Development of Standard Geodatabase Model and its Applications for Municipal Water and Sewer Infrastructure

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ABSTRACT

Availability of organized data is required for accurate prediction of structural or functional deterioration in sewer and water pipes. Toward this end, GIS provides a means for viewing, understanding, interpreting, and visualizing complex geographically referenced information to reveal data relationships, patterns, and trends. The primary objective of this research is to develop a standard GIS data model and applications of the model. In the future, these can be used to develop protocols and methods for predicting the remaining life of water and wastewater assets.

The source data for this study is the utility data and other publicly available data from resources such as USGS, SSURGO etc. Field mapping files are generated from the source files and the standard data model. These are then programmed to the common Extensible markup Language (XML) file developed as a base which is then converted to the data model where the final form of utility data is stored. The data taken from the utilities is cleansed and analyzed to match the standard data model which is then uploaded through the common XML and stored in the data warehouse as a geospatial database. The geospatial database is an aggregated water and wastewater infrastructure data consisting of the utility data in standard data model format. The data warehouse is developed for utilities to store their data at a centralized server, such as the San Diego Super Computer Center.

Web applications demonstrate the publishing, querying and visualization of aggregated data in a map-based browser application. This aggregation of data of multiple utilities will help in providing timely access to asset management information and resources that will lead to more efficient programs. This tool also furnishes the public with a convenient tool to learn about municipal water and wastewater infrastructure systems. This document gives an overview of how this process can be achieved using the above mentioned tools and methodologies.

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Utility Participants

• City of Atlanta, Atlanta, Georgia; Mr. John Griffins

• Seattle Public Utility, Seattle, Washington, Mr. Terry Martin

• Orange County Sanitation District, Fountain Valley, California; Mr. Kevin Hidden

• Pittsburgh Water and Sewer Authority, Pittsburgh, Pennsylvania; Mr. Michael Lichte

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

The U.S. Environmental Protection Agency (EPA) has a special interest in the operations and management of public drinking water and sanitary sewer systems. Infrastructure utilities are facing increasing pressure to implement advanced asset management plans in order to improve the efficiency with which their systems are operated and maintained. As a result, most utility operators are actively working to develop GIS mapping and databases of their pipe networks. In GIS, the pipelines are usually modeled by lines and nodes by dots. Incorporating GIS into the decision making process for utilities provides insights that will affect which approach is chosen and the outcome obtained. However, there is no standard data model for water or sewer systems, thus each utility has developed its own method for storing data; this has created complex problems associated with multi-jurisdictional planning activities, research, and oversight. The value of using a standard data model for problem solving increases with the scale and complexity of the problem as the choices made will have profound and long-term consequences. Challenges currently faced by utilities such as resource shortages, repairs, rehabilitation, replacement of pipes require considering competing interests and interdependencies.

> *"New solutions are needed to what amounts to nearly a trillion dollars in critical water and wastewater investments over the next two decades. Not meeting the investment needs of the next 20 years risks reversing the public health, environmental, and economic gains of the last three decades."* [34].

Most cities and towns started building collection systems over 100 years ago and many of these systems have not received adequate upgrades, maintenance, repair, and rehabilitation over time [23]. Today, municipal governments are facing an infrastructure crisis requiring costly renewal beyond their capacity. There has been a steady decline in the state of our water infrastructure over the past two decades, and a growing concern is that these facilities may be inadequate both for current requirements and projected future growth [23]. Funding for these needs is limited, and a deferred maintenance, out-of-sight, out-of-mind philosophy still prevails in many regions. Recently, for example, the American Society of Civil Engineering (ASCE) in its 2005 assessment of the nation's infrastructure assigned the grade "D" and estimated the five-year investment needs to be in excess of $1.3 trillion [3]. It is estimated that the cost of replacing all water mains in the United States would run to $348 billion [1]. Although the federal government has spent more than $71 billion on wastewater treatment programs since 1973, the nation's 19,000 wastewater systems still face enormous infrastructure funding needs in the next 20 years to replace pipes and other constructed facilities that have exceeded their design life [2]. With billions of dollars being spent yearly for water infrastructure, the systems face a shortfall of at least $21 billion annually to replace aging facilities and comply with existing and future federal regulations [34]. Monetary investment alone will not resolve this dilemma; it may be met with a new approach to sustainable water infrastructure engineering and management. There is a critical disconnect between the methodological remedies for infrastructure renewal problems and the current sequential or isolated manner of renewal analysis and execution. This critical disconnect manifests the need for a holistic systems perspective. New tools are needed to provide the intellectual support for utility assets decisions necessary to sustain economic growth, environmental quality, and improved societal health.

The research includes modifying a data model to serve as a common foundation for future analysis and research. In addition, applications of the data model are developed to highlight the importance of such a data model. The tools developed as part of the research provides utility decision makers with information necessary to understand the pipe system and allocate the limited resources efficiently.

This research accomplished the following objectives:

- To modify the data model by adding tables and attributes to improve the practicality of the model.

- To translate the existing utility data into the modified data model structure and create a master Geodatabase each for water and waste water systems.

- To develop a visualization tool (Risk Visualization and Google Earth Simulation) for the available data with the help of Google Earth.

- To develop a dynamic map based query tool to extract useful information or retrieve data for further analysis.

The results illustrate the challenges inherent in any effort to conflate disparate municipal utility datasets into a common data model, and demonstrated the scarcity of data relevant to water and sewer infrastructure condition assessment. By incorporating additional attributes related to condition assessment in publicly-promoted data models, municipal utilities will be better able to manage their infrastructure internally, and share their utility data with neighbors, researchers, and regulators. The task of translating the utilities data into the common data framework is not enough to understand the system; however it is the first step of the process. Visualization and Query tools enable a fuller understanding of the data. Data exploration through visualization is an effective means to perceive and obtain insights from large collections of data [13].

Data Visualization includes development of a Google Earth simulation tool and a risk visualization model. The time span command enables the time slider in Google Earth where the slider is related to the attribute of the simulation. Attributes like condition, age, risk, likelihood of failure and consequence factor of failure can be simulated to view the change with time. Such visualization usually serves the needs of the utility that is responsible for the pipe network. Over and above this, a querying tool like the map based dynamic web application provides the utility personnel the ability to initiate a query over the internet. The use of web application promotes collaboration among utilities and allows developers to take advantage of the work that has been previously done.

Thus the objective is to lay the foundation for a common data management framework that can facilitate better overall utility asset management (operations, maintenance, rehabilitation and replacement) through access to good information. Although the data model and tools have been developed for water, wastewater and storm water utilities, the concepts could be applicable to other areas of municipal infrastructure. The later chapters in this document describe all the tools and applications in detail.

CHAPTER 2: LITERATURE REVIEW

The initial work consisted of forming relationships with municipal utilities and reviewing literature related to the development of a standard database model. This review of literature addresses current and proposed research related to the development of pipe database models, GIS applications, and infrastructure management practices in other localities, states, and countries.

Autodesk Homeland Security Initiative Data Model [4]

The Autodesk Homeland Security (HLS) Data Model is a collection of several individual data models that share the stated objective of supporting homeland security and promoting interoperability. The data models developed through this initiative are intended to serve as the core of day-to-day utility management. Most users will need to extend this data model with additional data relevant for common utility management applications.

The Homeland Security (HLS) Sanitary Sewer Data Model, diagrammed in Appendix A is limited to a representation of the physical composition of the sewer system. Sanitary lines, service connections, manholes, and other facilities are stored in separate feature classes, and related via a variety of key fields and relationship rules. All feature classes use a "global ID" (GID) attribute to uniquely identify any feature in the database.

In the model, sanitary lines and manholes store an attribute key linking them to the nearest road in a road network feature class, to facilitate access planning without the need for an intermediate proximity analysis step. Additionally, the data model proposes that service connections store an attribute key linking them to the locality's address (or parcel) database. This relationship between the sewer system and outside databases are an example of how individual utility data models may participate in an enterprise-wide GIS database.

The data model is largely incomplete when viewed from specific application viewpoints such as maintenance tracking, condition assessment, or flow monitoring and modeling. The authors acknowledge this, and suggest that the model may be extended through the use of additional attributes.

Atlanta Track – Paper: Clean Water Atlanta Enterprise GIS [12]

This paper was presented at Pipelines 2007: Advances and Experiences with Trenchless Pipeline Projects. The 2007 ASCE International Conference on Pipeline Engineering and Construction was held in Boston, Massachusetts from July 8-11, 2007.

Spurred by legal issues from the EPA and the Georgia Environmental Protection Division, the City of Atlanta embarked on an overhaul of the city's management of their sewer system. This program is called the clean water Atlanta program. The city's new management system uses an enterprise GIS with web-based user interface applications. The system is built on an Oracle database, with ESRI's ArcSDE providing a geographic interface to the database. Various tools are attached to the database for multiple system renewal activities, and the system is available online to utility users. To move the city from CAD drawings to the enterprise GIS, a new sanitary sewer data model was implemented and significant data conversion was performed.

This paper does not present the technical details of the enterprise GIS; rather, it discusses the advantages of the system, and the applicability of the system to a variety of departments. The enterprise GIS project has focused on a variety of sewer management applications, such as rehabilitation and cost estimating applications, infiltration and inflow (I&I) reporting based on CCTV inspections, flow monitoring, and integration with work order systems such as Hansen and Maximo.

Shamsi, U.M.: GIS Tools for Water, Wastewater, and Storm Water Systems [28]

U.M. Shamsi's book, *GIS Tools for Water, Wastewater, and Storm Water Systems*, neatly condenses the concepts necessary for an asset manager to consider before implementing a GIS system to manage water, sewer, and/or storm water assets. In general, infrastructure data is divided into two categories: assets data and applications data. Asset data describes the composition, geometry, and physical properties of the infrastructure and is typically the core of the GIS data model. Application data extends the assets database into fields such as maintenance operations, business and accounting, planning, and modeling.

A general listing of features and attributes commonly found in a water/wastewater system assets management GIS is included in Shamsi's book, and has been partially excerpted for this report in Appendix B. The bulk of the water/wastewater system is represented spatially as a network of lines and nodes, with these nodes (representing manholes, pump stations, valves, etc.) having a spatial or topological relationship to the lines (representing mains, services, laterals, etc.). In addition to the network of lines and nodes, there may be other types of features for an enforced spatial or topological relationship with the network; examples of these could include door/vent locations, vaults, and cleanout locations. All features are given system-wide unique identifiers, as well as source IDs that link to documentation of the data source for each feature. In developing an organized assets database, Shamsi notes the importance of defining the intended scale of representation. This includes deciding not only which features are significant enough to warrant inclusion/documentation, but also deciding how GIS graphical elements such as line segments will relate to physical features such as sewer mains.

For example, one line segment in the GIS may be used to represent a real pipe segment from joint to joint, or the GIS line segment may represent a series of identical pipe segments linking one manhole to the next. Common applications data elements relevant to wastewater systems noted by Shamsi include documentation of flow rates and/or system loading, pipe condition ratings, maintenance records, test results, TV inspection results, and documentation of illegal connections to the system. Using a relational database, much of this application data can be stored in a separate table related to system features via the unique system ID.

Michael, G. and Zhang, J.: Simplified GIS for Water Pipeline Management [17]

As discussed throughout this review, the development of prioritization tools and evaluation of an asset system is generally made easier by using GIS technologies. GIS is being increasingly used by utilities to manage their assets as it provides a platform to view and integrate diverse datasets into one database. The authors of this paper describe the quantity and diversity of data and the challenges associated with managing such a GIS-enabled database. The authors then highlight the steps to create a successful GIS environment. It gives an insight into the development of data structure after assessing the needs of the utility by considering things such as the diversity of data, or the need to support decision making. The authors of the paper stressed the importance of data model by stating that accurate failure assessment requires not only knowledge of a pipe segments condition but also the position of defects on the pipe. Storing this information in the data model allows users to track defect growth on both a pipe-by-pipe basis and global basis. However, the authors did not suggest any standard data structure. Also, while discussing the development of GIS, a case study of a sample utility would have been helpful to fully understand the process.

Once the data structure is implemented, the challenge is to create custom user applications that enhance the GIS experience and help manage and analyze pipeline data. Additionally these tools should be simple to use and provide results as needed. The paper discusses various common applications and how GIS should fit a common user's daily work. However the authors of the paper did not give a detailed description or a sample demonstration for any of the applications. In the end, the authors describe the importance of a robust asset management program and how GIS-enabled database can be a center point for such a program.

Magelky, R.: Assessing the risk of water utility pipeline failures using spatial risk analysis [15]

The spatial risk analysis methodology may increase the return on investment for asset management and data collection in certain scenarios. The author uses an analysis method derived from the oil and gas pipeline industry to evaluate risks associated to the pipeline systems. The case study discussed gives a better idea of demonstration of this methodology. The author suggests the fact that the predicted shortfalls in infrastructure budgets for capital and operations and maintenance for the water industry exceed $500 billion in the United States alone over the next two decades.

In this paper, an overview of the role of GIS in risk analysis is given by defining risk and highlighting the seven steps that are used in the oil and gas integrity management programs. The author strongly believes that any pipeline risk analysis will encounter a major challenge of identifying and using the data to fully evaluate risk. Dynamic segmentation technique is used to assign risk scores and the results of the spatial risk analysis are shown illustrating the variation of risk along any given length of the pipe.

The author summarized the whole paper stating that the risk analysis methodology described can be used to evaluate risks to the integrity of water pipeline systems increasing the return on investment for asset management and GIS data collection. On the whole, the risk methodology can be used to provide a quantitative guide for investment in future inspections, pipe replacement, repair, or rehabilitation to reduce the risks to the utility.

Pickard, B.D. and Levine, A.D.: Development of a GIS based infrastructure replacement prioritization system; a case study [19]

This paper discusses the activities of Tampa Water Department (TWD), which has developed a tool for prioritizing infrastructure replacement based on the existing water infrastructure. For the purpose of study, the TWD have slated 500 miles of water mains for replacement or rehabilitation. The department strongly believes that GIS tool can be applied to project prioritization and also use the software to integrate the databases into a single location.

The main purpose of the paper is to present a case study on the feasibility of applying GIS to prioritize water infrastructure rehabilitation, replacement and improvement projects. The main objective of the department is to perform geospatial analysis to associate existing databases with the locations of planned projects and determine a benefit to cost ratio for each planned project based on a prioritization matrix agreed upon by TWD policy makers.

In this paper, surveys of TWD policy makers were used to rank the relative importance of individual prioritization factors. This data was compiled to yield a prioritization matrix to aid utility policy makers in the planning process. The results show that total construction cost of all planned rehabilitation or replacement projects is around $388 million. GIS is used to evaluate planned infrastructure projects and to estimate societal benefit to cost basis. The authors of the paper conclude that the use of GIS coupled with historic information can provide a framework for developing a prioritized infrastructure replacement master plan while the integrated approach can be used to identify short-term budgetary issues and plan for long-term budget recommendations.

Wernecke, J.: The KML Handbook: Geographic Visualization for the web [30]

This KML handbook attempts to make people around the world understand the hidden logic behind Google Earth's data format. It gives a quick overview of many different uses of KML, ranging from simple sets of placemarks to elaborate informative presentations of geographic data.

The author elaborates on the powerful mapping capabilities of Google Earth including the Timespan element. This technique is used in cases where only one feature is in view at a given time and the features occupy the same location. A number of applications use this element varying from linking the individuals of a person's family tree viewing a path following the movements during their lifetime or use it as a 4D simulation tool to play the construction phases through the timeline or typically used to show the changes in polygons and in images such as ground overlays—for example, to show the retreating path of glaciers, the spread of volcanic ash, and the extent of logging efforts over the years.

An example of Timespan sample KML seen below animates a series of ground overlays based on data collected by Ron Blakey. This example shows three of the 26 geologic eras contained in the original visualization by Valery Hronusov. These simulation examples paved the way to create a similar model using pipeline data.

```
<Folder>
      <name>Latest Precambrian - 560M</name>
      <open>1</open>
      <TimeSpan>
        <begin>2000-02-09</begin>
        <end>2000-02-29T23: 00:00Z</end>
      </TimeSpan>
      <Style>
        <ListStyle>
          <listItemType>checkHideChildren</listItemType>
          <bgColor>ff0039ff</bgColor>
        </ListStyle>
      </Style>
      <Placemark>
```

ESRI: ArcGIS server resource center [8]

The resource center has tutorials related to the development of web applications in various developer frameworks including Javascript, Flex, Silverlight, .NET, Java, and Sharepoint. The ArcGIS server platform provides a set of components that can be used to create a web based mapping and analysis application. These components not only provide a broad array of functionality but they have also been designed to allow for easy extension, working with multiple data sources such as ArcGIS server and ArcIMS. The resource center has samples demonstrating custom tasks to perform different kinds of calculations. The sample GIS Services include services for mapping, address location and geoprocessing. The web applications are pertinent to a variety of industries ranging from technology, arts, health, risk assessments and training purposes. A sample web application case study is described in Appendix J. The resource center also provides access to online basemap and reference map services, map layers and documents, and tools to use in the web applications.

The ArcGIS Server Manager creates a predefined web application based on web mapping application template that is ready for deployment without writing code. However it has numerous limitations in building queries and customizing the application. The resource center has a suite of server side components that provides interoperability, mission-critical support and secure infrastructure. The center acts as a great resource for developers to learn more about the capabilities and configuration options of an ArcGIS server system. Thus this resource center assisted a lot in the present research in developing a dynamic map based web application.

CHAPTER 3: DATA MODEL

This chapter forms the foundation for the present research of modifying the data model developed as part of the BAMI project and developing applications complementing the data model.

The data model development is a very prevalent process considering many different sources, data structures, modeling, and results [26]. The preliminary standard data model is developed in collaboration with the Center for Geospatial Information Technology (CGIT), a part of Virginia Tech's Geospatial Information Sciences, while the project was funded by BAMI/USEPA. The overall framework for developing the preliminary standard data model is described in this chapter [26]. An updated version of the standard data model is developed as part of this research after contacting the utilities to improve the applicability of this model. The comments and suggestions from the utilities are incorporated into the updated data model version by adding new attributes and tables which is described later in this chapter.

Preliminary Data Model (BAMI project)

The process of development of the data model began by contacting utilities for sharing their data for research purposes. The Virginia Tech research team signed a memorandum of understanding with all the utilities for the safety, security and sharing restrictions of their data. The meetings have consisted of conference calls between the Virginia Tech research team and GIS managers of the utilities. The meeting process followed a standard protocol of introductory meeting, data transfer meeting, and follow up questions regarding the data. In addition to these, meetings have taken place with the San Diego Supercomputer Center (SDSC) to set up the database connection between Virginia Tech and the SDSC [26].

Most of the utilities have data stored in a compatible format with ArcMap such as shape files or Geodatabase tables. However, small utilities do not have access to ArcMap so they store data in traditional ways such as Excel spreadsheets or hand-written documentation [26].

"The proposed effective structure to store data is to create a feature dataset for each city on its name and then create individual feature classes for manholes, pipelines etc in each dataset" [26].

Each city's data is stored separately and is retrieved in a similar fashion which is one of the main advantages of the data structure [26]. In addition to the individual databases, all the utilities' data is aggregated into one common mega database each for water and sewer. A common data framework has been defined and populated by combining different datasets from several utilities as illustrated in Figure 1.

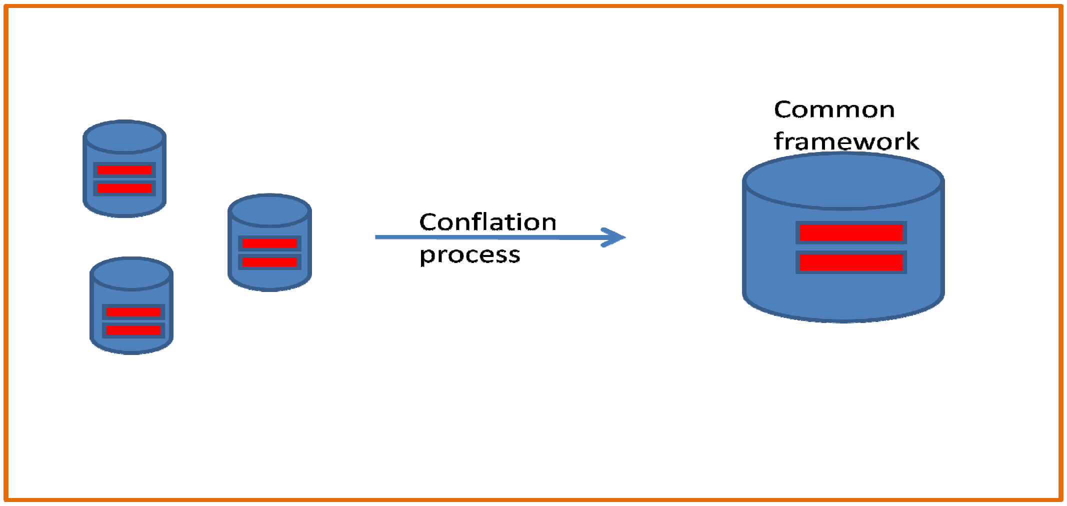


Figure 1: Conflation process between Municipal Utilities

As part of a project funded by Water Environmental Research Foundation (WERF) under Strategic Asset Management (SAM) challenge, Virginia Tech identified about 100 parameters which may affect the pipe infrastructure. The goal is to eventually create a national standard data model for the pipe infrastructure [26]. "The data model can be used in developing of condition index, prediction model, prioritizing repair and rehabilitation, prioritizing inspection, planning operation and maintenance, developing capital improvement program and making high level decision" [26].

"The data model was broken into four separate models: Wood, Bronze, Silver, and Gold. Also, due to the utilities' lack of readily available number of parameters, the utility pipe data model was broken into essential and preferable/desirable data" [26]. The BAMI report has a detailed description of this classification. Once the data parameters are identified, each of the utility's data (Appendix E) is analyzed to evaluate the challenges for translation of data.

Data Translation

The data translation process is developed as part of the BAMI project, the procedure of translating the utilities data into the data model framework starts with preparing mapping files. Data mapping is the technique of relating attributes from distinct data models namely the source and the destination. It is used as an aid for the data translation process using the data interoperability tool, an extension of the ArcMap tools.

"These mapping files are prepared manually for all the participating utilities in excel to map these data models. A snapshot of the excel file is illustrated in Figure 2**;** the basic idea of the mapping files is to link the field of the standard data model to the corresponding field/attribute used by the utility" [26].

1	USF - Utility Shape File, DSF - Downloaded Shape File, null- Not Available									
2	**No.**	**Field Name**	**Alias**	**Brief Explanation**	**Data Type**	**Relation to data model**	**Shape File/Table**	**Attribute**	**Allow Null?**	**Source**
3	**Node (Hydrants)**									
4	1	Node_ID	Node Identification Number	Definition of node (Hydrants)	number	ess, 1	hydrant	Hyd_FeaKey	No	USF
5	2	WmnFea1	Water main line 1	Water Main Line 1 connected to the node	number		hydrant	WMN1FEAKEY	yes	USF
6	3	WmnFea2	Water main line 2	Water Main Line 1 connected to the node	number		hydrant	WMN1FEAKEY	yes	USF
7	4	node_elev	node elevation	Elevation of hydrant	number	pre, 20	hydrant	Tee_Elev	yes	USF
8	5	ntype	node type	type of node - hydrant, valve, fitting	text		hydrant	Fea_Type	yes	USF
9	6	node_hyd	node hydraulic	hydraulic of node	number	pre, 21	hydrant	PRSRZN_ID	yes	USF
10	7	node_inf	node information	node - hydrant, valve information	text	pre, 24,25	hydrant	FEA_DESC	yes	USF
11	8	install_dt	installation date	date of installation of the hydrant	date		hydrant	install_yr	yes	USF
12	9	street_no	street number	street number in which the hydrant is located	number				yes	null
13	10	street_name	street name	name of street in which the hydrant is located	text				yes	null

Figure 2: Screenshot of a Mapping file

There are several databases related to soil, land use, elevation etc which are part of the pipe system. This data is available online for free and can be downloaded in a shapefile or tabular format. Such data can be used to populate the pipe databases which otherwise would be impractical for the utilities to collect this kind of data [26]. This publicly available data complements the data collected by the utilities.

Geospatial ETL (Extract, Transform and Load) tool is used to load existing utility data and the downloaded data into the new data model. The Data Interoperability Extension, like ESRI's other extensions provides such functionality. This tool was a suitable choice because most of the utilities' data related to the project was already in ESRI environment. An independent translation tool was developed for each participating utility [26]. This framework can be used in future to make changes to the source data or to the destination data structure.

The Data Interoperability Extension (Figure 3) provides the framework to develop the translation tools. An individual tool is developed for each municipal utility to translate its existing data into the standard. The tool can be used to process basic calculations such as adding a new field, joining tables, calculating depths and more. The source attributes and the destination attributes are linked using the mapping files and the joiners if necessary. Thus the translation of data is performed for all the participating utilities using the spatial ETL tools [26]. Eventually all the translated utilities' data is integrated into a mega database each for water and sewer.

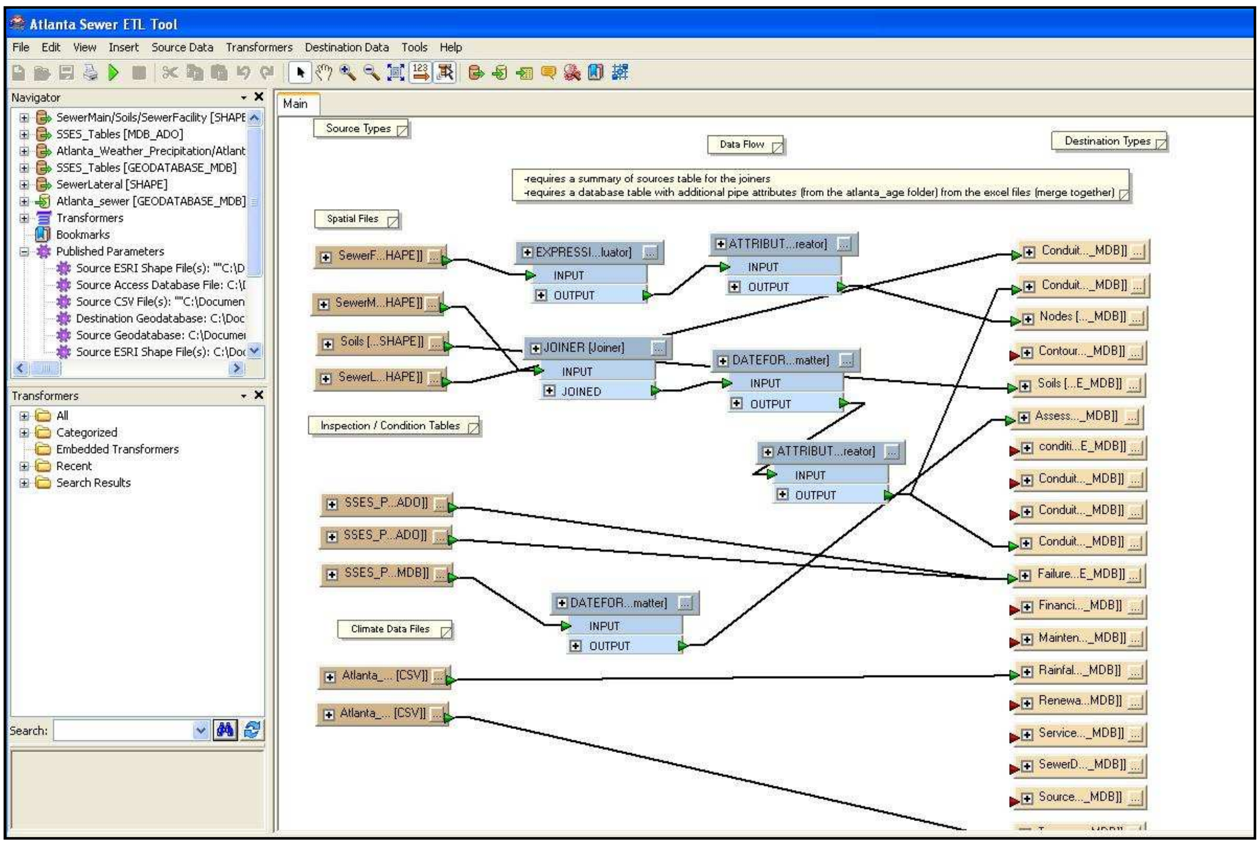


Figure 3: Screenshot of Data Interoperability tool

Thus the preliminary data model and data translation process is developed as part of BAMI project which acts as the background for the research work described in the later sections and chapters.

Modified Data Model

As part of the present research, changes and updates have been made to the standard data model described in the previous section. The list of parameters is sent to various utilities in and outside the United States in order to get feedback to improve the data models. Also, the data models of some of the utilities were closely examined while incorporating the changes to the data model. Additional tables and attributes are added to the existing structure to improve the practicality and usability of the data model. In the future, improvements and changes to the data model are also expected.

Table 1 gives a list of all the changes made to the water and sewer data model. The base XML document is updated with the changes and then exported to Microsoft Visio program to create a readable version of the data model. The tables of the Geodatabase are then related in the Visio program to design a visually enhanced version of the model as shown in Appendix K. Once the data model is modified, simultaneous changes are made to the mapping files and the ETL tools which are used to translate the raw data into the modified data model structure. The whole process of translation of data into the data model is done as described in the previous section. All the modified individual databases are combined into a mega database each for water and sewer.

Table 1: Changes to the modified data model

Data Model	Added tables	Corresponding Attributes
Sewer	Conduits_lateral	StructID, PipeID, jointtype, material, dim, lat_shape
Sewer and Water	Contour	ObjectID, shape, shape_len
Sewer and Water	Renewal record	StructID, renewalyr, age, type, remarks
Sewer and Water	Failure record	Failureyr, age, type, remarks, StructID
Sewer	Assessment	Pipe condition

Once the databases are created, applications are developed to complement the data. The later chapters of this document outline various such applications.

CHAPTER 4: RISK VISUALIZATION

Risk is defined as:

"*The chance of something happening that will impact upon objective, and is measured in terms of a combination of the likelihood and consequences of events*" [27].

The risk/performance of the system is determined by two basic measures:

- Event: The probability of failure or breaches
- Consequence: The impact of failures or breaches

Likelihood of Events

There are many ways in which the likelihood of each event can be estimated. If reliable statistical records of system performance have been kept over a long period and conditions have either remained constant or followed steady trends, then predictions of future performance with associated probabilities can be made using the associated data: standard probability theory can be used to manipulate the data. Alternatively, where the system is well defined but perhaps there is little data on its performance, the likelihood of a particular event can be calculated using Event Trees or Bayesian Belief Network, based on knowledge of the likelihood of breaches or failure of pipe infrastructure system.

Consequence of Events

Consequences of events can be evaluated from real life observations, tests, models or opinions. Whatever the means of evaluation, a good understanding of the system, its components and interactions is essential. Many models exist that can be used to calculate aspects of system performance given various input configurations. For more complex system models, techniques such as fuzzy logic or conditional probability have been used.

Likelihood Rating Criteria

The analysis of risks requires an objective assessment of their frequency of occurring based on historical events and assessment of what has changed and may occur in the future. An example of a typical scale used to rate the likelihood of different risks occurring is shown in Table 2.

Table 2: Risk management process

	Rating	Description	Probability	Frequency
1	Very likely	The event will very likely occur	xx	yy
2	Likely	The event will likely occur	xx	yy
3	Possible	The event may possibly occur	xx	yy
4	Rare	The event will rarely occur	xx	yy
5	Very rare	The event will very rarely occur	xx	yy

Consequence Rating Criteria

In a qualitative risk assessment using the matrix method, scales are employed to describe the magnitude of the consequence. An example of possible qualitative scale to rate the consequence of different risks occurring is shown in Table 3.

Table 3: Consequence rating matrix

		Criteria				
	Rating	**Health(H)**	**Environment (E)**	**Reputation (R)**	**Regulation (R)**	**Financial (F)**
5	Very high	H5	E5	R5	R5	F5
4	High	H4	E4	R4	R4	F4
3	Moderate	H3	E3	R3	R3	F3
2	Low	H2	E2	R2	R2	F2
1	Very low	H1	E1	R1	R1	F1

Risk Rating Criteria

Risk levels are displayed in a matrix that applies rules to combine likelihood and consequence. In the example shown in Table 4, the outcomes of the assessment previously explained are separated into five categories, i.e. extremely high risk (5), high risk (4), moderate risk (3), low risk (2), and extremely low risk (1).

Table 4: Risk rating matrix

	Likelihood of Failure				
Consequence of Failure	1	2	3	4	5
5	Medium	Medium	High	Extreme	Extreme
4	Medium	Medium	High	Extreme	Extreme
3	Medium	Medium	High	High	High
2	Low	Low	Medium	Medium	Medium
1	Low	Low	Medium	Medium	Medium

Pipe Failure Consequences

A system is always considered to be in relation to its environment. The environment can be defined as a set of parameters which affects the system or on the contrary, be affected by the system. The system in this case is the pipe which can often fail and impact the environment and society. Seven impacts of failures for pipe have been identified: environmental, traffic flow, service disruption, time, financial, financial on private property, and other impacts. Any of these impacts may result in serious consequences. For example, a failed pipe under a road can ultimately cause the road to collapse. Upon collapse, vehicles may be damaged from the disaster and an alternative route may be needed. Another impact that will affect the society is time. If a pipe fails, the source may be turned off to surrounding residents in order to fix the failure or leak. Realistically, pipe service cannot be shut down for an extended period of time. Thus, the consequences of failure are used to capture the criticality of the societal impact of pipe failure.

The complexity of repair/rehabilitation/replacement (R/R/R) should also be considered. The complexity involves nine issues: access to pipe, utility density, type of utility, utility pattern, traffic volume, quality of utility record, availability of repair materials, contaminated soils, and other issues. For example, consider the utility density. Depending on the area multiple utilities involving municipal, energy, and communication may exist in close proximity. When considering the repair, rehabilitation, and replacement of a pipe, construction specifications and local utilities should be contacted to determine if other utility services might be disrupted during construction. Breaking or disrupting another utility may cause a disastrous situation.

Pipe classifications may also be important to consider when investigating failure consequences. These classifications include the function of pipe, depth of pipe, size of pipe, location of pipe, age of pipe, material of pipe, and other factors. Classifications can help to explain why a pipe failure may occur. For example, an old pipe, defined as 51 years or older, may display many cracks and failures helping to conclude that older pipes have a greater rate of cracks and failures in comparison to newer pipes. These failure consequences are fundamental in prioritizing the repair/rehabilitation/replacement investment, as well as the overall rating condition in pipe infrastructure system. The pipe sections that have high failure consequences and a low overall rating condition will be selected first in the renewal process.

Empirical risk rating

The risk rating scores can vary for a pipe as shown in the risk rating matrix for likelihood of failure and consequence impact factor in Appendix F. The risk rating is a relative risk system where the results of likelihood of failure (Figure 4) are calculated on a 0-1 scale, as are the score for the consequence impact factor (Figure 5). The total risk is the product of these two, which is also reported on a 0-1 scale. The pipes are color coded according to the rating for better visualization as illustrated in Figure 6.

The parameters used to calculate the risk rating are taken from the standard data model. Taking into consideration the risk rating as defined by Washington Suburban Sanitary Commission (WSSC) in Appendix H and the definition of risk, the empirical equation is formulated as below.

Risk rating = LOF* consequence factor

LOF = average of (PD+MD)

Consequence Impact = average of (EI+TFI+SDI+FI+PHI+DI+FP+ON)

Risk = (PD+MD)/2 * (EI+TFI+SDI+FI+PHI+DI+FP+ON)/8

Where,

PD – Pipe Defects

MD - Manufacturing Defects

EI - Environmental impact

TFI - Traffic flow impact

SDI - Service Disruption Impact

FI - Financial Impact

PHI - Public health impact

DI – Diameter

FP - Function of Pipe

ON - Operational

Each utility can change the parameters according to their needs and importance. For example, length of a pipe can also be added as an attribute to calculate likelihood of failure; considering all other parameters equal, a long segment has a greater likelihood of failing than a shorter one by virtue of the additional exposure to conditions that could cause a failure. The risk methodology can incorporate diverse data sources to provide a quantitative analysis of the probability and consequences of failure.

Figure 4: Likelihood of failure

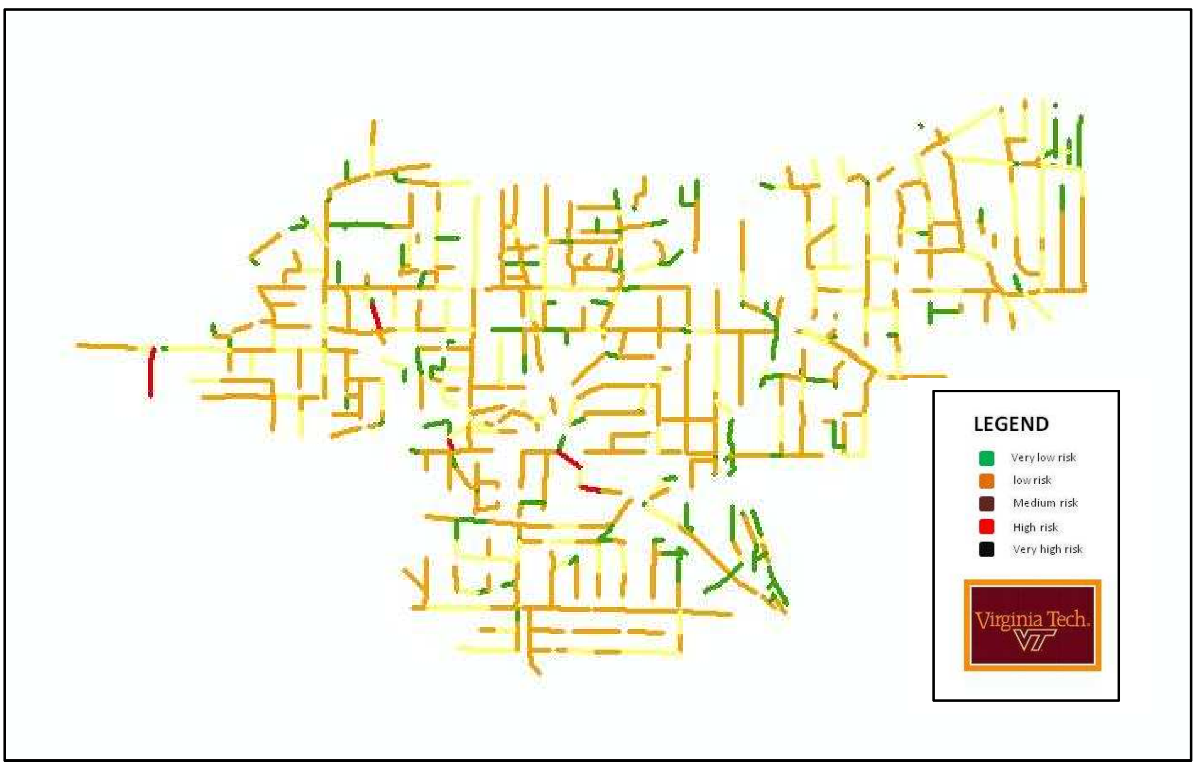


Figure 5: Consequence Impact

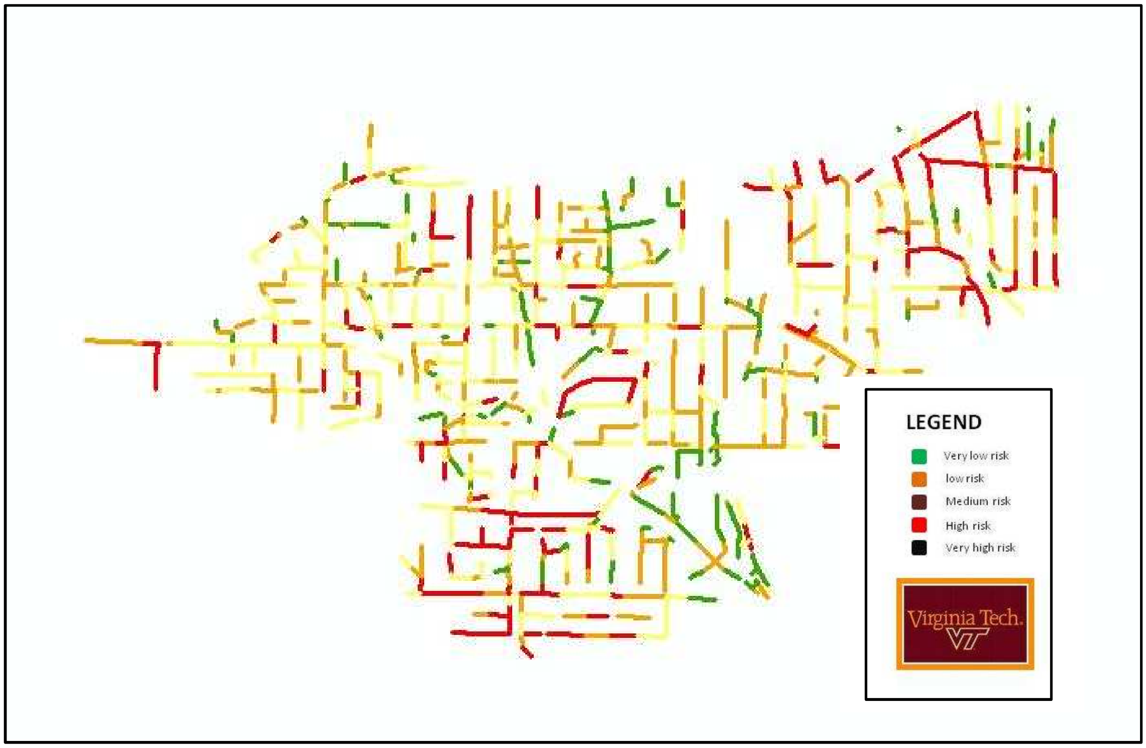


Figure 6: Total risk of pipes

The risk methodology may be used to provide a quantitative guide for investment in future inspections, pipe replacement or repair, changes in security measures, and other mitigation activities to reduce the risks of pipe failures to the utility and community. The methodology can also incorporate the impact of failures on the surrounding community, whether that is due to overland flow resulting in damages, loss of service, or other consequences [15].

The spatial risk analysis can be a powerful tool when imported into Google Earth as shown in Figure 7**.** This tool provides decision makers with additional information to optimize the investment of limited funding.

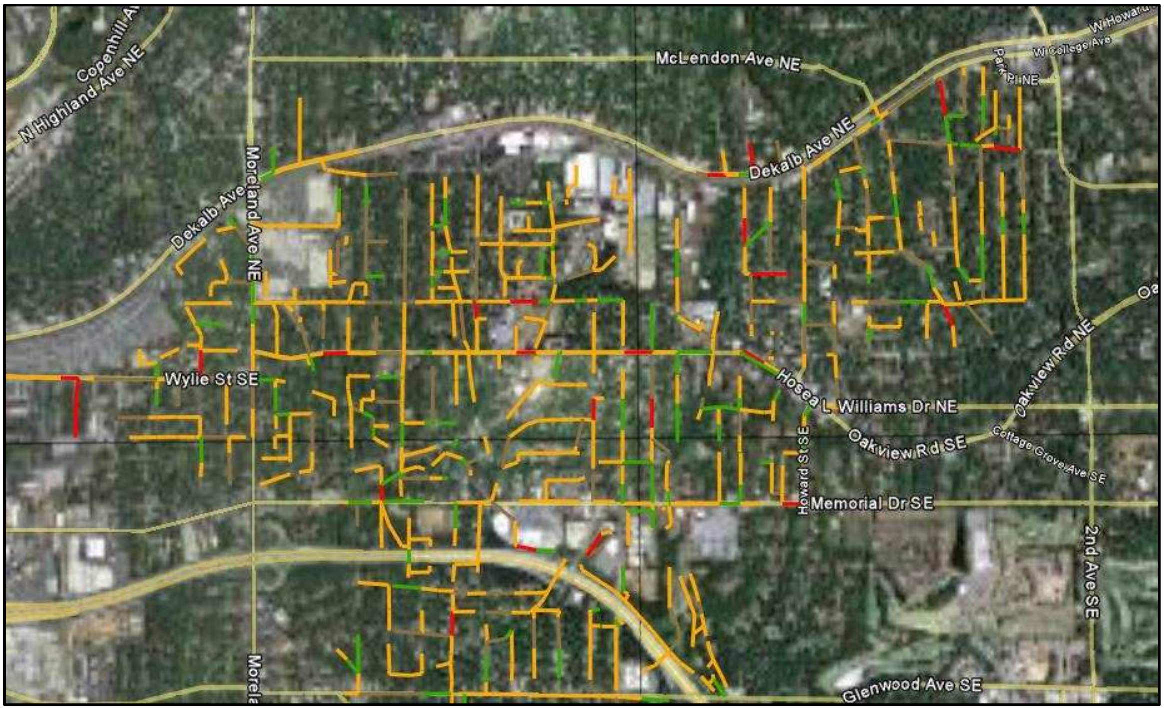


Figure 7: Overlay of risk rated pipes on Google Earth

This enhanced visualization tool assists utilities to evaluate a quantitative analysis of the likelihood of failure and consequence impact factor. It can also assist when it is necessary to allocate limited funds in the most effective manner. The risk algorithm is a relative risk system. A utility can use this output and determine a threshold score at which a remedial activity is warranted for use in planning future expenditures.

GIS can play a vital role in the process of knowing and evaluating all the threats of the system. The following steps need to be considered while developing the risk visualization model for the utility pipeline network:

1. Know the system and evaluate all the threats to the pipe system.
2. Identify all the attributes to be considered for determining likelihood of failure and consequence impact factor.
3. Calculate the weights of each attribute what the utility thinks is the relative importance of a particular attribute when compared to others. In the model shown here, all attributes are considered to be of equal weight.

4. Develop the risk rating matrix for each attribute considered to affect the risk rating as shown in Appendix F. The classification levels can differ for each utility.
5. Calculate the final risk rating using the empirical formula.
6. Decide on the threshold levels and color code the pipes according to the risk rating.
7. Convert the layer into a KML file which is compatible with Google Earth for a better visualization.

Each utility can develop an individual risk rating system facilitating their needs and limitations. Also, the utility can visualize the likelihood of failure factor and the consequence impact factor individually on Google Earth for a better idea of the whole pipe system. However, the challenge for any utility would be to identify and use all the data needed to evaluate risk. The utility has to incorporate all the available data into one process for quantitatively evaluating the risk of the pipe system.

CHAPTER 5: GOOGLE EARTH SIMULATION

Google Earth is a cost-effective means to explore rich geographical content that is ideal as a collaboration tool for location-specific information. It helps organizations with imagery and other geospatial data make that information accessible and useful to all who need access via an intuitive, fast application. This tool is used to visualize, explore and understand information on a fully interactive 3D globe or 2D browser based maps. It also enables collaboration, improved decision-making, and faster and more informed action based on geospatial information.

Google Earth also allows users to explore the world in more than just three dimensions. It uses Keyhole Markup Language (KML), which is XML based language schema for expressing geographic visualization on three dimensional earth browsers. The KML file specifies a set of features (placemarks, images, polygons, 3D models, textual descriptions, etc.) for display in Google Earth.

A Placemark is one of the most commonly used features in Google Earth. It marks a position on the Earth's surface. By adding a TimeSpan to the placemarks, it is possible to explore and animate the content through time. To display polygons and image overlays that transition instantly from one to the next, the beginning and ending of a time period is specified using the Timespan object. This technique is typically used to show the changes in polygons and images such as ground overlays—for example, to show the retreating path of glaciers, the spread of volcanic ash, and the extent of logging efforts over the years [30].

Timespans are used in cases where only one feature is in view at a given time, and an instant transition from one image to the next is desired. The Timespans must be contiguous and cannot overlap. A time slider appears in the upper-right corner of the 3D display in Google Earth for all of the time-enabled placemarks. The time slider allows the user to control the visibility of placemarks by adjusting the active time range and play through the timeline as an animation.

For data sets with Timespan, the Google Earth user interface time slider includes a pointer that moves smoothly along the time slider from the beginning to the end of the time period. The transition from one feature to the next is an instant change [30].

The syntax for the time span command is given below. It represents an extent in time bounded by begin and end *dateTimes*.

```
<TimeSpan id="ID">
  <begin>...</begin>     <!-- kml:dateTime -->
  <end>...</end>         <!-- kml:dateTime -->
</TimeSpan>
```

If <begin> or <end> is missing, then that end of the period is unbounded. The *dateTime* is defined according to XML Schema time. The value can be expressed as *yyyy-mm-dd*T*hh:mm:ss*zzzzzz, where T is the separator between the date and the time, and the time zone is either Z (for UTC) or *zzzzzz*, which represents ±*hh:mm* in relation to UTC. Additionally, the value can be expressed as a date only. The elements specific to time span are <begin> and <end>where **<begin>** describes the beginning instant of a time period and **<end>** describes the ending instant of a time period. If these commands are absent their respective places are unbounded.

For the time being, pipe deterioration curve is assumed to be a simple straight line with no repairs or rehabilitation conducted over the lifecycle of the pipe as shown in Figure 8. In the future, sophisticated pipe deterioration models might be developed which can be incorporated into the simulation. The simulation at various future time periods is shown in Figure 9.

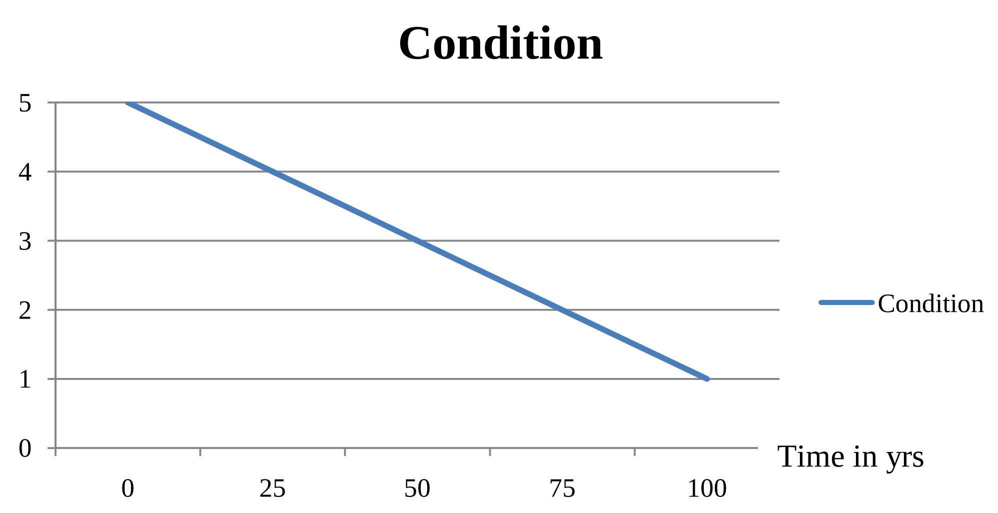


Figure 8: Straight line deterioration of pipes

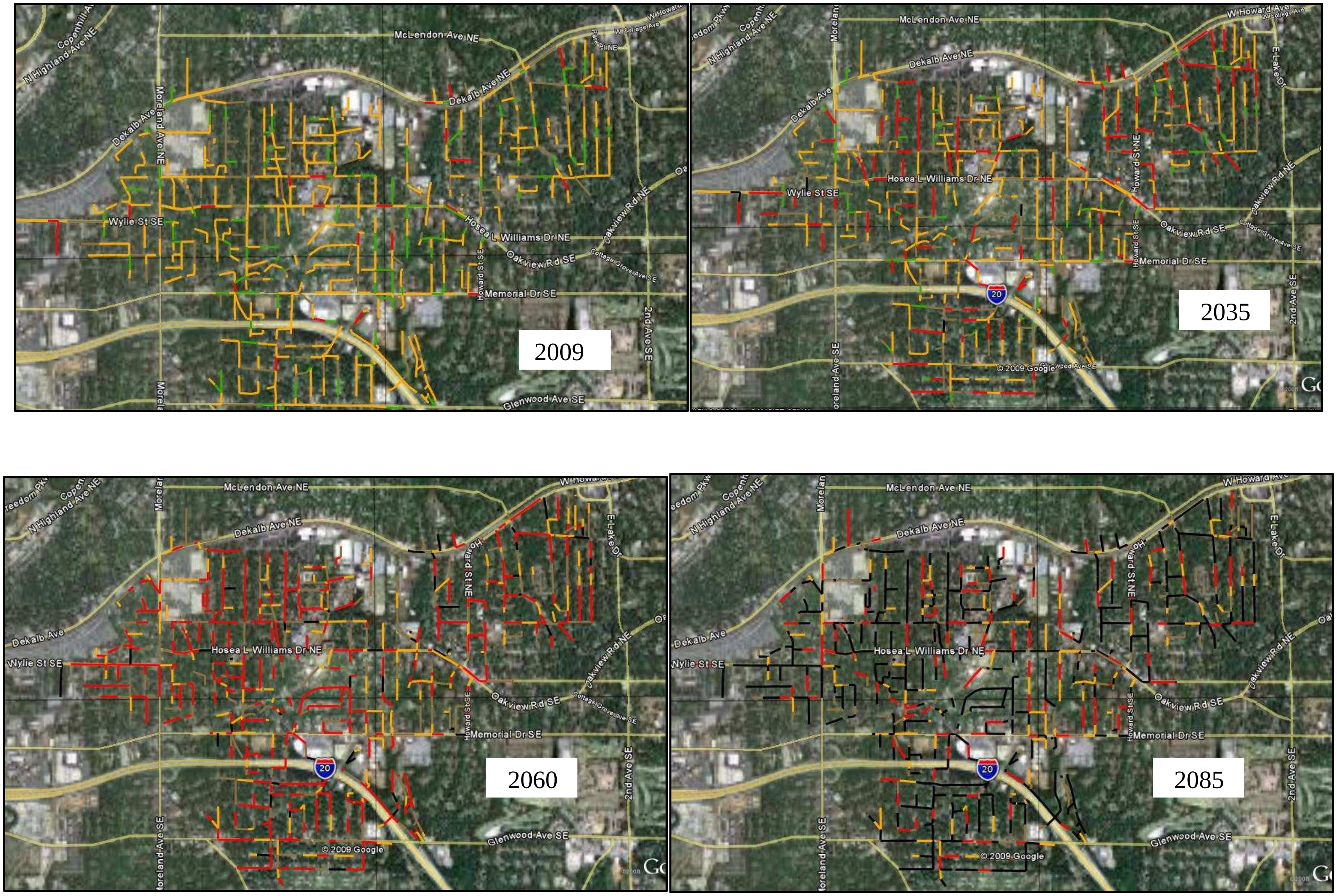


Figure 9: Pipe deterioration simulation at various time periods

The present simulation animates a series of pipelines based on projected data derived according to the straight line deterioration. The illustration in Figure 9 shows four of the different stages of pipe condition at various time intervals in the future. A separate <Folder> contains the name and data for each stage. Each <Folder> contains a <Placemark> with a <name> that is used as the label for the pipe. The <Timespan> is defined with each such <Placemark>. Also, each <Folder> has a <Linestyle> element that specifies a background color for its entry in the list view. An example KML file structure is illustrated in Appendix G

The number of pipes considered in the simulation is huge while the timespan command being described is to be added to each of the placemarks of the KML file. The process of adding the timespan command to each of the placemarks manually is nearly impossible and time consuming. As an alternative, a Perl code (Appendix G) is developed to automate the process of adding <timespan> to all the placemarks of the KML file.

Each stage of pipe condition is stored in different folders. The Perl code is run for each data set and the final KML is prepared by integrating all stages of pipe condition into one folder. The final KML is then imported onto Google Earth and the play button on the time slider is clicked to start the simulation. In the settings tab on the time slider, the speed of the simulation can be changed according to the requirements as shown in Figure 10.
The following steps need to be considered while developing the Google Earth Simulation model for the utility pipeline network:

1. Evaluate the system and decide on the attributes that change with time and need to be simulated to understand the system better.
2. Collect all the available historical data for the attributes and project data if needed using forecasting methods.
3. Color the pipes of the various data files according to the threshold value decided by the utility decision makers.
4. For each of the data file, run the Perl code to add the <Timespan> command to all the placemarks in the data file.
5. Also for each data file, change the time period according to the needs of the utility.

6. Integrate all data files into one master KML file after adding the <Timespan> command to all the individual data files.
7. Import the master KML file onto Google Earth and run the simulation.

Each utility can develop an individual Google Earth Simulation model facilitating to their needs and limitations. Also, the utility can visualize any time variant attributes like risk rating, age, condition of pipe on Google Earth for a better idea of the whole pipe system. This provides the decision makers with additional information to allocate the limited resources of the utility. In addition, this helps the utility to prioritize repair and rehabilitation and other mitigation activities to reduce the unpredictability of the system. However, the challenge for any utility would be to identify and use all the data needed to develop such a model. The utility has to incorporate all the available data into one process for quantitatively simulating the attributes of the pipe system. Such a simulation tool assists the utility personnel to foresee pipe failures or any undesirable service interruptions.

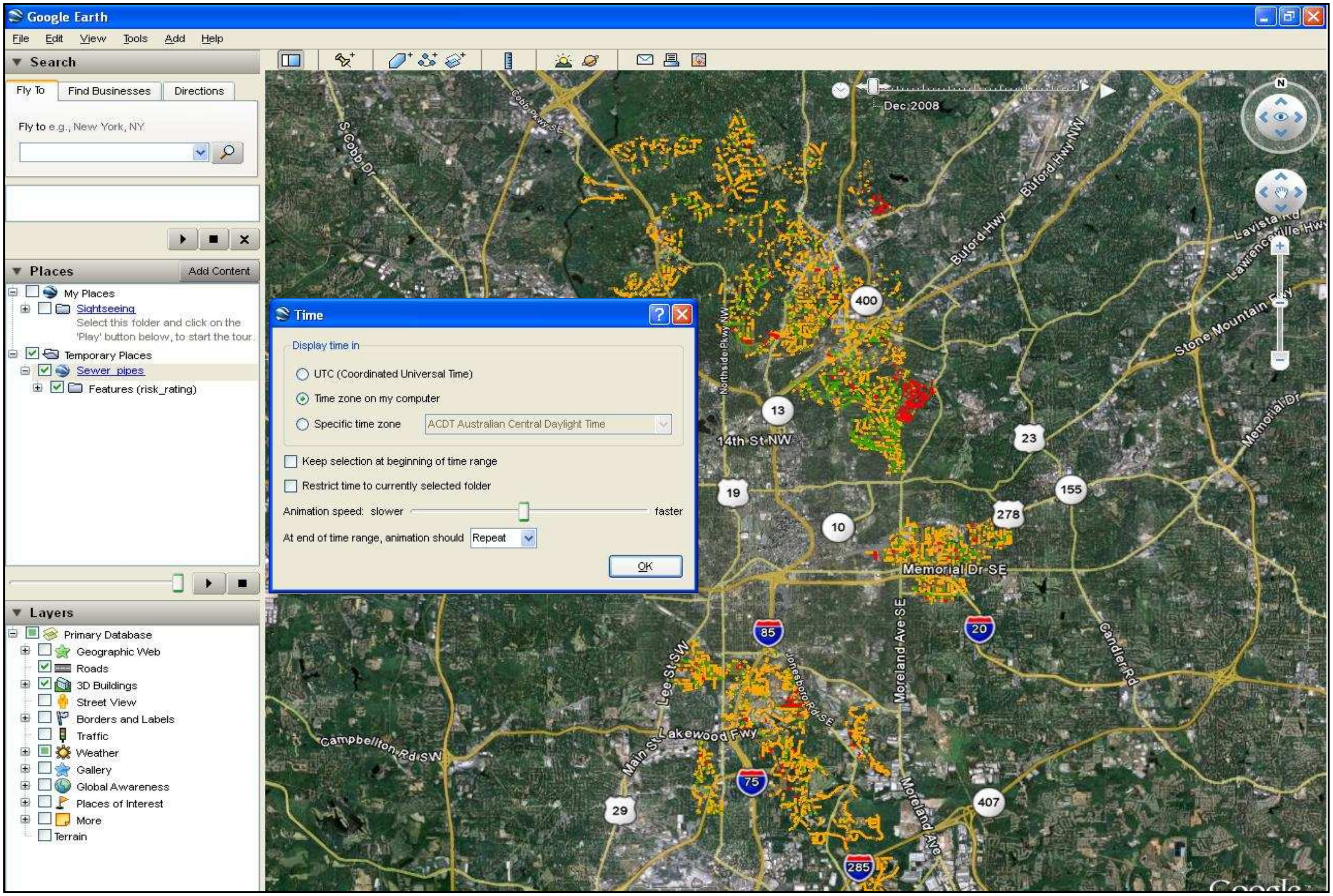


Figure 10: Google Earth Simulation

CHAPTER 6: WEB APPLICATION

A web application is an application that is accessed via a web browser over a network such as the Internet. The ability to update and maintain web applications without distributing and installing software on potentially thousands of user computers is a key usability factor.

ArcGIS server Manager (Figure 13) allows distributing maps and geographic information system capabilities via web mapping applications and services to improve internal workflows and communicate vital information. With ArcGIS server simple applications can be created that use very sophisticated functionality and large volumes of data [8].

ArcGIS Server provides the platform for sharing GIS resources, such as maps, with the user community. It also allows sharing GIS resources across an enterprise and across the Web. GIS resources are the maps, globes, address locators, and Geodatabase. One can share these resources by first hosting them on an ArcGIS Server system, or GIS server, and then allowing client applications to use and interact with the resources. The main advantages of sharing the GIS resources on a GIS server are the same as sharing any data through any kind of server technology for instance; the data is centrally managed, supports multiple users, and provides clients with the most up-to-date information [9].

ArcGIS Server is fundamentally an object server that manages a set of ArcObjects running on a server. It works on two components as shown in Figure 11. The Server Object Manager (SOM) manages the set of server objects that are distributed across one or more SOC machines. The SOC machine host the server objects that are managed by the SOM. Each SOC machine is capable of hosting multiple SOC processes. A SOC process is a process in which one or more server objects are running [8]. The Application Developer Framework (ADF) provides the framework, Web controls and convenience classes to build and deploy Web applications and Web services that make use of ArcObjects running in the GIS server.

In addition to providing access to GIS resources, the GIS server also provides access to the GIS functionality that the resource contains. For example, one might be able to share a map with someone through a server, but it would be even better if that person could also interact with the map. Thus, the GIS server not only allows sharing resources, like maps, but also allows accessing the embedded GIS functionality in them [9]**.** While creating web applications with ArcGIS Server, one can integrate content from their own server with content from other GIS servers. Web applications can also make use of the GIS resources to create custom applications that focus on the requirements of a particular user.

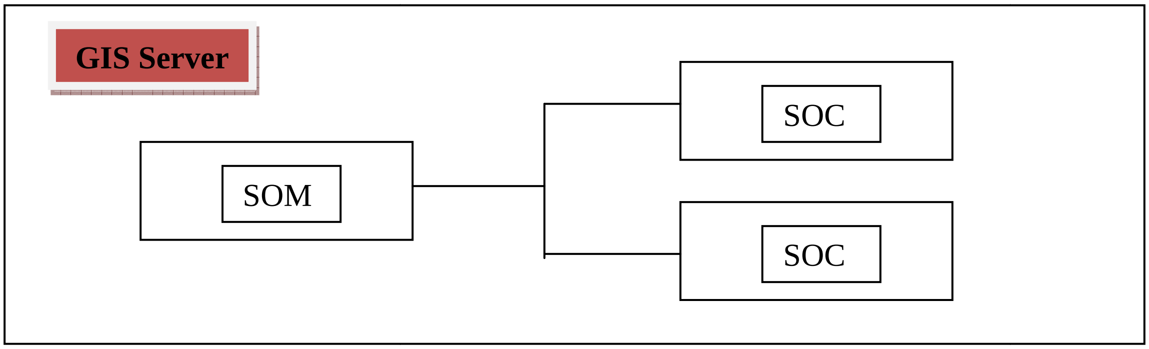


Figure 11: ArcGIS Server Components

ArcGIS Server Manager allows creating geospatial enterprise applications that showcase the geographic information running on the server. With Manager, one can create and deploy standard Enterprise java beans (EJBs), which can provide geospatial services such as mapping, querying, routing, and geocoding. The ArcGIS Server for Java Eclipse plug-in has a template for building and deploying the samples. For creating map based web application (Figure 12), java was chosen as the programming language. Developing the source code in java, the Geodatabase and the ArcGIS sever are connected to create a map based web application that answers specific questions.

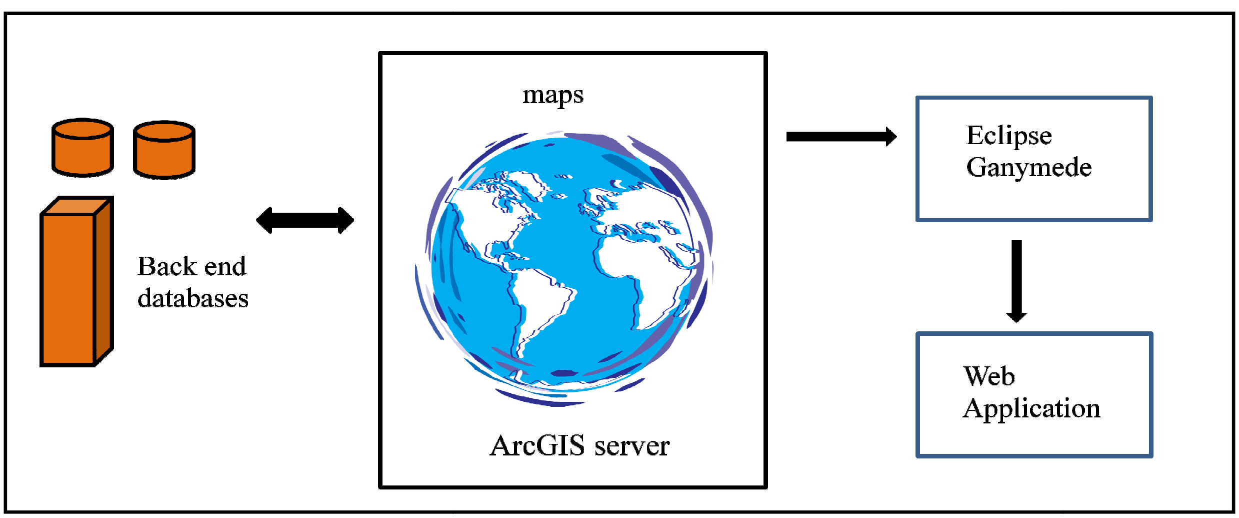


Figure 12: Web Application architecture

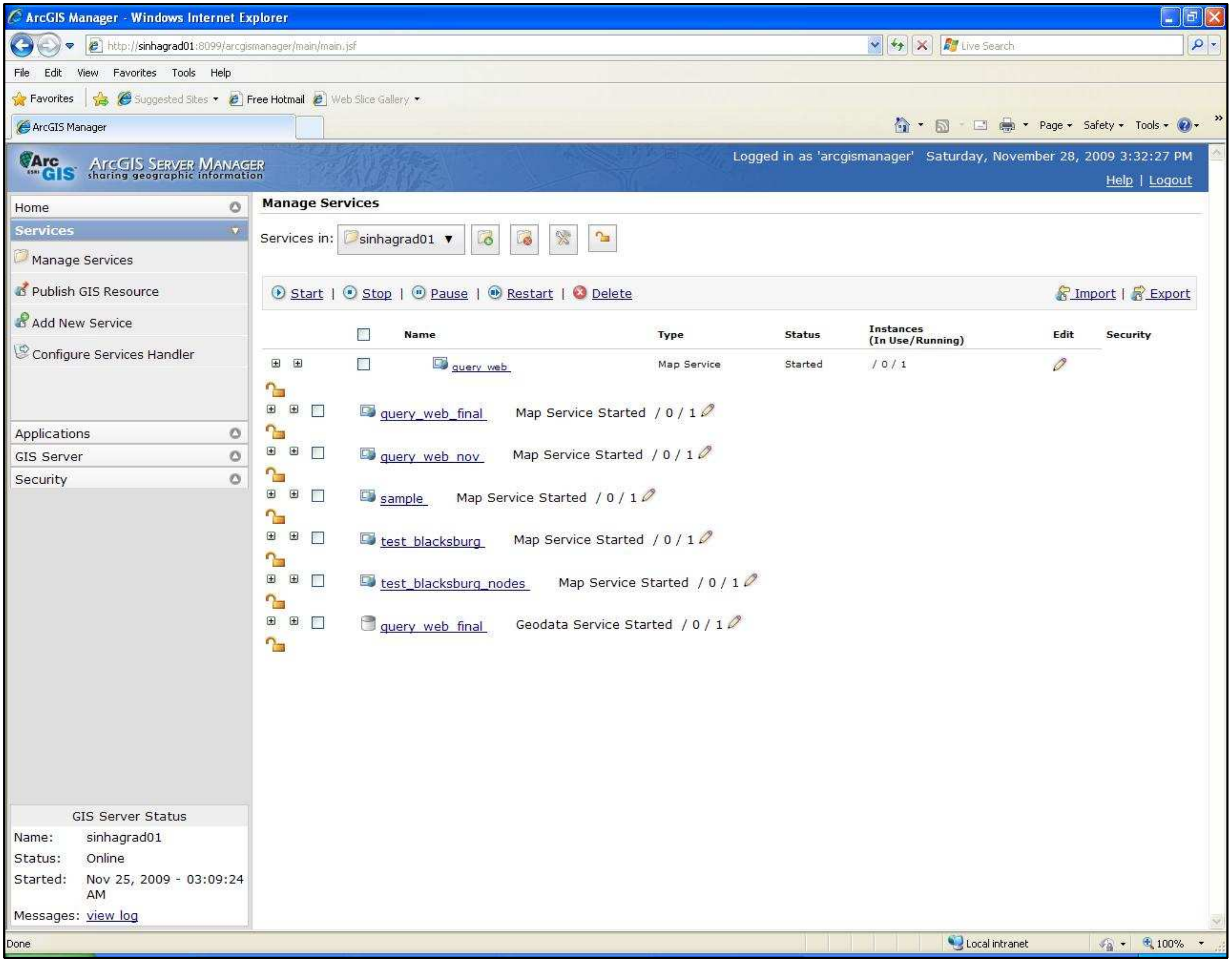


Figure 13: ArcGIS server Manager

Appendix I outlines the process of importing GIS server for a java sample as an Eclipse project. To implement a query attribute task, it is added as a managed bean to the faces-config.xml file

```
<managed-bean>  <managed-bean-name> queryTask</managed-bean-
name>
<managed-bean-
class>com.esri.adf.web.tasks.QueryAttributesTask</managed-bean-
class>
….
<property-name>webcontext</property-name>
                  <value>#{mapcontext}</value>

….
<property-name>taskConfig</property-name>
<value>#{queryTaskConfig}</value>
<managed-bean>  <managed-bean-name> queryTaskConfig</managed-
bean-name>
<managed-bean-
class>com.esri.adf.web.tasks.QueryAttributesTaskConfig</managed-
bean-class>
….
</managed-bean>
```

Task Info (Figure 14) provides metadata about the task such as parameter, action and tool descriptors while Task Config gives access to properties of the task such as labels, messages and functionality.

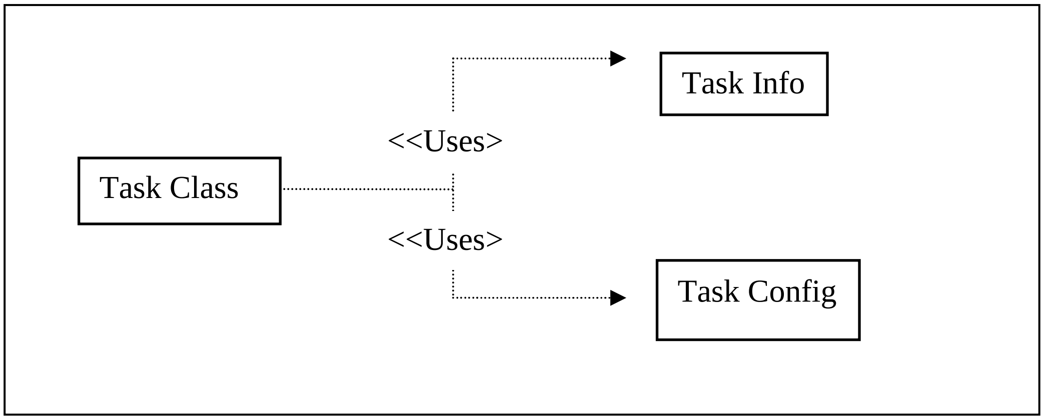


Figure 14: Task Info and Task Config

The final web application is illustrated in Figure 15 while a sample query is demonstrated in Figure 16**.** It is connected to the data services managed by the ArcGIS server manager. All the services must be up and running with all the maps to be queried in the web application. The web application has various tools to query, search for any attributes of the pipe. It also has tools such as pan tool, zoom tool, measure tool for a better interaction with the map data for the utilities. The data to be queried by the web application can be changed by changing the maps in the Arc Server Manager Service. When a query is submitted, the queried pipes are highlighted in the map and the list of pipes is identified in the results panel located on the left side of the web application. The queried pipes are also zoomed to the layer for a better distinction from the rest of the pipes.

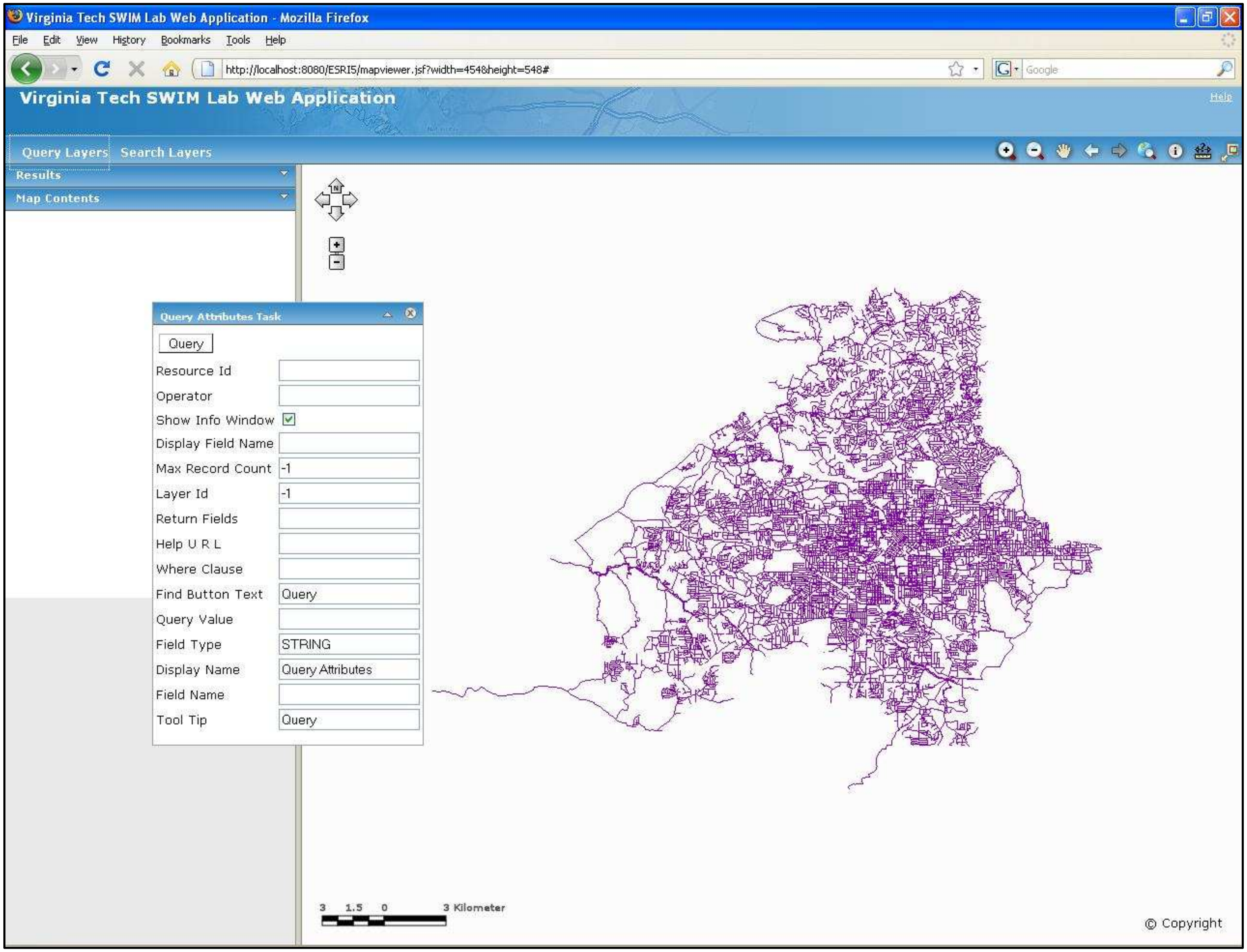


Figure 15: Web Application

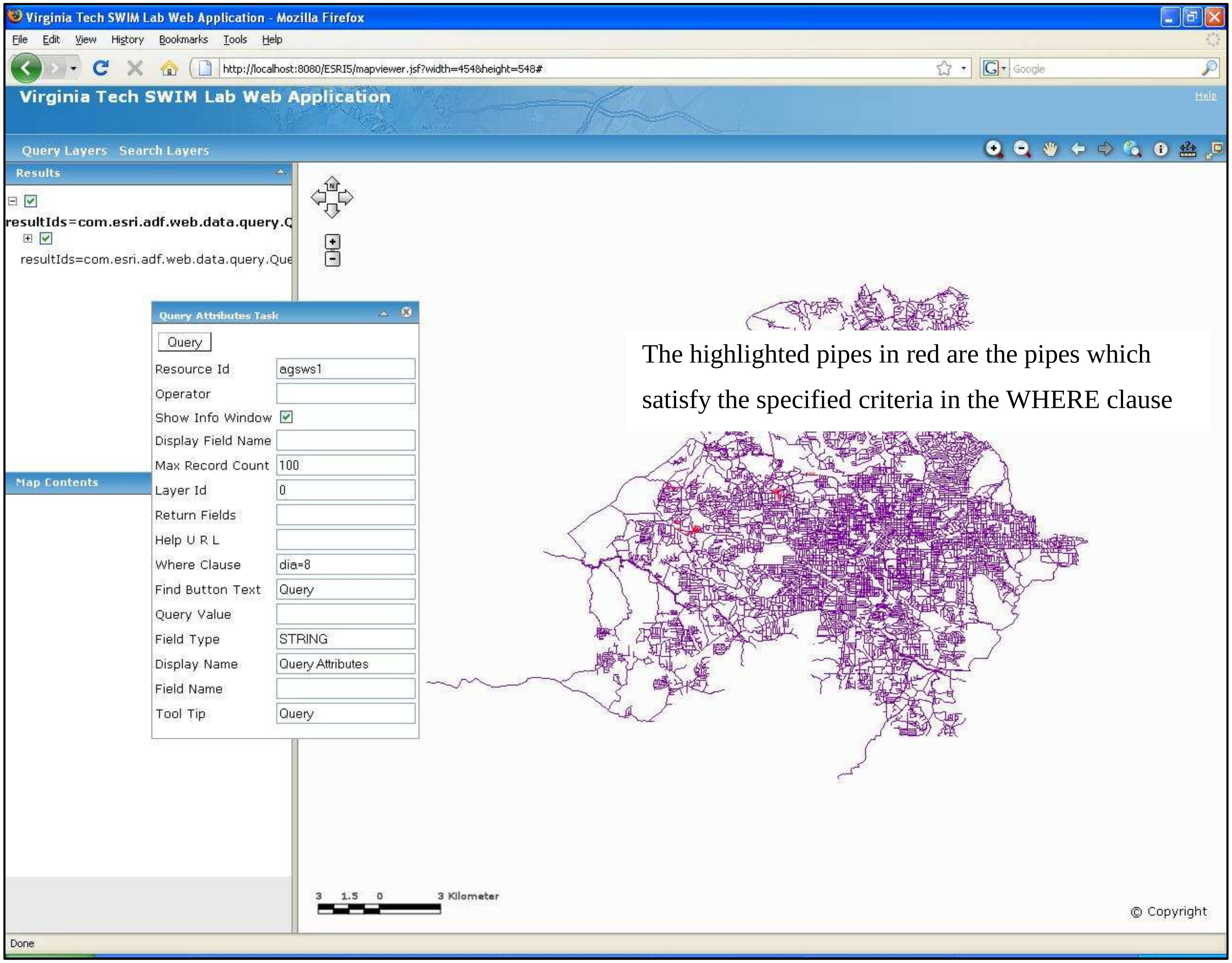


Figure 16: Sample Web Query

Web Application

This section explains various tools and functionalities of the web application. The application has a variety of tools in Figure 17 for a better interaction with the maps. The various tools in Table 5 include zoom in, zoom out, pan, measure etc.

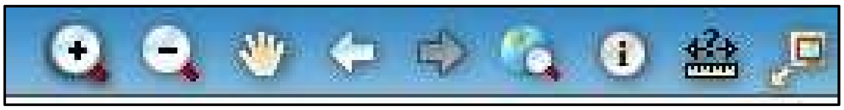


Figure 17: Tools of the web application

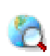
Name	Icon	Description
Zoom in		**Click and drag a rectangle**: Click and hold the left mouse button down on the map at one corner of the rectangle to zoom in to. Drag the mouse to the other corner of the rectangle, and release the mouse button. The map will zoom in to the area of the rectangle.
Zoom out		**Click and drag a rectangle**: the map will zoom out so that the current map area will fit into the rectangle drawn. The smaller the rectangle you draw, the more the map will zoom out.
Pan(recenter)		**Click and drag the map**: Click and hold the left mouse button on the map, and drag the map. The map will be recentered with the location dragged at the location you dropped it.
Full Extent		**Full extent**: Immediately zooms the map out to the area of all features and layers. The active tool does not change.
Identify		**Click to identify**: Click with the left mouse button on the map.
Measure		Measure distance or area
Extents (Back)		Navigates back the map one extent in the extent history for this session.
Extents (Forward)		Navigates forward the map one extent in the extent history for this session.

Table 5: Description of various tools

Query layers Tab

The Query layers tab helps users select or view certain data on the map based on that data's attributes. For example, to select pipes by entering a city name and a diameter, the expression in the WHERE Clause for this selection might look something like this: “dia = 8 AND city = ‘Atlanta’”. The users of the Web application might have to know the field names of the data (Table 7). However a higher level web application can be developed by using the Query Attributes task to create an easy-to-read form with text like the following: "I want to select pipes in the state of: (user picks a state from a drop-down list) whose average pipe diameter size is greater than or equal to: (user types a number in a text box)."

The query layers tab (Figure 18) is used to perform queries while the explanation of each field in the query attribute task combo box is given in Table 6.

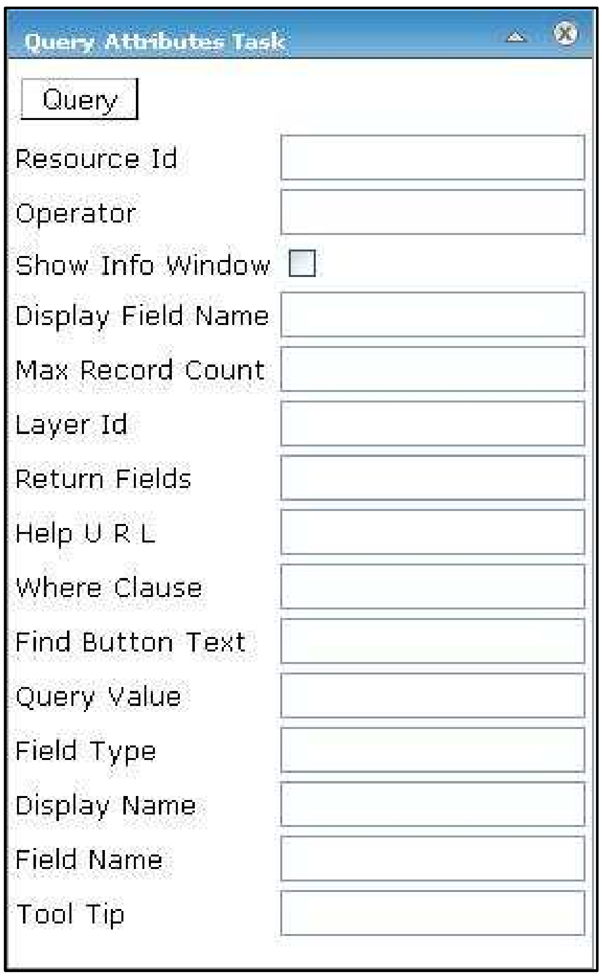


Figure 18: Query Attributes Task Window

Table 6: Description of the fields

Field Name	Explanation
Resource ID	A constant value “agsws1”
Operator	Expressions like <, >, =
Display field name	The display field name of the return fields
Max record count	The maximum number of records to be returned in the query
Layer ID	Layer ID of the layer being queried. To query pipes from the conduits layer, the value is set to be ‘0’
Return fields	All the fields that are returned with the query
Help URL	Help page for this query, if any
Where clause	The criteria for which the pipes are being queried. This field can recognize all the Boolean operators like AND OR NOT
Find button text	Refers to the query button at the top of the window
Query value	The specific value of the criteria being queried
Field type	The type of the field like text, number, date
Display name	Display name of the query in the results panel.
Field name	The name of the field being queried
Tool tip	The information about a specific button describing its functions

By default, ArcGIS Server map services limit the number of records returned by a query to 500 records. Queries that return more than 2000 records can cause performance to degrade. The combination of any of the attributes listed in Table 7 can be queried from the existing data. Querying other attributes returns a null value as the data for all the attributes does not exist. In the future, as the fields in the database are populated, additional attributes can be added to the list.

Table 7: List of attributes which can be queried

Attributes (Field names)	**Type**
Content	text
Material	text
FromNode	text
ToNode	text
XSshape	text
Dia	number
FromInv	number
ToInv	number
DateInst	Date/Time
Status	text
street_no	text
city	text
state	text
zip	text
pipe_len	number
pipe_loc	text
condition	text
Boolean operators	AND, OR, NOT etc

Search Layers Tab

The Search layers tab (Figure 19) is used to search pipes which satisfy the search criteria. The drop down menu in the layer list provides all available layers of interest and search string is entered to search pipes. Clicking the search tab returns the pipes of certain search criteria. This kind of search is similar to the simple Web search. After searching for something, the user can then select, zoom to, or pan to any features in the list of results.

Figure 19: Search Attributes task window

Results window

The Results tab is used to display the results returned from a Selection by either the rectangle or polygon tool.

The following steps need to be followed while developing the web application for the utility pipeline network:

1. Know the system and collect the data for the attributes of the pipe
2. Store all the data in a geodatabase format and map all the conduits, nodes of the utility pipe network
3. Create an .mxd file with all the layers of the pipe data in the map.
4. Log into Arc Server Manager and start a service with the mxd file created in the previous step
5. Now add the maps into an Eclipse project by adding the ArcGIS server
6. Customize the application by adding a custom task into the faces-config.xml file
7. Run the application to perform the dynamic queries on the map data

Utilities can develop their own web applications like the one developed by Western Virginia Water Authority as discussed in Appendix J**.** However these applications are limited to the utility needs while the web application developed as part of research considers the integration of data of all the utilities across the country. The web application is created as an interface for all the utilities to come together and share information, strategies and asset management techniques.

This online platform can promote effective collaboration with others who have a common interest. Web application is a powerful sharing tool that allows users to find layers and query information about the pipe network. The utilities can also choose with whom to share their maps and data by allowing or restricting access at the individual or group level or choose to share with anyone.

Utilities can identify urgent repair needs; query the database to locate pipes that possess a specific attribute or combination of attributes. It can also view attributes for a single pipe on a map as well as any other data set. The web application tool is particularly very useful for small utilities which do not have the manpower and resources to maintain the whole GIS enterprise system.

CHAPTER 7: CONTRIBUTIONS AND FUTURE WORK

The main contributions of this research are the following:

- Modified the standard data model by adding tables and attributes to improve the practicality of the model
- Translated the existing utility data into the modified data model structure and created a master geodatabase each for water and waste water systems.
- Developed a Visualization tool (Risk Visualization and Google Earth Simulation) for the available data with the help of Google Earth.
- Developed a dynamic map based query tool to extract useful information or retrieve data for further analysis.

In the future, the standard data model can lead to the development of condition and preventability indices which help in understanding the pipe networks. Spatial data of pipes, quantitative and qualitative models and expert knowledge can be combined to develop a spatial decision support system. Graphic user interfaces can be created using Eclipse software that allows decision makers to choose input variables.

Interactive maps are becoming more and more popular in web applications. It is very useful to implement dynamic interactive maps on the Java web application, using the Google Maps Application Programming Interface (API) for the web interface. Also, once the fields are populated in the database, the web application can be modified to perform multi-layer dynamic queries. Example queries might include pipes within 50ft of water bodies or the total length of concrete pipes in US.

Risk management requires knowledge about pipe assets: where they are, what is happening to them, what bad things might happen to them and, most importantly, the costs associated with the bad things that could happen to them. Database auditing and monitoring can be performed by the utilities to mitigate data risk by discovering critical data in the database. Furthermore, the viability of the risk visualization model can be improved with the development of sophisticated deterioration models.

Machine learning algorithms can be used to eliminate the need for human interaction in data analysis. A major focus of machine learning research can be to automate the process of learning to recognize complex patterns and make intelligent decisions based on data.

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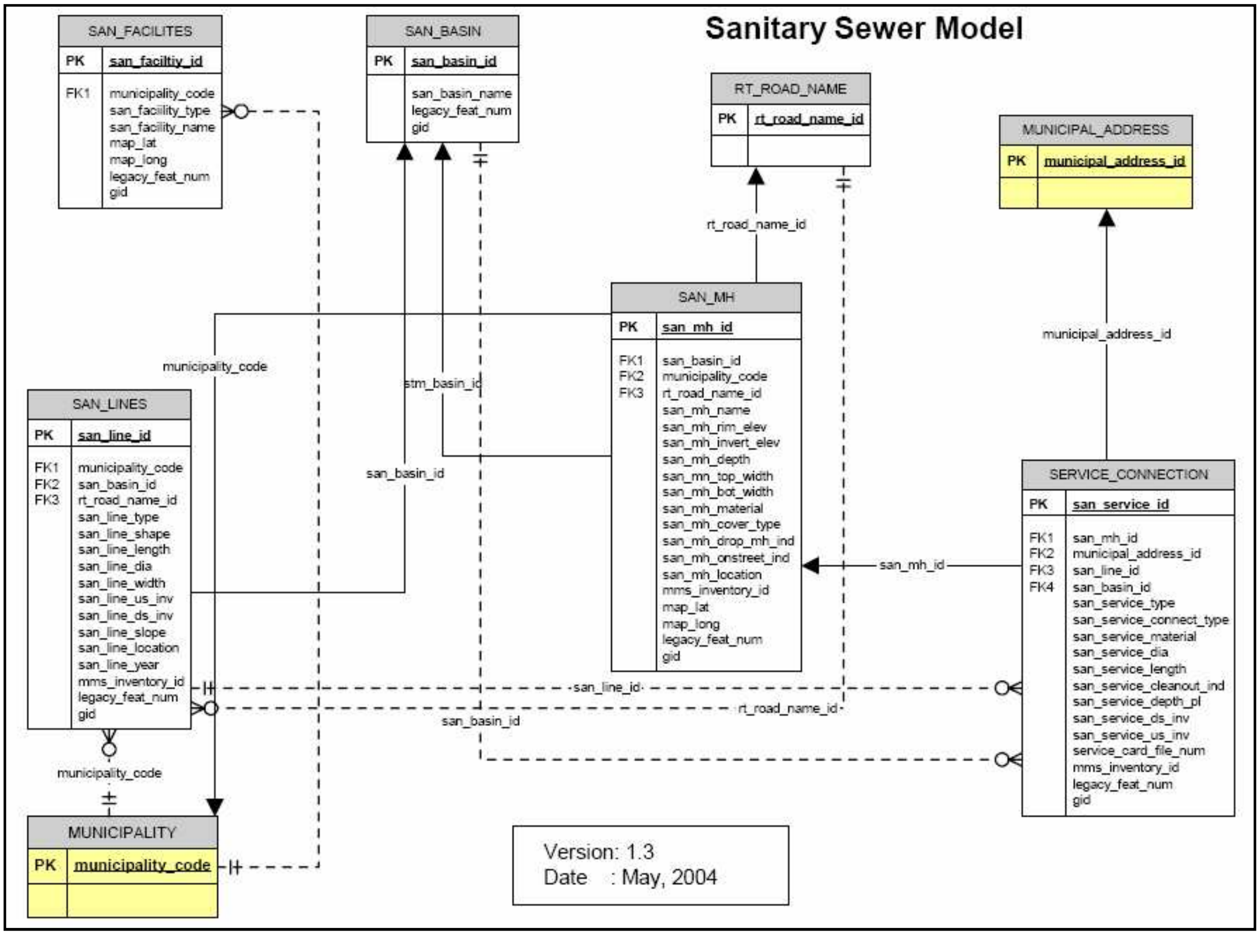
APPENDIX A

AUTODESK HLS SANITARY SEWER MODEL



Sanitary sewer model [4]

APPENDIX B

WATER AND SEWER ATTRIBUTES AND FEATURES

BY U.M. SHAMSI

Typical Wastewater System Features [28]

Point	Node	Line
Cleanout	Cleanout	Casing
Monitoring Location	Combined Sewer Overflow (CSO) Regulator	Force Main
Sampling Location	Diversion Chamber	Gravity Sewer
Tunnel Door	Lift Station	Reuse Main
Tunnel Shaft	Manhole	Reuse Service
Tunnel Vent	On-lot Disposal System	Service Lateral
Valve	Outfall	Siphon
Vault	Pipe Fittings	Tunnel
	Pumping Station	
	Treatment Plant	
	Valve	
	Wet Well	

Lists of Typical Wastewater System Attributes [28]

Sewers	Manholes
Structure ID	Structure ID
Hydraulic model ID (if different from structure ID)	Hydraulic model ID (if different from structure ID)
Source ID (drawing or map number)	Source ID (drawing or map number)
Street address or street location	Street address or street location
Owner	Manhole type
Status	Number of inlets
Collection system (watershed, sewershed, subbasin, subarea, or municipality)	Number of outlets

Upstream (from) ID	Pipe(s) in and out
Downstream (to) ID	Cover material
Pipe type	Cover type
Cross-sectional shape	Top (rim) elevation
Diameter, if circular	Bottom (invert) elevation
Dimensions, if not circular	Depth
Dimension units	Shape
Length	Diameter, if circular
Length units	Dimensions, if not circular
Upstream invert elevation (from elevation)	Ring
Downstream invert elevation (to elevation)	Wall
Slope	Frame
Depth	Steps
Depth units	Bench
Roughness coefficient	Channel
Pipe material	Meter
Joint length	Distance to hydrant
Date installed or installation year	Road traffic conditions
Pipe age	Date installed or installation year
Groundwater level	Status

Typical Water System Features [28]

Point	Node	Line
Backflow Preventer	Analysis/Monitoring point	Casing
Flow meter	Fire hydrant	Fire line
Leaks	Pipe fitting	Hydrant line

Manholes	Pump node	Raw water intake
Pump Station	Service connection	Service
Reservoir	Surge relief	Service main
Vault	tank	Water main
	Tower	
	Treatment plant	
	Valve	
	Well	

Lists of Typical Water System Attributes [28]

Pipes	Fittings	Valves	Hydrants
Structure ID	Device ID	Device ID	Device ID
Hydraulic model ID	Cross	Type	Type
Source ID	Tee	Status	Owner
Owner	Coupling	Direction to open	Status
Status	Reducer	Number of turns	Size
Upstream ID	Bend	Manufacturer	Flow rate
Downstream ID	Flange	Size	Color
Diameter	Joint	High/low pressure	Packing
Length		Operator depth	Feeder information
Upstream invert elevation		Water main and valve cross – referencing	Number of outlets
Downstream invert elevation			Make
Depth			Serial number
Installation Date			Model number
Pipe age			Parcel
Pipe type			Water main and hydrant cross-referencing
Material			
Joint			
Corrosion Factor			
Friction Factor			

APPENDIX C

WATER DATA MODEL ATTRIBUTES

ESSENTIAL AND PREFERABLE

Water Data Model – Essential [25]

No.	Parameter	Unit	Brief Explanation
	1	2	3
Physical/Structural Parameters			
1	Node Identification Number	node	Definition of a node (Valves, Reducers, Tee, etc.)
2	Node Length	feet	Length between nodes
3	Pipe Material	type	Material of pipe
4	Pipe Internal Diameter	inch	Different pipe sizes may fail in different failure modes
5	Pipe Age	year	Older pipes may deteriorate faster than newer pipes
6	Pipe Depth	feet	Pipe depth affects pipe loading and deteriorating rate
7	Pipe Joint Type	type	Some types of joints may undergo premature failure
8	Pipe Location	area	Geographical location may affect the performance of the pipe
9	Pipe Lining	Yes/No - type	Lined pipes have higher resistance to corrosion
10	Pipe Cathodic Protection	Yes/No - type	Technique used to control the corrosion of a metal surface
11	Pipe Bedding	Yes/No - type	Inadequate bedding may cause premature pipe failure
12	Trench Backfill	type	Some backfill materials are more corrosive or frost susceptible, as well as load
13	Pipe Wall Thickness	inch	Wall thickness affects rupture resistance and corrosion penetration rate
14	Construction Specification	spec.	Construction specifications
15	Design Life of Pipe	year	The pipe design life
16	External Coating	Yes/No-type	Pipes with an external coating have a higher resistance to corrosion
17	Thrust Restraint	Yes/No - type	Inadequate restraint may increase longitudinal pipe stresses
Operational/Functional Parameters			
18	Pipe Water Pressure	psi	Internal water pressure affects pipe stresses and deterioration rate; operating pressure, surge pressure, static pressure variations, etc.
19	Pipe Renewal Record	record	All records of pipes repaired - type of repair/rehabilitation method
20	Pipe Failure Record	record	All records of pipe, watermain, service, joint, valve, and hydrant failures
21	Water Temperature	°F	Average water temperature inside pipe

22	Operational & Maintenance Practices	type, time, number, percent	Poor practices can compromise structural integrity and water quality. Types of operation and maintenance practices used
23	Leakage Allowance	percent-Yes/No	Leakage allowance. Leakage may erode pipe bedding, increase soil moisture, and pipe stresses
24	Water Flow Velocity	ft./sec	Flow velocity may affect internal corrosion of unlined/coated pipes
25	Pressure Surges	Yes/No - psi	Changes in fluid velocity can increase pressure within pipelines. If extreme surge the life expectancy of pipe will decrease or pipe will fail.
26	Hydraulic Capacity	gal/min-model	Hydraulic capacity of pipe and information of hydraulic model for pipe network
27	Pipe Inspection Record	record	Record of inspection, method used, and date of inspection
Environmental Parameters			
28	Soil Type	type	Some soils are corrosive, expansive, and compressible. Some soils contain hydrocarbons and solvents that may cause pipe deterioration.
29	Climate - Temperature	°F	Regions may accelerate pipe deterioration
30	Loading Condition (Dead Load)	lbs/sq.ft.	Dead loads (building, quarry, etc.) nearby may affect the pipe
31	Loading Condition (Live Load)	level	Live loads (traffic, railway, etc.) nearby may affect the pipe
32	Water Quality	level	Color, odour, taste, lead level, microbiological tests; Very Good, Good, Fair - report
33	Soil Corrosivity	level	Soil present may be corrosive or frost susceptible
34	Soil pH	pH	Low pH (<4) means soil is acidic and likely to promote corrosion; high alkaline conditions (pH>8) can also lead to high corrosion
35	Topography	map	Topography is very important for pipe performance
36	Groundwater Table	feet	Groundwater affects soil loading on the pipe and pipe deterioration rate
37	Ground Cover	type	Paved ground or vegetation cover result in different deterioration mode and rate
38	Frost Penetration	Yes/No - depth	Soil ever frozen around the pipe, depth of frost penetration
39	Extreme Events	Yes/No - type	Events may threaten pipe sustainability
40	Soil Moisture Content	percent	Moisture present in the soil may affect loading and pipe deterioration rate
41	Water Corrosivity	level	Water present may be corrosive and may affect pipe material
42	Stray Currents	Yes/No	Stray electrical currents may cause electrolytic corrosion
43	Water Source	type	Source of water (Ground water,surface water, reservoir, etc.)

Financial Parameters			
44	Annual Capital Cost	dollar/year	Annual capital cost of pipe
Other Parameters			
45	Customer Complaints	type	Complaints related to service pressure, continuity, flooding, pollutions, etc.

Water Data Model – Preferable [25]

No.	Parameter	Unit	Brief Explanation
	1	2	3
Physical/Structural Parameters			
1	Pipe Vintage	year	Pipes made at a different time and place may deteriorate differently
2	Pipe Section Length	feet	Length of each pipe sections
3	Pipe Shape	type	Different pipe shapes may result in different failure modes and deteriorations
4	Pipe Manufacture/ Class/Date	record	Defects in pipe walls produced by manufacturing errors can make pipes vulnerable to failure. This problem is most common in older pit cast pipes
5	Pipe Quality	level	Imperfect pipes may deteriorate faster
6	Pipe Installation	rating	Improper installation may cause pipe damage and increase deterioration
7	Dissimilar Materials	Yes/No	Dissimilar materials/metals are more susceptible to galvanic corrosion
8	Degradation of Pipe Material	Yes/No	Different pipe materials deteriorate at different rates
9	Pipe Slope	gradient	Slope affects the velocity of water flow
10	Pipe Trench Width	feet	Trench width may affect soil loading on the pipes and deterioration rate
11	Valve Type	type	Type of valve used
12	Absorption Capacity	percent	Mortar absorption greater than 8% leads to higher corrosion rates
Operational/Functional Parameters			
13	Consumption	gallon/day	Consumption and peak factors and other water volume data
14	Connection Density	no./mile	Connections within an area.
15	Service Connections	type	Some types of service connections may undergo premature failure
16	Main Connections	type	Type of connections-residential, industrial, commercial, agricultural, etc.
17	Interruptions	record	Interruption of wastewater collection services
18	Hydrant Density	no./mile	Number of hydrants per mile
19	Valve Density	no./mile	Number of valves per mile
20	Node Elevation	feet	Node/pipe elevation
21	Node Hydraulic	gallon/min	Hydraulic of pipe
22	Backflow Potential	Yes/No	Cross connections with systems that do not contain potable water can contaminate water distribution system
23	Backlog of Maintenance	Yes/No	Backlog of maintenance, rehab, or replacement in time and money

24	Hydrant Information	record	Information on hydrants
25	Valve Information	record	Information on valves
Environmental Parameters			
26	Compliance	Yes/No	Leakage in pipe may create environmental problems
27	Soil Disturbance	Yes/No	Disturbance of soil near the pipe may cause pipe damage or change soil support or loading
28	Runoff Rate	cu.ft./sec.	Excess water flow which can be caused by rainfall, evaporation, snow melting, etc.
29	Rainfall/Precipitation	inch/year	Rainfall in the areas should be monitored
30	Nonuniform Soil	Yes/No	Non-uniform soil support in longitudinal axis may increase shear and bending stresses
31	Unstable Slope	Yes/No	Pipes in unstable slope may be subjected to downslope creep displacement
32	Tidal Influences	Yes/No	Coastal areas with tidal influences may affect pipe bedding
33	Catchment area (Watershed)	sq.ft.	Information of watershed
34	Seismic Activity	Yes/No	Seismic loading may lead to pipe rupture and pressure surge
35	Average Closeness to trees	feet	Average distance between pipe and trees
36	Presence of Scale/Tuberculation	Yes/No	The formation of scale and tuberculation can reduce the water flow through the pipe
37	Wet/Dry Cycle(s)	Yes/No	Changing environments promotes corrosion of wires if chloride concentration exceeds 140 mg/kg (140 ppm)
38	Soil Chloride	pH	Mortar coating usually creates a pH environment of >12.4. Low chloride levels in high pH(>11.5) environments can lead to serious corrosion
39	Soil Sulfate	percent	Accounts for microbial induced corrosion (MIC) and possible food source for sulfate reducing bacteria in anaerobic conditions under loose coatings
40	Soil Sulfide	percent	Sulfate reducing bacteria giving off sulfides which are excellent electrolytes
41	Water Quality Violations	Yes/No-type	Water quality violations or waterborne disease outbreaks
42	Failing Utilities	Yes/No	Failing water utilities in close proximity of water pipes may create a problem
Financial Parameters			
43	Annual Maintenance Cost	dollar/year	Cost of maintenance
44	Annual Rehabilitation Cost	dollar/year	Cost of repair/rehabilitation/renewal/replacement - methods
45	Annual Operational Cost	dollar/year	Cost of pipe operation
46	Annual Energy Cost	dollar/year	Cost of energy
47	Installed & Replacement Cost	dollar	Original cost of installation and replacement cost

48	Depreciated Value	percent	Depreciated value and method of calculation
49	Benefit/Cost	record	Benefit-Cost analysis
50	Consequence/Risk of Failure	level and dollar	Consequence of Failure: To system, surroundings, and customers
Other Parameters			
51	Third Party Damage	Yes/No	Damages due to third parties
52	Other Information	-	Information that is related to pipe deterioration

APPENDIX D

SEWER DATA MODEL ATTRIBUTES

ESSENTIAL AND PREFERABLE

Sewer Data Model – Essential [24]

No	Parameter	Unit	Brief 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 Age	Year	*Older pipes may deteriorate faster than newer pipe*
5	Pipe Depth	Feet	*Pipe Depth affects pipe loading and deteriorating rate*
6	Node Length	Feet	*Length of pipe between nodes (MH-MH)*
7	Pipe Wall Thickness	Inch	*Wall thickness affects rupture resistance and corrosion penetration rates*
8	Pipe Location	Area	*Some locations may receive roadway salt intrusion; urban, sub-urban, rural, costal, etc.*
9	Pipe Shape	Type	*Different pipe shapes may result in different failure modes and deterioration*
10	Pipe Joint Type	Type	*Some types of joints may undergo premature failure*
11	Function of pipe	Type	*Different use of sewer may deteriorate at different rates; Combined, Sewer, Forced*
12	Pipe Bedding	Yes/No-Type	*Inadequate bedding may cause premature pipe failure, special bedding use*
13	Trench Backfill	Type	*Some backfill materials are more corrosive or frost susceptible*
14	Construction Specification	Spec.	*Construction specifications; Installation Circumstances*
15	Pipe Slope	Gradient	*Slope affects the velocity of gravity flow and may result in different pipe deterioration rates*
16	Design life of pipe	Year	*The pipe design life in year*
17	Design strength of pipe	psi	*the pipe design strength (ring, longitudinal)*
18	Pipe Lining	Yes/No-Type	*Lined pipes have higher resistance to corrosion*
19	Manhole Condition	Record	*Manhole condition and relevant data*
Operational/Functional			
20	Wastewater Quality	Record	*records of wastewater quality tested including PH, BOD, COD, and temperature*
21	Wastewater Pressure	psi	*Internal water pressure affects pipe stresses and deterioration rate*
22	Pipe Hydraulics	Gallon/Min	*Capacity of the sewage gravity conveying pipe*
23	Pipe Surcharging	Yes/No - Ft.	*Surcharging in gravity sewers in dry & wet weather should be considered, head level in feet*
24	Operational &	Type- Level	*Poor practices can compromise structural integrity and water quality;*

	Maintenance Practices		*very good, good, fair*
25	Pipe Renewal Record	Record	*All records of pipes renewal- type of renewal method*
26	Pipe Failure Record	Record	*Record of Failure that occur, Failure mode should be specified*
27	Infiltration/Inflow	Level-Gal/Min	*infiltration/inflow may cause soil erosion, and increasing flow volume; Low,Med,High - also gal./min.*
28	Exfiltration	Level	*Exfiltration may cause erosion of soil and change soil loading on pipe; Low,Med,High*
29	Blockage/stoppage	Yes/No-Type	*Blockage make the pipeline network inoperative, sewer pipe is no longer functional*
30	Sediments	Ton/Feet	*Sediments per unit length*
31	Inspection record	Yes/No-Record	*Record of inspection, method use, date of inspection*
32	Flow Velocity	Feet/Second	*Low velocity accumulate deposits; excessive velocity accelerate deterioration at invert*
No	**Parameter**	**Unit**	**Brief Explanation**
Environmental			
33	Soil Type	Type	*Corrosive, expansive, & compressible; hydrocarbons & solvents cause deterioration*
34	Soil Corrosivity	Level	*Condition of the soil related to pipe deteriorate; low, medium, high*
35	Soil Resistivity	Level	*Soils with low electrical resistivity are more likely to have high corrosion rates*
36	Redox Potential	Level, mV	*Low Redox potentials are more favorable for sulphate reducing bacteria leading to corrosion*
37	Soil Moisture Content	Percent	*Moisture percentage in the soil may affect loading and pipe deterioration*
38	Stray Currents	Yes/No	*Stray currents may cause electrolytic corrosion of metal pipes*
39	Groundwater Table	Feet	*affecting soil loading on the pipes and pipe deterioration rate; above, below sewer, fluctuating*
40	Ground Cover	Type	*Paved ground or vegetation cover result in different deterioration mode and rate*
41	Loading Condition (Dead Load)	Lbs/sq.ft.	*Death load can be determined from infrastructure loading*
42	Loading Condition (Live Load)	ADT-Level	*Live load can be determined from average daily traffic volume and railway loading etc.*
43	Rainfall/Precipitation	Inch/year	*Rainfall in the areas should be monitored*
44	Climate - Temperature	°F	*Frost action in cold regions and seasonal soil water content variation in warmer regions*
45	Topography	Map	*Topography is very important for the performance of pipes; contour maps*
46	Extreme Events	Yes/No -	*Information related to extreme events*

		Type	
Financial			
47	Annual Capital Cost	$/Year	*Utility annual capital Cost and allocation criteria*
Others			
48	Customer Complaint	Type	*Complaints related to blockage, flooding, pollutions, etc.*
49	Chemistry	Event	*Hydrogen sulphide may corrode pipe, etc.*
50	FOG	Yes/No	*Fats, Oils, and Grease entering the sewer system*
51	Overall Pipe Condition	Rating	*Condition of the pipe may be ranked from inspection tests; CCTV, smoke test, etc. (1-5)*

Sewer Data Model – Preferable [24]

No	Parameter	Unit	Brief Explanation
Physical/Structural			
1	Pipe Quality	Level	*Imperfect pipes may deteriorate faster; poor, fair, good*
2	Pipe Section Length	Feet	*Length of pipe section (Joint - joint)*
3	Pipe Vintage	Year	*Pipes made at different time and place may deteriorate differently*
4	Pipe Lateral	Type	*Some types and materials of laterals may undergo premature failure*
5	Dissimilar Materials	Yes/No	*Dissimilar metals/materials are more susceptible to galvanic corrosion*
6	Pipe Installation	Rating	*Improper Installation may cause pipe damage and increase deterioration rate*
7	Pipe Manufacture	Record	*Defects in pipe walls produced by manufacturing errors can make pipes vulnerable to failure*
8	Pipe Trench Width	Feet	*Trench width may affects soil loading on the pipes and deterioration rate*
9	Pipe external Coating	Yes/No - type	*external coating prevents corrosion of the pipe*
10	Pipe Cathodic Protection	Yes/No - type	*Technique used to control the corrosion of a metal surface*
11	Pipe Thrust Restraint	Yes/No - Type	*Inadequate restraint may increase longitudinal pipe stresses*
12	Lateral Connections	Record	*Condition of lateral connections and other related information such as type of connection*
13	Pumping Station and WWTP	Record	*Location of the pumping stations and wastewater treatment plants*
Operational/Functional			
14	Sewer Odors	Yes/No	*Solids build-ups, poor system hydraulics, flat grade, etc.*

15	Sewer Flooding	Yes/No	*Flooding may change property of surrounding soil and loading on pipe*
16	Sewer Overflow (SSO/CSO)	Yes/No	*Overflow may inundate surrounding soil and change loading on pipe*
17	Backup floodings	Number	*Number of properties affected by flooding in Dry & Wet weather*
18	Leakage allowance	%	*Percentage of Leakage allowance*
19	Interruptions	Record	*Interruption of wastewater collection services*
Environmental			
20	Soil Disturbance	Yes/No	*Disturbance of soil may cause damage or change soil support or loading to the pipe*
21	Runoff Rate	Cu. Ft/Sec.	*Excess water flow which can be caused by rainfall, evaporation, snow melting, etc.*
22	Non-Uniform Soil	Yes/No	*Non-uniform soil support in longitudinal axis may increase shear and bending stresses*
23	Frost Penetration	Yes/No-depth	*Soil ever frozen around the pipe, depth of penetration in feet.*
24	non-Uniform slope	Yes/No	*non-uniform slope may reduce the operating performance*
25	Unstable Slope	Yes/No	*Pipes in unstable slope may be subjected to down slope creep displacement*
26	Seismic Activity	Yes/No	*Seismic loading may lead to pipe rupture and pressure surge*
27	Catchment Area (Sewershed)	Sq.Ft	*Extent of area receiving the wastewater feeding a part or the totality of sewer*
28	Average Closeness to Trees	Feet	*Average distance between sewer and trees*
29	Tidal Influences	Yes/No	*Sewer in Coaster area may be subjected to tidal influence affecting bedding of the pipe*
30	Soil pH	pH	*Low pH (<4) means soil is acidic and likely to promote corrosion; high alkaline conditions (pH>8) can also lead to high corrosion*
31	Soil Chloride	%	*Mortar coating usually creates a pH environment of >12.4. Low chloride levels in high pH(>11.5) environments can lead to serious corrosion*
No	**Parameter**	**Unit**	**Brief Explanation**
32	Soil Sulfate	%	*Accounts for microbial induced corrosion (MIC) and possible food source for sulfate reducing bacteria in anaerobic conditions under loose coatings*
33	Soil Sulfide	%	*Sulfate reducing bacteria giving off sulfides which are excellent electrolytes*
34	Pipe Connections	Type	*Type of connections - Residential, Industrial, Commercial, Agricultural, others*
Financial			
35	Annual Maintenance	$/Year	*Routine Cleaning, etc.; Method and Cost of Maintenance*

	Cost		
36	Annual Repair/Rehabilitation Cost	$/Year	*Method and Cost of Preservation and Improvement like grouting, lining, etc.*
37	Installed and Replacement Cost	$	*Original cost of installation and replacement cost*
38	Annual Operational Cost	$/Year	*cost spent each year for operating and functioning sewer system*
39	Annual Energy Cost	$/Year	*Cost of energy use in sewer system i.e. Forced Main, Pumping station etc.*
40	Depreciated Value	%	*Depreciated value and method of calculation*
41	Benefit/Cost	Record	*Benefit-Cost Analysis*
Others			
42	Density of Connections	Number/ Mile	*Number of properties connected to the sewer per mile*
43	Resident Population Served	Number	*Total population living in the area that is responsibility of the system*
44	Failing Utilities	Yes/No	*Failing wastewater or water pipes in a close proximity of the system*
45	Consequence/Risk	Level	*Consequence of failures: low, medium, high*
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 E

CASE STUDIES OF UTILITIES

To assist in research development and obtain crucial feedback, various utilities were met with via personal visits and net meetings. The purpose of the visits was to meet and discuss with city officials on their cities' progress toward the effective asset management of wastewater pipes. All were very helpful and excited to contribute to the wastewater infrastructure research due to the infrastructure crisis. It was found that all of the cities had the same idea of compiling the data through GIS; however, many of the parameters are not within one system and must be derived indirectly. In past years this pipe infrastructure data has been kept in other forms besides an electronic database. Many utilities are in the process of transferring their data from paper formats and other sources into their GIS electronic database. The five case studies discussed below give an overview of each city wastewater system as well as the utilities' data collection and GIS systems.

Case Study 1: Atlanta, Georgia

There are approximately 40,000 manholes and 1,900 miles of sewer main and laterals with in right-of-way and easements of the City of Atlanta wastewater collection and transmission systems. The combined sewers are estimated to be 85 percent of the system and the rest are separate sanitary sewers. Cities of Hapeville, College Park and East Point, DeKalb, Clayton and Fulton counties are six other entities that have a wastewater treatment contract with the city. The city of Atlanta generates 55 percent of sewage flows and the wholesale agencies have 45 percent. The total population that benefit from the system is 1.6 million [12]. In 1999, Atlanta entered into the First Amended Consent Decree (FACD) with the EPA. The FACD requires Atlanta to implement many of the programs associated with EPA's widely discussed wastewater collection system management initiative for capacity, management, operation and maintenance known as CMOM.

The Atlanta Public Utilities Board (APUB) has given shapefiles, geodatabase tables and work management tables stored in Hansen on a DVD that was mailed to the research group at Virginia Tech. Altogether there were 14 shapefiles, 29 geodatabase tables and around 1200 Hansen file tables. The shapefiles consists mainly of the main pipelines, laterals, sewer facilities consisting of manholes, rehab work related files along with transportation, soils, catch basins and city limits. A brief description of the main files given by APUB is given below.

- **Sewer Main**

The sewer main shapefile consists of all sewer mains in Atlanta city limits which are spatially mapped in the projected coordinate system NAD_1983_StatePlane_Georgia_West. The sewer main attribute table consists of various pipe parameters such as Pipe ID, pipe mailing address (as in the street name, street number), pipe shape, diameter, material, length, and elevation of the upstream and downstream nodes. Also, the slope of the pipe was calculated and added as an attribute. The surface cover and geographical location of each pipe is given along with the sewershed and basin references. Although a few columns were left blank, a considerable amount of information was collected for around 40,000 pipes.

- **Sewer Facility**

Sewer Facility consists of manholes in the Atlanta city limits which are spatially mapped in the projected coordinate system NAD_1983_StatePlane_Georgia_West. The shape file consists of various manhole parameters such as facility ID, facility mailing address (as in the street name, street number), topographical location, depth of the manhole, diameter and the geographical coordinates. Some inner details like cover type, cover diameter, and wall type are also given along with sewershed and basin references. Although a few columns were left blank, a considerable amount of information was collected for around 37,000 manholes.

- **SSES Tables**

The Sewer System Evaluation Survey (SSES) tables are geodatabase tables which can be used to store general information that does not need to be spatially mapped. The SSES tables given by APUB have all the codes used by utility officials. In general, location type, manhole type, street type codes are specified. Adding to these, pipe condition data, defects, type of leaks, inspection and inventory data are also stored. However, all these tables contain several null valued columns which might require some metadata to explain the purpose of the attributes.

- **Hansen Tables**

The Hansen tables given by APUB were numerous in number, around 1200, most of which are empty. Hansen is a work order management system used by the Atlanta utility officials. These tables mainly consist of the work orders issued by the officials. Some tables also consist of codes and other information which cannot be understood by the research team at Virginia Tech. In this regard, the APUB was contacted for further detailed information.

Table 8 below presents the existing data parameters

Table 8: Existing data received from city of Atlanta (COA)

Parameter			
Physical/Structural		**Operational/Functional**	
1	*Node Identification Number	11	*Pipe Renewal Record
2	*Pipe Material	12	*Pipe Failure Record
3	*Pipe Diameter	13	*Infiltration/Inflow
4	*Pipe Age	14	*Exfiltration
5	*Pipe Location	15	*Blockage/Stoppage
6	*Pipe Shape	16	*Sediments
7	*Function of the Pipe	17	*Inspection Record
8	Pipe Lateral		
9	Lateral Connections		
10	Pumping Station and WWTP		

Note: * Essential Parameter for Gold Standard

Table 9 below presents the derivable or downloadable attributes.

Table 9: Derived or Downloadable data from COA

Parameter			
Physical/Structural		**Environmental** (Cont.)	
1	*Pipe Depth	18	*Extreme Events
2	*Node Length	19	*Soil Corrosivity
3	*Pipe Slope	20	*Soil Moisture Content
4	*Design Life	21	*Soil Type
5	*Design Strength	22	Runoff Rate
6	Pipe Quality	23	Soil pH
7	Pipe Vintage	24	Non-Uniform Soil
8	Dissimilar Materials	25	Non-Uniform Slope
9	Pipe Installation	26	Unstable Slope
Environmental		27	Seismic Activity
10	*Stray Currents	28	Catchment Area(sewershed)
11	*Groundwater Table	29	Average Closeness to Trees
12	*Ground Cover	30	Tidal Influences
13	*Loading Condition (dead load)	31	Pipe Connections
14	*Loading Condition (live load)	**Others**	
15	*Rainfall/Precipitation	32	Density of Connections
16	*Climate - Temperature	33	*Overall Pipe Condition
17	*Topography		

Note: * Essential Parameter for Gold Standard

Table 10 below presents the non-existent attributes.

Table 10: Missing gold standard data for COA

Parameter			
Physical/Structural		**Environmental**	
1	*Pipe Wall Thickness	26	*Soil Resistivity
2	*Pipe Joint Type	27	*Redox Potential
3	*Pipe Bedding	28	Soil Disturbance
4	*Trench Backfill	29	Frost Penetration
5	*Construction Specification	30	Soil Chloride
6	*Pipe Lining	31	Soil Sulfate
7	*Manhole Condition	32	Soil Sulfide
8	Pipe Section Length	**Financial**	
9	Pipe Manufacture	33	*Annual Capital Cost
10	Pipe Trench Width	34	Annual Maintenance Cost
11	Pipe External Coating	35	Annual Repair/Rehabilitation Cost
12	Pipe Cathodic Protection	36	Installed and Replacement Cost
13	Pipe Thrust Restraint	37	Annual Operational Cost
Operational/Functional		38	Annual Energy Cost
14	*Wastewater Quality	39	Depreciated Value
15	*Wastewater Pressure (Force	40	Benefit/Cost
16	*Pipe Hydraulics	**Others**	
17	*Pipe Surcharging	41	*Customer Complaint
18	*Operational & Maintenance	42	*Chemical
19	*Flow Velocity	43	*FOG
20	Sewer Odors	44	Resident Population Served
21	Sewer Flooding	45	Failing Utilities
22	Sewer Overflow (SSO/CSO)	46	Consequence/Risk
23	Backup Flooding	47	Third Party Damage
24	Leakage Allowance		
25	Interruptions		

Note: * Essential Parameter for Gold Standard

Case Study 2: Pittsburgh, Pennsylvania

The Pittsburgh Water and Sewer Authority (PWSA) was founded in 1984. In 1995, the City of Pittsburgh's Water Department became a part of PWSA and became responsible for operating and maintaining the entire City of Pittsburgh sewer system in 1999. The PWSA serves approximately 250,000 consumers throughout the City of Pittsburgh [21].

Recently PWSA has proposed the Combined Sewer Overflow (CSO) program which aims to identify cost-effective CSO control alternatives that, when fully implemented, protect water quality [20]. The development of this program required monitoring and sampling plans that proposed data collection and characterization activities to be a CSO Long Term Control Plan (CSO LTCP). The CSO LTCP is the characterization of the combined sewer system operation and the assessment of CSO impacts on river and stream water quality during wet weather events. This Monitoring and Sampling Plan presents the proposed data collection and characterization activities to be undertaken.

The PWSA and their consultant have given shapefiles on a DVD, which was mailed to Virginia Tech. Altogether there were 8 shapefiles. These consist mainly of the main pipelines, manholes, junctions and diameter changes. A brief description of the main files given by PWSA is described below. One unique characteristic of these shapefiles is that the same attributes are listed for all though they are unrelated-such attributes are given a null value.

- **Mainline**

The sewer main shapefile consists of all the sewer mains in the Pittsburgh city limits which are spatially mapped in an undefined projected coordinate system. The sewer main attribute table consists of various pipe parameters such as pipe ID, pipe shape, diameter, material, length, installation year, and elevation of the upstream and downstream nodes. Although a few columns were left blank, a considerable amount of information was collected for around 44,000 pipes.

- **Manhole**

This consists of all the manholes in the Pittsburgh city limits which are spatially mapped in an undefined projected coordinate system. The shapefile consists of various manhole parameters such as facility ID, depth of the manhole, diameter and the geographical coordinates. Although a few columns were left blank, a considerable amount of information was collected for approximately 30,000 manholes.

- **Diameter change**

This is a unique collection of data from other utilities. All the diameter change points are noted and spatially mapped in an undefined coordinate system. The junction points are given a node ID and the types of reducers used are listed. Table 11 below presents the existing data parameters.

Table 11: Data received from PWSA

Parameter			
Physical/Structural			
1	*Node Identification	6	*Pipe Shape
2	*Pipe Material	7	*Function of the Pipe
3	*Pipe Diameter	8	Pipe Lateral
4	*Pipe Age	9	Lateral Connections
5	*Pipe Location	10	Pumping Station and WWTP

Note: * Essential Parameter for Gold Standard

Table 12 below presents the derivable or downloadable attributes.

Table 12: Derived or Downloadable data for PWSA

Parameter			
Physical/Structural		**Environmental** (Cont.)	
1	*Pipe Depth	17	*Topography
2	*Node Length	18	*Extreme Events
3	*Pipe Slope	19	*Soil Corrosivity
4	*Design Life	20	*Soil Moisture Content
5	*Design Strength	21	*Soil Type
6	Pipe Quality	22	Runoff Rate
7	Pipe Vintage	23	Soil pH
8	Dissimilar Materials	24	Non-Uniform Soil
9	Pipe Installation	25	Non-Uniform Slope
Environmental		26	Unstable Slope
10	*Stray Currents	27	Seismic Activity
11	*Groundwater Table	28	Catchment Area(sewershed)
12	*Ground Cover	29	Average Closeness to Trees
13	*Loading Condition (dead load)	30	Tidal Influences
14	*Loading Condition (live load)	31	Pipe Connections
15	*Rainfall/Precipitation	**Others**	
16	*Climate - Temperature	32	Density of Connections

Note: * Essential Parameter for Gold Standard

Table 13 below presents the non-existent attributes.

Table 13: Missing gold standard data for PWSA

Parameter			
Physical/Structural		**Environmental**	
1	*Pipe Wall Thickness	33	*Soil Resistivity
2	*Pipe Joint Type	34	*Redox Potential
3	*Pipe Bedding	35	Soil Disturbance
4	*Trench Backfill	36	Frost Penetration
5	*Construction Specification	37	Soil Chloride
6	*Pipe Lining	38	Soil Sulfate
7	*Manhole Condition	39	Soil Sulfide
8	Pipe Section Length	**Financial**	
9	Pipe Manufacture	40	*Annual Capital Cost
10	Pipe Trench Width	41	Annual Maintenance Cost
11	Pipe External Coating	42	Annual Repair/Rehabilitation Cost
12	Pipe Cathodic Protection	43	Installed and Replacement Cost
13	Pipe Thrust Restraint	44	Annual Operational Cost
Operational/Functional		45	Annual Energy Cost
14	*Wastewater Quality	46	Depreciated Value
15	*Wastewater Pressure (Force	47	Benefit/Cost
16	*Pipe Hydraulics	**Others**	
17	*Pipe Surcharging	48	*Customer Complaint
18	*Operational & Maintenance	49	*Chemical
19	*Flow Velocity	50	*FOG
20	*Pipe Renewal Record	51	*Overall Pipe Condition
21	*Pipe Failure Record	52	Resident Population Served
22	*Infiltration/Inflow	53	Failing Utilities
23	*Exfiltration	54	Consequence/Risk
24	*Blockage/stoppage	55	Third Party Damage
25	*Sediments		
26	*Inspection Record		
27	Sewer Odors		
28	Sewer Flooding		
29	Sewer Overflow (SSO/CSO)		
30	Backup Flooding		
31	Leakage Allowance		
32	Interruptions		

Note: * Essential Parameter for Gold Standard

Case Study 3: Seattle, Washington

Seattle Public Utilities (SPU) owns and operates the wastewater collection system for the city of Seattle, which is comprised of 1,491 miles of combined sewer and sanitary pipelines. The wastewater from the city is treated at King County sewage treatment plants. The city's wastewater system services 570,000 people [23]. SPU's management system includes a 20 year comprehensive plan providing long-term direction setting, a three-year strategic plan setting the objectives and targets in line with the comprehensive plan, and specific management systems supporting the objectives and targets of the strategic plan [23]. The system plan, which was set in 2006, has focused on describing all of SPU's existing wastewater policies and identifies areas where additional policies need to be developed. This plan also focuses on minimizing sewer backups, street flooding in combined sewer areas, control of combined sewer overflows, and emergency response. Finally it presents strategies and an implementation plan to meet the established customer service levels and establishes a financial program to fund the programs and activities in the plan.

SPU has given shapefiles, geo-guide, CCTV Excel files on a DVD which was mailed to Virginia Tech. Altogether there were 14 shapefiles along with a geo-guide which actually is like a metadata file describing all the attributes in the shapefiles . These consist mainly of the main pipelines, laterals, manholes, catch basins and drainage basins along with transportation and terrain. A brief description of the main files given by SPU is given below.

- **Mainlines**

This shapefile consists of all the sewer mains in Seattle city limits which are spatially mapped in the projected coordinate system NAD_1983_StatePlane_Washington_South. The sewer main attribute table consists of various pipe parameters such as Pipe ID, pipe shape, diameter, installation year, material, length, and elevation of the upstream and downstream nodes. Although a few columns were left blank, a considerable amount of information was collected for around 55,000 pipes.

- **Manholes**

This shapefile consists of manholes in Seattle city limits which are spatially mapped in the projected coordinate system NAD_1983_StatePlane_Washington_South. The shapefile consists of various manhole parameters such as facility ID, topographical location, depth of the manhole, diameter, and the geographical coordinates. Some inner details like case type, probable flow are also given. Although a few columns were left blank, a considerable amount of information was collected for around 55,000 manholes.

- **Drainage Basins**

This shapefile is a collection of parameters of the drainage basins in Seattle city limits like area, perimeter and outfall numbers. Nearest water bodies are also listed along with the catalog IDs of the basins. Altogether there are 159 drainage basins.

Table 14 below presents the existing data parameters

Table 14: Existing data received from SPU

Parameter			
Physical/Structural		**Operational/Functional**	
1	*Node Identification	11	*Pipe Failure Record
2	*Pipe Material	12	*Infiltration/Inflow
3	*Pipe Diameter	13	*Exfiltration
4	*Pipe Age	14	*Blockage/stoppage
5	*Pipe Location	15	*Sediments
6	*Pipe Shape	16	*Inspection Record
7	*Function of the Pipe		
8	Pipe Lateral		
9	Lateral Connections		
10	Pumping Station and		

Note: * Essential Parameter for Gold Standard

Table 15 below presents the derivable or downloadable attributes.

Table 15: Derived or downloadable data for SPU

Parameter			
Physical/Structural		**Environmental** (Cont.)	
1	*Pipe Depth	18	*Extreme Events
2	*Node Length	19	*Soil Corrosivity
3	*Pipe Slope	20	*Soil Moisture Content
4	*Design Life	21	*Soil Type
5	*Design Strength	22	Runoff Rate
6	Pipe Quality	23	Soil pH
7	Pipe Vintage	24	Non-Uniform Soil
8	Dissimilar Materials	25	Non-Uniform Slope
9	Pipe Installation	26	Unstable Slope
Environmental		27	Seismic Activity
10	*Stray Currents	28	Catchment Area (Sewer-shed)
11	*Groundwater Table	29	Average Closeness to Trees
12	*Ground Cover	30	Tidal Influences
13	*Loading Condition (dead load)	31	Pipe Connections
14	*Loading Condition (live load)	**Others**	
15	*Rainfall/Precipitation	32	Density of Connections
16	*Climate - Temperature	33	*Overall Pipe Condition
17	*Topography		

Note: * Essential Parameter for Gold Standard

Table 16 below presents the non-existent attributes.

Table 16: Missing gold standard data for SPU

Parameter			
Physical/Structural		**Environmental**	
1	*Pipe Wall Thickness	27	*Soil Resistivity
2	*Pipe Joint Type	28	*Redox Potential
3	*Pipe Bedding	29	Soil Disturbance
4	*Trench Backfill	30	Frost Penetration
5	*Construction Specification	31	Soil Chloride
6	*Pipe Lining	32	Soil Sulfate
7	*Manhole Condition	33	Soil Sulfide
8	Pipe Section Length	**Financial**	
9	Pipe Manufacture	34	*Annual Capital Cost
10	Pipe Trench Width	35	Annual Maintenance Cost
11	Pipe External Coating	36	Annual Repair/Rehabilitation Cost
12	Pipe Cathodic Protection	37	Installed and Replacement Cost
13	Pipe Thrust Restraint	38	Annual Operational Cost
Operational/Functional		39	Annual Energy Cost
14	*Wastewater Quality	40	Depreciated Value
15	*Wastewater Pressure (Force	41	Benefit/Cost
16	*Pipe Hydraulics	**Others**	
17	*Pipe Surcharging	42	*Customer Complaint
18	*Operational & Maintenance	43	*Chemical
19	*Flow Velocity	44	*FOG
20	*Pipe Renewal Record	45	Resident Population Served
21	Sewer Odors	46	Failing Utilities
22	Sewer Flooding	47	Consequence/Risk
23	Sewer Overflow (SSO/CSO)	48	Third Party Damage
24	Backup Flooding		
25	Leakage Allowance		
26	Interruptions		

Note: * Essential Parameter for Gold Standard

Case Study 4: Orange County, California

The Orange County Sanitation District (OCSD), formed in 1946, has collected, treated, disposed, and reclaimed the wastewater generated by 2.5 million people in central and northwestern Orange County [18]. OCSD includes nine former revenue areas joined into a single service district, forming the third largest wastewater agency in the western United States [23]. The OCSD operates two treatment plants and maintains 580 miles of wastewater pipes and 16 pumping stations, of which 250 million gallons of wastewater flows through daily. One treatment plant is located in Fountain Valley and the other in Huntington Beach.

Ten MGD of treated wastewater is reclaimed via microfiltration and reverse osmosis [18]. The reclaimed water will be used for landscape irrigation and for injection into the groundwater seawater intrusion barrier. Recently, in cooperation with Orange County Water District, the Ground Water Replenishment System was started. Using advanced water treatment facilities, water will be purified through microfiltration, reverse osmosis and ultraviolet disinfection to levels that far exceed drinking water standards [23]. In addition OCSD has undertaken management systems initiatives in two main areas: Optimized Asset Management and the National Biosolids Partnership Environmental Management System. The OCSD has also engaged in strategic planning activities and created the Unifying Strategies [23].

The OCSD has given shapefiles on a DVD which was mailed to Virginia Tech. Altogether there were 13 shapefiles consisting mainly of the main pipelines, manholes, land use, along with soils and city limits. A brief description of the main files given by OCSD is given below. The sewer system in the city also has some forced main pipes along with fittings and valves.

- **Mainlines**

The sewer main shapefile consists of all the sewer mains in Orange county city limits which are spatially mapped in the projected coordinate system NAD_1983_StatePlane_California_VI. The sewer main attribute table consists of various pipe parameters such as Pipe ID, pipe shape, diameter, material, length, and elevation of the upstream and downstream nodes. Also, the slope of the pipe was calculated and added as an attribute. Although a few columns were left blank, a considerable amount of information was collected for around 9000 pipes.

- **Manholes**

This consists of Manholes in Orange county city limits which are spatially mapped in the projected coordinate system NAD_1983_StatePlane_California_VI. The shapefile consists of various manhole parameters such as facility ID, installation date, depth, diameter and the geographical coordinates. The document numbers and project ID's are also noted. Although a few columns were left blank, a considerable amount of information was collected for around 8000 manholes.

Table 17 below presents the existing data parameters

Table 17: Existing data received from OCSD

Parameter			
Physical/Structural			
1	*Node Identification	6	*Pipe Shape
2	*Pipe Material	7	*Function of the Pipe
3	*Pipe Diameter	8	Pipe Lateral
4	*Pipe Age	9	Lateral Connections
5	*Pipe Location	10	Pumping Station and WWTP

Note: * Essential Parameter for Gold Standard

Table 18 below presents the derivable or downloadable attributes.

Table 18: Derived or downloadable data from OCSD

Parameter			
Physical/Structural		**Environmental** (Cont.)	
1	*Pipe Depth	17	*Topography
2	*Node Length	18	*Extreme Events
3	*Pipe Slope	19	*Soil Corrosivity
4	*Design Life	20	*Soil Moisture Content
5	*Design Strength	21	*Soil Type
6	Pipe Quality	22	Runoff Rate
7	Pipe Vintage	23	Soil pH
8	Dissimilar Materials	24	Non-Uniform Soil
9	Pipe Installation	25	Non-Uniform Slope
Environmental		26	Unstable Slope
10	*Stray Currents	27	Seismic Activity
11	*Groundwater Table	28	Catchment Area(sewershed)
12	*Ground Cover	29	Average Closeness to Trees
13	*Loading Condition (dead load)	30	Tidal Influences
14	*Loading Condition (live load)	31	Pipe Connections
15	*Rainfall/Precipitation	**Others**	
16	*Climate - Temperature	32	Density of Connections

Note: * Essential Parameter for Gold Standard

Table 19 below presents the non-existent attributes.

Table 19: Missing gold standard for OCSD

Parameter			
Physical/Structural		**Environmental**	
1	*Pipe Wall Thickness	33	*Soil Resistivity
2	*Pipe Joint Type	34	*Redox Potential
3	*Pipe Bedding	35	Soil Disturbance
4	*Trench Backfill	36	Frost Penetration
5	*Construction Specification	37	Soil Chloride
6	*Pipe Lining	38	Soil Sulfate
7	*Manhole Condition	39	Soil Sulfide
8	Pipe Section Length	**Financial**	
9	Pipe Manufacture	40	*Annual Capital Cost
10	Pipe Trench Width	41	Annual Maintenance Cost
11	Pipe External Coating	42	Annual Repair/Rehabilitation Cost
12	Pipe Cathodic Protection	43	Installed and Replacement Cost
13	Pipe Thrust Restraint	44	Annual Operational Cost
Operational/Functional		45	Annual Energy Cost
14	*Wastewater Quality	46	Depreciated Value
15	*Wastewater Pressure (Force	47	Benefit/Cost
16	*Pipe Hydraulics	**Others**	
17	*Pipe Surcharging	48	*Customer Complaint
18	*Operational & Maintenance	49	*Chemical
19	*Flow Velocity	50	*FOG
20	*Pipe Renewal Record	51	*Overall Pipe Condition
21	*Pipe Failure Record	52	Resident Population Served
22	*Infiltration/Inflow	53	Failing Utilities
23	*Exfiltration	54	Consequence/Risk
24	*Blockage/stoppage	55	Third Party Damage
25	*Sediments		
26	*Inspection Record		
27	Sewer Odors		
28	Sewer Flooding		
29	Sewer Overflow (SSO/CSO)		
30	Backup Flooding		
31	Leakage Allowance		
32	Interruptions		

Note: * Essential Parameter for Gold Standard

Case Study 5: Blacksburg, Virginia

Blacksburg's wastewater system is operated by Blacksburg VPI Sanitation Authority Inc. and the Town of Blacksburg (TOB). Founded in 1962, VPI Sanitation Authority is a non-profit organization resulted from a collaborative effort between the Town of Blacksburg and Virginia Tech. The authority owns and operates one treatment plant at Stroubles Creek, and about 15 miles of sewer main with 14 employees. All sanitary and industrial wastewater treated by the plant comes from three customers which are Town of Blacksburg, Virginia Tech and part of Montgomery County. Proportions of the wastewater collected from each customer are calculated based on their tap water usage. On average, 22 percent, 75 percent, and 3 percent of wastewater traveling to the plant is from Virginia Tech, Town of Blacksburg and Montgomery County, respectively [32].

The Town of Blacksburg (Figure 20) owns and operates 21 pumping stations and about 145 miles of sanitary sewer. The Town's system is divided into 17 basins called sewer sheds. Each of these basins is further divided into sub-sewer sheds.

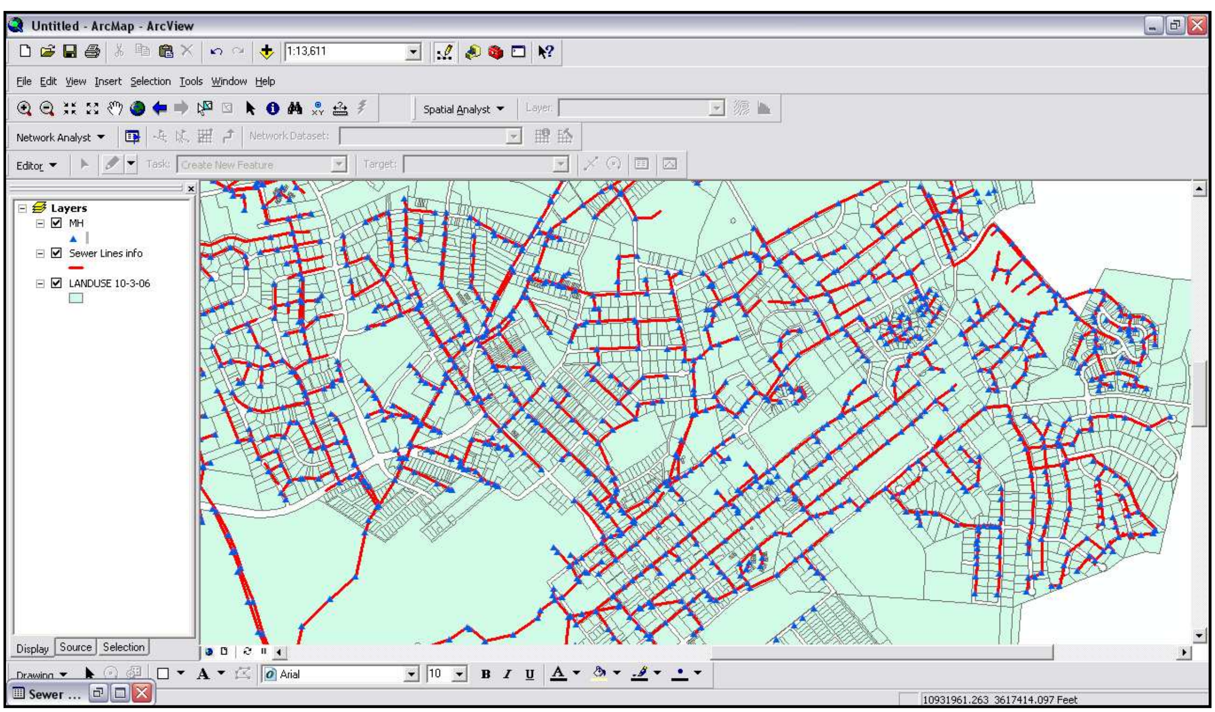


Figure 20: Town of Blacksburg's GIS data

The town of Blacksburg has experienced overflows and surcharges in their wastewater collection system mostly during wet weather events. In order to resolve the problem, the Town of Blacksburg has recently contacted Wiley & Wilson, a wastewater system management company based in Lynchburg, VA to conduct the sanitary sewer study [32]. The objectives of the study are assessing the capacity of the existing wastewater collection system to determine if, when, and where surcharging or overflows occur, and assessing the overall condition of the existing wastewater collection system to determine if any portions of the system need repair, replacement, or rehabilitation.

The Town of Blacksburg Utility has given two shapefiles and a geo-database table. The shapefiles consist of the main pipelines, manholes and a sewer shed geo-database table. A brief description of the main files is given below.

- **Mainlines**

The sewer main shapefile consists of all the sewer mains in Town of Blacksburg limits which are spatially mapped in the projected coordinate system NAD_1983_StatePlane_Virginia_South. The sewer main attribute table consists of various pipe parameters such as Pipe ID, diameter, material, section length, joint type, street address, connected manhole, manhole condition and pipe condition. Also, the length of the pipe was calculated and added as an attribute. Although a few columns were left blank, enough information was collected for around 4700 pipes. A screenshot of Blacksburg's GIS is shown in Figure 20.

- **Manholes**

This consists of manholes in the town of Blacksburg limits which are spatially mapped in the projected coordinate system NAD_1983_StatePlane_Virginia_South. Except for the manhole's condition which presents in mainline shapefiles, there is a small amount of information in the manhole shapefile.

Table 20 below presents the existing data parameters.

Table 20: Existing data received from TOB

Parameter			
Physical/Structural			
1	*Node Identification	6	*Pipe Joint Type
2	*Pipe Material	7	*Manhole Condition
3	*Pipe Diameter	8	*Overall Pipe Condition
4	*Pipe Location	9	Pipe Section Length
5	*Pipe Length		

Note: * Essential Parameter for Gold Standard

Table 21 below presents the derivable or downloadable attributes.

Table 21: Derived or downloadable data for TOB

Parameter			
Physical/Structural		**Environmental (Cont.)**	
1	Dissimilar Materials	13	Unstable Slope
Environmental		14	Seismic Activity
2	*Stray Currents	15	Catchment Area(sewershed)
3	*Groundwater Table	16	Average Closeness to Trees
4	*Ground Cover	17	Tidal Influences
5	*Loading Condition (dead	18	Pipe Connections
6	*Loading Condition (live	19	*Soil Corrosivity
7	*Rainfall/Precipitation	20	*Soil Moisture Content
8	*Climate - Temperature	21	Runoff Rate
9	*Topography	22	Soil pH
10	*Extreme Events	23	*Soil Type
11	Non-Uniform Soil	**Others**	
12	Non-Uniform Slope	24	Density of Connections

Note: * Essential Parameter for Gold Standard

Table 22 below presents the non-existent attributes.

Table 22: Missing gold standard data for TOB

Parameter			
Physical/Structural		**Operational/Functional** (Cont.)	
1	*Pipe Age	36	*Flow Velocity
2	*Pipe Depth	37	Sewer Odors
3	*Pipe Wall Thickness	38	Sewer Flooding
4	*Pipe Shape	39	Sewer Overflow (SSO/CSO)
5	*Function of Pipe	40	Backup Flooding
6	*Pipe Bedding	41	Leakage Allowance
7	*Trench Backfill	42	Interruptions
8	*Construction Specification	**Environmental**	
9	*Pipe Slope	43	*Soil Resistivity
10	*Pipe Design Life	44	*Redox Potential
11	*Pipe Design Strength	45	Soil Disturbance
12	*Pipe Lining	46	Frost Penetration
13	Pipe Quality	47	Soil Chloride
14	Pipe Vintage	48	Soil Sulfate
15	Pipe Lateral	49	Soil Sulfide
16	Pipe Installation	**Financial**	
17	Pipe Manufacture	50	*Annual Capital Cost
18	Pipe Trench Width	51	Annual Maintenance Cost
19	Pipe External Coating	52	Annual Repair/Rehabilitation Cost
20	Pipe Cathodic Protection	53	Installed and Replacement Cost
21	Pipe Thrust Restraint	54	Annual Operational Cost
22	Lateral Connections	55	Annual Energy Cost
23	Pumping Station and WWTP	56	Depreciated Value
Operational/Functional		57	Benefit/Cost
24	*Wastewater Quality	**Others**	
25	*Wastewater Pressure (Force	58	*Customer Complaint
26	*Pipe Hydraulics	59	*Chemical
27	*Pipe Surcharging	60	*FOG
28	*Operational & Maintenance	61	Resident Population Served
29	*Pipe Renewal Record	62	Failing Utilities
30	Pipe Failure Record	63	Consequence/Risk
31	*Infiltration/Inflow	64	Third Party Damage
32	*Exfiltration		
33	*Blockage/Stoppage		
34	*Sediments		
35	*Inspection Record		

Note: * Essential Parameter for Gold Standard

APPENDIX F

RISK RATING MATRIX

Likelihood of Failure								
Factors\Rating	**0.12**	**0.25**	**0.37**	**0.5**	**0.62**	**0.75**	**0.87**	**0.99**
Pipe Condition								
a. Sewer shape change or small cracks		X						
b. Obstruction, debris or silt deposit			X					
c. Root or infiltration or a longitudinal fracture				X				
d. Hole or deformed or fracture						X		
e. Collapsed or broken								X
Manufacturing Defects								
a. Lap Joint Weld (pipe greater than 60")	X							
b. Class III 8 ga pre 1991	X							
c. 36" and greater in dia lined cylinder pipe		X						
d. poured concrete coating			X					
e. class IV wire 5/16 dia				X				
f. class IV 1/4 dia								
g. class IV 6 ga (post 1977)					X			
h. class IV 6 ga (pre 1977)						X		
i. class IV wire 8 ga (post 1977)						X		
j. class IV wire 8ga (pre 1977)							X	
k. Grade E cylinder								X

Consequence Impacts								
Factors\Rating	**0.12**	**0.25**	**0.37**	**0.5**	**0.62**	**0.75**	**0.87**	**0.99**
Environmental impact								
a. Not applicable	X							
b. Impacts on Conservation/Protection zones		X						
Factors\Rating	**0.12**	**0.25**	**0.37**	**0.5**	**0.62**	**0.75**	**0.87**	**0.99**
c. Quality impacts on surface waters and/or surroundings						X		
d. Legal issues (agency fines/ non compliance issues)								X
e. Others				X				
Traffic flow impact								
a. Alternative route Available		X						
b. Limited Alternative Route					X			
c. No Alternative Available								X
Service Disruption Impact								
a. Limited damage caused by pipe rupture	X							
b. home water damage greater than 75ft from pipe or down stream	X							
c. structural damage limited use road		X						
d. major road likely flooding			X					

e. home within 75ft of pipe - potential structural damage				X				
f. commercial facility likely water damage					X			
g. commercial facility within 75ft of pipe						X		
h. major road - structural damage							X	
i. bridge structural damage								X
Financial Impact								
a. Low ($)		X						
b. Moderate ($$)					X			
c. High/Very High ($$$)								X
Public health impact								
a. Water contamination						X		
b. Noncompliance								X
c. Others					X			
Function of Pipe								
a. Water main						X		
b. Transmission Line								X
Factors\Rating	**0.12**	**0.25**	**0.37**	**0.5**	**0.62**	**0.75**	**0.87**	**0.99**
c. Service Line				X				
d. Others					X			

Operational								
a. Local effect only	X							
b. water restriction during peak demand		X						
c. water restriction in non peak demand								X
Diameter								
a. 42" or less	X							
b. 42" to 54"		X						
c. 60" to 66"				X				
d. 72" to 78"						X		
e. 78" and greater								X
Access to pipe								
a. Access available		X						
b. Limited access available					X			
c. Restricted access: under railway, bridge, building, river, etc.								X
Traffic volume								
a. Low (≤ 1,500 ADT per lane)		X						
b. Moderate (> 1,500 and ≤ 6,000 ADT per lane)					X			
c. High (> 6,000 ADT per lane)								X

APPENDIX G

GOOGLE EARTH SIMULATION CODE

KML File

```
<?xml version="1.0" encoding="UTF-8"?>
<kml xmlns="http://earth.google.com/kml/2.2">
<Document>
  <name><![CDATA[Sewer_pipes]]></name>
  <open>1</open>
  <Snippet maxLines="2"></Snippet>
  <description><![CDATA[Exported from Sewer_pipes on
8/3/2009]]></description>
  <Style id="0.19">
    <LineStyle>
      <color>FF00A838</color>
      <width>3</width>
    </LineStyle>
    <BalloonStyle>
      <text>
.
.
.
  <Folder>
    <name>Features (risk_rating)</name>
    <open>0</open>
     <Folder>
       <name><![CDATA[0.110769 - 0.190000]]></name>
       <Placemark>
     <TimeSpan>
          <begin>2009</begin>
          <end>2035</end>
     </TimeSpan>
         <name><![CDATA[0.1107688]]></name>
```

```
         <Snippet maxLines="2"></Snippet>
         <styleUrl>#0.19</styleUrl>
           <LineString>
             <extrude>0</extrude>
             <tessellate>1</tessellate>
             <altitudeMode>clampedToGround</altitudeMode>
             <coordinates>
               -84.3395530409999,33.80255149,0
               -84.340327553,33.8023617790001,0
             </coordinates>
           </LineString>
       </Placemark>
.
.
.
  <Placemark>
     <TimeSpan>
          <begin>2085</begin>
          <end>2099</end>
     </TimeSpan>
         <name><![CDATA[3956.547]]></name>
         <Snippet maxLines="2"></Snippet>
         <styleUrl>#4250.31884765625</styleUrl>
           <LineString>
             <extrude>0</extrude>
             <tessellate>1</tessellate>
             <altitudeMode>clampedToGround</altitudeMode>
             <coordinates>
               -84.389392842,33.8181523440001,0
               -84.3933243219999,33.819020407,0
             </coordinates>
```

```
            </LineString>
        </Placemark>
      </Folder>
   </Folder>
</Document>
</kml>
```

Perl Code

```
#!/usr/bin/perl
my $data_file = "risk_trial_2085.kml";
open DATA, "$data_file";
open DATA1, ">risk_output_2085.kml";
my @array_of_data = <DATA>;
my $i=0;
my $j=0;
foreach(@array_of_data)
{
if (grep(/<Placemark>/,$array_of_data[$j]) eq 1) {
#    print "\npattern here!: ($i)";

#    if(grep(/<\/styleUrl>/,$array_of_data[$j]) eq 1)
# {
      print DATA1 $array_of_data[$j];
      print DATA1
"\t<TimeSpan>\n\t\t<begin>2085</begin>\n\t\t<end>2099</end>\n\t<
/TimeSpan>\n";
#    }
    $i=$i+1;
```

```
}
else
{
 print DATA1 $array_of_data[$j];
}
$j = $j+1;
}
close DATA;
close DATA1;
```

APPENDIX H
WSSC RISK MODEL CASE STUDY

WSSC Operates and Maintains:

- 4 – reservoirs – Triadelphia, Rocky Gorge, Little Seneca and Jennings Randolph with total holding capacity of 14 billion gallons (Note: both Little Seneca and Jennings Randolph are regionally shared)
- 2 – water filtration plants – the Patuxent (max 56 MGD) and the Potomac (max 285 MGD) plants produce an average of 167 million gallons per day (MGD) of safe drinking water
- 6 – wastewater treatment plant – Western Branch, Piscataway, Parkway, Seneca, Damascus and Hyattstown, with a total capacity to handle 74.1 million gallons of wastewater per day
- The Blue Plains Water Pollution Control Plant handles as much as an additional 169 MGD under a cost sharing agreement with the WSSC
- Nearly 5,500 miles of water main lines and over 5,300 miles of sewer main lines

Pre-stressed Concrete Cylinder Pipe (PCCP)

- WSSC has approximately 400 miles of PCCP pipelines in water and sewer use.
- 150 miles of PCCP 36-96 inch diameter in water service.
- The ages of PCCP water mains range from 30 to 60 years with an average age of 45 years.
- Approx. 40 miles of WSSC PCCP were made with Class IV wire.
- WSSC has replaced critical 72-in and 84-in PCCP that had Class IV wire with Steel pipes and smaller diameter DIP.
- Currently WSSC has 6 miles per year PCCP water pipeline condition assessment program using internal inspection and testing. 6 miles of Fiber Optic cable are also installed inside the pipeline for continuous monitoring.
- PCCP inspection and testing methods include visual/sounding, seismic pulse echo, and P-wave electromagnetic.

- PCCP repair methods include replacement, internal strengthening with carbon fiber wrap, and external strengthening with post tension tendons.

The predictability index and preventability index have been modified after visit to WSSC and getting all relevant PCCP failure information. The predictability index has been modified considering the various WSSC PCCP failures.

The major changes are listed below for better understanding:

1. The list needs to be sub-divided into various levels. This is considering the fact that none of the utilities can collect all the 80 data parameters required for the prediction model. This implies there is a need for development of a procedure that could help the utility decide on the data parameters they should concentrate on collecting.
2. The Classification of the wires is a parameter that has been added to the data parameters. The wire classification is important as the class of wire defined the risk associated with the pipe in consideration.
3. Addition of "carbon-dioxide corrosion" to the data parameters since WSSC had observed corrosion of the mortar coating. The Carbon dioxide reacts with the mortar layer forming a carbonate layer, which is separated from the pipe layer.
4. Division of the Predictability Index as ECP and LCP depending on what kind of pipe it is, following the flow chart initially indicated.

WSSC follows a risk factor with six parameters to evaluate their pipes. The procedure followed helps them make a priority among pipe for decisions towards further inspection.

The risk factors are:

- Land Use Factor (LF): The Land Use Factors have been listed in Table 23.

Table 23: Land use factors of WSSC model

Description	Rating Factor
Limited Damage Caused by pipe rupture	0
Home water damage greater than 75ft from pipe or down stream	1
Structural Damage , limited use road	2
Major road likely flooding	3
Home within 75 ft of pipe- potential structural damage	4
Commercial facility likely water damage	5
Commercial facility within 75ft of pipe- potential structural damage	6
Major road- Structural Damage	7
Bridge Structural Damage	8
Other Risk assigned upon evaluation	?

- Repair History (RH)

- Operational Needs (ON): The Operational Needs are listed in Table 244.

Table 24: Operational Needs of WSSC model

Description	Rating Factor
Local Effect Only	1
Water Restriction during peak demand	2
Water Restriction in non peak Demand	8

- Known Manufacturing Defects (KD): Manufacturing Defects are listed in Table 25.

Table 25: Known Manufacturing Defects of WSSC Model

Description	Rating
Lap Joint Weld (pipe greater than 60”)	1
Class III 8 ga pre 1991	1
36” and greater in diameter lined cylinder pipe	2
Poured concrete coating	3
Class IV wire 5/16 diameter	3
Class IV wire ¼ diameter	4
Class IV wire 6 ga (post 1977)	5
Class IV wire 6 ga (pre 1977)	6
Class IV wire 8 ga (post 1977)	6
Class IV wire 8 ga (pre 1977)	7
Grade E Cylinder	

- Last Inspected (LI): The Last Inspected values are listed in Table 26.

Table 26: Last Inspected Values of WSSC Model

Description	Rating
Less than 5 years ago	1
5 to 8 years ago	2
9 to 12 years ago	3
13 to 15 years ago	4
16 to never	5

- Diameter (DI): The diameter factor values are listed in Table 27.

Table 27: The Diameter Factors of WSSC Model

Description	**Factor**
42” or less	0
42” to 54”	2
60” to 66”	4
72” to 78”	6
78” and greater	8

The combined risk factors

- General form
    - Defects* Operational Needs
- Empirical Formula
    - Risk- (RH+DI+KD)*(ON*4+LI)(LF)
- The factors DI, RH and KD are included in the predictability of the pipe barrel.
- The Factors ON and LF are included in the high-risk scenario and high-risk situations.

The combined risk factor formula does not have an upper limit. But WSSC considers any value above 80 to be at risk and a value above 100 to be at greater risk. This range is explained in Figure 21.

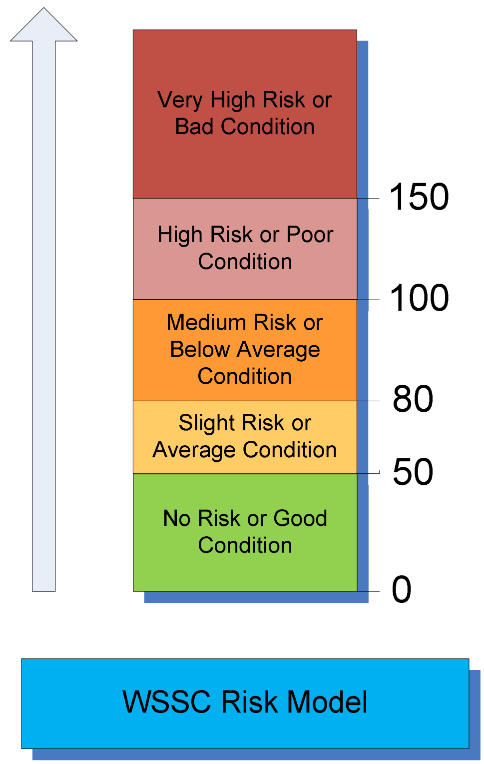


Figure 21: WSSC Risk Model Range

By studying and understanding the model used by WSSC for their risk assessment, one can understand the type of risks their pipelines are prone to. Most of the factors in this risk formula are factors considering the high-risk situations and scenarios faced by the pipeline system.

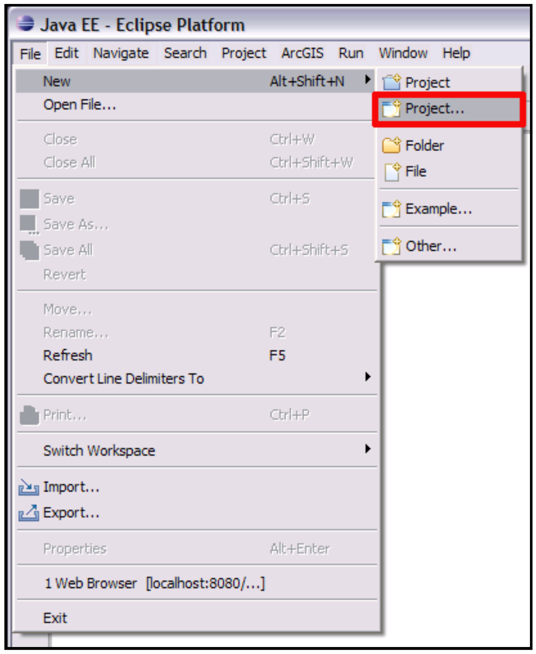
Factors like diameter and operational needs guides the utility towards the high-risk scenarios of the pipeline while factors like the known manufacturing defects and land-use guides the utility towards the high-risk situations the pipelines exist in.

APPENDIX I

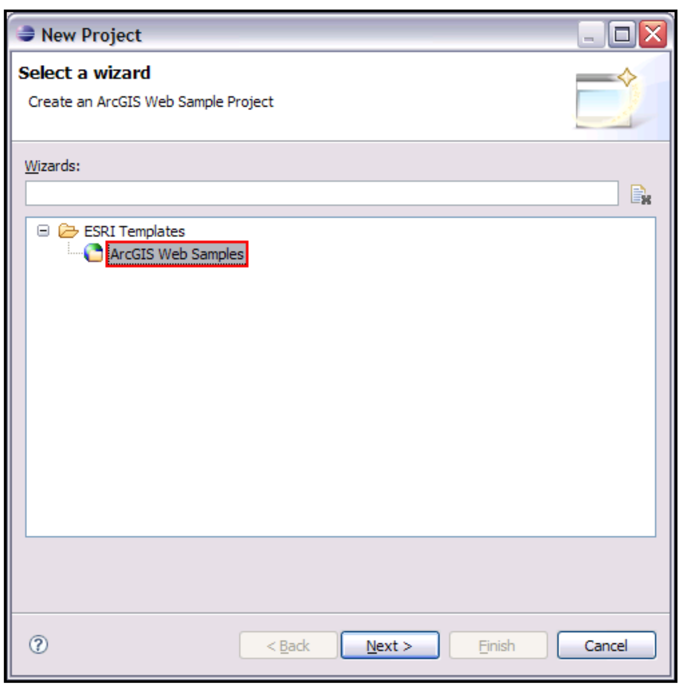
IMPORTING GIS SERVER INTO ECLIPSE

The following steps detail how to import [8] an ArcGIS Server for Java sample as an Eclipse project:

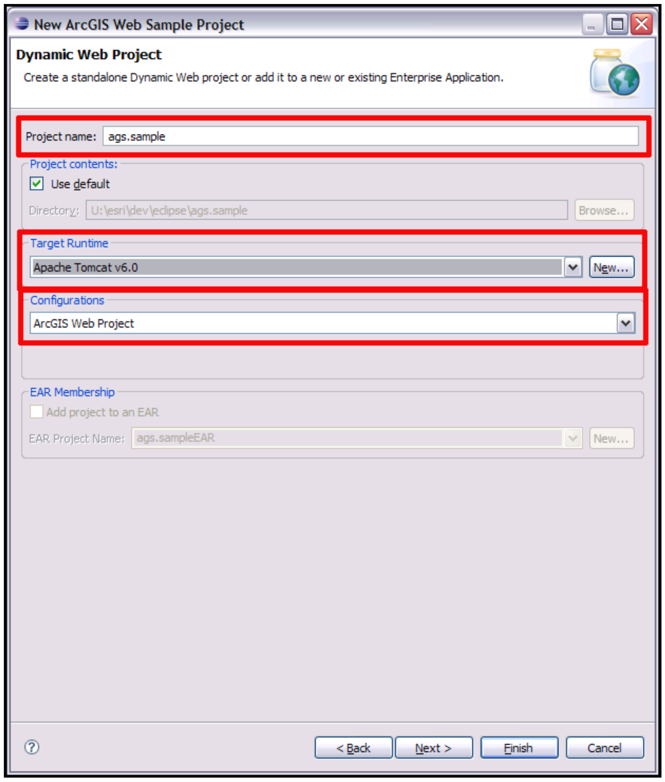
1. Create an ArcGIS Web Sample Project. From the Eclipse main menu, select 'File->New->Project'.



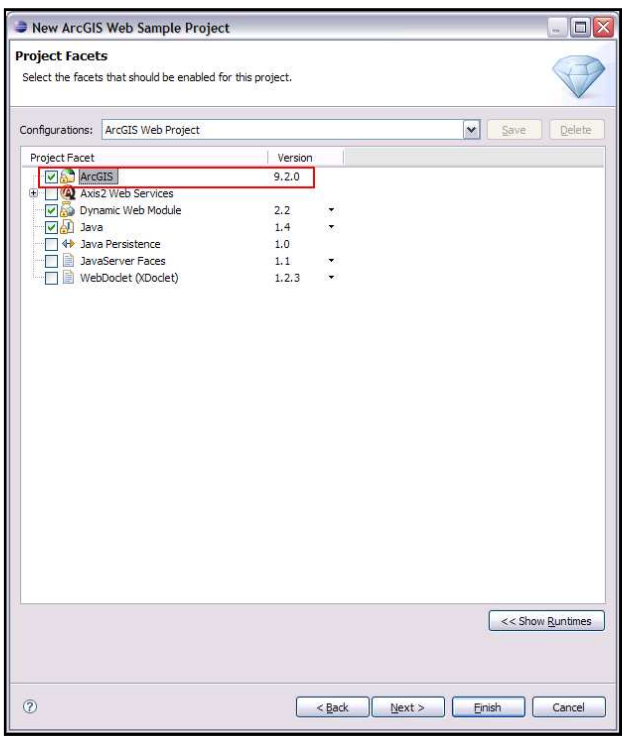
2. From the ESRI templates, select 'ArcGIS Web Samples' from the list and click Next



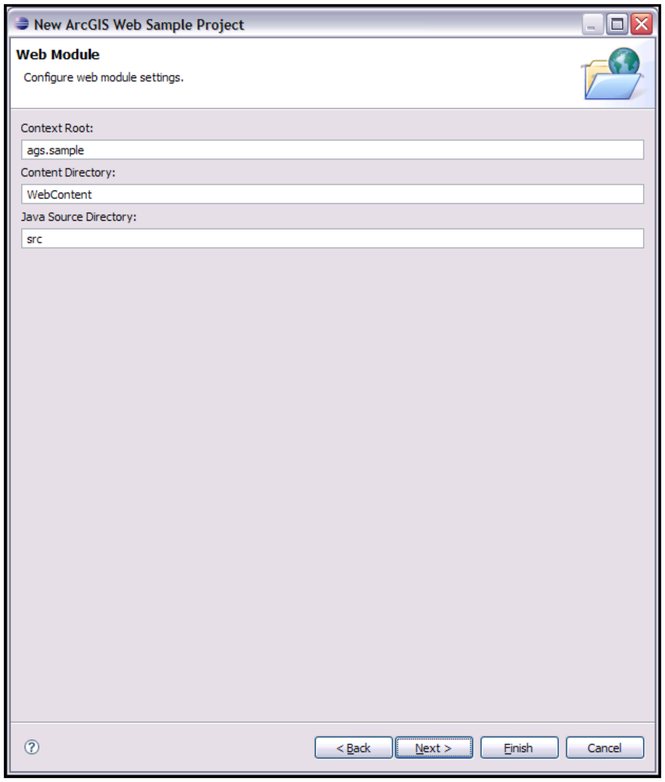
3. In the Dynamic Web Project dialog, name the project, select the target runtime, and choose 'ArcGIS Web Project' from the Configurations drop down. Click Next.



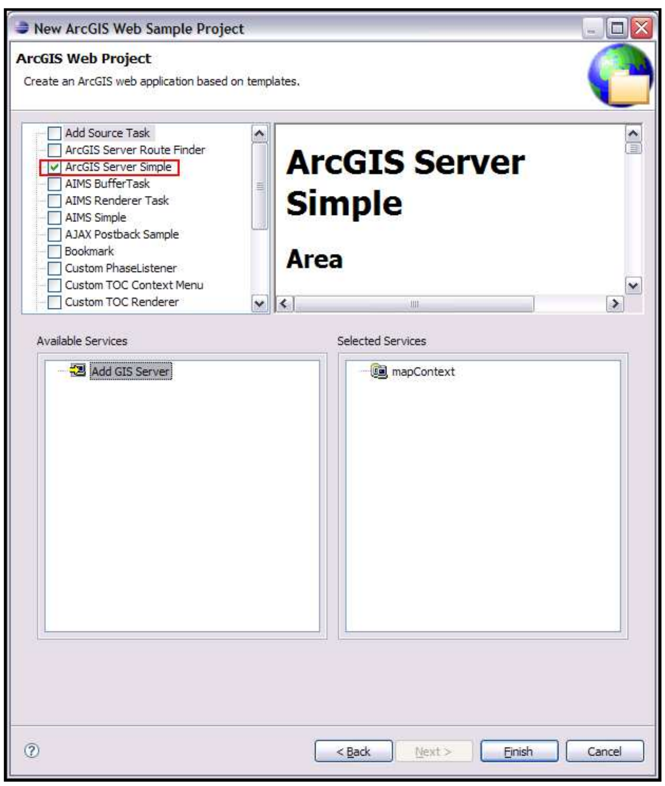
4. In the Project Facets dialog, ensure that the ArcGIS facet is checked and click next.



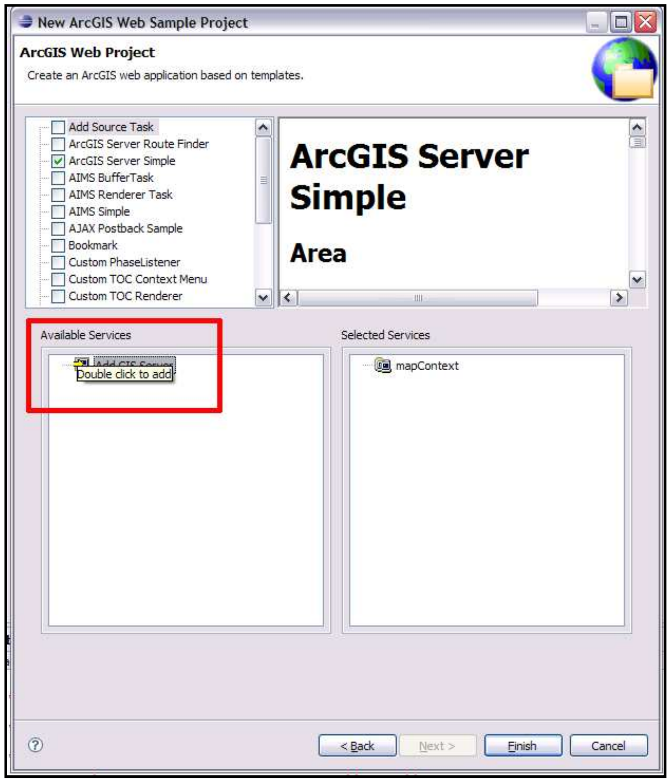
5. Accept the default settings in the Web Module dialog and click Next.



6. In the ArcGIS Web Project window, select the sample project that is to be created.

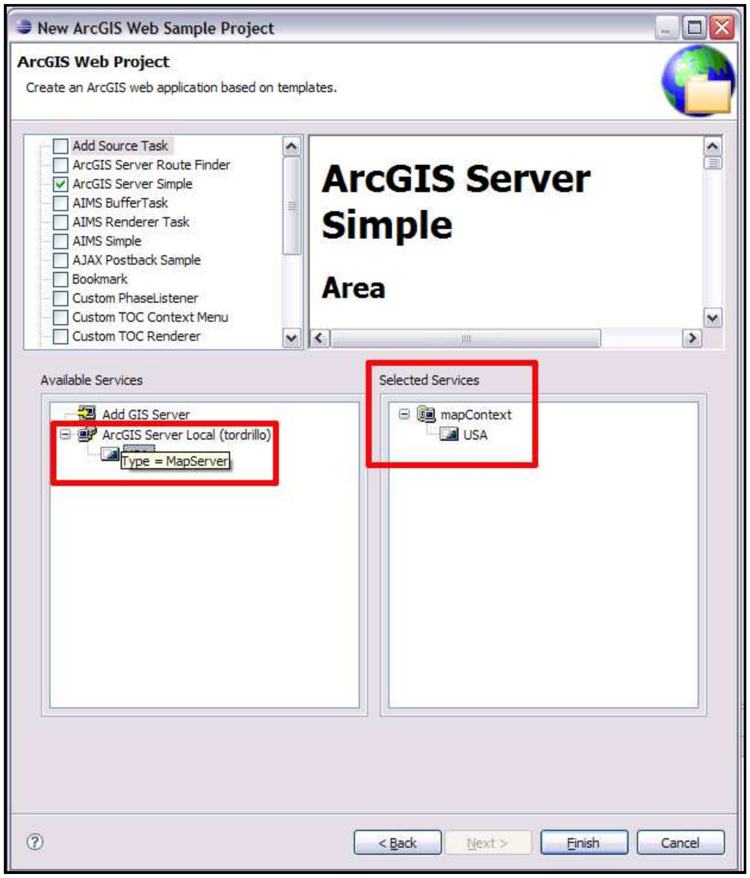


7. Double click the Add GIS Server icon under Available Services.



8. Input valid server information for the GIS Server Host, User Name, Password, and Domain. In the type drop down menu, select ArcGIS server Internet.

9. Click the OK button to connect to the GIS Server and see a list of valid server objects. Double click on the server object that is to be used and the object will be added under Selected Services on the right hand side. Click Finish to build the project.



10. The workbench will now show the newly created ArcGIS Sample Project in the respective perspective and the application is ready for deployment.

APPENDIX J

WVWA WEB APPLICATION

The mission of the Western Virginia Water Authority (WVWA) is to protect and manage essential water resources through the delivery of quality water and wastewater service to the customers.

On July 1, 2004, the water and wastewater operations of the City of Roanoke and Roanoke County consolidated to become the WVWA, providing water service to 155,000 citizens and wastewater service to more than 120,000 citizens in the city and county. Five years later, on November 5, 2009, Franklin County officially joined the WVWA [33].

The WVWA is responsible for providing safe, reliable and sustainable drinking water sources and managing drinking water production, storage and distribution facilities for its present and future customers. In addition, the WVWA is responsible for operating the Roanoke Regional Water Pollution Control Plant, which treats 40 million gallons of wastewater a day from throughout the Roanoke Valley. The WVWA meets these responsibilities by maintaining and expanding the water and sewer infrastructure, including 900 miles of water lines, 960 miles of sewer lines and 4,000 fire hydrants, while incorporating environmental, social and regulatory issues in the decision-making process.

The WVWA has a GIS based web application running on the website. The application gives access to all the data of the utility, view layers such as railways, water bodies, etc. The query builder guides the user to develop a query confined to any of the layers listed in the builder. The criteria to query can be specified once the layer and the attributes of interest are decided. However, the query is just limited to one layer and a multi-layer query cannot be performed. The web application has a map-based user interface with all the basic tools such as pan tool, select box tool, identify tool, etc. The web application of WVWA is illustrated in Figure 22.

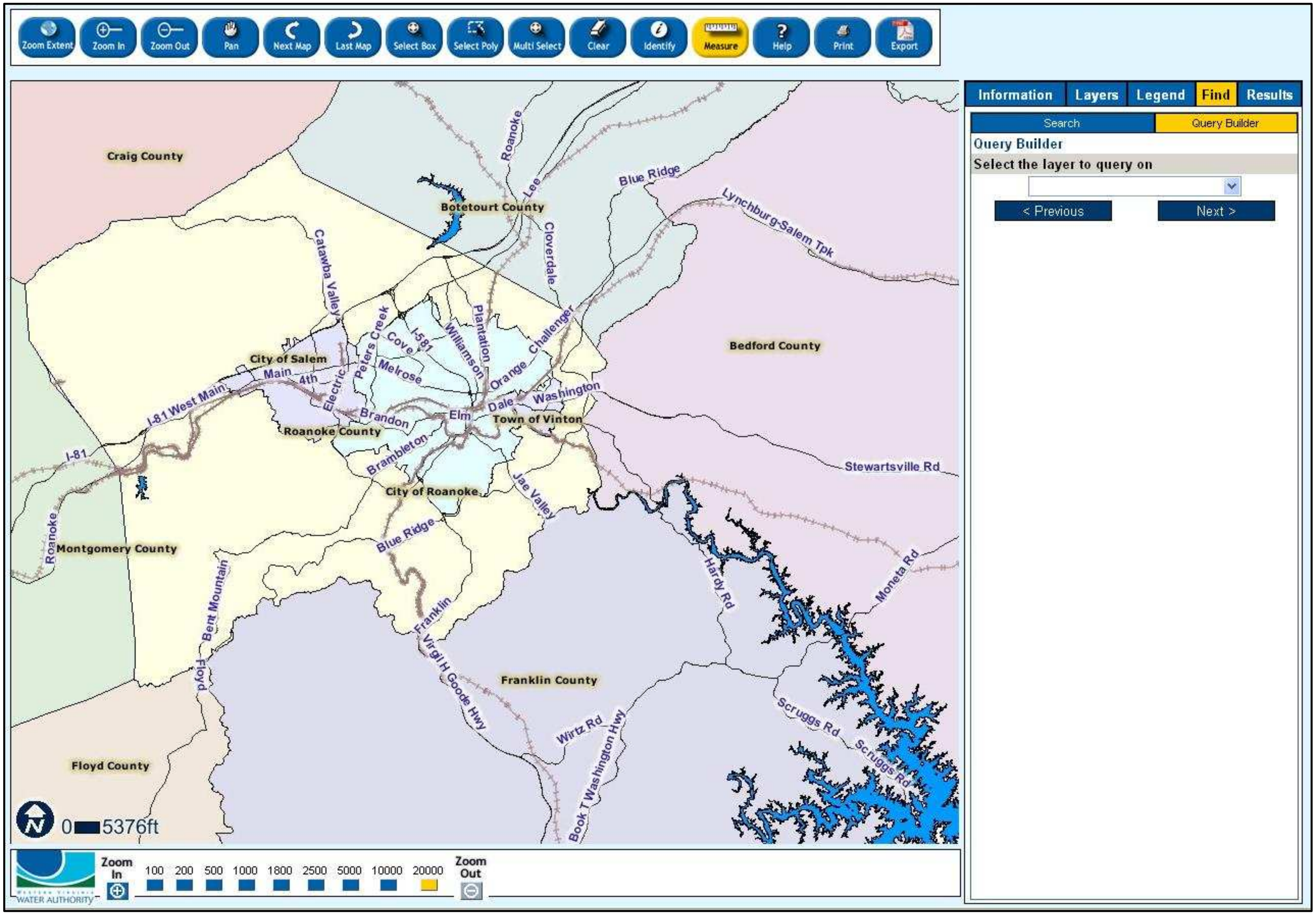
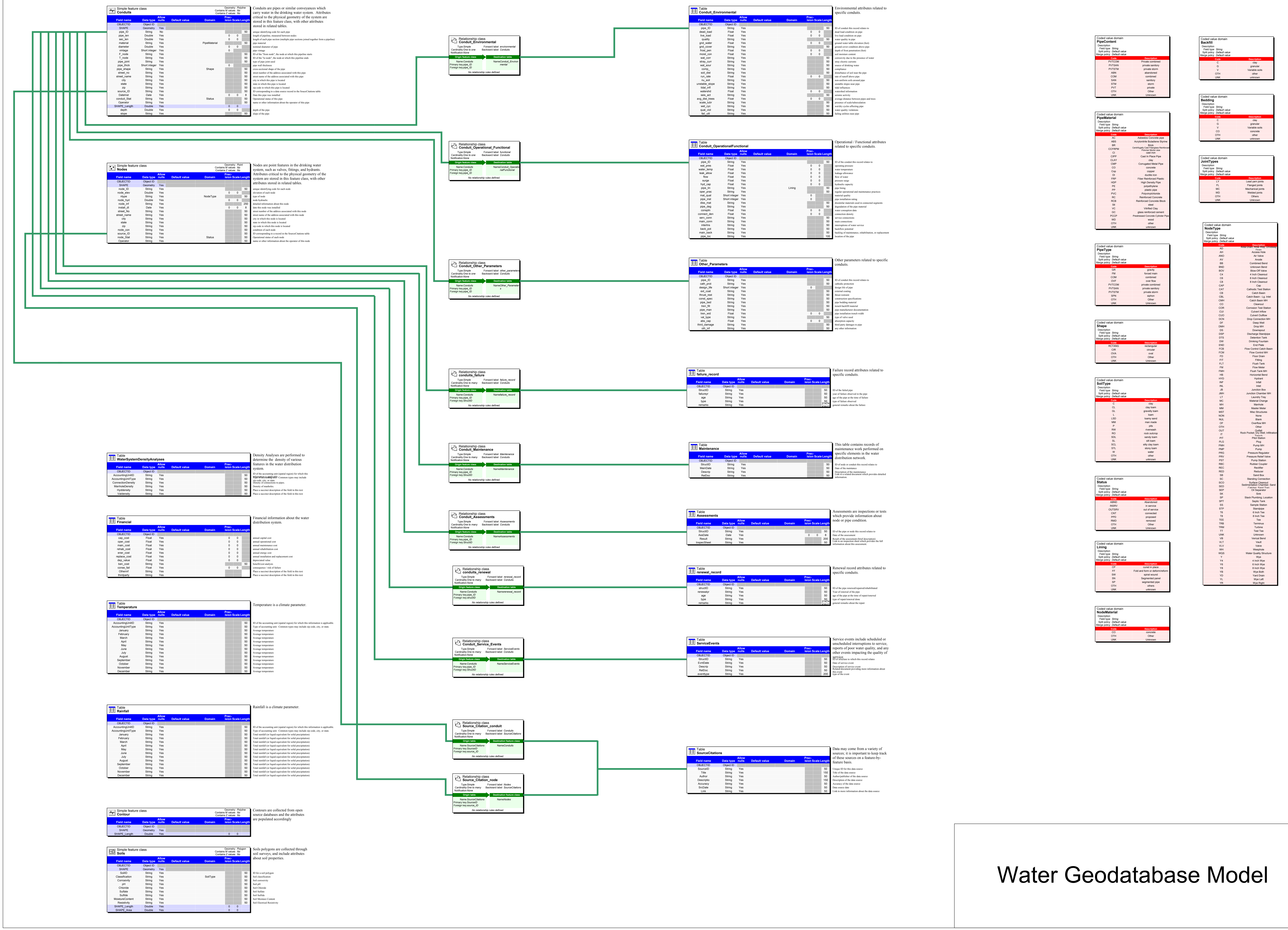


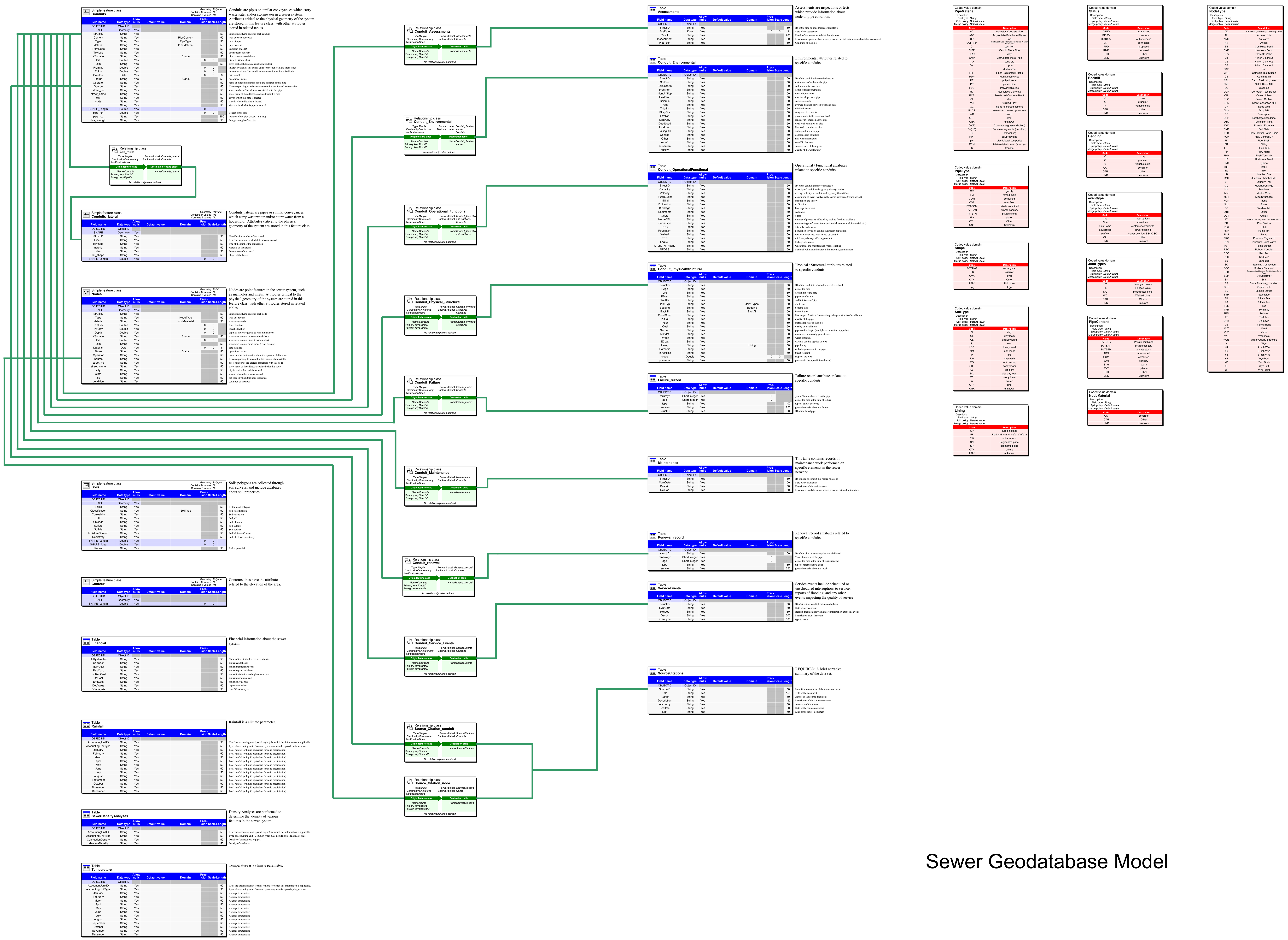
Figure 22: Web Application of WVWA

APPENDIX K

MODIFIED WATER AND SEWER DATA MODEL



Water Geodatabase Model



Sewer Geodatabase Model