the costs associated with the equipment management, data collection and processing proved expensive. An economic assessment of the available technology should be performed prior to implementation. The factors that influence various costs of implementation are:

- Site Location Cost: Distance between project site and location of operator equipment and Distance between a project's deployment locations.
- Site Setup Cost: 1.Traffic control or other security measures, 2. Number of deployment locations, 3. Special procedures required for setup on site, 4. Special equipment or personnel, 5. Awareness of locations and accessibility of manholes or access points.

- Environmental Cost: 1. Impacts of weather on deployment procedures, 2. Unusual site conditions that pose health and safety concerns, 3. Abnormally high flows, 4. High volumes of sediment, known structural failures, or other issues that would slow progress through the pipe, 5. Sewer cleaning disposal costs.

The quality and the quantity of data depend on the type of inspection technology. The key characteristics of the inspection technologies are presented below.

3.2.2.1 Internal CCTV and Laser Profiling

- Suitable Materials: Gray Iron, Ductile Iron, Steel, Plastic, PCCP, Cast Iron
- Diameter Range: Suitable for greater than 6 in.
- Defects detected: Metal loss and pit depth
- Access Requirement: Requires dewatering of the pipe
- Operation of line: The line cannot be in operation
- Scanning Capabilities: Cannot scan through coatings and linings
- Data characteristics: Continuous data and good quality data
- Economic Information:
  - Low Mobilization cost
  - Low investigation cost
  - Medium cost involved in reporting and processing the data
  - Medium costs are involved in preparing the pipe and accessing the pipe
  - Medium costs are involved in bypass operations
- Implementation information:
  - Specialist inspection services are available
  - Buried pipes require access excavations
  - Requires pre-cleaning of the pipe
  - Contact to the pipe is not required
  - Navigation through bends is limited
  - Limited navigation through obstacles
  - Can inspect several hundred feet in a day

3.2.2.2 Internal Ultrasonic Wall Thickness

- Suitable Materials: Gray Iron, Ductile Iron, Steel
- Pipe Length: Suitable for up to 1600 ft.
- Wall thickness: No restriction
- Defects detected: Metal loss, pit depth, graphitization and cracks
- Access Requirement: Requires access for pig launcher
- Operation of line: The line can be in operation
- Data characteristics: Continuous data and very good quality data
- Economic Information:
  - Very high mobilization cost

- High investigation cost
  - High cost involved in reporting and processing the data
  - Medium costs are involved in preparing the pipe and accessing the pipe
- Implementation information:
  - Specialist inspection services are available
  - Requires pre-cleaning of the pipe
  - Navigation through bends is possible
  - Limited navigation through obstacles
  - Can inspect 600 ft./ hour

3.2.2.3 Internal Remote Field Eddy Current

- Suitable Materials: Steel, PCCP
- Diameter Range: Suitable for less than 15 in.
- Wall thickness: Suitable for up to 0.5 in
- Pipe Length: Suitable for up to 10,000 ft.
- Defects detected: Metal loss, graphitization and cracks
- Access Requirement: Requires access for pig launcher
- Operation of line: The line can be in operation, but a lower capacity
- Scanning Capabilities: Can scan through coatings and linings
- Data characteristics: Continuous data and very good quality data
- Economic Information:
  - Medium Mobilization cost
  - High investigation cost
  - Medium cost involved in reporting and processing the data
  - Medium costs are involved in preparing the pipe and accessing the pipe
- Implementation information:
  - Specialist inspection services are available
  - Buried pipes require access excavations
  - Requires pre-cleaning of the pipe
  - Contact to the pipe is not required
  - Navigation through bends is possible
  - Limited navigation through obstacles
  - Can inspect 5000 ft. in a day

3.2.2.4 Internal Broadband Electromagnetic

- Suitable Materials: Gray Iron, Ductile Iron, Steel
- Diameter Range: Suitable for greater than 6 in.
- Wall thickness: Suitable for up to 2 in.
- Pipe Length: Suitable for up to 3000 ft.

- Defects detected: Metal loss, graphitization and cracks
- Access Requirement: Requires dewatering the pipe
- Operation of line: The line cannot be in operation
- Scanning Capabilities: Can scan through coatings and linings
- Data characteristics: Continuous data and very good quality data
- Economic Information:
  - Low Mobilization cost
  - Low investigation cost
  - High cost involved in reporting and processing the data
  - Medium costs are involved in preparing the pipe and accessing the pipe
  - High costs are involved in bypass operations
- Implementation information:
  - Specialist inspection services are available
  - Buried pipes require access excavations
  - Requires pre-cleaning of the pipe
  - Contact to the pipe is not required
  - Navigation through bends is limited
  - Limited navigation through obstacles
  - Can inspect several hundred ft./ hour

3.2.2.5 External Broadband Electromagnetic

- Suitable Materials: Gray Iron, Ductile Iron, Steel
- Diameter Range: Suitable for greater than 2 in. diameters
- Wall Thickness: Suitable for less than 2 in. thickness
- Pipe Length: No restriction
- Defects detected: Metal loss, Graphitization and Cracks
- Access Requirement: Requires access length of 3 ft. to 12 ft.
- Operation of line: The line can be in operation
- Scanning Capabilities: Can scan through coatings and linings
- Data characteristics: Continuous data and high quality data
- Economic Information:
  - Low Mobilization cost
  - Low investigation cost
  - High cost involved in reporting and processing the data
  - Low costs are involved in preparing the pipe and reinstating
  - Significant cost is involved in excavations
- Implementation information:
  - Specialist inspection services are available
  - External coatings need not be removed

    - Buried pipes require access excavations

3.2.2.6 External Magnetic Flux Leakage

- Suitable Materials: Gray Iron, Ductile Iron, Steel
- Diameter Range: Suitable for greater than 6 in. diameters
- Wall Thickness: Suitable for less than 2 in. thickness
- Pipe Length: No restriction
- Defects detected: Metal loss, Graphitization and Cracks
- Access Requirement: Requires access length of 3 ft. to 12 ft.
- Operation of line: The line can be in operation
- Scanning Capabilities: Can scan through coatings and linings
- Data characteristics: Continuous data and high quality data
- Economic Information:
    - High Mobilization cost
    - Medium investigation cost
    - High cost involved in reporting and processing the data
    - Low costs are involved in preparing the pipe and reinstating
    - Significant cost is involved in excavations
- Implementation information:
    - The inspection equipment is not available for rent or purchase
    - Specialist inspection services are available
    - External coatings need not be removed if they are less than 5 mm thick
    - Buried pipes require access excavations

3.2.2.7 Leak Detection

- Suitable Materials: Gray Iron, Ductile Iron, Steel, Asbestos Cement, PCCP, PVC
- Diameter Range: No restriction. Sahara tool is suitable for diameter greater than 4 in. and SmartBall is suitable for greater than 10 in.
- Pipe Length: Correlators can scan up to 300 ft. and Sahara tool can scan up to 4000 ft.
- Access Requirement: Access is obtained through valves or 4 in. tapping
- Defects Detected: Joint leaks and wall perforation leaks
- Operation of line: The line can be in operation
- Implementation information: Specialist inspection services are available for Sahara and SmartBall
- Economic Information:
    - High Mobilization cost for Sahara tool and Medium Mobilization cost for SmartBall tool
    - Medium investigation cost for Sahara and SmartBall tools
    - High cost involved in reporting and processing the data for Sahara and SmartBall tools

3.3 Condition Assessment

The data obtained from the inspection of the force mains should be analyzed to understand the trends in the system. The raw data obtained can be used to mitigate the risk associated with the assets. Therefore, the data needs to be analyzed further to estimate the likelihood and consequence of failure. The current condition of the asset can be measured through the collection of data from the inventories, records, observations, and inspections. The force main inspection data can be analyzed to quantify the defects and determine the level of service.

Literature Review

The defects detected through structural inspection techniques can be coded according to Water Research Centre (WRc)'s system or NASSCO's PACP and MACP programs. A defect index similar to the PACP defect coding for force mains was developed to assist with re-inspection, repair, rehabilitation, or replacement decisions (Derr and Gabriel, 2014). This defect system uses a grading scale which is similar to the PACP grading scale (1 to 5) and is based on the failure modes for various pipe materials. In addition, hydraulic analysis is used to assess the condition of the force mains by determining the friction loss in force mains.

Utilities provide efficient service to the customers by defining the service goals. Establishment of Level of Service (LOS) provides the basis for monitoring the performance of the assets against the defined goals. The social, environmental and economic objectives of the community can be met by establishing the key performance indicators. The key performance indicators that can be used to develop the target service levels are:

- Sewer Overflow Rate
- Collection System Integrity
- Wastewater Treatment Effectiveness Rate
- Operations and Maintenance Cost Ratio
- Planned Maintenance Ratio
- Customer Service Complaints and Technical Quality Complaints
- System Renewal/Replacement Rate

Practice Review

The risk of failure of the force main segments is determined by identifying the attributes that contribute to the likelihood of failure and consequence of failure of the force mains. Various utilities identify the risk parameters based on the information available in their data repository. Subsequently, a model is developed to characterize the risk of failure of the force mains. The model primarily employed by the utilities is the ranking system, wherein the force mains are ranked based on the risk of failure score. A score is assigned capturing level of severity of the parameters and a weighting factor is assigned to the individual parameter. The weights assigned are based on the relative importance of the attributes in defining risk. In addition to the ranking system, two other likelihood of failure assessment models were identified through practice review: Linear Extended Yule Process (LEYP) and Finite Element Analysis (FEA) Model. The Predicted Break Numbers (PBNs) and Predicted Break Rates (PBRs) for each main and each year in the future are estimated by the LEYP model for risk calculation. The FEA model is based on the AWWA 301 and AWWA 304 design standards which determines the structural consequences of the broken prestressing wire wraps.

3.3.1 Assessing the Current Condition and Performance

A condition rating system can be developed to assess the current condition of the assets. A numerical based rating of the assets is a key grading system that can be employed to assess the assets condition. The extent of failure is quantified through the rating scale which assigns a value to individual assets. The information from visual inspection can be used to define the rating or grading system. The sewer is graded based on the defects observed in the line. A value is assigned to each defect and a cumulative defect score is allocated to each sewer segment by summing the defect values. The sewer defect values are assigned to the defects based on the impact on the service life. NASSCO's Pipeline Assessment and Certification Program is a methodology that is employed by utilities to assess gravity sewers.

A defect index similar to the PACP defect coding for force mains was developed to assist with renewal decisions. This defect system grading scale is similar to the PACP grading scale (1 to 5) and is based on the failure modes for various pipe materials (Derr and Gabriel, 2014). In addition to defect coding and grading, understanding the performance of the force mains at the time of inspection is crucial.

3.3.2 Predicting the Performance Deterioration

The current utility practices on assessing the condition of the assets are focused on condition grading of assets and risk assessment. These models are appropriate for high level strategic decision making and cannot be employed to estimate the remaining service life of the individual assets.

The LEYP model developed by IRSTEA (National Research Institute of Science and Technology for Environment and Agriculture) calculates the Predicted Break Number (PBN) for each (small and medium) pipe which acts as a surrogate for the LOF score in the risk assessment. The risk scores are calculated by multiplying the COF, to select the mains for replacement. Furthermore, the Predicted Break Rates are calculated to create the aging curve. The ARCADIS GIS Replacement Planning Tool uses the main curves for long term planning. The system wide aging curve for the mains is developed through this model.

Performance prediction modeling can be employed to assess the remaining service life of pipelines. A limitation associated with employing performance index to predict the performance of force mains is the lack of historical performance data. Therefore, the useful life of the assets can be estimated through performance prediction curves using time and state dependent data.

3.3.3 Level of Service (LOS)

The social, environmental and economic objectives of the community can be met by establishing the key performance indicators. These performance indicators can be used to establish a rational level of service. Subsequently, the current service level of the force mains can be used to develop risk assessment and prioritization for decision making. The key performance indicators that can be used to develop the target service levels are (Crotty, 2004):

- Sewer Overflow Rate: measures the condition of the sewerage collection system and the effectiveness of maintenance activities. It is expressed as the ration of the number of overflows per 100 miles of collection piping
- Collection System Integrity: measures the frequency of collection system failures per 100 miles of piping
- Wastewater Treatment Effectiveness Rate: quantifies a utility's compliance with the effluent quality standards in effect at each of its wastewater treatment facilities
- Operations and Maintenance Cost Ratios: tally the cost of operations and maintenance and relate them on per account and per millions of gallons of wastewater processed bases. Separate tallies are recommended for total costs and those related to treatment
- Planned Maintenance Ratio: measures how effectively utilities are investing in planned maintenance. Two proposed ratios make comparisons to cost and to hours invested in maintenance activities.
- Customer Service Complaints and Technical Quality Complaints: per 1000 customer accounts complement one another. The first are service associated, the second quantify complaints of technical quality
- System Renewal/Replacement Rate: measures the degree to which a utility is renewing or replacing its infrastructure.

3.3.4 Risk Assessment and Prioritization for Decision Making

Risk evaluation is a method of predicting the risk of failure of the assets based on the consequence of failure and likelihood of failure. The consequence of failure of the force main segments is determined by identifying the attributes that contribute to the impact of failure of the force mains. The costs associated with high consequence of failure of the force mains can be categorized into:

- direct costs: include repair costs, cleanup costs, diversion costs and shut down costs
- environmental and health costs: impact on public due to flooding and subsequent contact
- socioeconomic costs: traffic disruptions, third party damages and claims

Furthermore, the attributes that affect the consequence of failure assessment are:

- Customer impacts: population density and critical assets like hospitals, government sites etc.
- Impact of location: location of the force mains (industrial, commercial and residential), assets surrounding the force main (highway, tunnel etc.)

- Environmental and physical factors: bypass alternatives, terrain conditions, traffic conditions etc.

The likelihood of failure of the assets was traditionally assessed through age and pipe material. The failure history data should be used in addition to age and material information for a realistic assessment of likelihood of failure. Nevertheless, lack of comprehensive failure risk data on force mains can be supplemented by qualitative data in terms of severity (high, medium, low). Various utilities identify the attributes based on the information available in their data repository.

3.4 Renewal Engineering

The risk associated with the deteriorated force mains can be mitigated through renewal engineering. Renewal engineering can be categorized into repair, rehabilitation and replacement. The renewal technology can be selected based on the operating condition of the force mains, site-specific attributes and the life-cycle cost of the renewal technique. The following sub-sections summarize the advantages and limitations of existing renewal engineering technologies for force mains.

3.4.1 Technologies for Renewal Engineering

The high risk pipes identified through condition assessment modeling and inspection needs to be renewed depending upon the remaining service life. The renewal strategy depends primarily upon the required performance, feasibility and cost effectiveness. The renewal strategy is based upon the data available on the failure modes and the break data. The data can be used to develop the consequence of failure and risk analysis to identify the high risk pipes for renewal. The deterioration of the pipelines can be modeled using the condition assessment models and the locations of failure can be identified for renewal.

The renewal technology can be selected based on the operating condition of the force mains, site-specific attributes and the life-cycle cost of the renewal technique. Additionally, cathodic protection and polyethylene encasement can be employed as a corrosion mitigation technique. The extent of deterioration of the force main dictates the renewal method that can be employed.

- Repair technologies can be classified into open cut repair and spot repair. The spot repairs can be addressed through clamps and pothole excavations. Installation of repair clamps entails open-cut excavation.
- Rehabilitation technologies that are applicable to force mains are spray-on linings, close-fit linings, CIPP, CFRP and woven hose liners.
- Replacement technologies that are applicable to force mains are sliplining, pipe bursting, pipe splitting, horizontal directional drilling, pipe jacking, auger boring and pipe ramming. Open-cut construction is also used for pipe replacement

The key parameters that should be considered for a renewal strategy are: bypass requirements, public disruptions, capacity requirements and structural requirements. The critical renewal techniques are addressed below.

- Sliplining is a cost effective method that can be installed under live flow conditions with minimum service disruption. A limitation associated with sliplining is the reduction of pipeline hydraulic capacity due to reduction in interior pipe diameter.
- Close-fit lining operates similar to sliplining and offers a better hydraulic capacity compared to sliplining. High strength structural rehabilitation can be provided by close-fit and sliplining.
- CIPP offers minimal reduction in hydraulic capacity, but requires bypass pumping. The service disruptions can be minimized through a rapid installation process.
- UV Cured CIPP method which employs a rapid UV curing process can be used to minimize public disruptions.

The most widely employed strategy by utilities to renew the force mains is pipe replacement due to limited available experience with force mains renewal strategies. Open cut and trenchless methods are the available renewal technologies and are addressed in this chapter under literature review. Force Main inspection and rehabilitation involves by-pass pumping and shut down for cleaning and dewatering activities. The cost associated with the repair and rehabilitation setup should be analyzed and compared with the replacement options. In addition to the costs, the renewal option that provides a longer remaining service life should be pursued. The key renewal technologies available through various vendors are presented in the Appendix A (EPA, 2010b).

3.4.2 Capital Investment and Funding Strategy

The unit costs of the feasible renewal option for the force main segments of different diameters and materials need to be estimated to establish a Capital Improvements Program (CIP) investment strategy. The unit costs should include all renewal costs not limited to equipment cost, installation cost, labor cost, clean up and disposal cost, by-pass cost etc. The required cost estimates can be acquired from contractors, manufacturers, recent projects with similar components and standard construction cost estimating manuals. Additionally, the life cycle cost and triple bottom line risks should be considered while developing a CIP investment strategy.

The projects included in the CIP investment program can be prioritized based on the factors that impact the failure of the assets in the project. A weight can be assigned to the factors and the total maximum score can be used to prioritize the projects in CIP investment program. The developed CIP program can be validated by estimating Confidence Level Rating (CLR) and Business Risk Exposure (BRE) (Sneesby et al., 2012). CLR provides a confidence level of the CIP by taking into account the quality of data used and the appropriateness of the renewal process. BRE provides the risk associated with implementing the project by analyzing the probability failure and consequence of failure.

A sustainable funding strategy can be ensured through continuous monitoring and adjustment of utility rates and investigating private, federal and state financing. The reserves required for each year to perform all the renewal activities should be updated and monitored on a regular basis as the utility experience changes in costs and budgeting. This financial forecasting would enable to determine the additional revenue required for the CIP. The key outcomes of financial planning are safety reliability timeliness, minimized annual rate impacts, cost minimization and optimum use of financial resources (AWWA, 2011).

3.5 Quality Assurance

Asset Management of pipeline infrastructure entails accurate prediction of the condition of the system to operate and maintain at the lowest overall costs. The departments involved in this process collect and store data, which support the decision making process. The lack of standard organized data disrupts the decision support system. The following sub-sections provide a data standard that can be employed by utilities.

3.5.1 Evaluation of Force Main Asset Management Plan

A continuous performance monitoring at every step (Step 1 to Step 8 in Table 3-1) should be performed to determine whether the performance requirements are met. Performance measures for each step should be established for quality assurance. Furthermore, a feedback mechanism should be created to assess the effectiveness of performance measures. Since asset management of force main infrastructure is a continuous improvement process, the performance measures should be updated and improved constantly.

3.5.2 Database to Support Advanced Asset Management

The key elements that need to be addressed to setup an asset management program are: current condition of assets, required level of service, identification of critical assets and optimum renewal strategies. Data collection and management is the crucial component to define the above mentioned aspects. The primary task involved in maintaining an asset registry is collecting information of the assets in an efficient manner.

Data pertaining to the failure modes and the location of failures of all force main materials should be collected and maintained. Since the deterioration of force mains progress over time, historical data on the pipe wall thickness and leaks would enable the utilities to understand the trends of failure. Additionally, the break records should reflect the cause of failure and external factors that contributed to the breaks and leaks. The data collection and management of the gravity sewers has been established by the utilities due to their ease of handling compared to force mains. An asset registry should be developed for force mains which include the information related to the life cycle of the assets. The primary component of the asset registry is to establish a unique identifier for each asset to which the attribute data can be linked.

Secondly, the level of asset management (i.e., asset -specific or system-wide) should be defined prior to establishing a database. Thirdly, the information regarding the components that support the force main infrastructure (pumps, valves etc.) should be maintained along with the pipe information. Lastly, incorporating cost information of the inspection technologies and renewal methodologies would enable to plan the operation and maintenance activities of the assets.

The lack of standard organized data disrupts the decision support system. A standard database can be developed based on the PIPEiD data standards and protocols. The units and ranges for these parameters are also established to be used for the data collection and condition assessment model development process. The data standard provides a framework for the utilities to collect the essential parameters for condition assessment of assets. Appendix B and Appendix C encompasses the list of parameters that are crucial to predict the performance of force mains, which can be further developed according to utility requirements and used as a data management protocol.

3.6 Conclusion

Inspection of force mains is critical to the management and maintenance of wastewater collection system. The current inspection practices and technologies employed by the utilities capture parameters that are crucial in prioritizing force mains for renewal. The current condition of the asset can be measured through the collection of data from the inventories, records, observations, and inspections. The force main inspection data can be analyzed to quantify the defects and determine the level of service. The risk associated with the deteriorated force mains can be mitigated through renewal engineering. Renewal engineering can be categorized into repair, rehabilitation and replacement. The renewal technology can be selected based on the operating condition of the force mains, site-specific attributes and the life-cycle cost of the renewal technique. The manuscript depicted the current scenario of the available methods for inspection, condition assessment and renewal engineering, and suggested a 10-step approach for force mains asset management.

CHAPTER 4.0

WEB-BASED PLATFORM FOR ADVANCED ASSET MANAGEMENT OF FORCE MAIN INFRASTRUCTURE

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4.1 Introduction

The integral part of assessing the condition of the infrastructure system is to analyze the existing data and design a renewal strategy to maintain the level of service. Asset management models and tools are required to design cost effective and reliable methodologies to prioritize the assets for repair, replacement or rehabilitation. The veracity of the models depends on the attributes considered to develop the model and furthermore on the availability of these quality attributes. Therefore, a robust appropriate data is required to build and validate a model. Eventually, the model results can be analyzed through a visualization tool to evaluate the behavior of the pipeline infrastructure system. These essential components: database management, model implementation and information visualization are considered to develop a web-based platform for advanced asset management of force main infrastructure. The components are integrated together and the interlinking elements of the components are identified for platform development. The interlinking elements identified are data requirements for model execution, data migration to standard format and model visualization.

The web-based platform is envisioned to be a data and model sharing platform, wherein:

1. the data collected from various utilities is analyzed and cleaned. Subsequently, the cleansed data is shared with the respective utilities.
2. the models developed by individual utilities are recreated and shared with other utilities. This is accomplished through a visualization tool which executes utility X's model with utility Y's data. The advantages of this tool are twofold:
    a. Utility X can validate the accuracy of the model
    b. Utility Y is presented with various models through which the utility can understand the current condition and future performance of the assets

4.2 Data Requirements for Model Execution

The data collected by the utilities depends on the parameters necessary for building a model to support the decision making process. The models demand a certain format of data and the raw data collected from the field or derived from other sources is in a different format. Therefore the data needs to be migrated to the necessary format.

The parameters affecting the performance of force mains are identified by the Virginia Tech research team. The parameters are used as a data standard to develop the data model. Subsequently, the data necessary for the platform development is obtained from various utilities across the nation. The data collected from the utilities is in varied formats and therefore is translated to the standard data model structure. The following sub-sections describe the data standard, data model and the data collection process.

4.2.1 Data Standard

The life cycle of pipe system consists of their planning; engineering; manufacturing; construction; operation and maintenance; and repair, rehabilitation, and replacement. Data standard is a list of parameters that are essential to support advanced pipeline infrastructure asset management through the life cycle of the pipeline system. The data standard encapsulates parameters that can support condition assessment and risk management. Furthermore, the parameters can be used to prioritize the inspection and renewal of the force main infrastructure. The parameters affecting the performance of the force mains are presented in Appendix B and Appendix C.

4.2.2 Data Model

Data model represents the organization of the parameters into different tables. The data model is created as a personal geo-database in ArcCatalog. The personal geo-database consists of three components: feature class, tables and relationship class (Figure 4-1). The feature class contains the parameters which have spatial significance. The tables contain parameters which do not have spatial significance. The relationship class defines the relationship between the feature class and tables. The contents of the standard data model are depicted in Figure 4-2. The organization of the tables into various tables and feature classes in a data model is presented in Appendix G. A personal geo-database can store spatial and non-spatial data and enables querying the data. In addition, the personal geo-database contains the domain values and data types.

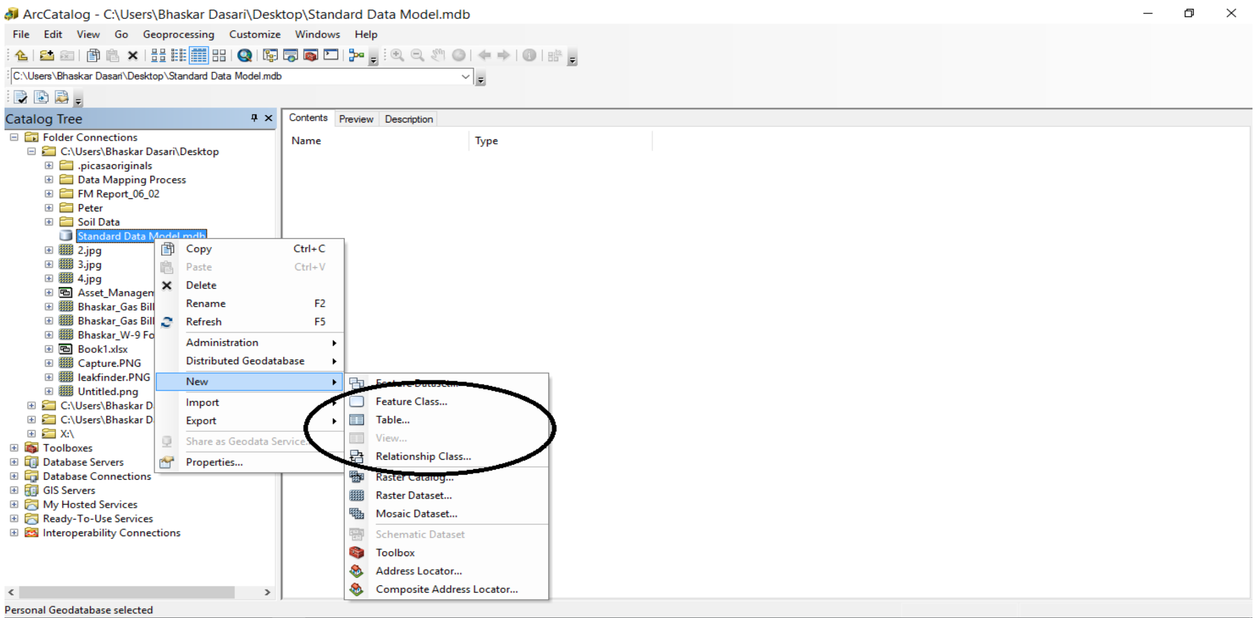

Figure 4-1. Components of Personal Geo-database.

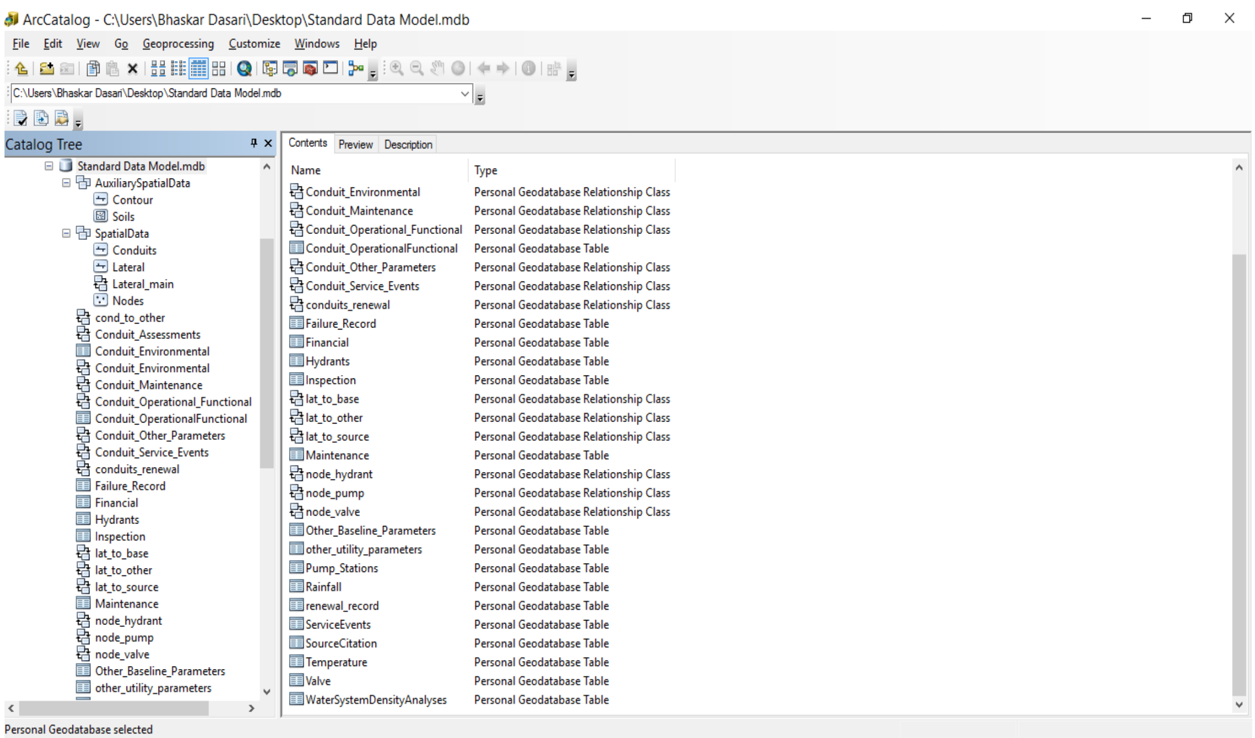

Figure 4-2. Contents of Standard Data Model.

4.2.3 Data Collection

The data is collected from the utilities through www.pipeid.org website. The website is developed using Drupal, which is an open source content management system. Drupal is used to organize, manage and publish content through dynamic websites. The major components of the drupal content management system are language, database, web server and operating system

(Quadri, 2011). PHP language is used to build the drupal core. Drupal requries a SQL database server that supports PHP. MySQL database server is used in this project. Drupal can be installed on Apache, Microsoft IIS and Lightpd web servers which can execute PHP scripts. Drupal is installed on Microsoft IIS web server for this project. Windows 2008 operating system is used to manage the drupal components in this project. The data submission guidelines developed for utilities is presented in Appendix D.

4.2 Data Migration to Standard Format

Once data is uploaded it was mapped into a standardized format which can facilitate analysis. A personal geo-database is created for each utility in ArcCatalog. Subsequently, the standard data model is imported to the utility personal geo-database (Figure 4-3). This creates an empty database which has the structure of the standard data model. Subsequently, mapping of utility data is conducted by loading the utility data into the feature classes and the tables in the personal geo-database (Figure 4-4). Mapping is carried out in two stages. Figure 4-5 presents an overview of the mapping process.

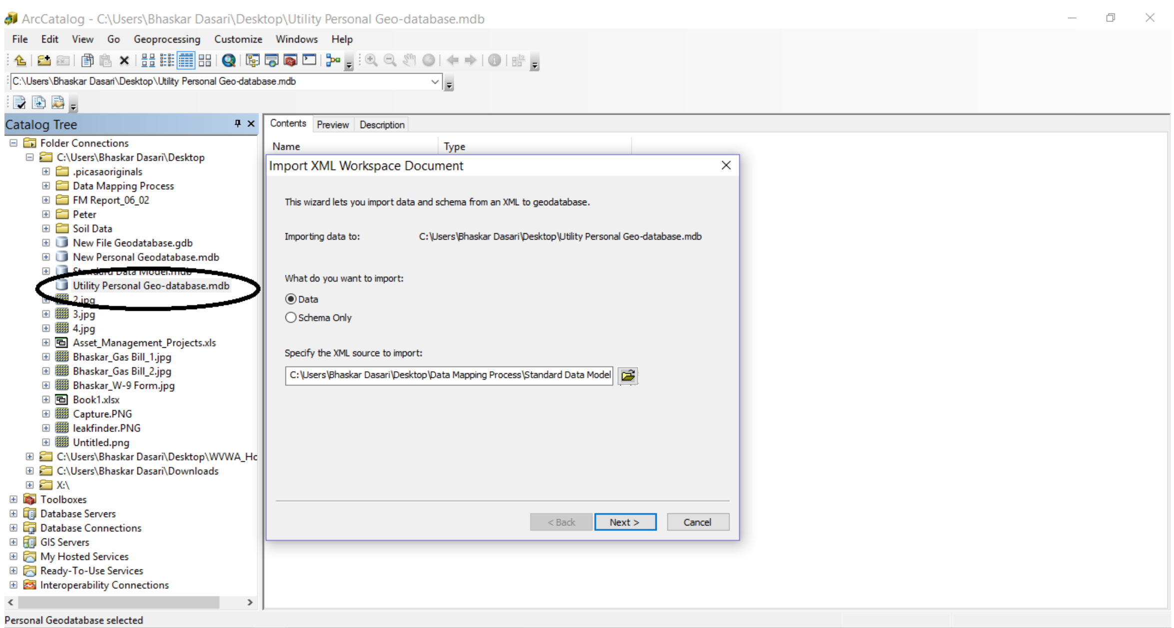

Figure 4-3. Importing Standard Data Model to Personal Geo-database.

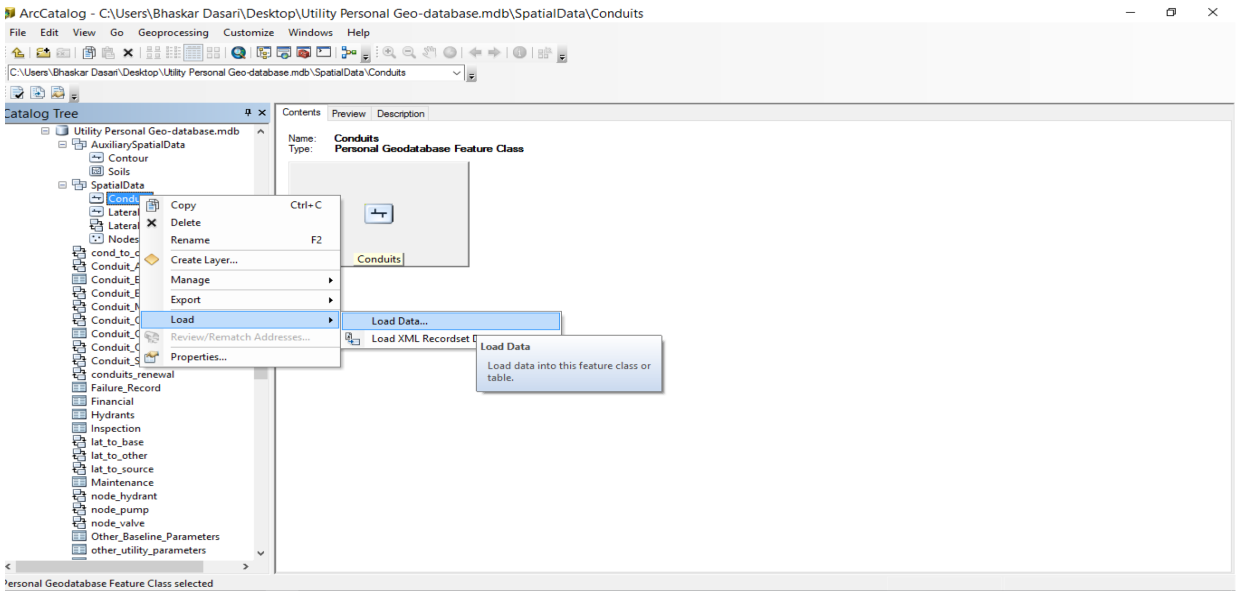

Figure 4-4. Loading the Utility Data.

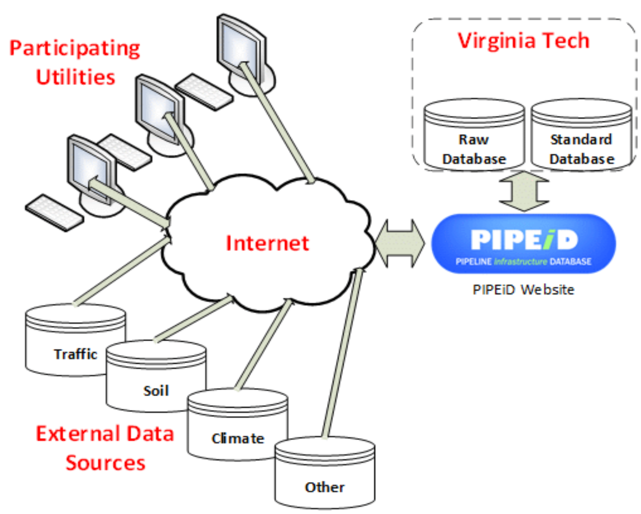

Figure 4-5. Overview of the Mapping Process.

In the first stage, column mapping was carried out by linking the columns in the external data to that of columns in the utility personal geo-database which is presented in Figure 4-6.

For each target field, select the source field that should be loaded into it.

Target Field	Matching Source Field
StructID [string]	<None>
Type [string]	serv_type [string]
Material [string]	material [string]
Diameter [double]	diameter [double]
FromNode [string]	<None>
ToNode [string]	<None>
XSshape [string]	<None>
FromInv [string]	<None>
ToInv [string]	<None>
Date_Inst [DATE]	<None>

Figure 4-6. Column Mapping.

Subsequently, in the second stage nomenclature was changed according to the domain values set for different columns in the data model. For example, for pipe material, Ductile Iron may be stored in utility database in different forms like "DI", "Ductile Iron", "D", etc. Also, some utilities combine different parameters into one. For example, the coating and lining information may be combined and stored along with the material like "Ductile Iron Epoxy Coated and Lined". In such cases the columns may need to be further split as shown in Figure 4-7.

pipe_type
Cement Lined Ductile Iron Polywrapped
Cement Lined Ductile Iron Polywrapped
Cement Lined Ductile Iron Polywrapped
Cement Lined Ductile Iron Polywrapped
Cement Lined Ductile Iron Polywrapped
Cement Lined Ductile Iron Polywrapped
Cement Lined Ductile Iron Polywrapped
Cement Lined Ductile Iron Polywrapped
Cement Lined Ductile Iron Polywrapped
Cement Lined Ductile Iron Polywrapped
Cement Lined Ductile Iron Polywrapped

Material	Lining	External_Coating
DI	Cement	Polyethylene Encasement
DI	Cement	Polyethylene Encasement
DI	Cement	Polyethylene Encasement
DI	Cement	Polyethylene Encasement
DI	Cement	Polyethylene Encasement
DI	Cement	Polyethylene Encasement
DI	Cement	Polyethylene Encasement
DI	Cement	Polyethylene Encasement
DI	Cement	Polyethylene Encasement
DI	Cement	Polyethylene Encasement
DI	Cement	Polyethylene Encasement

Figure 4-7. Column Splitting.

4.3 Model Visualization

A risk prioritization model employed by a utility is used as a prototype to develop the web-based platform. The model is developed in the GIS ModelBuilder platform wherein the sequence of steps associated with risk prioritization are built as geoprocessing workflows. Consequently, the model is published as geo-processing services through ESRI ArcGIS Server.

A visualization tool is developed for individual utilities that interacts with the geo-processing services and renders a web-based interactive map to visualize the model results. The overall platform description is discussed in the following sub-sections.

4.3.1 Utility Models

The model primarily employed by the utilities for condition assessment and risk management is the ranking system, wherein the force mains are ranked based on the risk of failure score. A value is assigned to the range of the attributes and a weighting factor is assigned to the individual attributes. The weights assigned are based on the relative importance of the attributes in defining risk. Consequently, likelihood and consequence of failure score for each applicable attribute is calculated by multiplying the values times the weight. The total risk of failure score for the force main segment is calculated by adding up the scores of individual attributes.

4.3.2 Model Development

The model is developed in the GIS ModelBuilder platform wherein the sequence of steps associated with risk prioritization are built as geoprocessing workflows (Figure 4-8). The ModelBuilder is used to represent the sequence of steps as a diagram wherein the output of the previous step is used as an input for the subsequent step. The final output are three map layers which represent the high risk, medium risk and low risk pipelines. Subsequently, the model is run on ArcMap and the results of the model are saved.

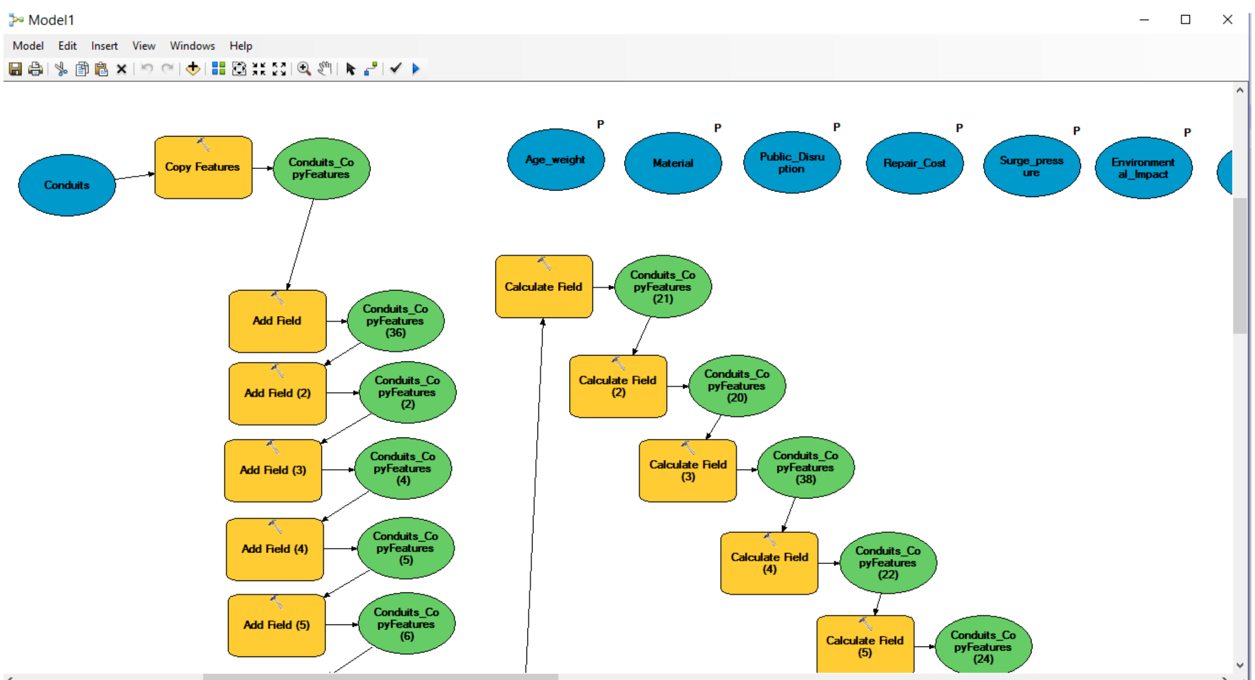

Figure 4-8. Model Development in GIS ModelBuilder Platform.

The model developed in GIS ModelBuilder is published to ArcGIS Server as geoprocessing services, and cartographic representations of utility data are published as map services. Geoprocessing services contain models, and a model takes the data captured in a database, processes it, and returns output in the form of features and maps. The steps involved in publishing the geoprocessing and map service from the results are presented in Appendix E.

4.3.3 Visualization Tool

A web-based geospatial platform enables the utility managers to visualize and query force main information along with associated information retrieved from other national databases. Advanced tools such as ArcGIS Viewer Flex Application Builder and ArcGIS Server are used in this research to build this web based visualization tool.

ArcGIS Viewer for Flex is used to develop interactive web maps. In addition, ArcGIS Server resources are integrated with Flex components. The REST URL's retrieved from the ArcGIS Server are embedded in the Flex application code. The steps involved in developing an interactive web based visualization tool are presented in Appendix F.

4.4 Results Dissemination

An exclusive working environment is provided for each utility, which provides access to their respective data and to the model results for their force mains. A utility hub page is created in the www.pipeid.org website for each utility. The model is run with individual utility's data and the standardized data, model description and the web based visualization tool is provided to the utility through the hub page. The registered utilities can access the hub page by clicking the ‘My Hub Page’ tab under the ‘My PIPEiD’ tab. The ‘My Hub Page’ contains three tabs: data management, model implementation and model visualization (Figure 4-9). The data management tab provides the utility's standardized data. The model implementation tab describes the model used to prioritize the utility's force mains based on risk assessment. The model visualization tab presents the web based visualization tool, which is run using the utility's data. The utility can change the model parameter weights and query the high risk, medium risk and low risk force mains in their system.

Figure 4-9. Example Hub Page.

4.5 Pilot Study

The web-based platform was pilot studied using the City of Houston (COH) risk prioritization model and Western Virginia Water Authority (WVWA) data.

The risk prioritization model employed by City of Houston is used as a prototype to develop the web-based platform. The cause of failure and effect of failure are recognized, wherein physical asset characteristics are emphasized in cause of failure criteria and impact of failure is emphasized in effect of failure. The attributes of cause of failure include: material, age, surge pressure, velocity, length, number of air release valves, discharge slope and chemical feed. The attributes of effect of failure include: public disruption, repair cost, environmental impact, ease of bypass/redundancy, failure history, population growth/capacity limitation, critical industries, elimination/consolidation potential and highway/railroad crossings. Subsequently, the weights for each factor and the risk scores used to assess the force mains risk value are defined. The model classifies the force mains into high risk, medium risk and low risk pipelines based on the cause of failure and impact of failure.

Subsequently, the visualization tool is developed is execute the COH model online using WVWA data and query the pipes in the WVWA database. The geo-processing widget (Figure 4-10) enables WVWA to assign the weights for each factor and execute the model online. WVWA can visualize the force mains in their network and also analyze the attributes associated with the force mains using the query widgets.

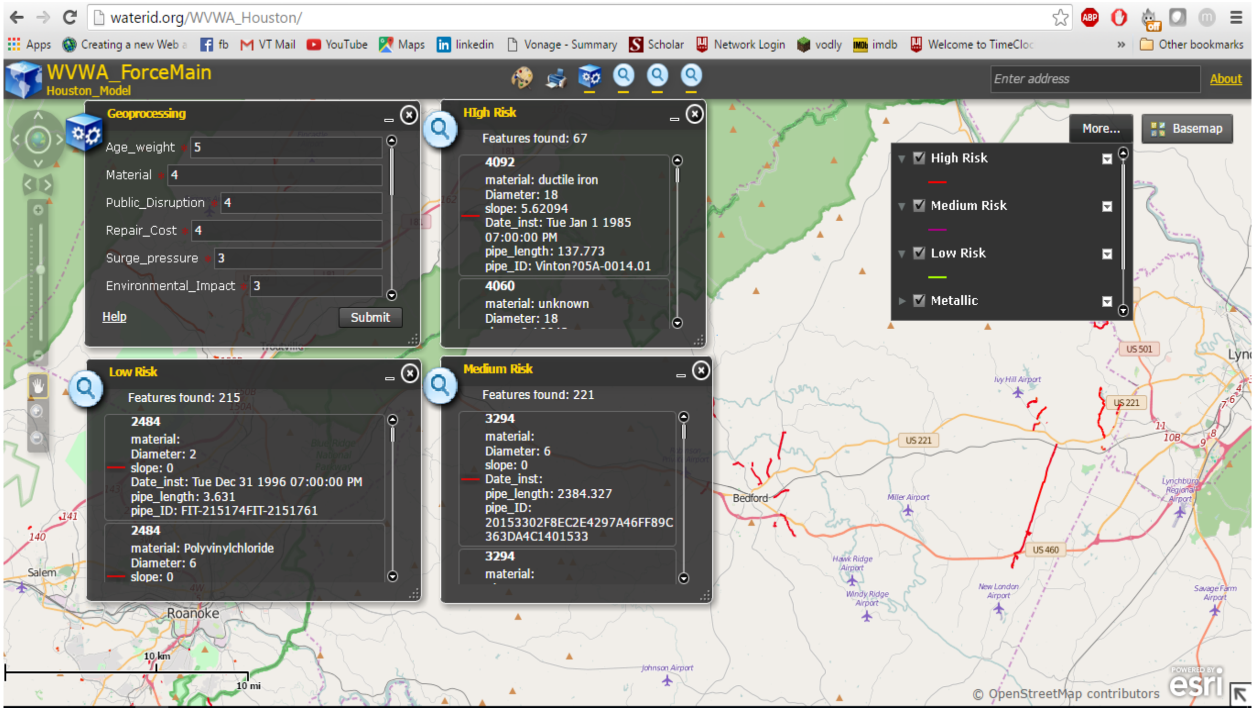

Figure 4-10. Web-Based Application.

4.6 Conclusion

The manuscript depicts various aspects involved in developing a web-based application for different utilities that store, collect and analyze the data in dissimilar methods. A risk prioritization model employed by a utility is used as a prototype to develop the web-based platform. Consequently, the model is published as geo-processing services through ESRI ArcGIS Server. A visualization tool is developed for individual utilities that interacts with the geo-processing services and renders a web-based interactive map to visualize the model results.

The standard data framework developed can be used by utilities to collect, store and analyze the pipeline infrastructure data. The organized data can be used by various models and tools through the GIS web-based interface. Furthermore, the models can be executed using the web-based interface and additionally the results of the models can be queried using various tools incorporated in the application. A secure access to the transformed data and the models is provided to the utilities which can act as a decision support system for various asset management needs.

CHAPTER 5.0

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Force mains are installed at critical points in the wastewater distribution system. The key elements that significantly influence the need to address the inspection, condition assessment and renewal strategies of force mains are: lack of sufficient redundancy, high consequence of failure and accessibility. These limitations for the management of the force mains can be mitigated by following a structured asset management program. The thesis report suggests a guideline, a 10 step structured approach for comprehensive asset management.

Furthermore, advanced asset management of force main infrastructure entails accurate prediction of the condition of the system to operate and maintain at the lowest overall costs. The key components involved in a comprehensive asset management of the pipeline infrastructure are data management, model implementation and information visualization. The thesis addressed the issues involved in implementing the key components through the web-based platform. The main contributions of the web-based platform included:

- Eliminated the obsolete data collection process through an FTP server and created a robust data collection platform through the website (www.pipeid.org).
- Updated the standard data model for wastewater infrastructure and modified the model by incorporating tables and attributes that represent performance of the force main infrastructure
- Mapped the utilities data to the standard geo-database model and created a master geo-database for force main infrastructure systems.
- Developed a web-based geo-spatial platform for risk prioritization by using advanced tools such as ArcGIS Viewer Flex Application Builder and ArcGIS Server.
- Disseminated the prototype model which contains a geo-processing tool that executes the model online and provides the flexibility to change the parameter weights, and a query tool to retrieve force mains data. The model is provided to utilities through the website (www.pipeid.org).

5.2 Recommendations

The gaps and limitations in the force main infrastructure asset management can be partially addressed by standardizing the utility asset management practices. A standardized defect index and grading scale should be established by the utilities. The performance index and prediction models can be combined with consequence of failure indices to establish the business risk exposure associated with assets for prioritization and renewal decisions. A major need is to have some independent test platforms where tools can be tested for their abilities to identify and quantify defects in varying types of pipes. Tools could then be given an initial classification based on the results from the test bed. Such independent tests would allow engineers and utilities to have some basis for choosing an inspection vendor. The current industry scenario has no benchmarks or comparisons among different methods and tools.

The future research should focus on the following aspects to improve the web-based platform:

- The integration of data from external sources to a master geo-database. Data from other sources such as USGS, NRCS can be conflated into the existing database.
- The development of an open source web application to publish the models and reduce the dependency on the licensed software applications.
- The development of geo-processing task using a python wrapper to execute fuzzy-based models, MATLAB based models and other non-python script models.

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APPENDIX A

KEY RENEWAL TECHNOLOGIES AVAILABLE THROUGH VARIOUS VENDORS

Renewal Technologies Using PE Liners.

Vendor/Technology	Key Features	Technical Information
Advantica/ Close Fit Symmetrical Reduction (Installed in USA)	♦ Product: Swagelining ♦ Applicable for Rehabilitation and Replacement of all pressure pipe categories. ♦ Outside Diameter of the pipe greater than inside diameter of the host pipe ♦ Diameter of the pipe is temporarily reduced using a reduction die before installing in the host pipe ♦ Lined pipe is pressed tightly against host pipe ♦ PE pipes are butt fused which alleviates the development of leaks in the joints ♦ Less setup time due to compact and lightweight equipment ♦ Does not require shrinkage, curing, field chemistry or heating ♦ Installation Method: Sliplining ♦ The pipe should be in tension during the installation process	♦ Material: Polyethylene ♦ Diameter Range: 4-44 in. ♦ Thickness Range: Diameter Ratio 11-42 ♦ Renewal Length: Up to 3000 ft. between excavations ♦ Temperature Range: 80 ºF-100ºF
United Pipeline Systems/ Close Fit–Symmetrical Reduction (Installed in USA)	♦ Product: Titeliner ♦ Application: Leak Stoppage ♦ Outside Diameter of the pipe greater than inside diameter of pipe to be lined ♦ Butt fused ♦ Diameter of the pipe is temporarily reduced using a roller reduction unit and winch ♦ The pipe is radially compressed during insertion process ♦ Tension of the liner is released after the insertion which expands the liner radially to fit the host pipe ♦ Internal and external loads are carried by the host pipe ♦ Requires bypass pumping ♦ Installation is a continuous process without disruption ♦ Liner is prone to damage during installation	♦ Material: HDPE PE3408 or PE4710 ♦ Diameter Range: 2-52 in. ♦ Renewal Length: Up to 2600 ft.

Vendor/Technology	Key Features	Technical Information
Insituform Blue/ Close Fit–Symmetrical Reduction (Installed in USA)	♦ Product: InsituGuardTM–Flexed ♦ Application: Rehabilitation ♦ Inserted into new or existing pipe ♦ Eliminates internal corrosion by isolating the host pipe wall from the flow stream ♦ Requires by-pass ♦ Factory bends cannot be accommodated	♦ Material: PE4710 ♦ Diameter Range: 6-48 in. ♦ Thickness Range: Less than Diameter Ratio 17 ♦ Temperature Range: 140 ºF ♦ Renewal Length: Greater than 2000 ft. based on winching capacity ♦ Pressure Capacity: 150 psi ♦ Design Life: 50 years
Subterra/ Close Fit–Symmetrical Reduction (Not Installed in USA) Country of Origin: UK	♦ Product: Rolldown ♦ Emerging technology for Sewer Pumping Mains ♦ Inserted by pushing PE80 through a series of concentric rollers ♦ Liner is pressurized with water after insertion to revert to original size	♦ Material: PE80 ♦ Diameter Range: 4-20 in. ♦ Temperature Range: 73 ºF ♦ Renewal Length: 5000 ft. in one insertion ♦ Pressure Capacity: 232 psi ♦ Design Life: 50 years
Subterra/ Close Fit–Fold and Form (Not Installed in USA) Country of Origin:UK	♦ Product: Subcoil ♦ Emerging technology for Sewer Pumping Mains ♦ Factory folded in C shape ♦ Liner is pressurized with water after insertion to form a close fit	♦ Material: PE80 ♦ Diameter Range: 4-12 in. ♦ Temperature Range: 73 ºF ♦ Renewal Length: 3500 ft. in one insertion ♦ Design Life: 50 years
Mainsaver/ Close Fit–Fold and Form (Installed in USA)	♦ Product: Mainsaver ♦ Application: Renew pipes with holes, displaced joints and leaking joints ♦ Flexible MDPE tube with grout key hooks on the outside surface ♦ Cement grout is placed between the tube and host pipe after the tube is inserted into the main ♦ Grout is distributed against the host pipe surface ♦ Applicable for small diameter pressure pipes only	♦ Material: Medium Density Polyethylene (MDPE), Cement Mortar ♦ Diameter Range: 4-12 in. ♦ Thickness Range: 3 mm ♦ Temperature Range: 37 ºF ♦ Pressure Capacity: Less than 294 psi ♦ Renewal Length: 500 ft.
Subterra/ Close Fit–Fold and Form (Not Installed in USA) Country of Origin: UK	♦ Product: Subline ♦ Application: Prevents leaks and stops internal corrosion ♦ Temporary bands are used to restrain PE80 into a C shape ♦ The temporary bands are broken after insertion by pressurized water and thereby reverting the pipe to original size ♦ Can navigate 45º angle bends	♦ Material: PE80 ♦ Diameter Range: 3-60 in. ♦ Thickness Range: 3-20 mm ♦ Temperature Range: 73 ºF ♦ Renewal Length: 3500 ft. ♦ Design Life: 50 years

Vendor/Technology	Key Features	Technical Information
Insituform Blue / Close Fit–Fold and Form (Installed in USA)	♦ Product: InsituGuard - Folded HDPE ♦ Application: Stops leaks ♦ Continuous Liner ♦ Eliminates internal corrosion by isolating the host pipe wall from the flow stream ♦ Installed with close-fit against host pipe ♦ Factory bends cannot be accommodated ♦ Requires Bypass ♦ Wall thickness depends on the diameter	♦ Material: PE100 ♦ Diameter Range: 12-48 in. ♦ Thickness Range: Less than Diameter ratio 17 ♦ Temperature Range: 80 ºF-140ºF ♦ Renewal Length: Above 2000 ft. based on winching capacity ♦ Pressure Capacity: 150 psi ♦ Design Life: 50 years

Renewal Technologies Using PVC Liners.

Vendor/Technology	Key Features	Technical Information
Miller Pipe/ Close Fit Fold and Form (Installed in USA)	♦ Product: EX Pipe ♦ Application: Infiltration and Exfiltration, Root Intrusion and Soil Loss is stopped ♦ Can be installed in 90º angle bends and small diameter variations ♦ High Strength un-plasticized PVC ♦ Softened with heat and continuously inserted into the host pipe ♦ Pipe is expanded 10% to fit against the host pipe ♦ Resistance to abrasion and chemicals ♦ Low coefficient of thermal expansion ♦ Available in small diameter ranges	♦ Material: PVC base with 12334B cell classification ♦ Diameter Range: 6-15 in. ♦ Thickness Range: 0.20-0.43 in. ♦ Temperature Range: 140 ºF ♦ Renewal Length: 350-600 ft. ♦ Design Life: 50 years
American Pipes and Plastics/ Close Fit Fold and Form (Installed in USA)	♦ Product: AM – Liner II ♦ Application: Rehabilitation ♦ Pulled into the host pipe and thermoformed ♦ Resistant to chemical attacks ♦ Not employed in pressure pipe, applied in gravity wastewater and stormwater	♦ Material: HDPE PE3408 or PE4710 ♦ Diameter Range: 2-52 in. ♦ Renewal Length: Up to 2600 ft.
Underground Solutions/ Close Fit – Expandable	♦ Product: Duraliner ♦ Application: Rehabilitation and Replacement ♦ Resistant to water disinfectant induced oxidation and resistant to hydrocarbon permeation ♦ The flow is maintained in the pipe which is accomplished through improved coefficient of friction which offsets the reduction in internal area	♦ Material: PVC ♦ Diameter Range: 4-16 in. ♦ Design Life: 100 years ♦ Pressure Capacity: Greater than 150 psi

Vendor/Technology	Key Features	Technical Information
Underground Solutions/ Sliplining and HDD (Installed in USA)	♦ Product: Fusible PVC (FPVC) ♦ Emerging technology which employs butt fusion process to fuse the PVC pipes ♦ Resistant to corrosion and abrasion ♦ High C Factor at 15º ♦ Larger inside diameters are available ♦ Applications: Sliplining, HDD, Pipe Bursting, Direct Bury and Pipe Bursting (commonly used) ♦ Impacted by fatigue pressures ♦ Fusion time is 1.5-2 minutes per diameter inch ♦ Limited bending radius of FPVC requires longer insertion pits over softer thermoplastics	♦ Material: Fusible PVC ♦ Diameter Range: 4-12 in. for Fusible C-900, 14-36 in. for Fusible C-905 and 4-36 in. for FPVC ♦ Thickness Range: Diameter Ratio of 14,18,25 for C-900, Diameter Ratio of 14,18,21,25,32.5,41,51 for C-905 and Diameter Ratio of 14,18,21,25,26,32.5,41,51 for FPVC ♦ Temperature Range: Less than 140 ºF ♦ Renewal Length: Pipe Bursting: 300-500 ft., Slipline length of 3500 ft. and 5100 ft. of HDD length ♦ Pressure Capacity: 165 psi -305 psi for C900 and 80 psi - 235 psi for C905 ♦ Design Life: 100 years

Renewal Technologies Using Polyester Liners.

Vendor/Technology	Key Features	Technical Information
Inliner Technologies/ CIPP (Installed in USA)	♦ Product: Inliner ♦ Installation Method: Inversion or Pulled-In Place ♦ Resin impregnated tube can be stored in refrigerated environment for two to three weeks ♦ Patented features: StretchGuardTM and ResinGuardTM ♦ Limited excavation is required	♦ Material: Isophthalic Polyester Resin, Epoxy Vinyl Ester and Enhanced Polyesters ♦ Diameter Range: 4-120 in. ♦ Thickness Range: 0.12-2.4 in. ♦ Temperature Range: Less than 140 ºF ♦ Renewal Length: 5 ft.-2400 ft. ♦ Pressure Capacity: 60 psi ♦ Design Life: 50 years
Insituform Technologies/ CIPP (Installed in USA)	♦ Product: Pressure Pipe Liner ♦ Application: Eliminate leaks, prevent internal corrosion ♦ Small holes, pits or open joints in the host pipe can be spanned ♦ Additional glass fiber reinforcement is included to the standard Insituform CIPP tubes for pressure applications ♦ Can be installed in 90º angle bends ♦ Internal and external loads are carried by the host pipe ♦ Insertion of the liner requires shut down or bypassing	♦ Material: Vinyl ester or epoxy resins (special epoxy for potable water), standard Insituform CIPP non-woven felt tube but with special glass reinforcement included. ♦ Diameter Range: 8-60 in. ♦ Thickness Range: 0.3-0.7 in. ♦ Temperature Range: 120 ºF ♦ Renewal Length: 200 ft.-1000 ft. ♦ Pressure Capacity: 200 psi ♦ Design Life: 50 years

Vendor/Technology	Key Features	Technical Information
National Environ Tech Group / CIPP (Installed in USA)	♦ Product: National Liner ♦ Key Features: ♦ Minimum excavation is required ♦ A new composite with glass fiber reinforcement is under development for pressure pipes	♦ Material: Non woven polyester saturated with isophthalic or vinylester polyester resin ♦ Diameter Range: 6-120 in. ♦ Thickness Range: 4.5-33.5 mm ♦ Temperature Range: PE resin up to 205 ºF and VE resin up to 248 ºF ♦ Renewal Length: 800 ft. to 2000 ft. based on the diameter ♦ Pressure Capacity: Greater than 50 psi ♦ Design Life: 50 years
Karl Weiss Technologies GmbH/ Woven Hose – Adhesive (Not Installed in USA) Country of Origin:Germany	♦ Product: Starline HPL-S ♦ Pressed through calibrated rollers prior to pushing into the pipe ♦ Liner is inverted inside the pipe segment until it reaches the catch basket	♦ Material: Polyester woven liner, adhesive and epoxy coatings ♦ Diameter Range: 3-24 in. ♦ Temperature Range: 78 ºF ♦ Pressure Capacity: Less than 430 psi ♦ Design Life: 50 years

Renewal Technologies Using Glass Fiber Reinforced Liners.

Vendor/Technology	Key Features	Technical Information
NOVOC Performance Resins/CIPP (Installed in USA)	♦ Product: Paraliner FM ♦ Installed by inversion method using head of water or pulled into place by winch and inflated with air ♦ A continuous watertight liner from start to end ♦ Minimum excavation is required ♦ Requires bypass during installation ♦ The line must be cleaned before installation	♦ Material: One or more layers of absorbent non-woven felt fabric, fiberglass, NOVOC 4900 PW resin ♦ Diameter Range: 6-96 in. ♦ Thickness Range: 4.5-52.5 mm ♦ Temperature Range: 220 ºF ♦ Pressure Capacity: 230 psi ♦ Renewal Length: 1000 ft. based on diameter ♦ Design Life: 50 years
Insituform Technologies/ CIPP (Installed in USA)	♦ Product: Reinforced Pressure Liner ♦ Installation method: Inversion with Hot Water Cured ♦ Emerging technology to prevent internal corrosion ♦ Does not rely on the host pipe ♦ Additional glass fiber reinforcement is included to the standard Insituform CIPP tubes for pressure applications ♦ Small holes, gaps or open joints can be spanned ♦ 45º angle bends can be accommodated ♦ The pipe should cleaned before installation ♦ Requires bypass during installation	♦ Material: Two or more layers of absorbent non-woven synthetic fiber combined with glass fiber reinforcement ♦ Diameter Range: 8-72 in. ♦ Thickness Range: 5-26 mm ♦ Temperature Range: 120 ºF ♦ Design Life: 50 years ♦ Pressure Capacity: Less than 80 psi ♦ Renewal Length: 200 ft. to 1000 ft.

Vendor/Technology	Key Features	Technical Information
Norditube Technologies/ CIPP (Not Installed in USA) Country of Origin:Sweden	♦ Product: Nordipipe ♦ No support from host pipe is required ♦ Resistance to high pressure ♦ 45º angle bends can be navigated ♦ Installed by Air Inversion method with air or steam cure. Also installed by Water column inversion with circulated water cure	♦ Material: Polyethylene coating in contact with potable water, non-woven felt and glass fiber chopped mat, with epoxy or vinyl ester resin. ♦ Diameter Range: 5-48 in. ♦ Thickness Range: 4.6-24 mm ♦ Temperature Range: 100 ºF with Epoxy and 160ºF with vinyl ester ♦ Renewal Length: 500-600 ft. ♦ Pressure Capacity: 60-250 psi ♦ Design Life: 50 years
BKP Berolina Polyester GmbH/CIPP (Not Installed in USA) Country of Origin: Germany	♦ Product: Berolina Liner ♦ UV cured Liner ♦ Glass fiber layer provides the axial strength to pull the liner in place ♦ Can be CCTV inspected prior to UV cure ♦ Circular and Oval profiles can be installed	♦ Material: Five layers of glass-fiber and/or polyester web that is impregnated with a UV-light curing polyester resin. ♦ Diameter Range: 6-40 in. ♦ Thickness Range: 2-12 mm ♦ Temperature Range: 122 ºF with Polyester resin and 158 ºF with Vinylester resin ♦ Renewal Length: 1200 ft. ♦ Pressure Capacity: 45 psi ♦ Design Life 50 years
Reline America/CIPP (Installed in USA)	♦ Product: Bue-Tek ♦ Higher strength and stiffness achieved through glass fiber reinforce wall ♦ Fast curing times for all diameters ♦ Less styrene emission while curing	♦ Material: Advantex® EC-R glass fiber from Owens Corning and polyester, vinylester or ortho resin depending on application. ♦ Diameter Range: 6-48 in. ♦ Thickness Range: Greater than 3.5 mm ♦ Renewal Length: 1000 ft. ♦ Design Life: 50 years
Insituform Blue/ Close Fit–Fold and Form (Installed in USA)	♦ Product: Insitumain ♦ Can withstand internal and external loads ♦ Leakage and Corrosion are eliminated ♦ Adheres to existing host pipe ♦ 45º angle bends can be navigated ♦ Requires Bypass	♦ Material: Epoxy composite layer reinforced with glass and polyester fiber ♦ Diameter Range: 6-36 in. ♦ Temperature Range: 120 ºF ♦ Pressure Capacity: 150 psi
Sanexen Environmental Services/ Close Fit–Fold and Form (Installed in USA)	♦ Product: Aqua-Pipe ♦ Can navigate less than 90º angle bends ♦ Resistant to corrosion ♦ Cannot navigate 90º bends	♦ Material: Five layers of glass-fiber and/or polyester web that is impregnated with a UV-light curing polyester resin. ♦ Diameter Range: 6-12 in. ♦ Thickness Range: 3-6 mm ♦ Temperature Range: 35 ºF-100ºF ♦ Renewal Length: Up to 500 ft. ♦ Pressure Limit: 150 psi ♦ Design Life: 50 years

Vendor/Technology	Key Features	Technical Information
Saertex Multicom GmbH / Woven Hose–Non Adhesive (Installed in USA)	♦ Product: Saertex-Liner ♦ External styrene film outside the structural layer followed by an opaque film protects against UV exposure and damage during installation ♦ Glass Fiber reinforcement provides high tensile strength in radial and axial directions ♦ Cured by UV or steam ♦ Can accommodate circular, egg-shaped and box sections ♦ Expensive than polyester felt material	♦ Material: Advantex® (ECR glass) glass fiber from Owens Corning. Polyester resin from DSM and Scott Bader. Vinylester resin from NRC. ♦ Diameter Range: 6-48 in. ♦ Thickness Range: 3-12 mm ♦ Renewal Length: Hose Liners Up to 500 mm
Raedlinger Primus Line GmbH/ Woven Hose–Non Adhesive (Not Installed in USA) Country of Origin: Germany	♦ Product: Primus Line ♦ Curing is not required ♦ 30º angle bends can be navigated ♦ Light weight, High strength, easy to install ♦ Can be used for temporary by-pass line ♦ Need special connectors to adapt to fittings ♦ Requires special coupling device to join steel, PE and other pipes with pressure rating greater than 16 bars	♦ Material: Five layers of glass-fiber and/or polyester web that is impregnated with a UV-light curing polyester resin. ♦ Diameter Range: 6-20 in. ♦ Thickness Range: 6.5 mm ♦ Temperature Range: 60 ºC ♦ Renewal Length: Up to 6000 ft. ♦ Pressure Capacity: 218-500 psi ♦ Design Life: 50 years
Aqualiner/Glass Reinforced Thermoplastic (Not Installed in USA) Country of Origin: UK	♦ Product: Aqualiner ♦ Emerging technology involving insertion of glass fiber reinforced polypropylene sock into the deteriorated pipe ♦ Long shelf life due to no mixing of chemicals ♦ Can withstand internal and external pressures ♦ Minimum excavation required	♦ Material: Five layers of glass-fiber and/or polyester web that is impregnated with a UV-light curing polyester resin. ♦ Diameter Range: 6-12 in. ♦ Thickness Range: 3-6 mm ♦ Temperature Range: -5 ºC-40 ºC ♦ Renewal Length: 500 ft. of 12 in. ♦ Pressure Capacity: 150 psi ♦ Design Life: 50-75 years
RS Technik/Glass Reinforced Liner (Installed in USA)	♦ Product: RS CityMain ♦ Product uses DOW resins that are styrene-free, HAP-free and VOC-free ♦ Available in two type of liners: Inversion and Pull-In ♦ Cured using hot water or steam	♦ Diameter Range: 6-48 in. ♦ Operating Pressure: 230 psi ♦ AWWA Class IV fully structural renewal

Renewal Technologies Using Carbon Fiber Liners.

Vendor/Technology	Key Features	Technical Information
Fibrwrap Corp./CIPP (Installed in USA)	♦ Product: Fibrwrap ♦ Applications: Repair, strengthening and retrofit of corrosion induced and distressed large diameter PCCP, RCCP and steel pressure pipes ♦ Limited to sectional repairs as they incur less cost	♦ Material: Layers of FRP ♦ Diameter Range: 30-201 in. ♦ Thickness Range: 0.08-1 in. ♦ Temperature Range: 220 ºF ♦ Renewal Length: 16-20 ft. ♦ Pressure Capacity: 150 psi ♦ Design Life: 50 years

Vendor/Technology	Key Features	Technical Information
CarbonWrap/CIPP (Installed in USA)	♦ Product: CarbonWrap ♦ Key Features: ♦ Application: Strengthening buried PCCP pipes with broken wires ♦ Can be used for concrete and steel pipes ♦ No excavation is required ♦ Cannot be used in temperatures less than 200 ºF	♦ Material: Epoxy resin and carbon fiber ♦ Diameter Range: Greater than 36 in. ♦ Thickness Range: Greater than 0.125 in. ♦ Pressure Capacity: 150 psi ♦ Design Life: 25 years
Structural/Reinforced Composite Liner (Installed in USA)	♦ Product: V-Wrap ♦ Utilizes carbon fiber tensile reinforcement and epoxy binders placed onto the interior of an existing pipe. ♦ Well-suited for Prestressed Concrete Cylinder Pipe (PCCP) ♦ Fits straight and curved pipe sections ♦ Withstands high design pressure ♦ Watertight structural membrane	♦ Diameter Range: Greater than 30 in. ♦ Thickness Range: 6mm-19mm

Renewal Technologies Using Polyurea Liners.

Vendor/Technology	Key Features	Technical Information
3M /Spray-On Lining (Installed in USA) Country of Origin:	♦ Product: Skotchkote ♦ Suitable as an inner corrosion barrier or a semi-structural liner ♦ Applicable for Rehabilitation by Spray Lining ♦ Low viscosity for pumping to remote spray head locations ♦ Moisture tolerant to provide slump resistant coatings with good adhesion characteristics ♦ Low elastic modulus: internal pressure is carried by the host pipe ♦ Requires no secondary fittings as it is completely bonded to the host pipe ♦ Design Life: Greater than 30 years ♦ 1 mm-5 mm thick linings can be applied in a single pass ♦ Requires cleaning, drying and join-fitting ♦ Excavations: Approximately 1 every 100-150 m ♦ Disruption Time: Less than 8 hours ♦ Very flexible with low tensile strength	♦ Suitable as an inner corrosion barrier or a semi-structural liner ♦ Applicable for Rehabilitation by Spray Lining ♦ Low viscosity for pumping to remote spray head locations ♦ Moisture tolerant to provide slump resistant coatings with good adhesion characteristics ♦ Low elastic modulus: internal pressure is carried by the host pipe ♦ Requires no secondary fittings as it is completely bonded to the host pipe ♦ Design Life: Greater than 30 years
Questinspar/Manufactured -in-place (Installed in USA)	♦ Product: Pipearmor ♦ Any directional axis and bend radius up to 90° ♦ Self-supporting structural liner is delivered in a single pass vs. multiple passes ♦ Ultra-fast setting resin, with a 4-5 second snap cure ♦ Temperature, chemical and abrasion resistant	♦ Material: Polyurea ♦ Diameter Range: 6-174 in. ♦ Thickness Range: 0.02-1.5 in. ♦ Design Life: 75 years

Vendor/Technology	Key Features	Technical Information
Sprayroq/Elastomeric Polyurethane (Installed in USA)	♦ Product: Sprayshield Green 1 and Sprayshield Green 2 ♦ Ideally designed for applications on surfaces that are exposed to acids, corrosives and other caustic elements ♦ Environmental factors such as freeze/thaw cycling, vibration and seismic activities have no affect on the performance	♦ Design Life: 50 years ♦ Tensile Strength: 2780 psi(Sprayshield Green 1) ♦ Tensile Strength: 2900 psi(Sprayshield Green 2) ♦ Elongation: 115%(Sprayshield Green 1) ♦ Elongation: 43%(Sprayshield Green 2) ♦ Tear Strength: 580 pli(Sprayshield Green 1) ♦ Tear Strength: 593 pli(Sprayshield Green 2) ♦ Flex Modulus: 75000 psi Tear Strength: 580 pli(Sprayshield Green 2) ♦ Abrasion, mg loss/1000 cycles: 53(Sprayshield Green 1) ♦ Abrasion, mg loss/1000 cycles: 42(Sprayshield Green 2) ♦ Water Permeation g/day/m2: 1.49 ♦ Hardness, Shore D: 62-68 ♦ Density: 67.5 lbs/cu.ft.
HydraTech/Semi-Structural Polyurea Based Lining (Installed in USA)	♦ Product: PolySpray SS-100 ♦ Rapid setting semi-structural polyurea monolithic coating ♦ Not recommended for substrates subjected to significant movement. ♦ Advantages: ♦ Seamless, High-Build Liner ♦ Fast Cure (tack free in under 30 seconds) ♦ High Flexibility and Toughness ♦ Immediate Return to Service ♦ Chemical, Abrasion and Impact Resistant ♦ Environmentally Friendly (No V.O.C.) ♦ Elastomeric ♦ Excellent Mechanical Properties ♦ Insensitive to Environment ♦ Thermal Stability ♦ Moisture Tolerant	♦ Diameter Range: 30-120 in. ♦ Thickness Range: 0.25-2 in. ♦ Tensile Strength: 3400 psi ♦ Tensile Modulus: 41,200 psi ♦ Elongation: 100% ♦ Tear Strength: 555 pli ♦ Flexural Modulus: 93,000 psi ♦ Flexural Strength: 4300 psi ♦ Temperature Range: 60-130°F ♦ RESIN Viscosity: 800–1000 cP @ 77 °F ♦ ISO Viscosity: 400–600 cP @ 77 °F ♦ Gel Time: 5 sec. ♦ Tack Free: 10 sec. ♦ Back in Service: 30 minutes

Vendor/Technology	Key Features	Technical Information
HydraTech/Structural Polyurea Based Lining (Installed in USA)	♦ Product: PolySpray FS-250 ♦ A spray applied, structural, rapid curing, RIGID liner ♦ Installation is bonded and results in zero annulus with host pipe ♦ Not recommended for substrates subjected to significant movement. ♦ Advantages: ♦ Structural, Seamless, High-Build Liner ♦ Fast Cure (tack free in under 30 seconds) ♦ High Flexibility and Toughness ♦ Immediate Return to Service ♦ Exceeds all physical properties required by ASTM F1216 ♦ Chemical, Abrasion and Impact Resistant ♦ Environmentally Friendly (No V.O.C.) ♦ Elastomeric ♦ Excellent Mechanical Properties ♦ Insensitive to Environment ♦ Thermal Stability ♦ Moisture Tolerant	♦ Tensile Strength: 6000 psi ♦ Tensile Modulus: 250,000 psi ♦ Elongation: 15% ♦ Flexural Modulus: 250,000 psi ♦ Flexural Strength: 9300 psi ♦ Temperature Range: 70-130°F ♦ RESIN Viscosity: 700–900 cP @ 77 °F ♦ ISO Viscosity: 600–800 cP @ 77 °F ♦ Gel Time: 6 sec. ♦ Tack Free: 10 sec. ♦ Back in Service: 30 minutes
HydraTech/High Elongation Polyurea Based Lining (Installed in USA)	♦ Product: PolySpray HE-800 ♦ A rapid setting highly flexible and elastic polyurea coating ♦ Not recommended for applications requiring structural support ♦ Advantages: ♦ Seamless, High-Build Liner ♦ Bridges gaps up to 1/8" wide ♦ Fast Cure (tack free in under 30 seconds) ♦ High Coating elongation ♦ High Flexibility and Toughness ♦ Immediate Return to Service ♦ Chemical, Abrasion and Impact Resistant ♦ Environmentally Friendly (No V.O.C.) ♦ Elastomeric ♦ Excellent Mechanical Properties ♦ Insensitive to Environment ♦ Thermal Stability ♦ Moisture Tolerant	♦ Tensile Strength: 1700 psi ♦ Tensile Modulus: 1,200 psi ♦ Elongation: 800% ♦ Tear Strength: 445 pli ♦ Flexural Modulus: 22,500 psi ♦ Flexural Strength: 1400 psi ♦ Temperature Range: 60-130°F ♦ RESIN Viscosity: 400–600 cP @ 77 °F ♦ ISO Viscosity: 400–600 cP @ ♦ 77 °F ♦ Gel Time: 15 sec. ♦ Tack Free: 30 sec. ♦ Back in Service: 30 minutes

Vendor/Technology	Key Features	Technical Information
HydraTech/Extreme Corrosion Resistant-Acid Alkaline (Installed in USA)	♦ Product: PolySpray ECR-AA ♦ A spray applied, rapid setting elastomeric polyurea ♦ Provides a flexible alternative to brittle epoxies ♦ Not recommended for sustained immersion in organic solvents structural support applications ♦ Advantages: ♦ Seamless, High-Build Liner ♦ Fast Cure (tack free in under 30 seconds) ♦ High Flexibility and Toughness ♦ Immediate Return to Service ♦ Chemical, Abrasion, and Impact Resistant ♦ Environmentally Friendly (No V.O.C.) ♦ Elastomeric ♦ Excellent Mechanical Properties ♦ Insensitive to Environment ♦ Thermal Stability ♦ Moisture Tolerant	♦ Tensile Strength: 2300 psi ♦ Tensile Modulus: 18,200 psi ♦ Elongation: 200 % ♦ Tear Strength: 329 pli ♦ Flexural Modulus: 16,400 psi ♦ Flexural Strength: 1200 psi ♦ Temperature Range: 70-130°F ♦ RESIN Viscosity: 1000–1200 cP @ 77 °F ♦ ISO Viscosity: 400–600 cP @ ♦ 77 °F ♦ Gel Time: 8 sec. ♦ Tack Free: 20 sec. ♦ Back in Service: 24 hours

Appendix B

Wastewater Force Main Essential Performance Data List

Number	Parameter	Unit	Brief Explanation (See Attached Sheet for Detailed Explanation
			Physical/Structural
1.	Node Identification Number	Node	ID for each pipe segments (Manhole-Manhole) between nodes
2.	Pipe Material	Type	Different pipe materials deteriorate at different rates
3.	Pipe Diameter	Inch	Different pipe sizes may fall in different failure modes
4.	Pipe Installation Year	Year	Older pipes may deteriorate faster than newer pipe
5.	Pipe Depth	Feet	Pipe Depth affects pipe loading and deteriorating rate
6.	Pipe Wall Thickness	Inch	Wall thickness affects rupture resistance and corrosion penetration rates
7.	Pipe Location	Area	Some locations may receive roadway salt intrusion; urban, sub-urban, rural, costal
8.	Pipe Shape	Type	Different pipe shapes may result in different failure modes and deterioration
9.	Pipe Joint Type	Type	Some types of joints may undergo premature failure
10.	Pipe Bedding	Type	Inadequate bedding may cause premature pipe failure, special bedding use
11.	Trench Backfill	Type	Some backfill materials are more corrosive or frost susceptible
12.	Pipe Slope	Gradient	Slope affects the velocity of flow
13.	Design Life of Pipe	Year	The pipe design life
14.	Design Strength of Pipe	Psi	Original design strength of each pipe
15.	Node Length	Feet	Length of Node (Manhole-Manhole) Length of Node (Manhole-Manhole)
16.	Pipe Lining	Type	Presence of pipe lining significantly reduces internal corrosion
			Operational/Functional
17.	Operational & Maintenance	Type	Poor practices can compromise structural integrity and water quality
18.	Pipe Renewal Record	Type	All records of pipes renewal- type of renewal method
19.	Pipe Defect Type	Type	Record of Defects observed
20.	Pipe Defect Level	Level	The level of defects observed at pipe
21.	Pipe Defect Location	Orientation	Locations of the defects observed
22.	Leakage Allowance	Percentageee	Percentage of leakage allowance

Number	Parameter	Unit	Brief Explanation (See Attached Sheet for Detailed Explanation
23.	Blockage/stoppage	Yes/No	Blockage make the pipeline network inoperative, sewer pipe is no longer functional
24.	Sediments	Ton/Feet	Sediments per unit length
25.	Inspection record	Type	Record of inspection, method use, date of inspection
26.	Water Corrosivity	Level	Water present may be corrosive and may affect pipe material
27.	Hazen Williams C Factor	c factor	Hazen Williams C factor is used to determine the head loss in flow
28.	Operation Pressure	psi	Design operational pressure
Environmental			
29.	Soil Type	Type	Corrosive, expansive, & compressible; hydrocarbons & solvents cause deterioration
30.	Soil Corrosivity	Level	Condition of the soil related to pipe deteriorate; low, medium, high
31.	Soil Moisture Content	Percent	Moisture percentage in the soil may affect loading and pipe deterioration
32.	Stray Currents	Yes/No	Stray currents may cause electrolytic corrosion of metal pipes
33.	Groundwater Table	Feet	Affecting soil loading on the pipes and pipe deterioration rate; above, below sewer, fluctuating
34.	Ground Cover	Type	Paved ground or vegetation cover result in different deterioration mode and rate
35.	Loading Condition (Dead Load)	Lbs/sq.ft	Dead load can be determined from infrastructure loading
36.	Loading Condition (Live Load)	ADT-Level	Live load can be determined from average daily traffic volume and railway loading etc.
37.	Rainfall/Precipitation	Inch/year	Rainfall in the areas should be monitored
38.	Climate - Temperature	ºF	Frost action in cold regions and seasonal soil water content variation in warmer regions
39.	H2S	Ppm	Concentration of Hydrogen Sulfide can increase pipe internal deterioration rate
40.	Frost Penetration	Yes/No-depth	Soil ever frozen around the pipe, depth of penetration in feet.
41.	Tidal Influences	Yes/No	Sewer in Coaster area may be subjected to tidal influence affecting bedding of the pipe
Financial			
42.	Annual Capital Cost	Type	Record of Defects observed
43.	FOG	Level	The level of defects observed at pipe

APPENDIX C

WASTEWATER FORCE MAIN PREFERABLE PERFORMANCE DATA LIST

Number	Parameter	Unit	Brief Explanation (See Attached Sheet for Detailed Explanation
			Physical/Structural
1.	Pipe Section Length	Feet	Length of pipe section (Joint - joint)
2.	Dissimilar Materials	Yes/No	Dissimilar metals/materials are more susceptible to galvanic corrosion
3.	Pipe External Coating	Type	External coating prevents corrosion of the pipe
4.	Pipe Cathodic Protection	Yes/No/Unk	Technique used to control the corrosion of a metal surface
5.	Pipe Vintage	Year	Pipes made at different time and place may deteriorate differently
6.	Pipe Manufacturer Name	Name	Defects in pipe walls produced by manufacturing errors can make pipes vulnerable to failure
7.	Pipe Manufacture Class	Class	Manufacturing class determine the rate of deterioration for pipes
8.	Pipe Manufacture Date	Year	Manufacture date determines some deterioration characteristics
9.	Pipe Trench Width	Feet	Trench width may affects soil loading on the pipes and deterioration rate
10.	Cathodic Protection Installation	Year	The year cathodic protection installed
11.	Cathodic Protection Present	Percentage	As pipes age the cathodic protection potential decreases
12.	Pipe Thrust Restraint	Type	Inadequate restraint may increase longitudinal pipe stresses
13.	Type of Dissimilar Materials	Type	Different types of dissimilar materials effect the corrosion rates
14.	Height of Bedding	Inches	Height of bedding is an important factor in deterioration
15.	Lateral Connections	Record	Condition of lateral connections and other related information
16.	Lining Installation Age	Year	Year liner installed
			Operational/Functional
17.	Sewer Flooding	Yes/No	Flooding may change property of surrounding soil and loading on pipe
18.	Flow Depth/Diameter	Ratio	Pipes with different flow depth over diameter ratios deteriorate differently
19.	Maintenance Frequency	Level	Frequent maintenance performed will increase the life of the pipe
20.	Type of Cleaning	Type	Type of cleaning can affect the blockage and internal corrosion

Number	Parameter	Unit	Brief Explanation (See Attached Sheet for Detailed Explanation
		Environmental	
21.	Sewer Odors	Yes/No	Solids build-ups, poor system hydraulics, flat grade, etc.
22.	Sewer Overflow (SSO/CSO)	Yes/No	Overflow may inundate surrounding soil and change loading on pipe
23.	Backup Flooding	Number	Number of properties affected by flooding in Dry & Wet weather
24.	Soil Disturbance	Yes/No	Disturbance of soil may cause damage or change soil support or loading to the pipe
25.	Soil Chloride	Percentage	Low chloride levels in high pH(>11.5) environments can lead to serious corrosion
26.	Soil Sulfate	Percentage	Possible food source for sulfate reducing bacteria in anaerobic conditions under loose coatings
27.	Soil Redox Potential	mV	Redox potential of soils directly effects the external corrosion of pipes
28.	Soil Resistivity	ohm cm	External corrosion of pipes are reduced with higher resistivity of soil
29.	Wastewater pH	pH	Low pH (<4) and high alkaline conditions (pH>8) means conveyed water likely promotes corrosion
30.	Wastewater Sulfate	mg/l	Possible food source for sulfate reducing bacteria in anaerobic conditions under loose linings
31.	Wastewater Dissolved Oxygen	mg/l	Higher concentrations contribute to oxidization
32.	Wastewater Temperature	°F	Lower temperatures of wastewater contribute to failures
33.	Foreign Anode Bay Distance	ft.	Distance of the foreign anode bay causing stray current is proportional to external corrosion
34.	Runoff Rate	Cu. Ft/Sec.	Excess water flow which can be caused by rainfall, evaporation, snow melting, etc.
35.	Non-Uniform Soil	Yes/No	Non-uniform soil support in longitudinal axis may increase shear and bending stresses
36.	Non-Uniform slope	Yes/No	non-uniform slope may reduce the operating performance
37.	Unstable Slope	Yes/No	Pipes in unstable slope may be subjected to downslope creep displacement
38.	Soil pH	pH	Low pH (<4) and high alkaline conditions (pH>8) are likely to promote corrosion;
39.	Soil Sulfide	Percentage	Sulfate reducing bacteria giving off sulfides which are excellent electrolytes

Number	Parameter	Unit	Brief Explanation (See Attached Sheet for Detailed Explanation
			Financial
40.	Annual Maintenance Cost	$/Year	Routine Cleaning, etc.; Method and Cost of Maintenance
41.	Annual Renewal Cost	$/Year	Method and Cost of Preservation and Improvement like grouting, lining, etc
42.	Installation and Replacement Cost	$	Original cost of installation and replacement cost
43.	Annual Operational Cost	$/Year	Cost spent each year for operating and functioning sewer system
44.	Depreciated Value	Percentage	Depreciated value and method of calculation
			Other
45.	Density of Connections	Number/ Mile	Number of properties connected to the sewer per mile
46.	Third Party Damage	Yes/No	Information related to third party damage
47.	Other Information	-	Information relevant for pipe condition assessment and deterioration modeling

APPENDIX D

DATA SUBMISSION GUIDELINES

The data can be submitted by visiting www.pipeid.org. A new account should be created prior to data submission. 'Create new account' tab in the 'User login' section of the Home page will redirect the user to the 'User Account' page to create a new account (Figure D-1). The required account information should be entered in the 'User Account' page (Figure D-2). Please click the 'Create new account' button at the end of the page to submit user registration (Figure D-3). Subsequently, the user will receive an email upon approval of registration (Figure D-4). Please follow the instructions in the email to setup a password for the account.

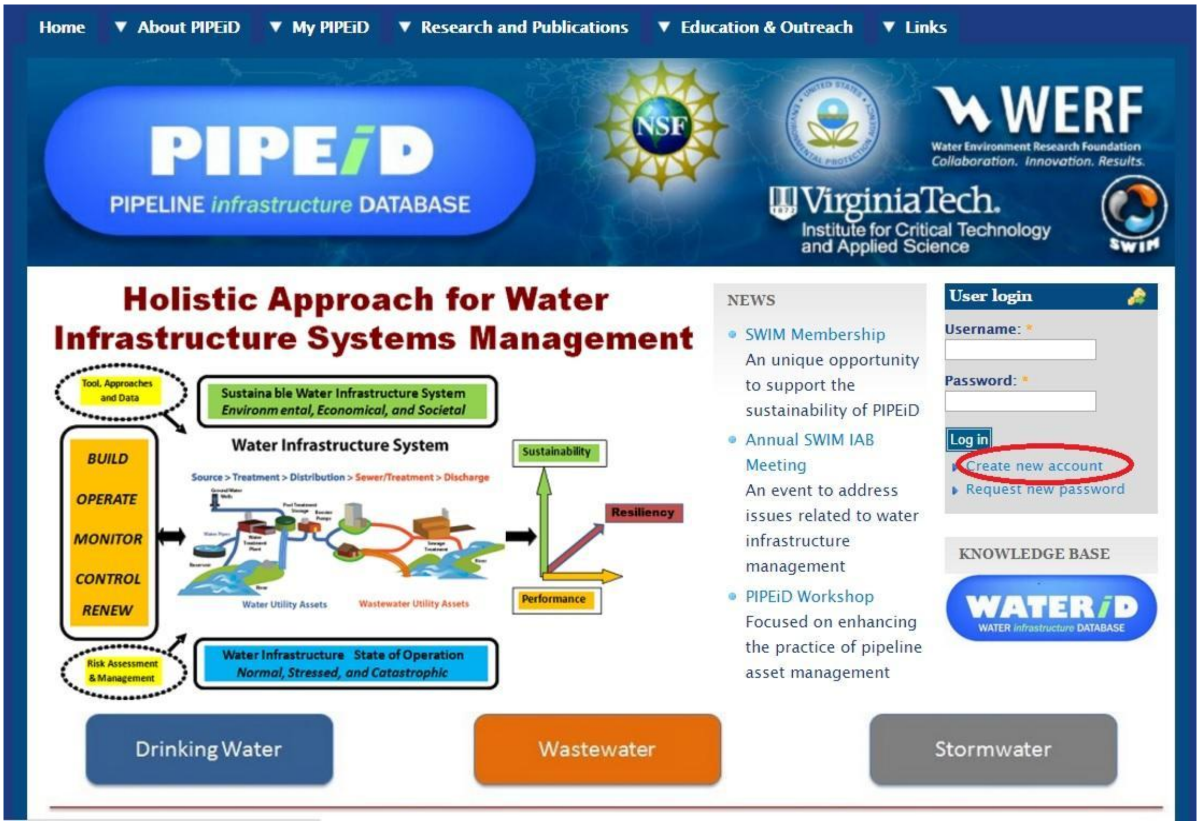


Figure D-1. Create new account tab on the Home Page.

Figure D-2. User Account Page.

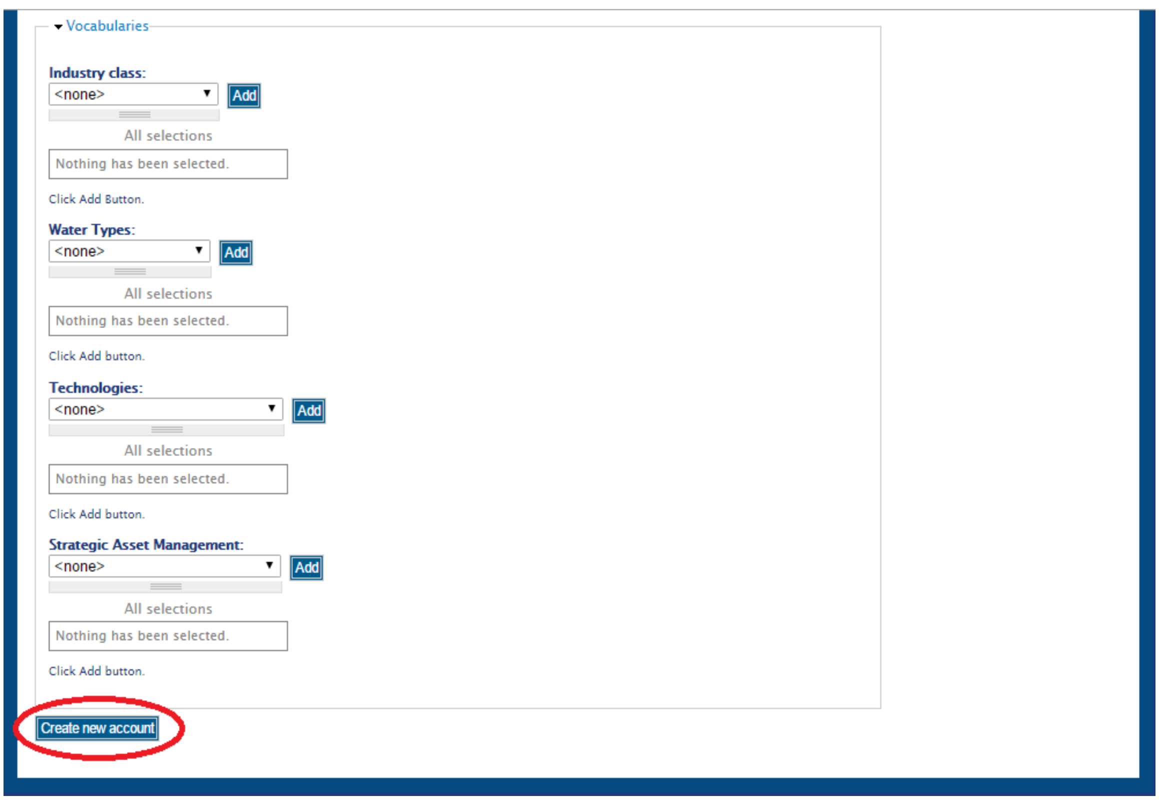
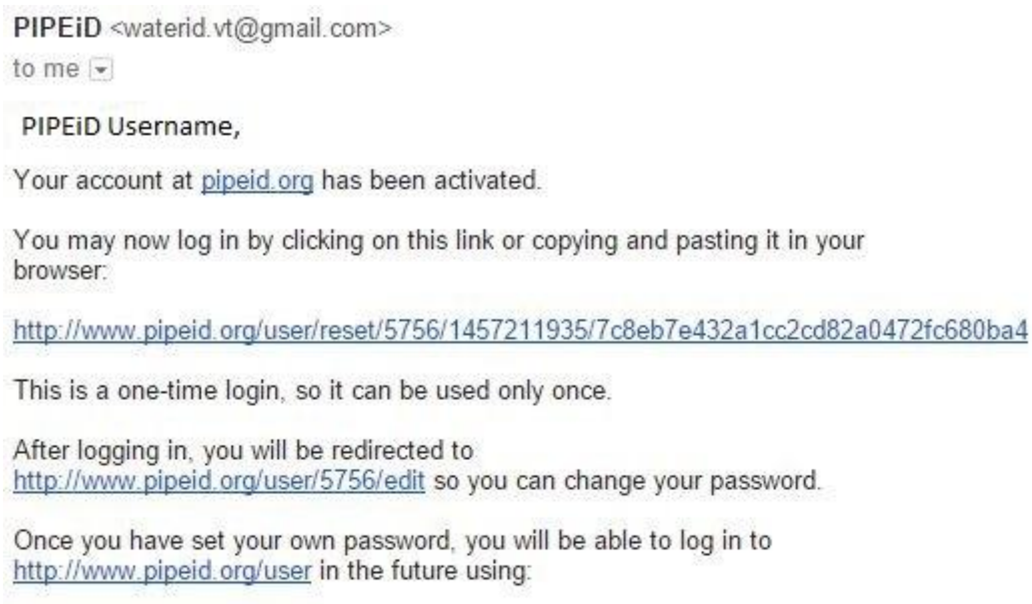


Figure D-3. Create New Account Button.



PIPEiD <waterid.vt@gmail.com>
to me

PIPEiD Username,

Your account at pipeid.org has been activated.

You may now log in by clicking on this link or copying and pasting it in your browser:

http://www.pipeid.org/user/reset/5756/1457211935/7c8eb7e432a1cc2cd82a0472fc680ba4

This is a one-time login, so it can be used only once.

After logging in, you will be redirected to http://www.pipeid.org/user/5756/edit so you can change your password.

Once you have set your own password, you will be able to log in to http://www.pipeid.org/user in the future using:

Figure D-4. Registration Approval Email.

After registering on the website, utilities click the 'Upload' tab under the 'My PIPEiD' tab to upload the data (Figure D-5). The 'Upload' tab will redirect the user to 'Create Upload' page (Figure D-6). Utilities enter the Utility Name in the 'Title' section, name and the contact number of the person to contact for additional information in the 'Contact Name' and 'Contact Phone' sections respectively. Utilities click the 'Choose File' button to select the file to upload from your system (Figure D-7). Utilities are suggested to compress the files before uploading them. Each compressed file size should not exceed 500MB. Subsequently utilities click the 'Upload' button upon selecting the file (Figure D-8). Multiple files can be uploaded by clicking the 'Add another item' button (Figure D-9). Another item should be added after uploading the previous file. 'Save' button at the bottom of the page after uploading all the files will upload the data on the server (Figure D-10). The utilities data is stored on the ICTAS server at Virginia Tech.

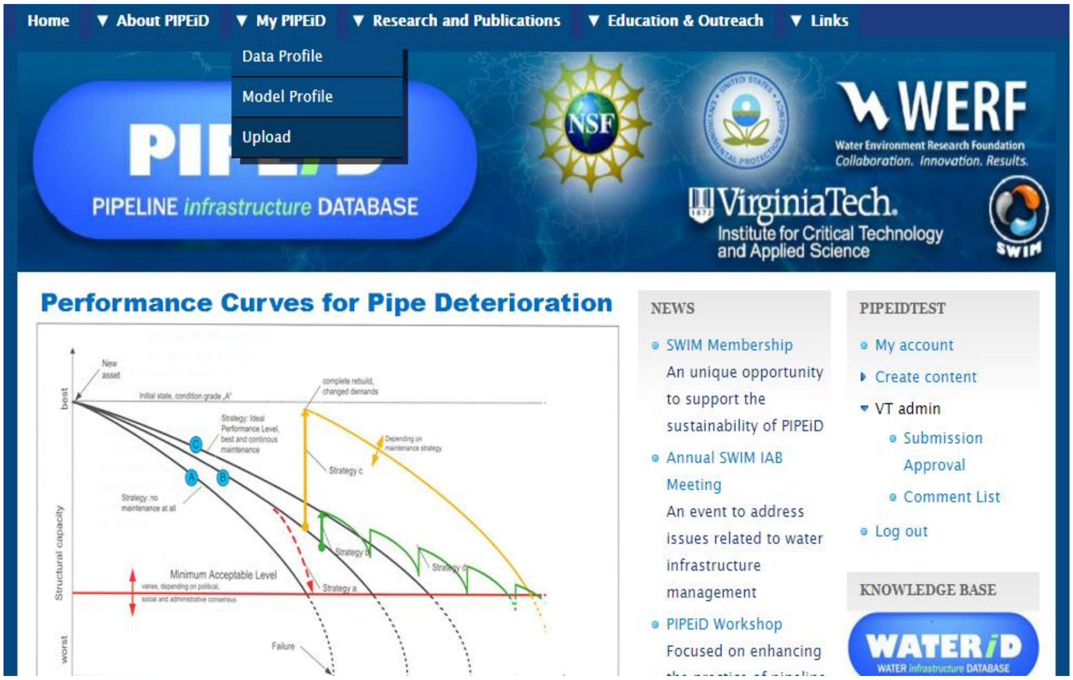


Figure D-5. Upload Tab Under My PIPEiD Tab.

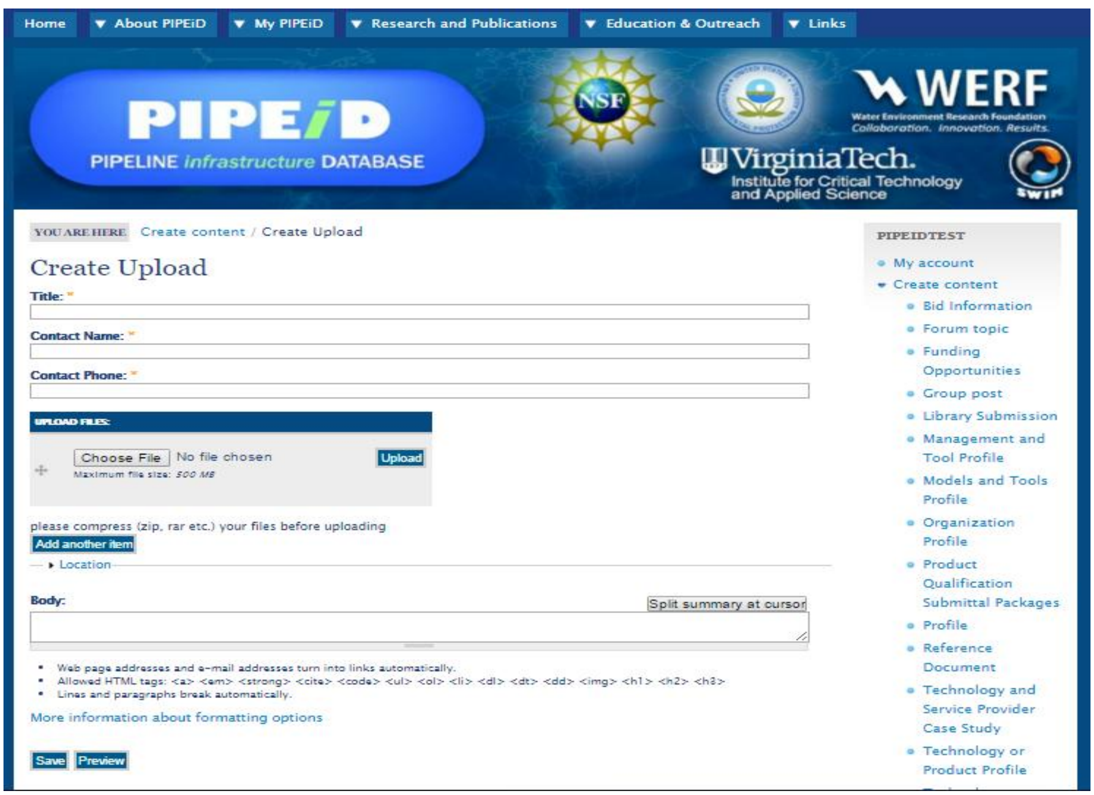


Figure D-6. Create Upload Page.

Figure D-7. Selecting the File to Upload.

Figure D-8. Uploading the Selected File.

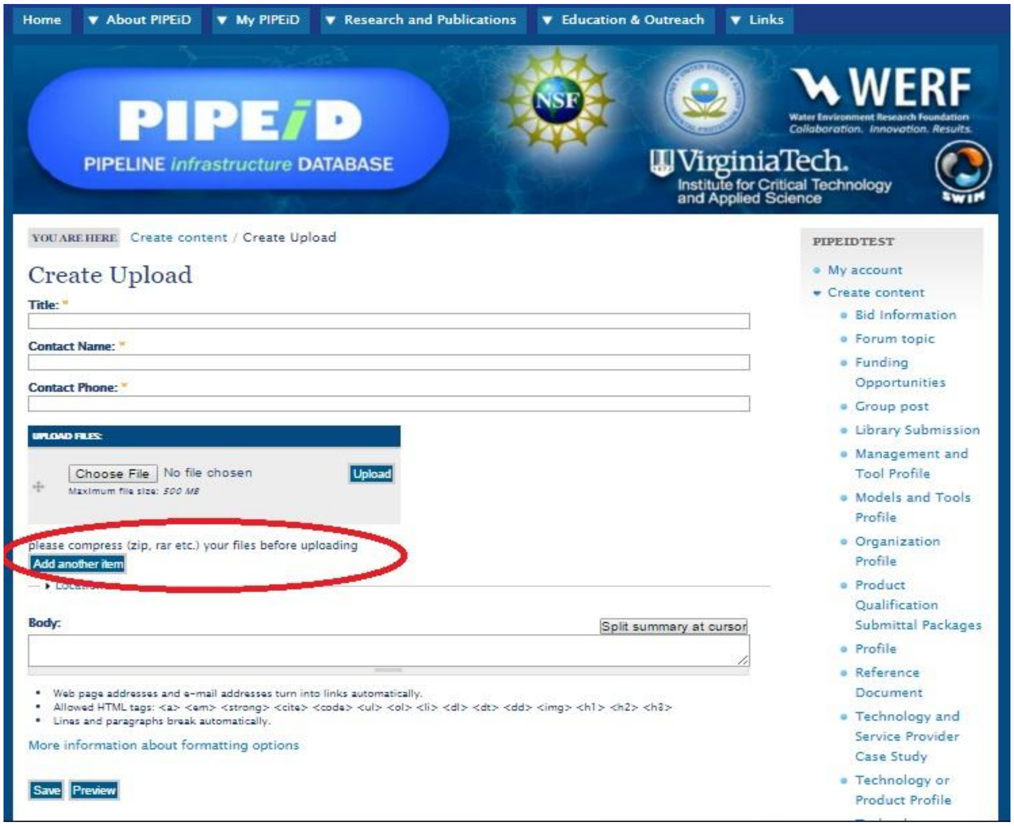


Figure D-9. Adding Multiple Files.

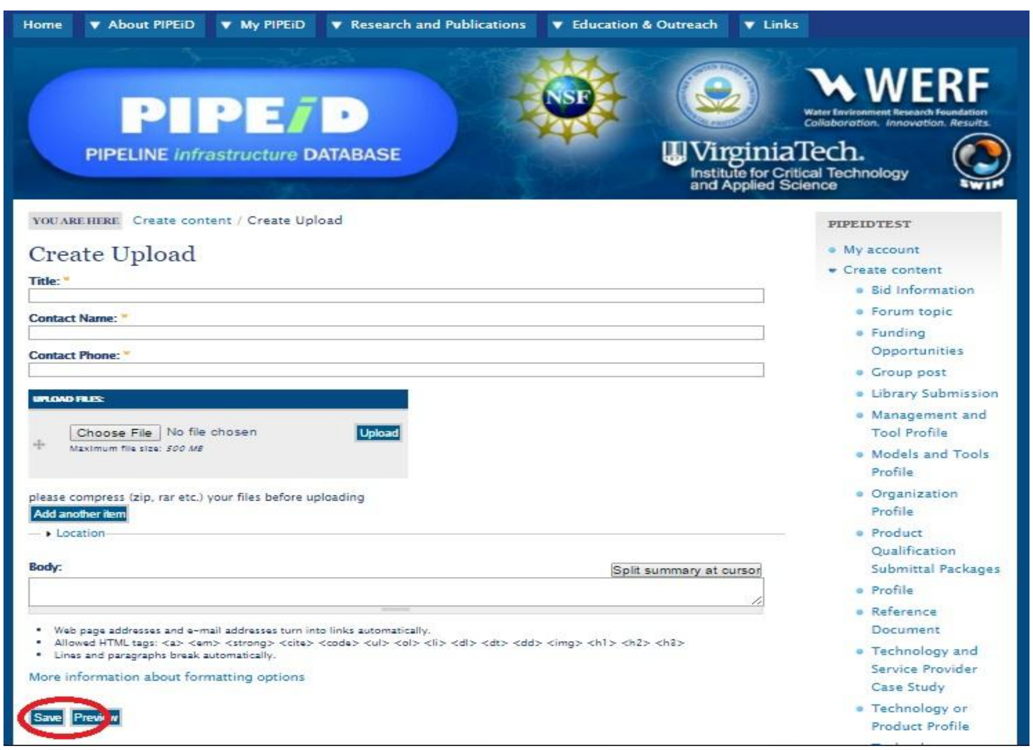


Figure D-10. Final Upload Step.

Appendix E

Steps Involved in Publishing the Model

1. A publisher account is setup on the ArcGIS Server and the account is connected through ArcCatalog
2. Right click on the model result in the "Geoprocessing Results" tab in arcmap and select Share as Geoprocessing service (Figure E-1)
3. Select "Publish a new service" (Figure E-2)
4. Select publisher account from the dropdown list as the server connection (Figure E-3)
5. Enter the name for the service (this will become part of the REST (Representational State Transfer) URL) (Figure E-3)
6. Click "next" (Figure E-3)
7. Select the folder from the dropdown list (Figure E-4)
8. Click "continue". This will bring up the Service Editor dialog (Figure E-5)
9. Click the "Analyze" button to correct any errors that needs corrected before publishing the geo-processing service (Figure E-5)
10. Expand an error group and double click each problem to fix it
11. Subsequently, click "Publish" button to publish the geo-processing service (Figure E-6)
12. The map and geo-processing information published to the ArcGIS Server is presented as a REST URL (Figure E-7).

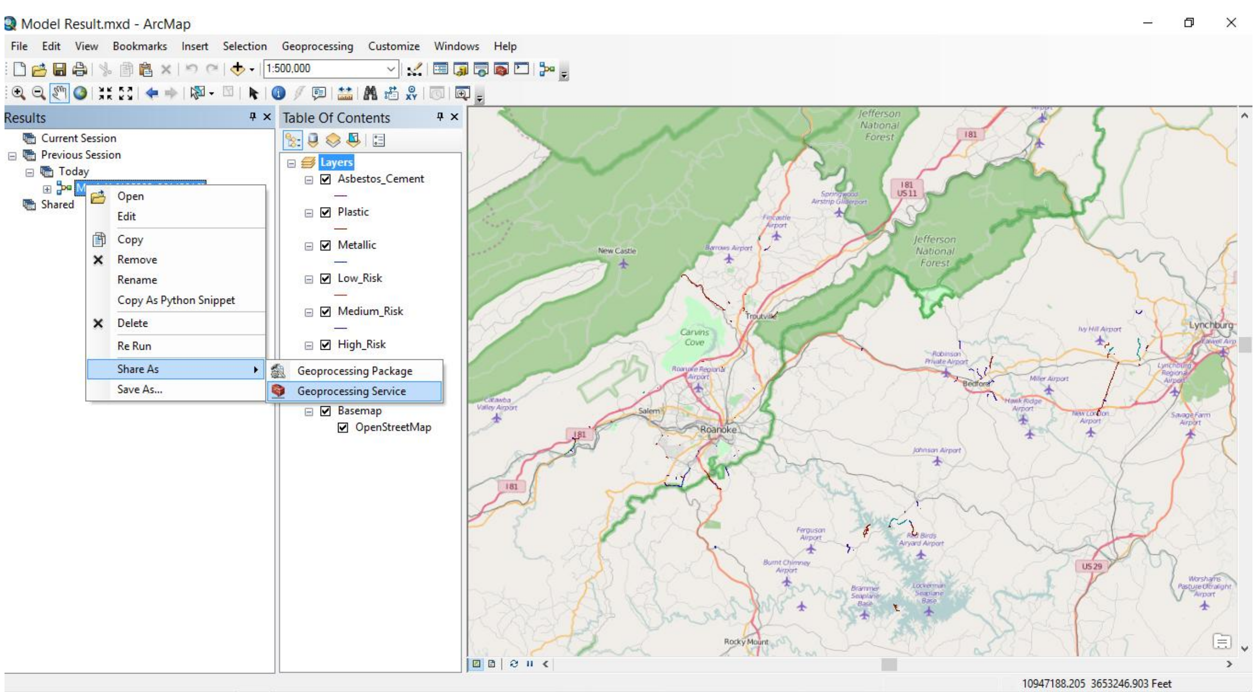


Figure E-1. Sharing the Model As a Geo-processing Service.

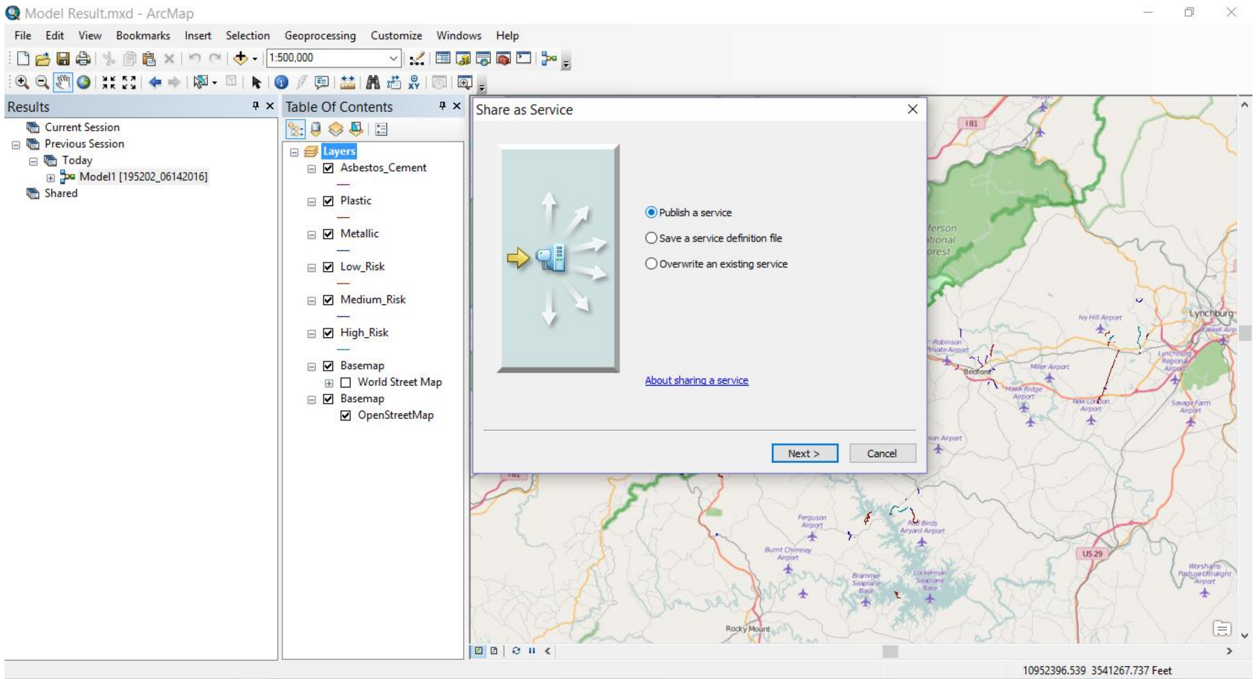


Figure E-2. Publishing the Geo-processing Service.

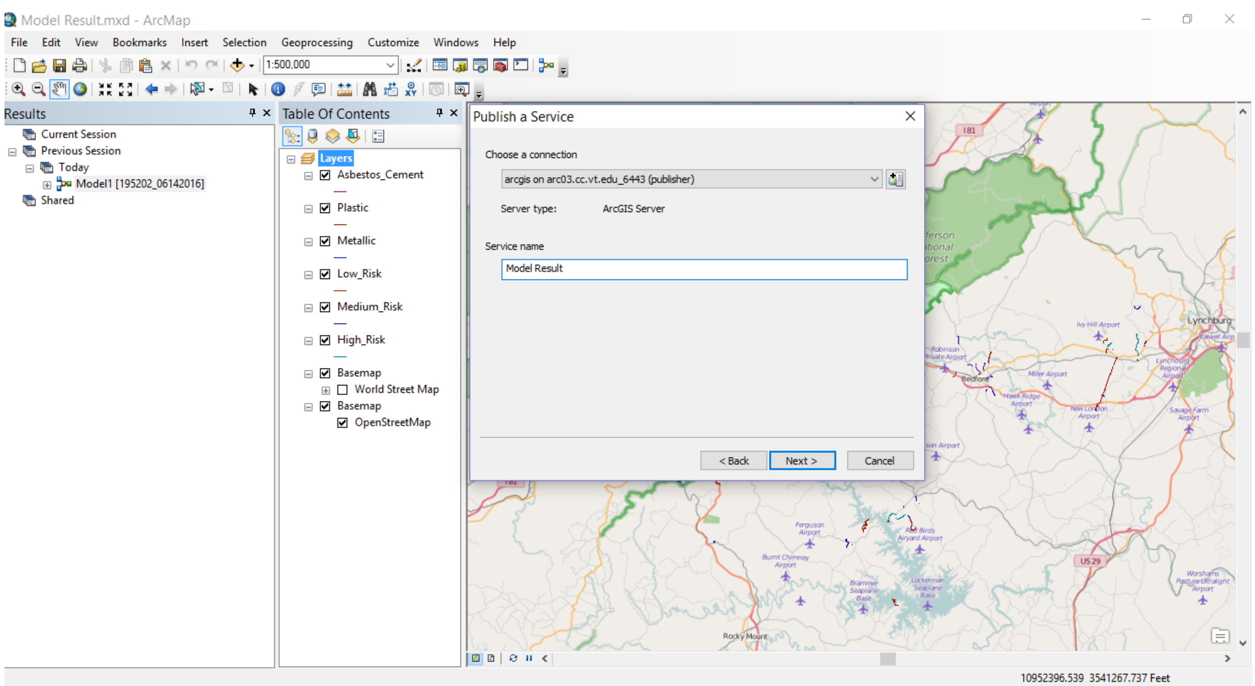


Figure E-3. Selecting the Publisher Account and Service Name.

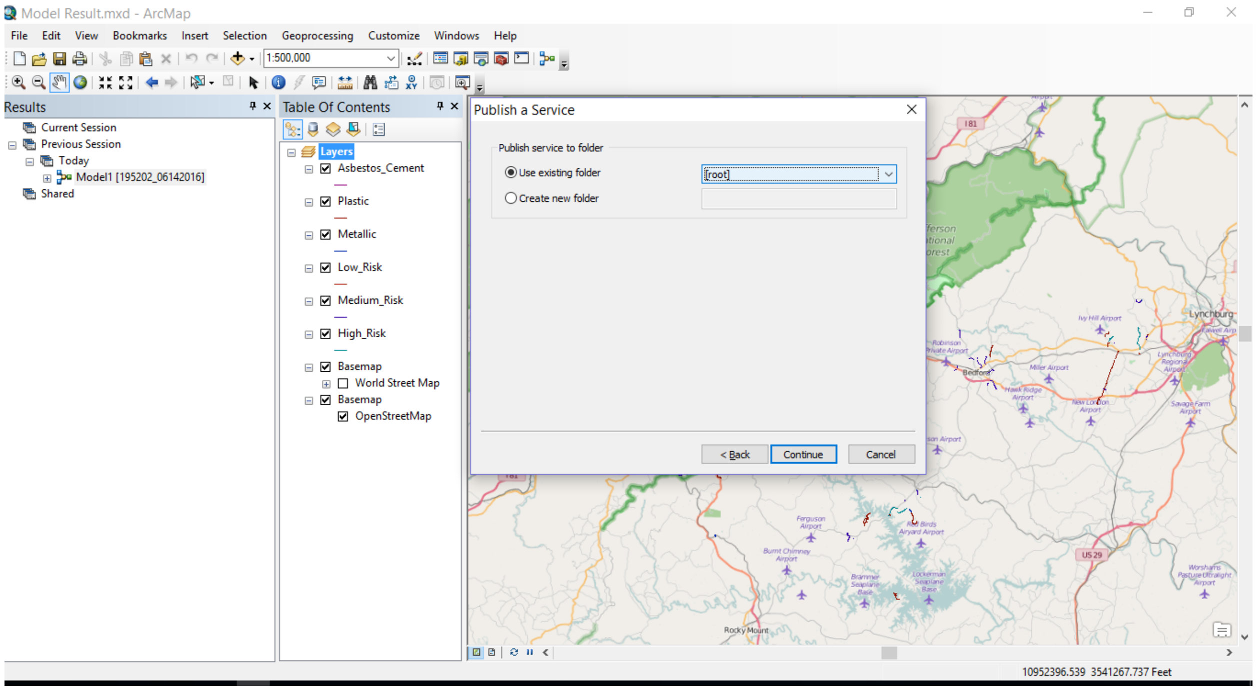


Figure E-4. Selecting the Folder to Publish the Service.

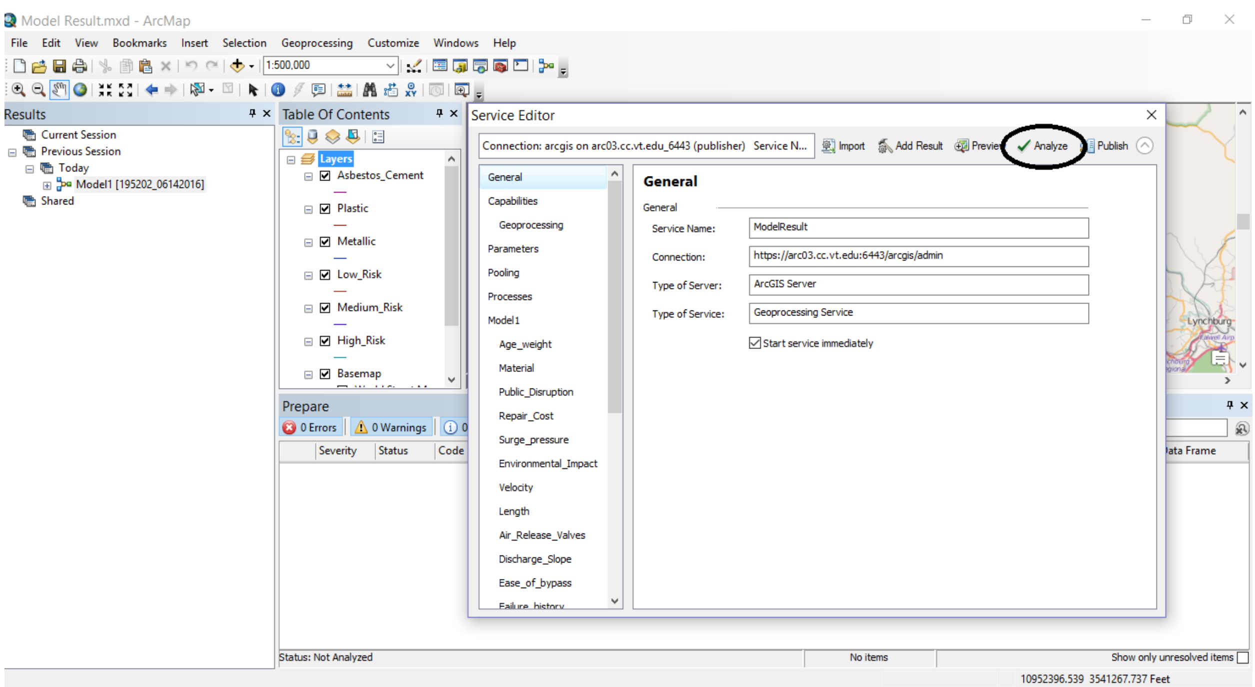


Figure E-5. Service Editor Dialog to Analyze the Errors.

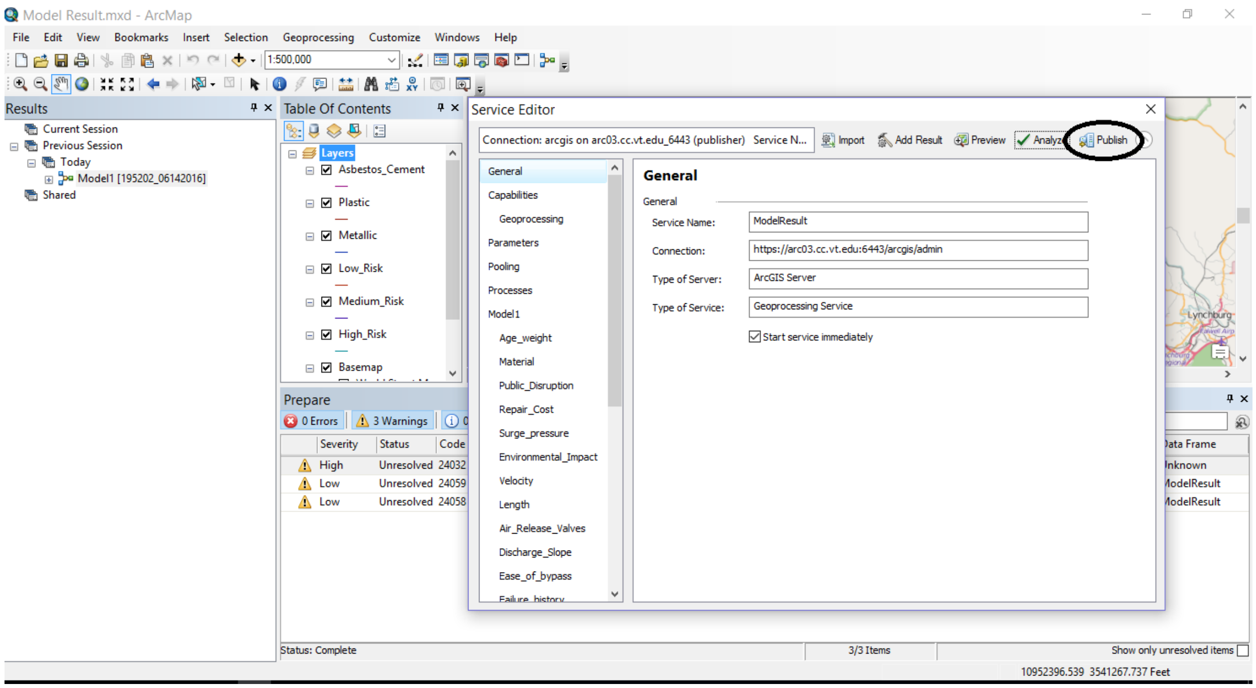


Figure E-6. Service Editor Dialog to Publish the Service.

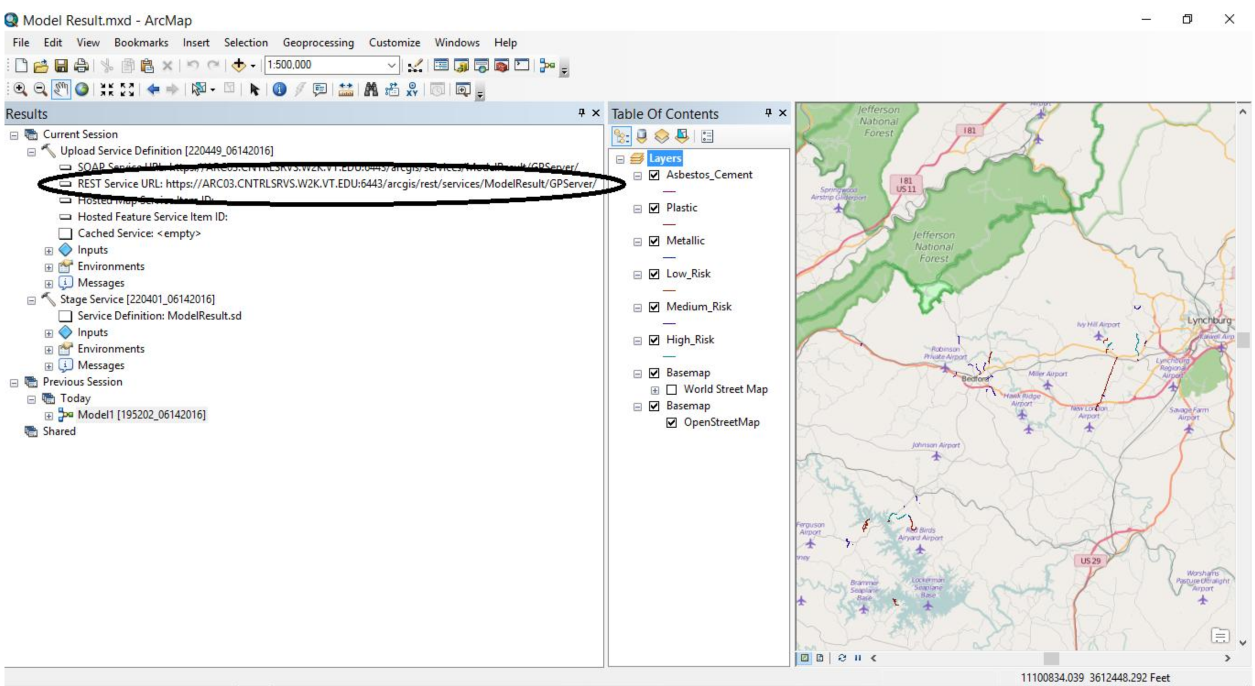


Figure E-7. REST URL for the Service.

APPENDIX F

STEPS INVOLVED IN DEVELOPING THE VISUALIZATION TOOL

1. A new application is created by clicking "Create a New Application" button in the ArcGIS Viewer Flex Application Builder (Figure F-1).
2. Base maps and operational layers option is selected in the maps tab of the ArcGIS Viewer Flex Application Builder to select the basemaps and operational layers from ArcGIS Online and ArcGIS Server (Figure F-2).
3. Basemap is selected from the ArcGIS Online featured basemaps (Figure F-3).
4. The REST URL of the map layers retrieved for map services from ArcGIS Server is consumed by the application to represent the operational layers (Figure F-4).
5. A Geoprocessing widget is created by selecting the "Geoprocessing" widget button and clicking "Include" button in the Widgets tab in the ArcGIS Viewer Flex Application Builder (Figure F-5).
6. The REST URL retrieved for geoprocessing services from ArcGIS Server is consumed by the application to represent the geoprocessing task. Additionally, the input and output variables of the model can be edited in the geoprocessing widget (Figure F-6).
7. A Query widget is created by selecting the "Query" widget button and clicking "Include" button in the Widgets tab in the ArcGIS Viewer Flex Application Builder (Figure F-7).
8. The REST URL of the output layers retrieved from ArcGIS Server is consumed by the application to configure the query widget (Figure F-8). Three query widgets are created in this manner to represent the high risk, medium risk and low risk forcemains.
9. Click the "Save" button after designing the tool (Figure F-9).
10. The web based visualization tool is represented in Figure F-10.

Figure F-1. Creating New Application in ArcGIS Viewer for Flex.

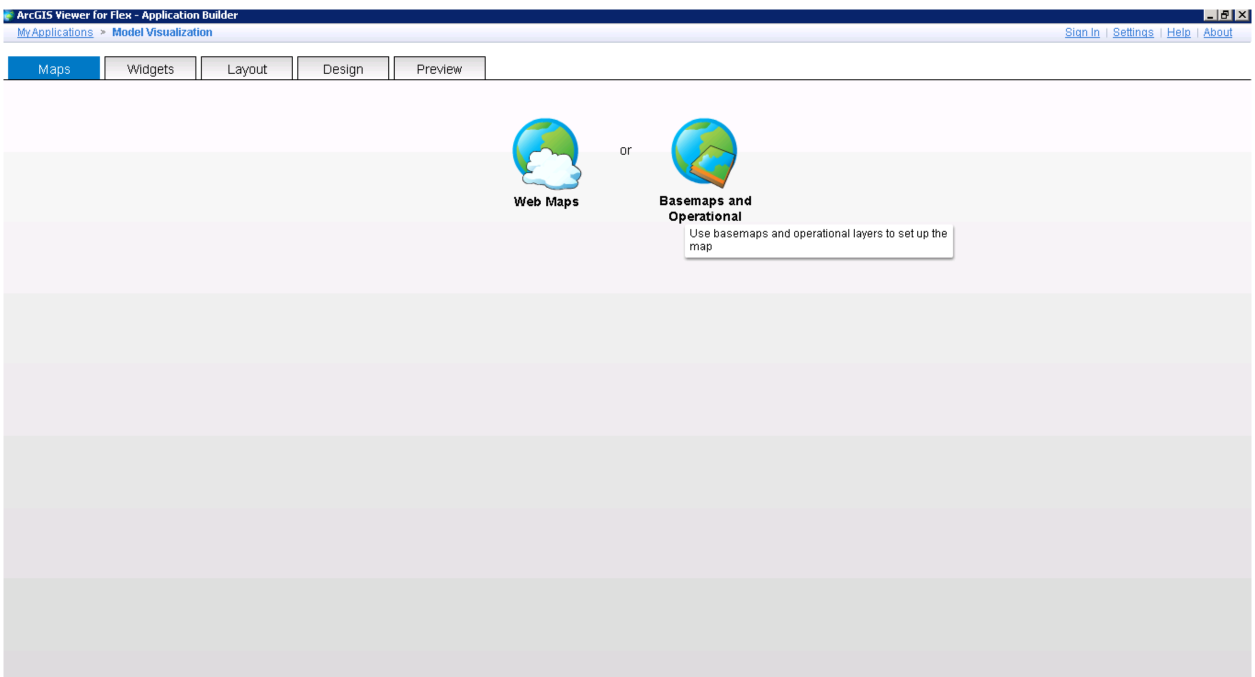


Figure F-2. Selecting Basemaps and Operational Layers.

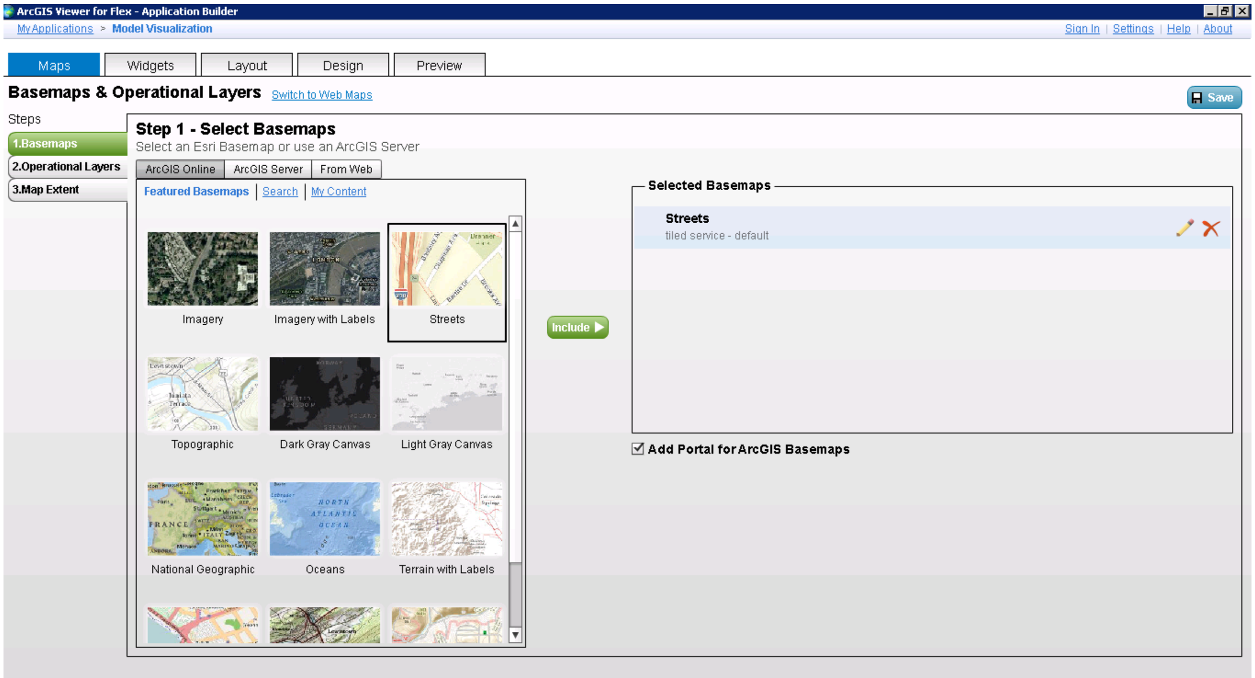


Figure F-3. Selectng Basemaps from ArcGIS Online Featured Maps.

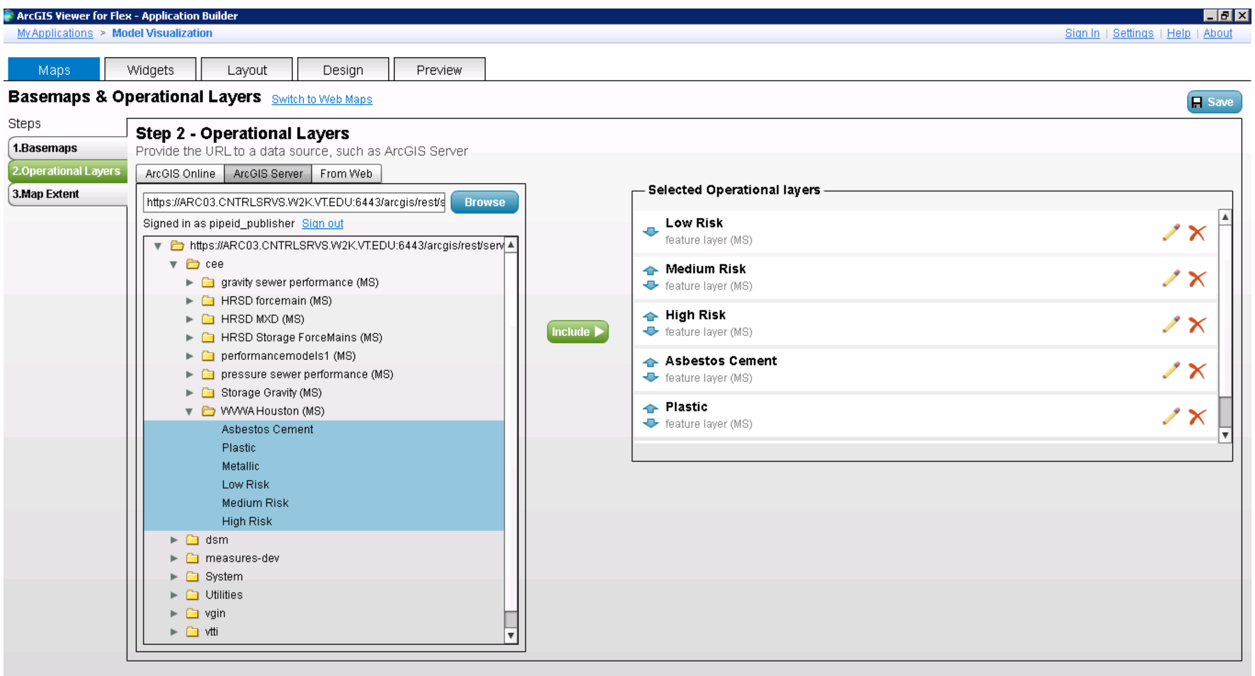


Figure F-4. REST URL for Operational Layers.

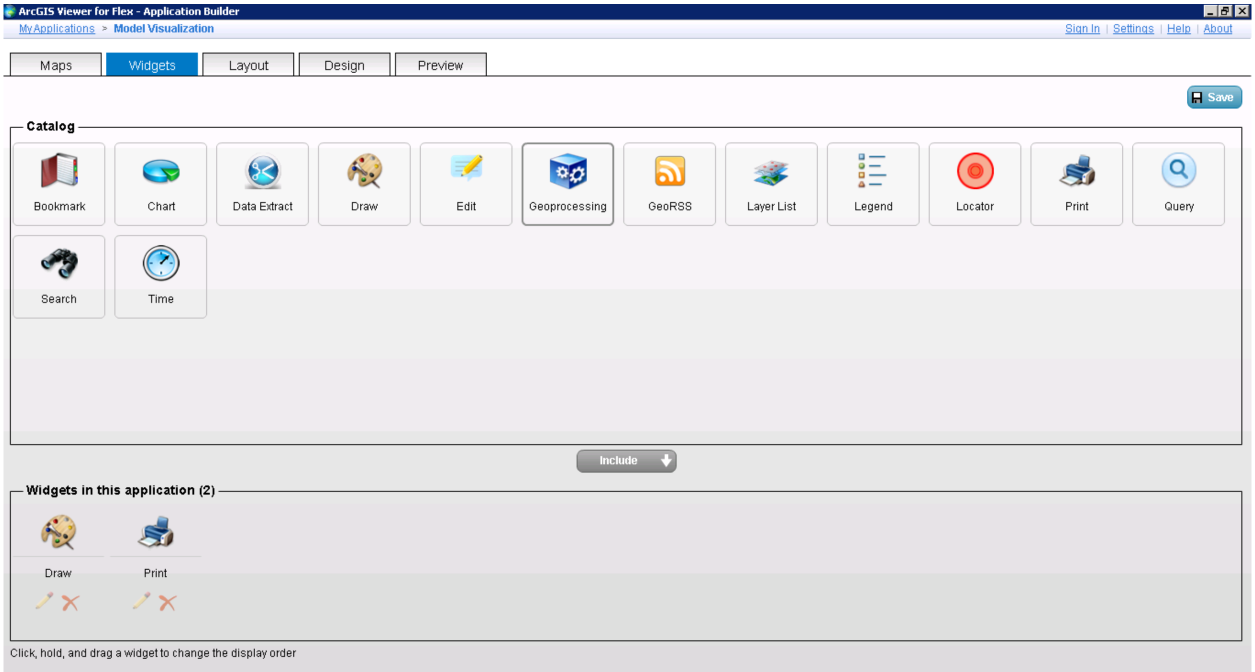


Figure F-5. Creating a Geo-processing Widget.

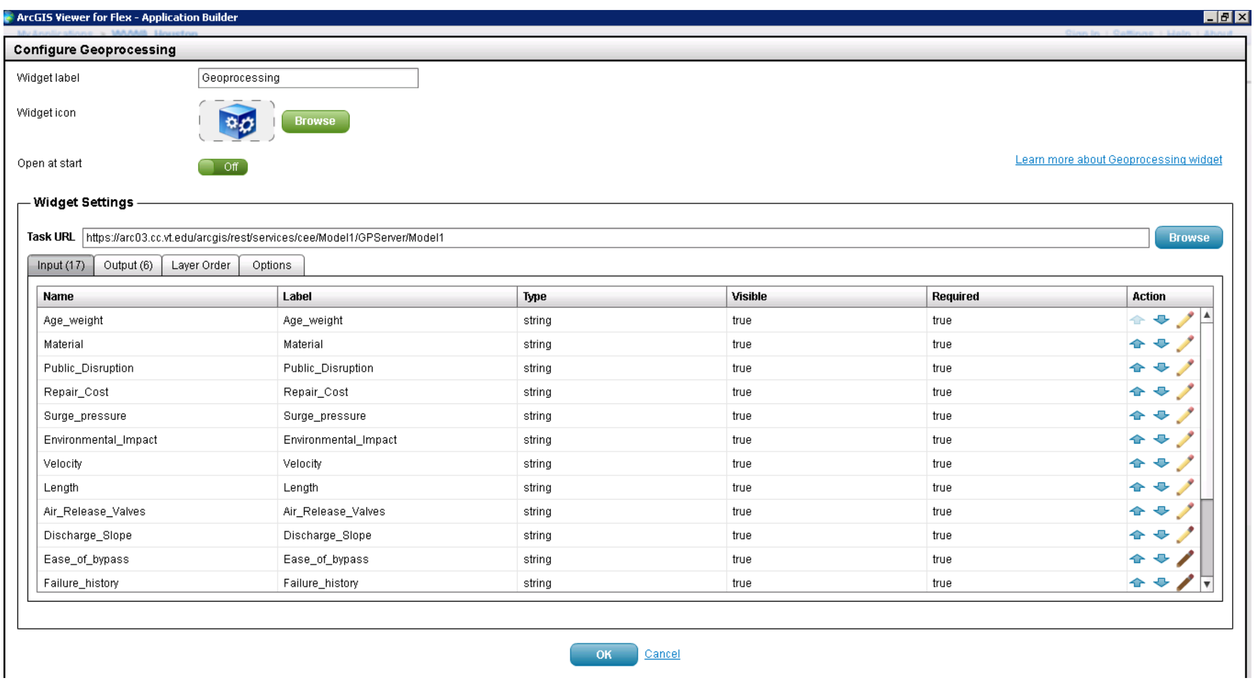


Figure F-6. REST URL for Geo-processing Service.

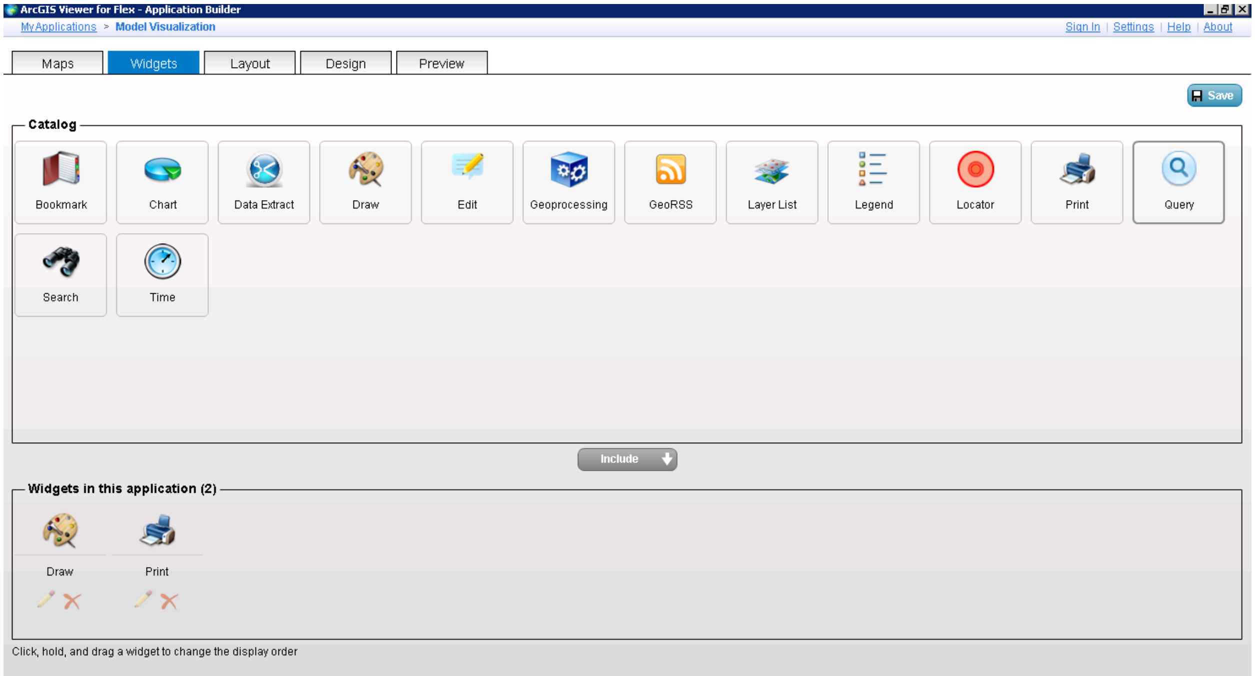


Figure F-7. Creating a Query Widget.

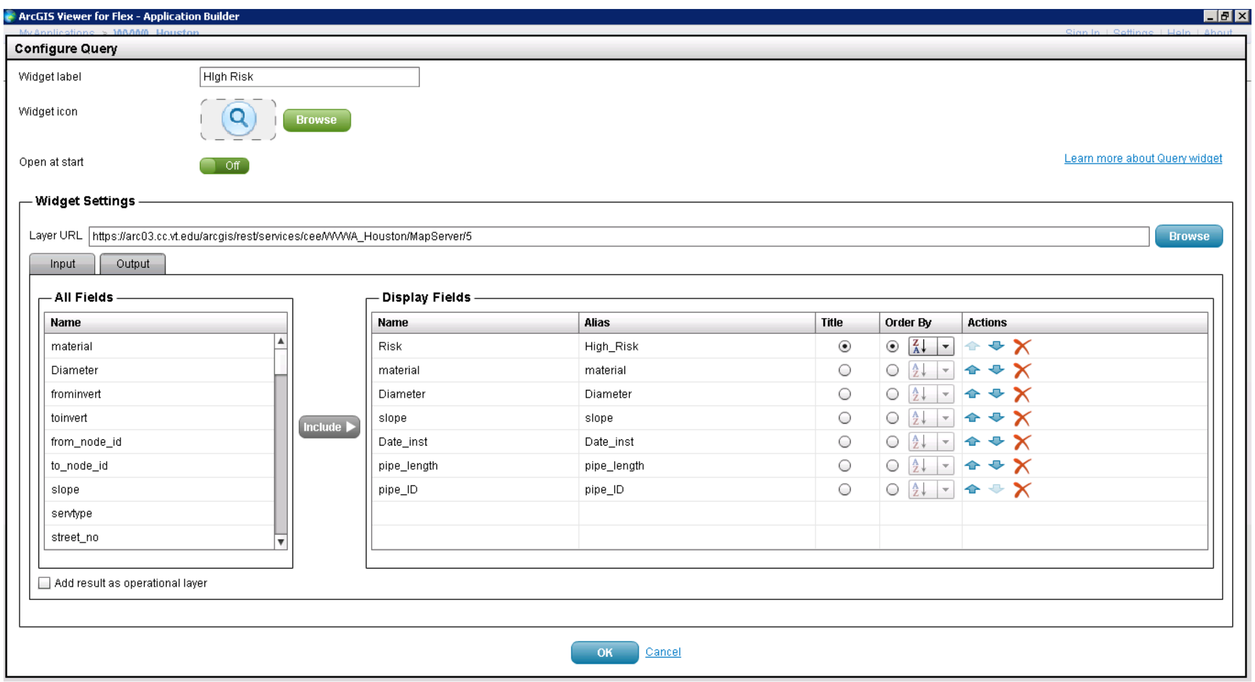


Figure F-8. REST URL for Output Layers.

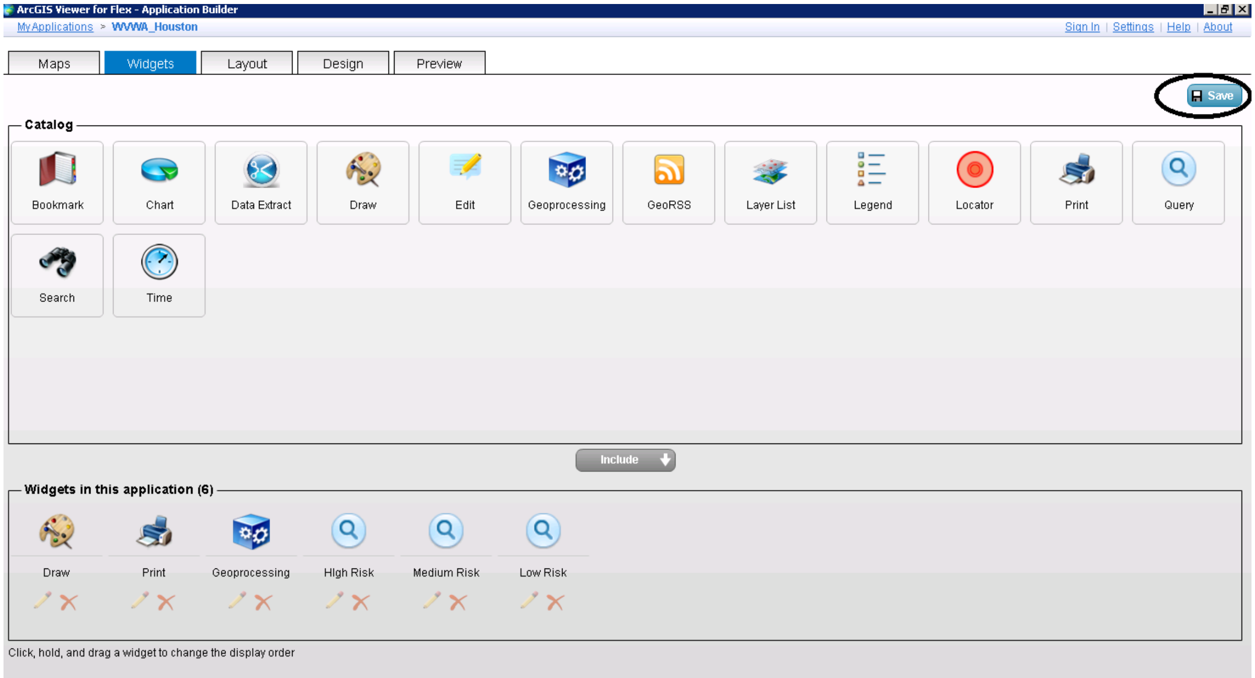


Figure F-9. Saving the Tool.

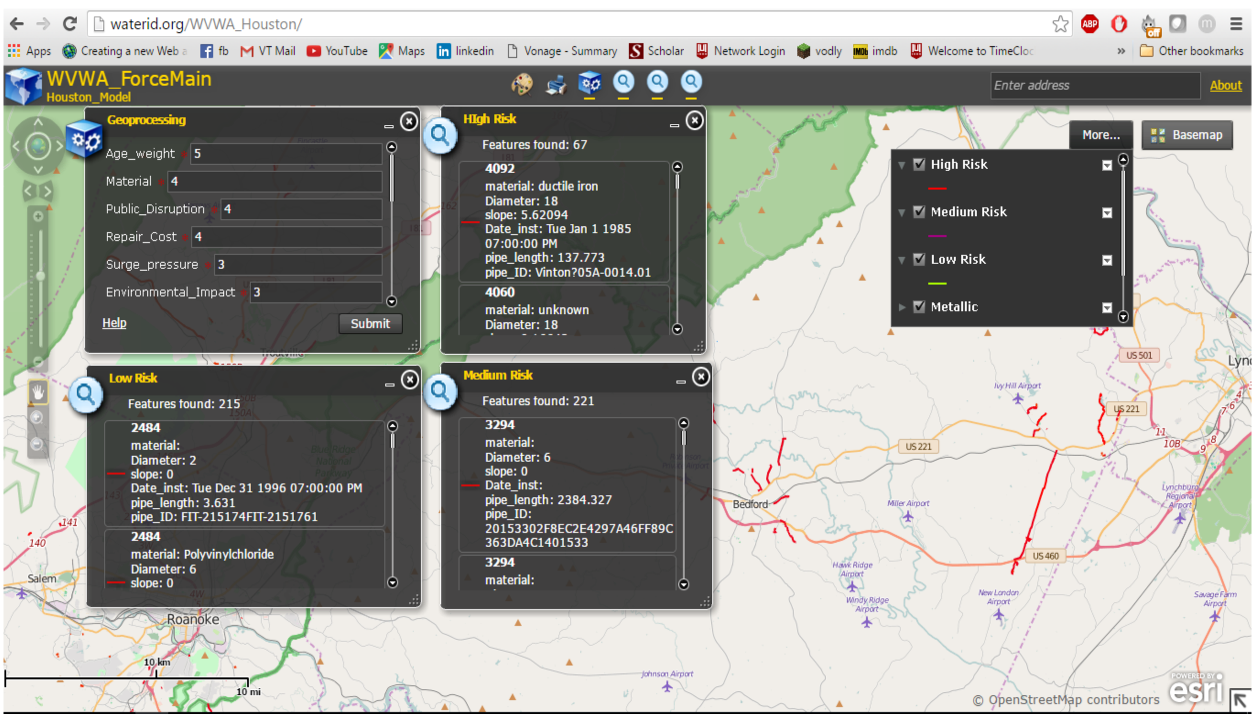


Figure F-10. Web-Based Application.

APPENDIX G - FORCE MAIN GEODATABASE MODEL