

GEOGRAPHICAL INFORMATION SYSTEM (GIS) WEB APPLICATIONS FOR DATA VISUALIZATION OF DRINKING WATER PIPELINE PERFORMANCE

PURURAJ SINGH SHEKHAWAT

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Sunil K. Sinha - Chair
Matthew H. Stolte
Peter M. Sforza

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ACADEMIC ABSTRACT

GEOGRAPHICAL INFORMATION SYSTEMS (GIS) WEB APPLICATIONS FOR DATA VISUALIZATION OF DRINKING WATER PIPELINE PERFORMANCE

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Robust decision support tools that aid water utilities to make informed, swift and precise decisions are becoming the need of the hour. Application of sophisticated models to aid the process of condition assessment and risk analysis on water pipelines have been limited owing to the lack of scalability, inability to incorporate external open source datasets and mathematically complicated output results. Interactive visualization of resultant model output is the key element in extracting valuable information to support decision making. This thesis presents a framework for visualization of data related to drinking water pipelines. Critical components of strategic, tactical and operational level decision making are explored in context with data presentation and information depiction. This thesis depicts various aspects of developing GIS web applications and their important functionalities for query and visualization of data. Multiple facets of data storage, standardization and application development are highlighted in this document. Publishing of application geo processing services in web environment is done through Virginia Tech enterprise geodatabase. Risk assessment and Performance models developed by a utility are projected in the application environment through help of widgets. Applications are coded into links on a Drupal website (www.pipeid.org) for model dissemination and utility engagement purposes.

GENERAL AUDIENCE ABSTRACT

GEOGRAPHICAL INFORMATION SYSTEMS (GIS) WEB APPLICATIONS FOR DATA VISUALIZATION OF DRINKING WATER PIPELINE PERFORMANCE

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Drinking water supply network primarily consists of pipelines, pumping stations, reservoir basins and treatment plants. Water pipelines are routinely inspected to check their condition and maintain appropriate water quality. Management of these subsurface assets should be given prime importance for maintaining high standards of services at acceptable cost to customers. An integral step in accomplishing this task is to view pipeline network in a geographic map. Different factors affecting pipeline condition are displayed on the map in the form of individual layers. Such real-world problems are analyzed with the help of Geographical Information System (GIS) tools that incorporate spatial features with tabular information. Moreover, interpretation of raw data into meaningful insights and distribution of allocated knowledge to all the concerned parties can be efficiently accomplished using rich internet applications.

This thesis presents a framework to use GIS tools for developing web applications using raw data samples from contacted water utilities. Sample web applications are created and discussed in the form of case studies. Also, the challenges in water utility sector with respect to utilizing GIS tools for supporting daily decision-making processes is highlighted in this document. The recommendation to improve the suggested framework and adding more functionalities to developed applications are presented at the end with references.

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I would like to dedicate this thesis to my late father, Mr. Ghanraj Singh Shekhawat for his continuous belief and encouragement in all stages of my personal and professional life.

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Chapter 1.0

INTRODUCTION

Drinking water pipeline infrastructure primarily consists of a network of pipelines, pumping stations, reservoir basins and treatment plants. Subsurface pipelines which comprise a substantial portion of drinking water infrastructure are nearing the end of their useful life (AWWA, 2012). This has led to an estimated 240,000 water main breaks annually (Economic Development Research Group) EDRG, 2013 further leading to widespread economic ramifications. The cost of rehabilitating existing water infrastructure is stipulated at USD 1 trillion in the coming decade (ASCE, 2017). Efficient management of these subsurface assets should be prioritized for maintaining current level of services at affordable prices. An integral aspect of this process is precise decision making through data visualization.

Data visualization is categorized as an extremely crucial step for extraction of easy-to-interpret knowledge from the analyzed output. The domain of Geographical Information System (GIS) encompasses tools and techniques that efficiently accomplish this purpose by overlaying multiple spatial layers of soil characteristics, road networks, catchment basins, land cover, elevation contours and other external datasets collected by the utilities (Sinha et al. 2007). Database refers to a structured set of data for efficient access and extraction. Assets like pumps, hydrants, pipelines, valves and storage tanks can be stored in the database as objects or shapefiles and contiguous parameters like temperature variations, land cover, soil pH, and precipitation can be stored in the form of matrices, images or raster datasets (Liu et al., 2007).

Although GIS provides a visualization environment locally on the user machine, however, integration of external data parameters for enriched data quality coupled with growing utility demands for user interactive visualization tools underscores the need for a visualization framework in water pipeline industry (Sinha et al., 2011).

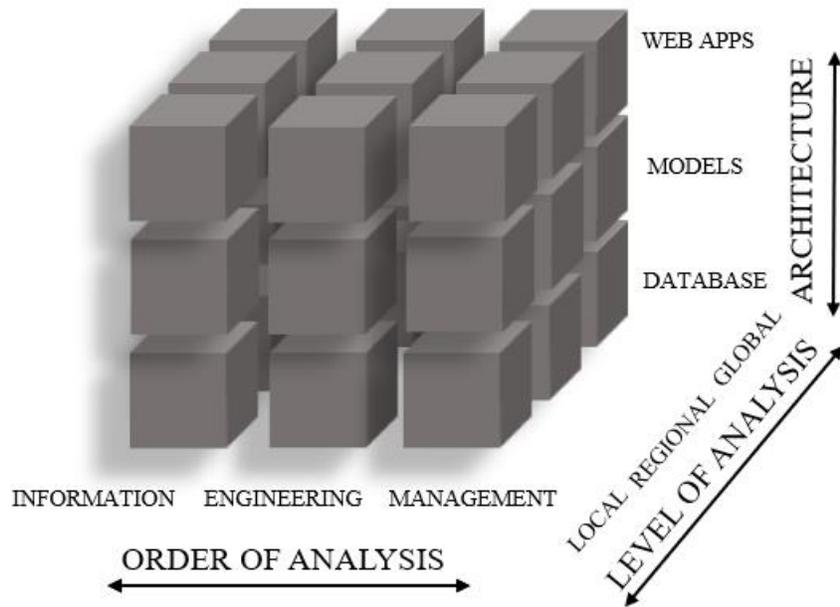


Figure 1.1 – Visualization Specification Overview

This thesis presents a multi-dimensional visualization framework for data related with drinking water pipelines. Fig 1 encapsulates this comprehensive visualization framework concept on 3 interlinked dimensions. Each axis depicts an individual component that when intertwined together serve as the foundation for a total enterprise GIS visualization blueprint.

Horizontal axis of Analysis Order (see Fig 2) reflects the increasing level of detail in accumulated information as one progresses from “left-to-right”. Information level decisions are made by aggregating information to visualize general trends and understand big picture. Engineering decision is intermediate in the sense that technicality of information increases, and they bridge the gap between information collated and subsequent management practices followed.

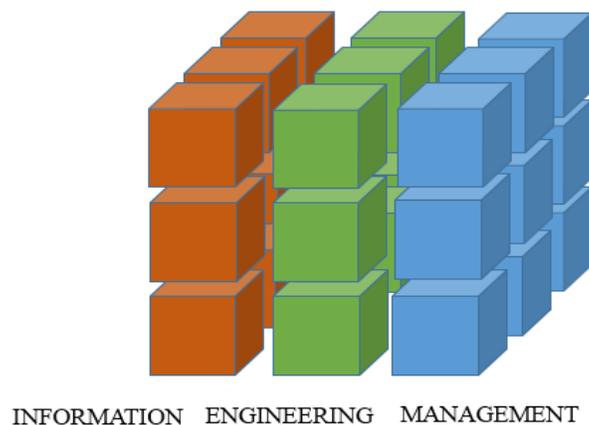


Figure 1.2 – Components of Order of Analysis

The transverse axis (see Fig 3) highlights the “Level of Analysis” that can be adhered to for data analysis process. Local analysis aims at identifying trends on limited to the domain of utility. Searching for patterns amongst a group of utilities is termed as regional analysis. Cohorts can be formed based on common characteristics within disparate datasets from different utilities. The global analysis comes into picture when data from different countries or around the globe is purged to mine useful information.

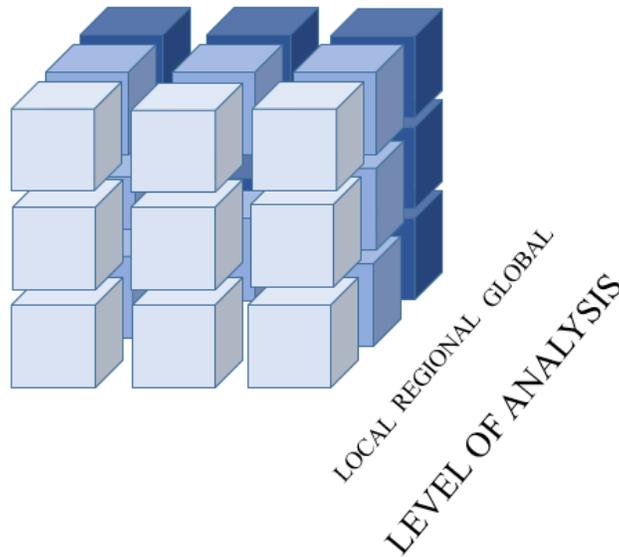


Figure 1.3 – Components of Level of Analysis

“Architecture” is the final axis (see Fig 4) that serve as building block for developing concrete analysis and visualization tools. It is branched into Database Structure, Modeling Platform, and Web GIS Framework. A “bottom to top” viewpoint is necessary to analyze this axis. A versatile database structure with the capability to store disparate data points affecting pipeline condition is at the bottom of the hierarchy. Database structure should be effective in handling massive data chunks. Structured data emphasizes the need for a flexible modeling platform whereby services ranging from heuristic analysis to fuzzy algorithms can be ran to identify high-risk zones that need immediate attention. Post successful modeling and verification, gathered insights are dispersed to respective stakeholders. Rich internet web applications that enhance the feasibility of knowledge dissemination process complete the topmost pillar of this hierarchy.

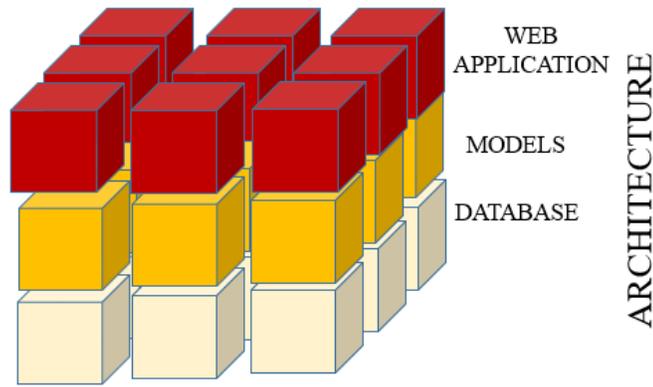


Figure 1.4 – Components of architecture axis

Bringing together data from disparate sources under a common umbrella serves for effective prioritization, monitoring, maintenance and decision making of sub-surface infrastructure assets (Baird 2011). However, this problem is not simple and requires handling of extremely large datasets that are not coherent. Also, there is a lack of accepted data storage standards and a common platform for data sharing and standardization which inhibits mapping of disparate data sources together (Sinha 2011). A GIS-centric enterprise asset management system is a foundational concept that standardizes data and allows interoperability, providing users the capability to visualize, coordinate, and share information in an efficient and effective manner. This thesis brings together the key elements of data visualization pertaining to drinking water pipelines and presents a methodology for development of GIS based web applications to showcase available tools and techniques in this area. Visualization service to respective utilities is provided via web development of individual utility hub pages on PIPEiD platform.

1.1 Research Goals and Objectives

Supporting decision making process is one of the most critical aspects of asset management process. Numerous water utilities across the country are performing this essential function based on analyzed output of in-house developed models or relying on the consulting agencies. While it is of extreme importance that the accuracy of models and their reliability should closely mimic the actual on-site conditions, once this step is accomplished, next crucial step is to present the analyzed complicated output for inferences. This can only be achieved if data is visualized in a manner that is consistent with stakeholder’s expectations. While GIS serves as an excellent tool to visualize spatial datasets like pipeline networks, hydrants, pressure zones and such, it can also serve as a tool to populate charts, project heuristic knowledge, comprehensive models and sophisticated operational level outputs in a user-friendly manner.

This objectives behind conducting this research are twofold:

- I. Synthesizing knowledge related to visualization techniques used for water pipeline performance data and its interpretation

II. Development of models on ArcMap model builder platform and publishing GIS Web Applications on ESRI's Web App Builder tool

1.1.1 Synthesizing knowledge related to visualization techniques used for water pipeline performance data and its interpretation

- Literature is summarized for the information depiction techniques in use across multiple industry domains
- GIS based visuals that can support decision making processes are highlighted and identified through literature and practice review
- Database architecture for data storage is explored with respect to ESRI's ArcMap software and File Geodatabase system is conceptualized for PIPEiD research
- External data factors that are sought to contribute towards pipeline performance ratings are explored through literature and their corresponding spatial layers are presented to be used in the applications.
- Local level utility data visualization techniques are developed with focus on strategic and tactical level decision making.

1.1.2 Development of models on ArcMap model builder platform and publishing GIS Web Applications on ESRI's Web App Builder tool

- Detailed stepwise procedure for model builder platform on local machine
- Configuration of widgets and data layers gathered from open source external datasets and intrinsic pipeline data parameters for utility specific web apps

1.2 Organization of Content

The content in this document is organized into 5 chapters as listed below:

Chapter 1. *Introduction* describes the data visualization framework in brief and enlists key objectives behind conducting this research

Chapter 2. *Literature Review* provides an overview of existing data visualization techniques and emphasizes the importance of GIS web applications as effective information depiction tools

Chapter 3. *Visualization platform* elaborates on an existing Drupal based website for information dissemination and modifications related with information dissemination

Chapter 4. *Geographic Information System (GIS) web applications for data visualization of drinking water pipelines* elaborates on the development and hosting of web applications to support decisions. It also presents a pilot study with sanitized utility data for risk rating and performance assessment models.

Chapter 5: *Conclusions and Recommendations* provides concluding remarks and recommendations to fill the gaps in the domain of drinking water data visualization.

Chapter 2.0

LITERATURE REVIEW

The underlying basis behind data visualization techniques is to support decision making process. Visualization is the culminating step in the hierarchy of processes for asset management of drinking water pipeline infrastructure. Identification of data parameters that affect pipeline condition is crucial to understand the interdependencies in a multi-variate analysis approach (St. Clair and Sinha 2014). Furthermore, assessing the risk on pipeline network involves studying failure modes and mechanism associated with these buried assets. There is a lack of available geospatial tools for performance assessment and risk screening that combine the location of asset to its probability and consequence of failure. Although commercial GIS software products catering to visualization are used by water utilities, they are limited in exposure across all utility departments. This is primarily owed to the level of technicality necessary to operate the software (Sekar et al., 2013).

Large utilities are financially equipped to hire consultants for creating localized models catering to individual utility requirements. However, medium and small-scale utilities owing to monetary and resource constraints are limited in their access to accurate model development environments. Nonetheless, in most of the cases, the developed models have experienced a lack of common platform for robust data query support and user interactive visualization (Bhaskar et al., 2016). GIS based web applications have come to the fore front of mapping and visualization techniques. Their popularity is largely attributed to seamless rendering of published spatial datasets and ease of deployment across multiple electronic devices (Adnan et al., 2010). Tagging asset location with their attribute values add a spatial dimension and hence significance to water pipeline databases. Determining applicable range for the domain value of attributes involve understanding of scientific knowledge available in literature and practice.

Exploring the dependencies between three interdependent components spanning Database, Models and Web application is paramount to grasp a comprehensive pipeline data visualization

blueprint. The literature review is summarized with respect to these broader concepts which combine to provide decision support. Fig 2-1 graphically depicts this section as follows:

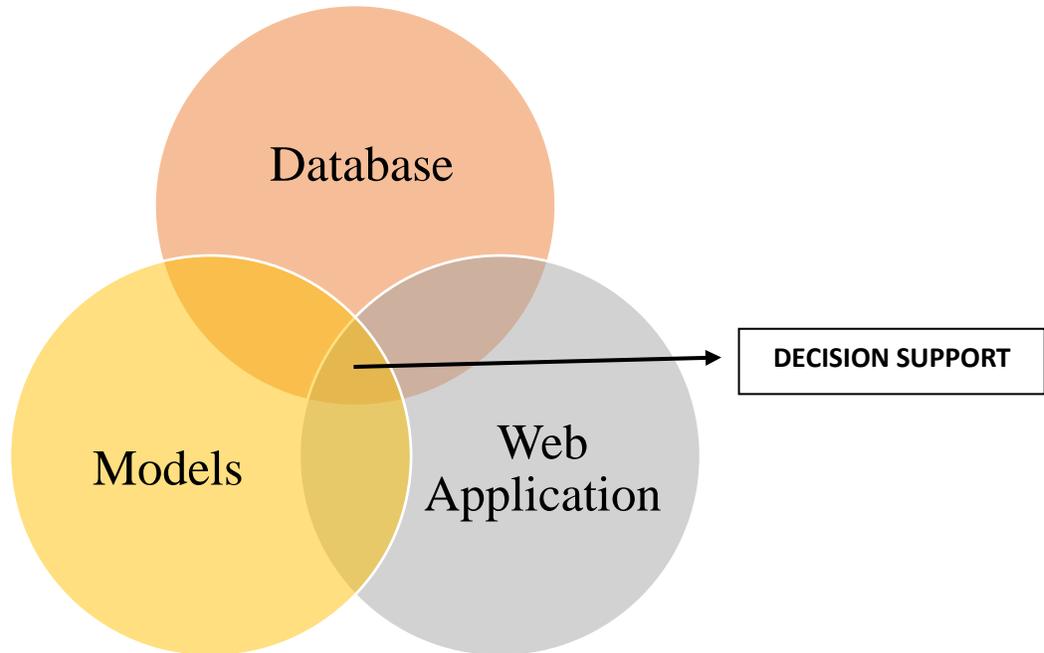


Figure 2.1 – Components of drinking water pipeline data visualization

2.1 Database Architecture

Defining relationships between numerous data parameters affecting water pipeline condition highlight the need for a structured data storage model inclusive of the asset location. At its most basic level, an ArcGIS geodatabase is a collection of geographic datasets of several types held in a common file system folder, a Microsoft Access database, or a multiuser relational DBMS such as Oracle, Microsoft SQL Server, PostgreSQL, Informix, or IBM DB2 ("What is a geodatabase? —ArcGIS Help | ArcGIS Desktop" 2018). For this research, Microsoft Access database was used because of easy availability and design requirements. Designing a geodatabase that aligns with utility requirements is a critical step in supporting visualization, it requires significant planning and revision (MahmudAdam and Shayboub Ali 2013).

Water utilities across the nation have experienced a lack of standard data model for asset registry and data collection (Sinha et al., 2009). Moreover, utilities have largely relied on in-house data management systems which are specific to the utility size and expectations. Data is collected and stored in varied formats and nomenclatures across diverse utility profiles. This research explains

a methodology for standardization of water pipeline infrastructure data. Mapping disparate datasets into corresponding tables involve loading data into the standard format.

The database design must incorporate the needs of the users and should be flexible enough to accommodate present and future data inflow (Waicelunas et al., 2007). An integral aspect of constructing a database for web-based GIS environment is the development of nested feature datasets which are further segmented into individual asset feature classes like pumps, hydrants, lateral conduits, mains, wells, and fittings. Depending on the scale of visualization, point features typically represent wells, fittings, hydrants and pumps while transmission and lateral mains are represented by line features. Pressure zones, political boundaries, catchment basins and pump station area classifications are zonal variables and hence are depicted via polygon features (Sinha et al., 2009).

Feature classes constitute a large number of attribute tables (dBASE files, Microsoft Access tables, Excel spreadsheets, DBMSs, and so forth) linked with a shape field. Images are represented by storing continuous values in a matrix called Raster dataset.

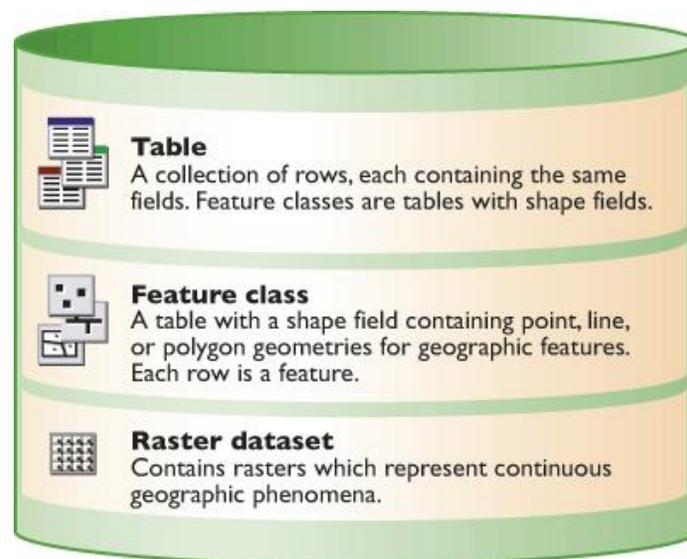


Figure 2.2 – Fundamental dataset types in GIS

Kumar et al., 2010 discussed the importance of integration between data management tools and physical models, essentially elaborating on the gap of poorly created data structure leading up to imprecise model outputs. Highlighting the need for development of new strategies for data representation, poorly constructed geodatabases lead to high processing times further tuning down the efficiency of the system. English Mark, 2008 elaborates on a geodatabase design for resources and land management GIS. Feature classes and relationship classes are modified

within an existing system to study the effect of the improved data structure on geospatial capabilities.

Design considerations of a geodatabase affect the integration of additional data associated with pipelines like cost details, repair details, high priority breaks, break locations, and affected customer counts to name a few. These parameters have separate feature classes in the geodatabase and can be attached to intrinsic pipeline parameters for risk visualization and performance assessment.

2.2 Model Development

Water utilities implement models and tools to better manage their assets. Condition assessment models are developed to determine the behavior of pipelines under external and internal stresses. Al-Barqawi and Zayed, 2006 proposed a condition assessment model on a ten-point scale using the analytic hierarchy process (AHP) to set up rehabilitation priority for water mains. Bai et al., 2008 proposed a hierarchical evidential reasoning approach for condition assessment of buried pipes. The framework's output discernment for condition states of a pipe is defined as good, fair, and bad.

Sekar et al., 2013 developed a risk screening model for renewal prioritization of water mains on a selected scale of 1 to 5 where likelihood of failure parameters was categorized into three classes of physical, environmental and operational. Consequence of failure parameters were classified into societal, environmental, operational and renewal complexity scenarios. St. Clair and Sinha, 2014 developed a fuzzy inference model for metallic drinking water pipelines. Parameters included in this model which assess the pipe performance level are previous breaks, break year, break defect type, break rehabilitation type, adequate fire flows, discolored water issues, and pressure complaints. The performance index scale ranges from values of one to five with 1.0 to 1.5 representing the pipe performance as excellent or near excellent and 4.5 to 5.0 signifying very poor condition or possibly failed scenarios.

Failure prediction models are developed to predict the probability of failure of water pipelines. The accuracy of model is largely dependent on collection of rich temporal datasets. Kleiner et al., 2006 described a fuzzy deterioration model where Markov process is used to establish a connection between fuzzy condition rating and respective probability of failure values. Nishiyama and Fillion, 2013 considered operational, physical and environmental pipe attributes to train an Artificial Neural Network for failure prediction.

Economic life of an asset is another area for model development in the drinking water pipeline sector. Khurana et al., 2017 described a Life cycle cost analysis (LCCA) approach for holistic asset management practices. The LCCA model presented in the paper compares different pipe

material, rehabilitation and replacement technologies to come up with a net present value of the investment.

Models are mathematical filters that help prioritize areas of high risk. Output function for majority of developed models is numerical in nature. Adding a visual layer to model output supplements the process of extracting trends and visualize patterns. GIS applications can project complicated model output for interactive visual inferences.

2.3 GIS Web Applications

A geographic information system (GIS) application provides framework for gathering, managing, and analyzing data. Multi layered visualization techniques utilizing maps and 3D scenes provide users with actionable insights on new patterns, trends and relationships ("What is GIS? | Geographic Information System Mapping Technology" 2018).

Kunapo et al., 2005 describe the development of a geotechnical information system web mapping program (GeoInfoSync) capable to store and query 3-D datasets. The paper discusses integration of GIS and RDMS to enable multifold information for borehole features. Customized tools for mobility, location search, selection and analysis are build for improved user experience. Singh et al., 2011 underscores the growing need for GIS web applications in disseminating natural resource information. The paper discusses the development of rich internet applications utilizing open source Mapserver platform and PHP programming language for user interface. The application is designed on a Thin Client framework where majority of the data processing is done on server. This kind of framework has been employed in the current research where developed application are hosted online through Virginia Tech enterprise geodatabase.

Mikovits et al., 2017 employs the capability of web GIS visualizations to display interactive risk maps for pluvial flooding in urban drainage networks. The application utilizes Open Geospatial Consortium (OGC) with a PostGIS database to populate temporal and scenario-based risk maps. Leaflet library, a JS API is used to design visualization interface on the client side. Figure 2.3 depicts a snapshot of the designed application.

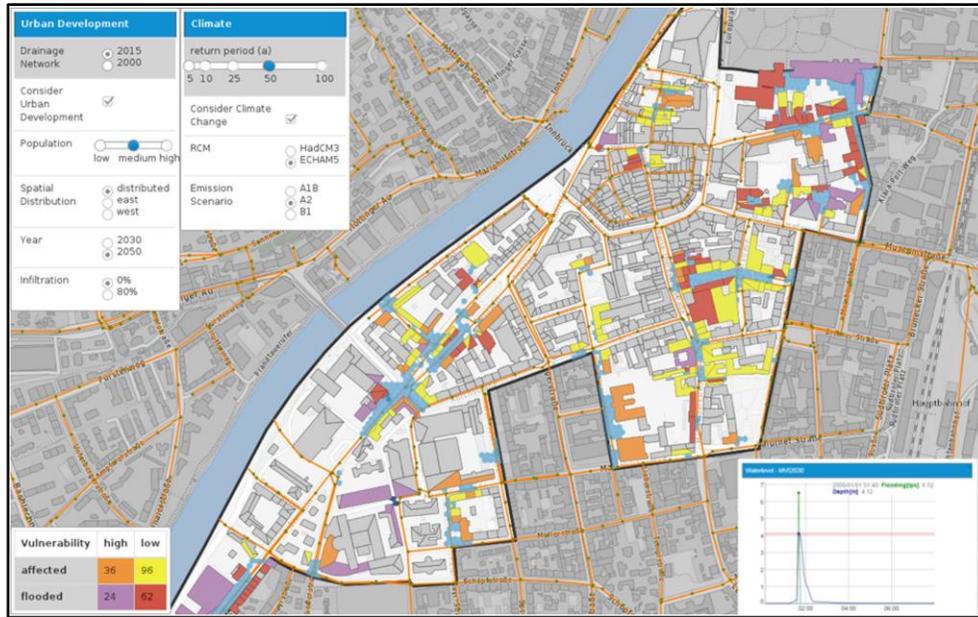


Figure 2.3 – Screenshot of web GIS showing visualized risk map

Bhaskar et al., 2016 discusses the importance of a visualization tool in water infrastructure sector. The paper elaborates on the development methodology used to prioritize risk on a pilot force main data. Risk model developed on ArcMap model builder platform is published online with a help of ArcGIS Viewer Flex application. REST URLs generated post publishing are embedded in the application to retrieve geospatial data. Figure 2.4 depicts a snapshot of the application interface.

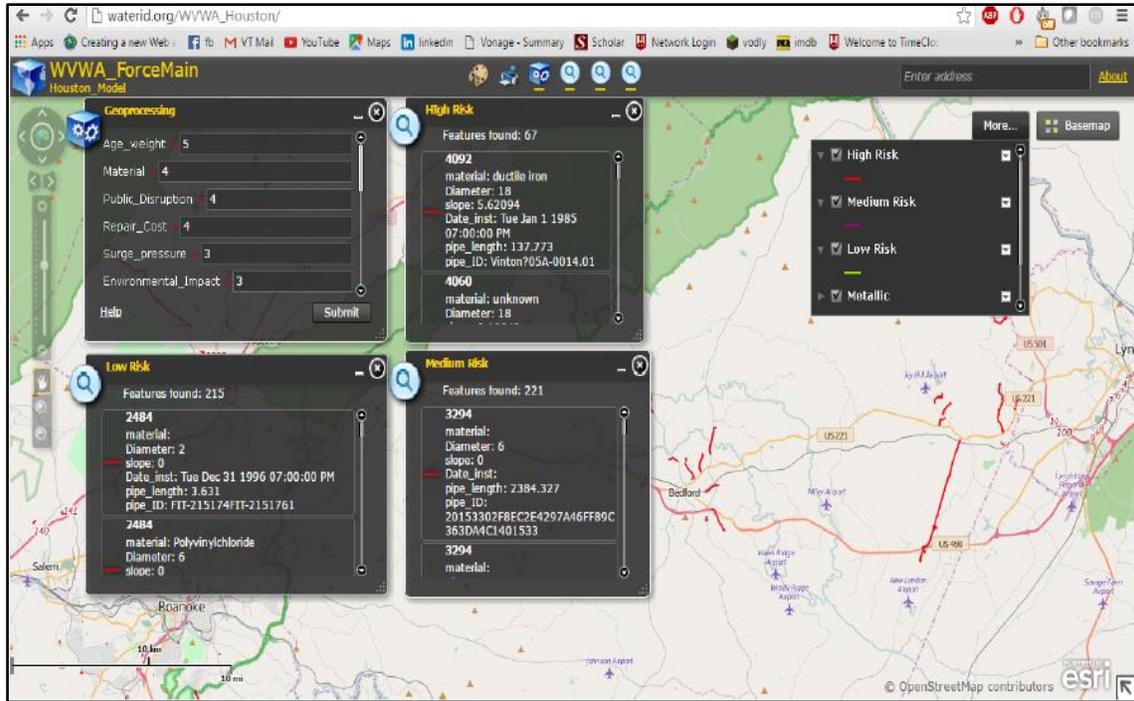


Figure 2.4 – Flex viewer GIS application user interface for risk on force mains

More recently with the advent of ESRI’s Web app builder tool, production of web application has become more streamlined and unhindered. Several water utilities across the country have deployed web application build using web app builder tool. For instance, Seattle Public Utility in the state of Washington uses a GIS web application for its homeowner research map program. This application allows customers to create and import a map of pipelines running beneath their individual house, gather information regarding water and drainage systems on a community network level. Web app builder tool is used in this research for building applications related to drinking water pipeline datasets. Capabilities like Analysis widgets, interactive charts, ease of data addition and deployment were considered before choosing web app builder tool.

Chapter 3.0

VISUALIZATION PLATFORM

Previous research (Bhaskar et. al, 2016) has contributed towards creation of a drupal based website (www.pipeid.org) to be used as the visualization platform for force main infrastructure analysis and information presentation. Implementing a similar methodology to drinking water pipeline data, major stakeholders including water utilities, consultants, researchers and customers are granted differential access to analysis and visualization capabilities of the platform. The primary purpose of such a platform is to provide effective and reliable models in the domain of information, engineering and management categories. To accomplish this, scalable visualization tools supporting dynamic and temporal datasets are integrated with the modeling platform. This research extends the capabilities of pipeid visualization platform via several site modifications.

ArcGIS viewer for FLEX was employed as the primary tool for visuals in the previous research studies. This tool was efficiently able to model risk scenarios on a selected force main network however user interactive capabilities were minimal and most of them required hard coding. This research contributes to web-based data visualization employing ESRI's Web App Builder tool. The framework presented can be utilized to create web applications that can be embedded as links into website content pages.

The following section describes in detail the modifications on visualization platform for targeted dissemination of information and elaborates on the functionalities of Drupal content management system which forms the core of PIPE*i*D website.

3.1 Drupal (CMS)

Drupal is a content management system developed by an open source community. Drupal can publish single websites and or share content across diverse devices. Drupal core is built on PHP while supported by an SQL database. Previous research has incorporated Microsoft IIS web server on a Windows 2008 operating system. This is the same setup that has been carried forwards in this research. Two important components of Drupal site development namely content and menus are elaborated in this section.

3.1.1 Content Types

CMS can host websites based on several content types, many of these can be predefined and much more can be customized by the user. Inserting content on the site requires one of the content type specified in the beginning stage of content addition. To have an overview of the available content types admin can hover over the content management tab at the top left of the admin panel and further go to Create Content tab from the drop-down menu, kindly refer to the Figure 3.1 provided.

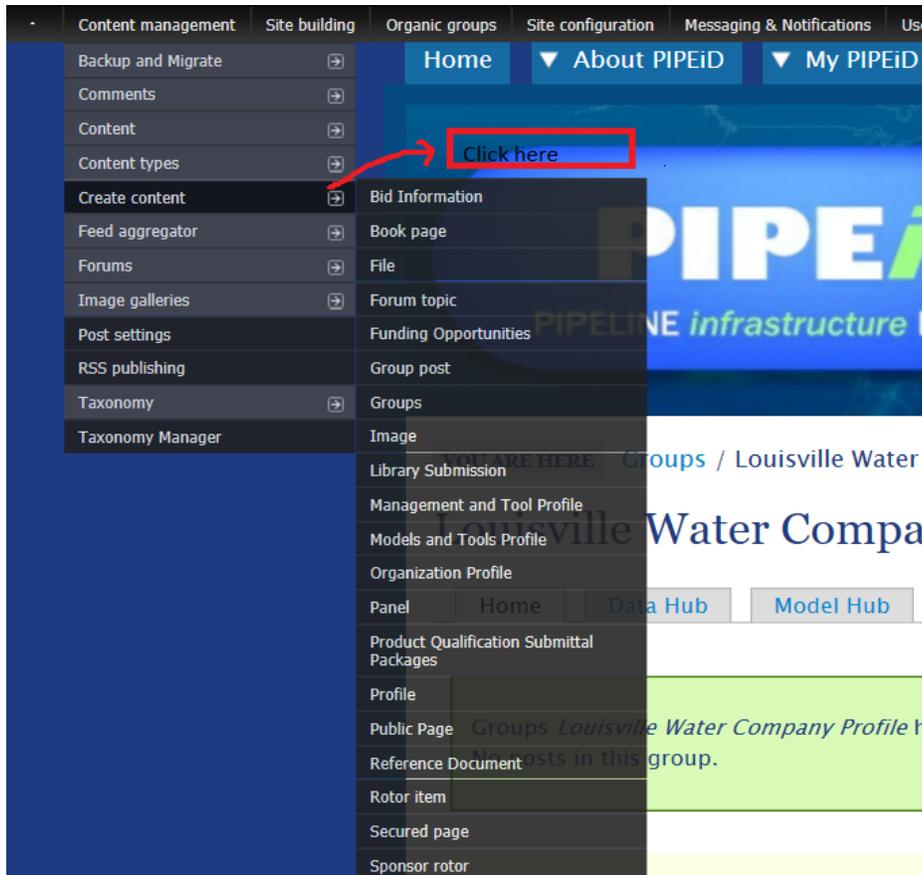


Figure 3.1 – PIPEiD Content Types

3.1.2 Menus

Menus and navigation links are extremely important from both user and admin perspective. Smooth browsing on the site is hinged on providing essential links on the home page that relate to backhand content for interested users. Drupal provides functionalities to customize admin panel as well depending on individual needs, new tabs can be added or deleted from their default locations. Menu functionality of Drupal can be accessed through Site Building tab drop-down (Figure 3.2).

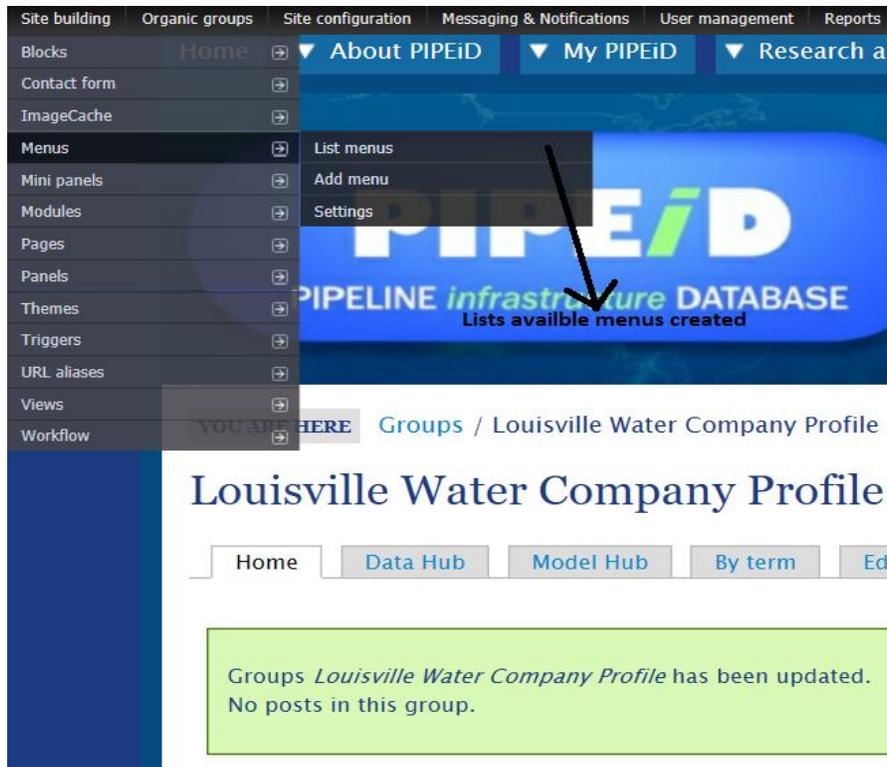


Figure 3.2 – PIPEiD Menus

There are three types of menus that Drupal offers are as follows:

Navigation: This is the main interactive menu for any site. It is usually the only menu that contains personalized links for authenticated users and often not visible to anonymous users.

Primary Links: Major sections of the site are shown through primary links. Broad tabs on the top of a website can be considered as primary links.

Secondary Links: Second tier information is depicted through secondary links. Contact details, Legal notices and so forth are embedded in secondary links.

Currently, PIPEiD site uses Primary Links for user navigation, as more content keeps integrating with site architecture, secondary links will be utilized in the due process.

3.2 Site Modifications

Participating utilities were provided secured access to respective Data, Models and GIS applications through creation of content pages on the website. These are called utility hubs and were organized into five geographical cohorts. Depending on the utility profile and size, each utility was categorized into three groups of large, medium and small. These utilities are arranged in an ordered list format within each category (Figure - 3.3)

Large Utilities List (Central Cohort)

Home By term Edit Track Broadcast Pages

No posts in this group.

UTILITY TABLE

UTILITY NAME	STATE
Colorado Springs Utilities>	Colorado
Louisville Water Company	Kentucky

Figure 3.3 – Utility size category page within a cohort

Utility hubs are divided into 4 main parts. These are home page, data hub, model hub and information hub.

Home Page

Home page provides utility specific general information like vision, mission and population served. It also gives a preview of project scope and details of data collection effort. Industry best practices, annual reports and latest news related with individual utilities are populated on the home page tab (Figure - 3.4).

Louisville Water Company Profile

Home Data Hub Model Hub Info Hub By term Edit Track Broadcast Pages

No posts in this group.

PROJECT INFORMATION

The goal of this project is to collect high quality field data on pipeline reliability performance for water pipelines of different materials.

Studies have shown that the performance of water pipelines is dependent on many factors, including age, type of soil, temperature, diameter, and the type of pipeline material utilized (Al-Bargawi 2006; Heger 1985; Rajani 1996; Boot 1998; Makar 2000; Sinha and St. Clair 2009). The American Water Works Association calls it the Replacement Era. An estimated 1.2 million miles of distribution pipes supply Americans with drinking water. Many of them are nearing or have past retirement age. A big investment – perhaps as much as \$US 1 trillion over the next two decades – must be made to replace them. The basics of the U.S. water transmission and distribution network are profiled in tables provided below based on studies and surveys conducted by American Water Works Association (AWWA) and Water Research Foundation (WaterRF) (AWWA and WaterRF, 1992; 1996; AWWA, 2004). Because these surveys are based on limited responses, there are some variations in percentage breakdowns by pipe materials. As shown in Table 1-1, about two thirds of the installed network consists of various forms of ferrous pipes, including cast iron, ductile iron, and steel pipes.

Region	Population	Water Supply	Water Demand	Water Loss	Water Quality
North America	300,000,000	1,000,000,000,000	1,000,000,000,000	1,000,000,000,000	1,000,000,000,000
South America	300,000,000	1,000,000,000,000	1,000,000,000,000	1,000,000,000,000	1,000,000,000,000
Europe	300,000,000	1,000,000,000,000	1,000,000,000,000	1,000,000,000,000	1,000,000,000,000
Asia	300,000,000	1,000,000,000,000	1,000,000,000,000	1,000,000,000,000	1,000,000,000,000
Africa	300,000,000	1,000,000,000,000	1,000,000,000,000	1,000,000,000,000	1,000,000,000,000
Oceania	300,000,000	1,000,000,000,000	1,000,000,000,000	1,000,000,000,000	1,000,000,000,000
Total	1,200,000,000	4,000,000,000,000	4,000,000,000,000	4,000,000,000,000	4,000,000,000,000

PARTICIPATING UTILITY INFORMATION

The chart depicts geographically tagged location for the major participating utilities, rich data pertaining to drinking water pipeline performance data has been collected from the utilities depicted in the map. Our analysis will use five separate cohort samples: Eastern; Southern; Central; Northern; and Western. Please refer to Figure below. The same data collection strategies will be administered for all five-cohort samples, stratification, confidence interval and other statistical analysis methods. These regions are not equal in population, but they roughly share certain similarities, including their soil and temperature dynamics and the historical patterns of water pipe installation. Cohort based collection methodology is being pursued for increased efficiency and confidence in analyzed output

Figure 3.4 – Snapshot of utility hub home page

Data Hub

A data hub tab was inserted next to home page to provide data download services. The tab contents were modified using HTML and CSS codes. Text hyperlinks with three separate download services of Raw data, Standardized data and External data were provided in the data hub page (Figure - 3.5).

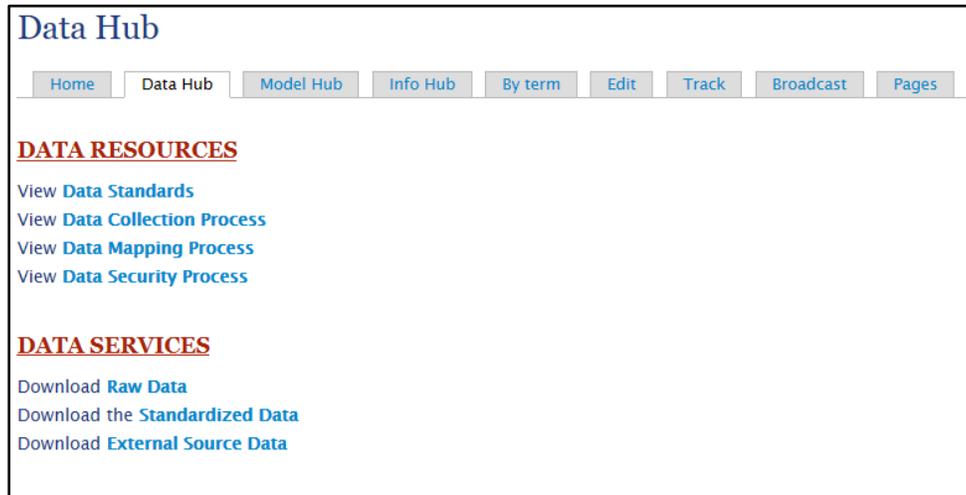


Figure 3.5 – Snapshot of Utility data hub page

Model Hub

Model hub is embedded into utility hub page as a tab next to data hub. It provides detailed description about models currently available to utility members. These models might vary from performance assessment of selected material type in the network to finite element analysis of a pipe section. Apart from providing model development methodology, model hub integrates GIS web applications hosted on ArcGIS as model hub content links. This is accomplished by linking the application URL to hub page content via html hyperlink tags.

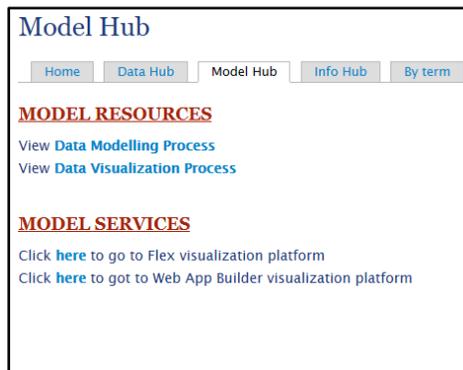


Figure 3.6 – Snapshot of model hub with applications from Flex tool and Web app builder tool

Info Hub

Information hub provides a map of contiguous united states with individual states hyperlinked in the map to statewide statistics. The basic purpose of information hub is to distribute gathered knowledge from collective analysis to all members as required. This hub contains an elaborate set of rejected/accepted hypothesis statements that were analyzed either by a singular large dataset or by combining multiple small datasets for high confidence.

Chapter 4

GEOGRAPHIC INFORMATION SYSTEM (GIS) WEB APPLICATIONS FOR DATA VISUALIZATION OF DRINKING WATER PIPELINES

Pururaj Singh¹, Sunil K. Sinha²

(1) Graduate Research Assistant, (2) Professor

Charles E. Via Department of Civil and Environmental Engineering
Virginia Tech, Blacksburg, VA

4.1 INTRODUCTION

Assessing the condition of pipeline systems requires implementation of sophisticated models that account for all major factors contributing to pipeline deterioration. Based on the results, stakeholders like utility managers, water operators, and government can plan their renewal and replacement strategies. However, this cannot be achieved unless data model results are presented in a way that leads to meaningful interpretations and patterns. Data visualization is an integral aspect in supporting decision across various hierarchical levels of an organization.

A necessary tool effective in disseminating drinking water pipeline datasets is the use of Geographic Information System (GIS) based applications. GIS provides a framework for storing, analyzing and mapping information to support robust decision-making processes. Water utilities are largely dependent on the in-house developed models to assess the risk on their pipeline systems. The reliability of these models is a function of external data parameters that can be incorporated in the analysis phase. Categorical representation of massive data chunks associated with drinking water pipelines helps water utilities to better design their capital improvement plans. A common platform for data sharing can facilitate increased understanding via bridging gaps in local utility knowledgebase and translating information on regional and national scale. This involves exploring the domains of data standardization, data enrichment and information visualization.

There are several open source tools available for development of GIS web platforms. These are Openlayers, Pmapper, GeoExt, Cadcorp, Flex viewer and ESRI's Web App Builder to list a few. Web App Builder tool was used in this research due to easy availability, scalable architecture and extensive widget catalogue. Virginia Tech enterprise geodatabase was used to store and host GIS data pertinent to this research. Techniques like buffer analysis, hotspot identification, interactive bar and line diagrams can be integrated with web apps to supplement existing functionalities.

This serves two purposes namely:

1. A robust GIS application capable to visualize intrinsic pipeline data in conjunction with external data parameters
2. Sharing models across multiple utilities for high confidence in accessing current and future conditions of assets.

4.2 DATA STANDARDIZATION

Data standardization is a crucial step in order to purge data under diverse profiles. Large, medium and small-scale utilities store data in disparate formats that are consistent with their organizational requirements. Pipeline parameters like material, data of installation, internal and external diameter, external coating, failure type, failure mode, replacement method, renewal cost etc. show great degree of variation as data from multiple utilities are compared. Moreover, no of data parameters available across different utility profiles also vary significantly. As data is collected through all phases of planning, engineering, manufacturing, operations, and maintenance, a standardized protocol to collect and code data values becomes imperative for quality analysis and visualization. The parameters affecting drinking water infrastructure and consequence of failure are listed in Appendix A and B respectively.

OBJECTID *	Subtype_Code	DIAMETER *	Pipe_Type *	AS_BUILT_LENGTH	MONTH_INSTALLED	YEAR_INSTALLED
1	Main	8"	Polyvinyl Chloride	<Null>	10	1999
2	Main	8"	Cement Lined Ductile Iron Polywrapped	3	2	2001
3	Main	8"	Cement Lined Ductile Iron Polywrapped	12	2	2001
4	Main	8"	Cement Lined Ductile Iron Polywrapped	7	2	2001
5	Main	4"	Cement Lined Ductile Iron Polywrapped	4	2	2001
6	Main	8"	Cement Lined Ductile Iron Polywrapped	413	2	2001
7	Main	4"	Cement Lined Ductile Iron Polywrapped	11	2	2001
8	Main	4"	Cement Lined Ductile Iron Polywrapped	41	2	2001
9	Main	12"	Polyvinyl Chloride	25	12	1999
10	Main	12"	Polyvinyl Chloride	560	12	1999
11	Main	12"	Polyvinyl Chloride	102	12	1999
12	Main	8"	Cement Lined Delavaud Cast Iron	<Null>	12	1947
14	Main	8"	Cement Lined Delavaud Cast Iron	<Null>	12	1947
16	Main	8"	Cement Lined Ductile Iron Polywrapped	35	10	1984
17	Main	8"	Cement Lined Ductile Iron Polywrapped	8	10	1984
18	Main	8"	Cement Lined Ductile Iron Polywrapped	3	<Null>	<Null>
19	Main	8"	Cement Lined Ductile Iron Polywrapped	<Null>	12	1947
20	Main	6"	Undesignated Cast Iron	<Null>	<Null>	<Null>
21	Main	8"	Cement Lined Ductile Iron Polywrapped	2	9	1986
22	Main	8"	Cement Lined Ductile Iron Polywrapped	242	9	1986
23	Main	8"	Cement Lined Ductile Iron Polywrapped	76	3	1991
24	Main	8"	Cement Lined Ductile Iron Polywrapped	363	3	1991
25	Main	6"	Cement Lined Delavaud Cast Iron	325	12	1934
26	Main	8"	Cement Lined Ductile Iron Polywrapped	4	3	1991
27	Main	8"	Cement Lined Ductile Iron Polywrapped	<Null>	3	1991
28	Main	8"	Cement Lined Ductile Iron Polywrapped	16	3	1991
29	Main	8"	Cement Lined Ductile Iron Polywrapped	20	3	1991
30	Main	12"	Cement Lined Ductile Iron Polywrapped	20	<Null>	<Null>
31	Main	12"	Cement Lined Ductile Iron Polywrapped	16	3	1991
32	Main	12"	Cement Lined Ductile Iron Polywrapped	<Null>	3	1991
33	Main	12"	Cement Lined Ductile Iron Polywrapped	11	3	1991
34	Main	12"	Cement Lined Ductile Iron Polywrapped	<Null>	<Null>	<Null>
35	Main	12"	Cement Lined Ductile Iron Polywrapped	<Null>	<Null>	<Null>

Figure 4.1 – Snapshot of Utility Raw Data sample

SHAPE *	pipe ID *	pipeline length	pipe material	pipe diameter	pipe joint type	city	conduit_Stat
Polyline	PM000156028	<Null>	Polyvinylchloride		8 Slip on	<Null>	Active
Polyline	PM000108504		3 Ductile Iron		8 Slip on	<Null>	Active
Polyline	PM000091881		12 Ductile Iron		8 Slip on	<Null>	Active
Polyline	PM000038923		7 Ductile Iron		8 Slip on	<Null>	Active
Polyline	PM000066368		4 Ductile Iron		4 Slip on	<Null>	Active
Polyline	PM000041503		413 Ductile Iron		8 Slip on	<Null>	Active
Polyline	PM000044201		11 Ductile Iron		4 Slip on	<Null>	Active
Polyline	PM000053438		41 Ductile Iron		4 Slip on	<Null>	Active
Polyline	PM000035473		25 Polyvinylchloride		12 Slip on	<Null>	Active
Polyline	PM000091660		560 Polyvinylchloride		12 Slip on	<Null>	Active
Polyline	PM000029825		102 Polyvinylchloride		12 Slip on	<Null>	Active
Polyline	PM000076881	<Null>	Delavaud Cast Iron		8 Leadite	<Null>	Active
Polyline	PM000120144	<Null>	Delavaud Cast Iron		8 Leadite	<Null>	Active
Polyline	PM000079831		35 Ductile Iron		8 Slip on	<Null>	Active
Polyline	PM000024472		8 Ductile Iron		8 Slip on	<Null>	Active
Polyline	PM000064888		3 Ductile Iron		8 <Null>	<Null>	Active
Polyline	PM000047528	<Null>	Ductile Iron		8 Leadite	<Null>	Active
Polyline	PM000083527	<Null>	Undesignated cast iron		6 <Null>	<Null>	Active
Polyline	PM000024898		2 Ductile Iron		8 Slip on	<Null>	Active
Polyline	PM000027157		242 Ductile Iron		8 Slip on	<Null>	Active
Polyline	PM000054888		76 Ductile Iron		8 Slip on	<Null>	Active
Polyline	PM000132794		363 Ductile Iron		8 Slip on	<Null>	Active
Polyline	PM000009297		325 Delavaud Cast Iron		6 Leadite	<Null>	Active
Polyline	PM000124054		4 Ductile Iron		8 Slip on	<Null>	Active
Polyline	PM000106895	<Null>	Ductile Iron		8 Slip on	<Null>	Active
Polyline	PM000112378		16 Ductile Iron		8 Slip on	<Null>	Active
Polyline	PM000018543		20 Ductile Iron		8 Slip on	<Null>	Active
Polyline	PM000146447		20 Ductile Iron		12 <Null>	<Null>	Active
Polyline	PM000116194		16 Ductile Iron		12 Slip on	<Null>	Active
Polyline	PM000022995	<Null>	Ductile Iron		12 Slip on	<Null>	Active
Polyline	PM000162625		11 Ductile Iron		12 Slip on	<Null>	Active
Polyline	PM000036324	<Null>	Ductile Iron		12 <Null>	<Null>	Active
Polyline	PM000066925	<Null>	Ductile Iron		12 <Null>	<Null>	Active

Figure 4.2 – Snapshot of standardized utility data sample

Organizing data requires the development of a database schema that underlines relationships between spatial and non-spatial tables storing data values. Previous research has contributed to the development of a personalized geodatabase for force main infrastructure (Bhaskar et al., 2016). Feature classes, tables and relationship classes are interlinked to store attribute values and spatial datasets. Building on the similar methodology, a data model for drinking water pipeline infrastructure has been created. Data storage limitations of a personal geodatabase (2 GB) lead to the creation of a file geodatabase with unlimited storage capacity. The complete data model schema is presented in Appendix C.

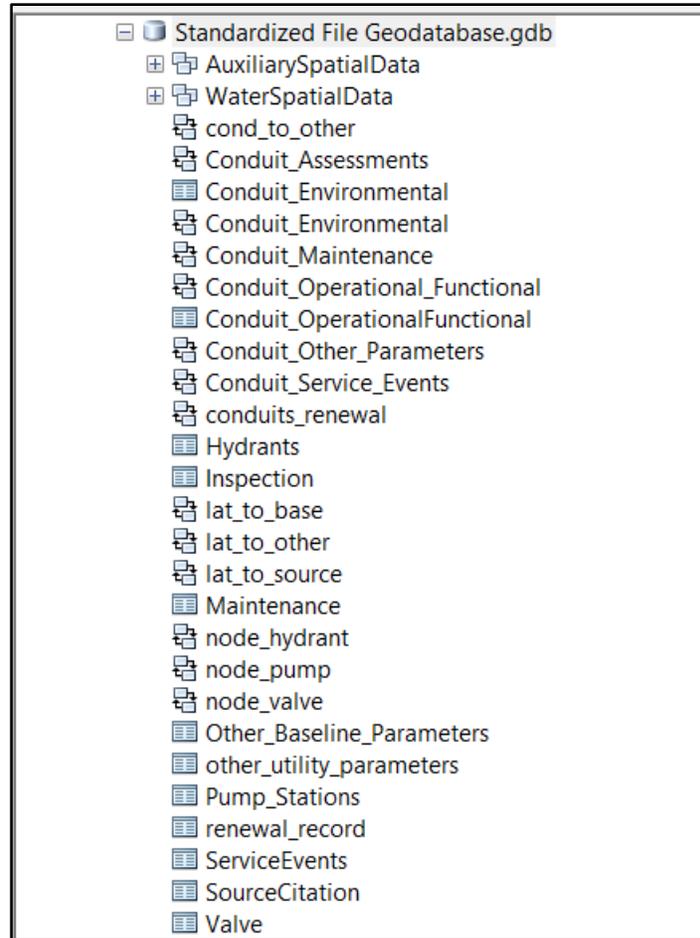


Figure 4.3 – Components of the standardized file geodatabase

4.3 EXTERNAL DATA COLLECTION AND INTEGRATION

External datasets when coupled with the pipeline internal parameters present true picture of pipeline surrounding and the effects these surrounding have on the condition of the individual pipe segments. Major external influences considered for this research are soil characteristics, overhead traffic loading pattern, land cover and stray currents. There are many open source platforms for data collection. USGS, SSURGO, Tiger Files, American fact finder and NLCD are some of the sources for data capture. In addition to external factors directly linked with pipeline failure, risk of a water main break is accessed by collection of demographic data like population density, gross yearly household income and block group and county specific elevation data. GIS provide parallel analysis capabilities through overlay of multiple feature classes. The following section highlight the visualized data with respect to soil and traffic.

4.3.1 Soil data collection and analysis

Soil data is downloaded from USDA’s spatial soil survey map. Data for contiguous US is available up to county level. Specific soil characteristics of interest are pH, concrete corrosion

potential, steel corrosion potential, frost action potential, cation exchange capacity, clay content, and shrink swell potential. These parameters are stored under different tables in the soil data model and require a common column tabular join for integration with soil shape file. Shape file attribute table is joined to component table based on the 'mukey' column. The software used for this purpose is ESRI's ArcMap. The soil polygon shape file is color coded based on corresponding parameter to support heuristic analysis. In order to preserve anonymity of data, images in this section are deliberately zoomed in at a scale to mask specific geographic locations.

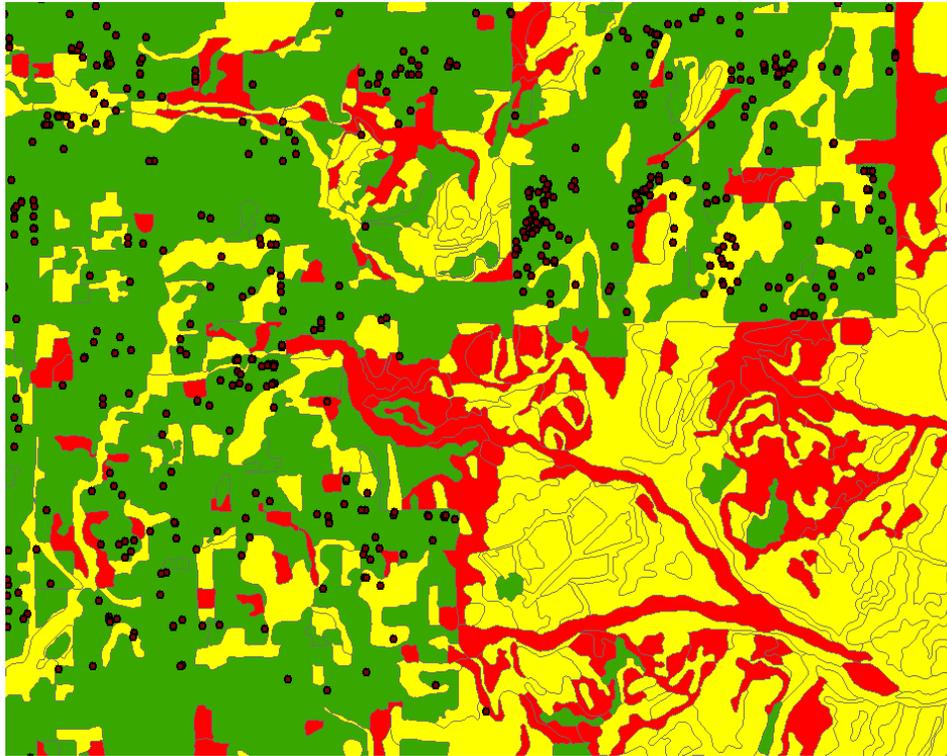


Figure 4.4 – Snapshot of soil steel corrosion color map with pipe break point layer

Pipe breaks in water pipeline networks are location specific data points and hence are represented by point shape files in the GIS model. In order to access risk or performance, a two-step process was employed

1. Selecting a subset of pipelines where breaks have occurred. This is done by using select by location function in arcmap.
2. Appending attributes from selected pipelines to surrounded polygon features, a spatial join based on location is performed to complete this step.

4.3.2 Traffic loading analysis and stray currents

Traffic loading on water pipelines that are buried at shallow depths can have an impact on the structural integrity of the system. Since majority of the network was installed before 1940, traffic loading patterns have changed substantially during this time. USGS tiger dataset contain line

shapefiles for all roads and railways. Pipelines in the vicinity of railway lines are susceptible to corrosion due to the effect of stray currents. This process is aggravated in the event of surrounding soil with high cation exchange potential. Corrosive effect on the reinforced concrete pipelines occurs through hydrogenation and the accumulation of corrosion products (Wang et al., 2017).

For analysis purpose, railway line shape file is imported in the arcmap environment. A buffer tool has been used to create a polygon shape file depicting the area of influence surrounding railway lines. Based on literature and previous research, buffer distance was set to 10 feet. Critical zones are identified based on the soil polygons having high cation exchange potential falling under 500 ft distance of buffered areas. Similar layers with arterial road network existing in the area of interest have been created. State DOTs provide access to GIS files with the Average Annual Daily Traffic (AADT) values. The roads are classified from high to low using Natural break classification in the dataset. Pipe burst locations are overlaid on the resultant file to identify potential hotspots of high traffic loading zones.

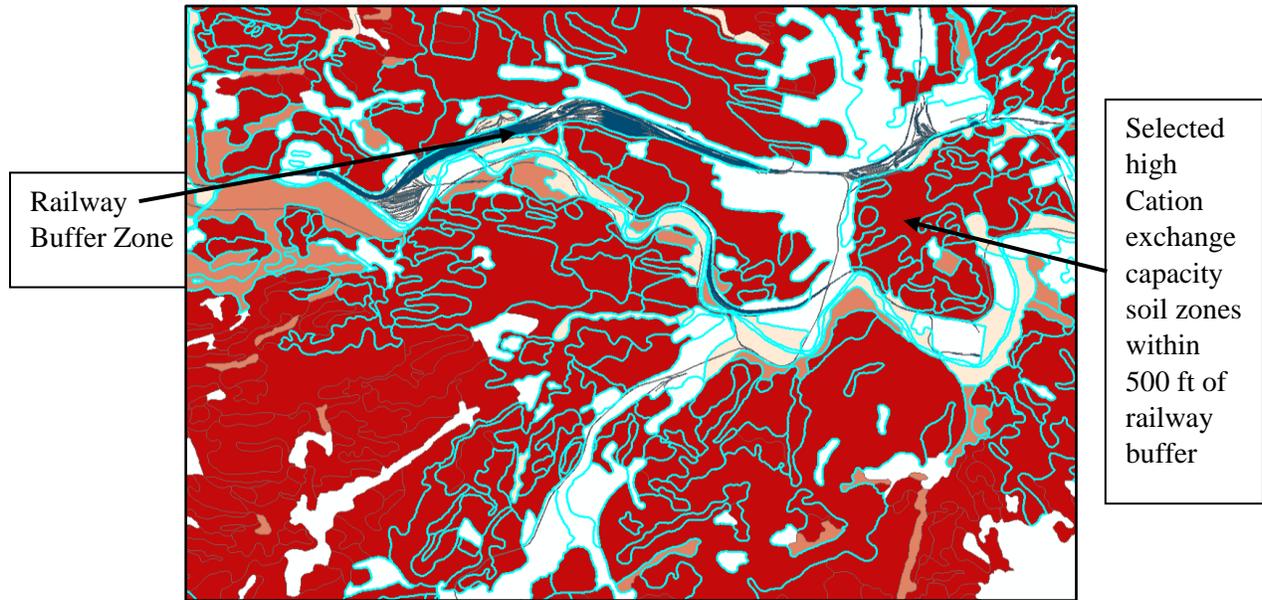


Figure 4.5 – Snapshot of stray current visualization approach

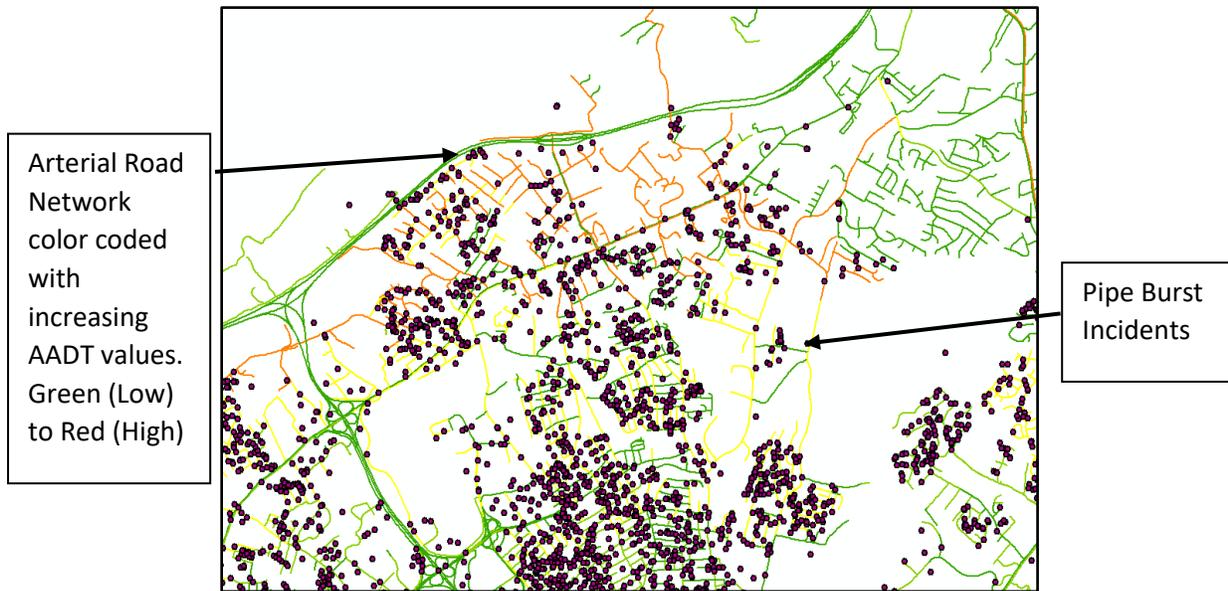


Figure 4.6 – Snapshot of road network traffic loading visualization approach

Visualization of layers is accomplished in the local environment of ArcMap 10.4.1 but saved layers and data are pushed to an enterprise geodatabase for publishing content online. Performance rating models and Risk rating models are first executed in the Excel environment on standardized utility data and final rating index is joined back to the pipeline shape file. A range of attributes are assigned weights according to their perceived importance on final rating index.

SR. NO	RISK RATING	OBJECT ID	RISK VALUE	LINGUISTIC VALUE	ACTION
1	1.700	1016	0-0.99	VERY LOW	NO ACTION REQUIRED
2	1.364	1304	1-1.99	LOW	WATCH OUT REQUIRED
3	1.364	1022	2-2.99	MEDIUM	MITIFATION ACTION IN LONG TERM
4	1.490	817	3-3.99	HIGH	MITIGATION ACTION IN SHORT TERM
5	1.934	658	4-5.0	VERY HIGH	IMMEDIATE MITIGATE ACTIONS REQUIRED
6	1.934	1120			
7	1.784	1121			
8	1.934	1125			
9	2.144	1337			
10	1.490	687			
11	1.352	1339			
12	1.688	1343			
13	1.688	690			
14	1.688	1340			
15	2.095	695			
16	2.095	1139			
17	1.866	1140			

Figure 4.7 – Risk rating index on excel environment with object ID field

4.4 GIS WEB APPLICATIONS AND VISUALIZATION EXAMPLES

Saved layers and map documents from analysis on arcmap are published online for development of web applications for information dissemination and decision support. This section highlights the techniques available for data visualization in the web application interface. Performance model and Risk rating model are depicted on sample utility data. ESRI's Web Application Builder tool was used to develop applications. A detailed process for web app development is presented in Appendix C.

4.4.1 Utility X

Model depicting pipeline performance was developed to tie individual sections/node-to-node length with a performance rating index. The resulting network was then color coded in three separate classes of Low, Medium and High performance. Cartographic map developed was combined with additional layers of hydrant counts, pipeline junctions, steel corrosivity index of soil and major roads in the service area to understand cumulative impact.

The map service is published online through ArcMap online functionality inbuilt on Arcmap Desktop. The service is published through Virginia tech enterprise account and is equipped with two tier authentication features. Post publication of the service, a web application utilizing hosted map layer was developed. The web application is built using Web App builder for ArcGIS and all the widgets configured on the application are available directly to users. Legend and Layer widgets are configured to provide users with information regarding layer classifications.

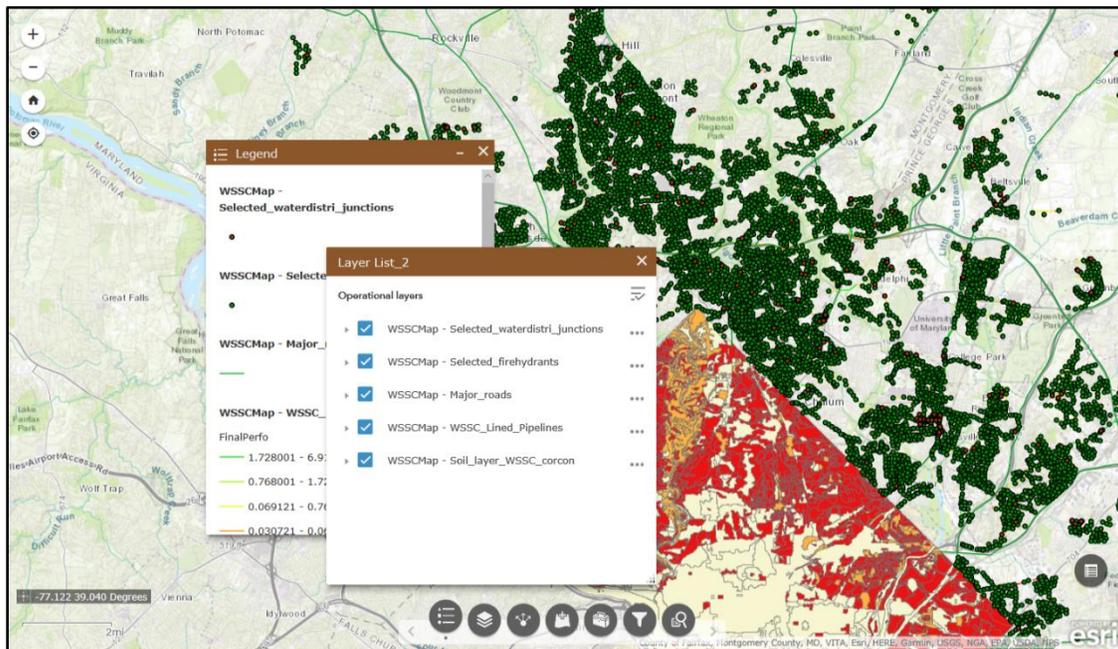


Figure 4.8 – Layer and Legend widgets in web application

Chart widget was configured to provide interactive bar and line charts for a user defined AOI. Data queries like material count, diameter distribution, performance rating with material, performance rating with diameter etc. were applied using widget configuration tab. Resultant charts populated have dynamic visualization capabilities as ‘zoom-on-click’ functionality is available to users. Feature selection is available through ‘Select’ widget at the bottom widget panel. Properties of selected features can be viewed from the attribute table and statistics related to final performance can be viewed for general interpretation.

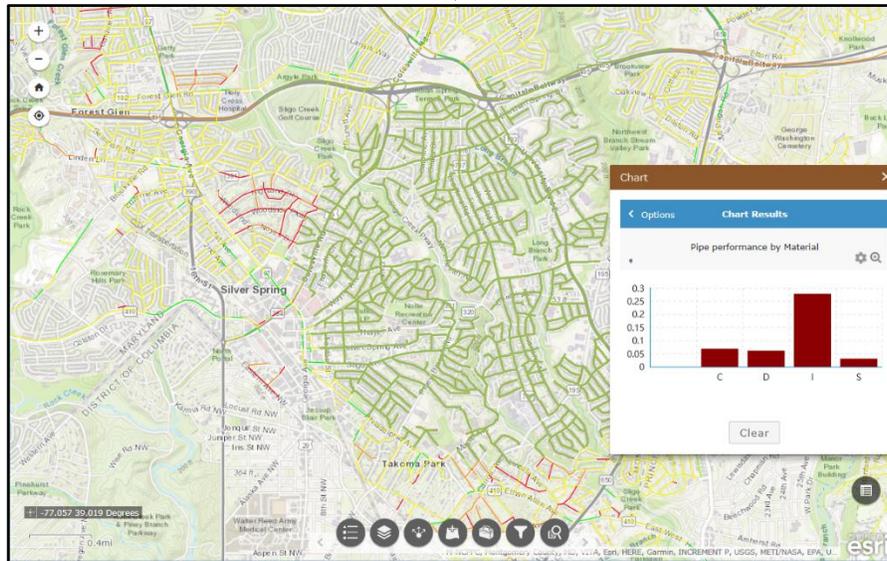
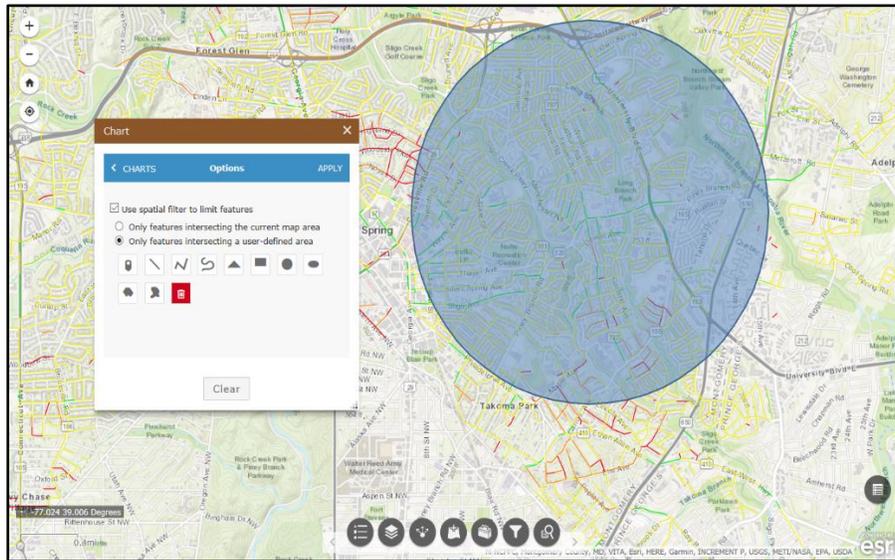


Figure 4.9 – Chart widget in the web application depicting pipe performance results with respect to material in a user defined spatial selection

4.4.2 Utility Y

Pipeline risk model was developed using probability and consequence of failure scores for a sample utility break data. The final risk rating index was attached to pipeline network segments using Object ID field. Symbology of the resultant layer was defined using 3 categories of low, medium and high-risk. Map document is published online with the intact symbology using tile mapping capabilities in the service publishing dialogue box. In addition to chart widget displaying line and bar diagrams of average risk ratings for selected pipelines in a user defined AOI, analysis widget has been configured with functionalities of buffer creation, density calculation, hotspot identification, point aggregation and data export.

Hotspot analysis of pipe break point layer with age at failure can be visualized in Fig 4.8. While ‘Calculate Density’ function can identify clusters in data, hotspot analysis determines the statistical significance of those clusters. Hotspots are statistically significant points possessing high values of the target attribute while cold spots are statistically significant data points possessing low values of target attribute.

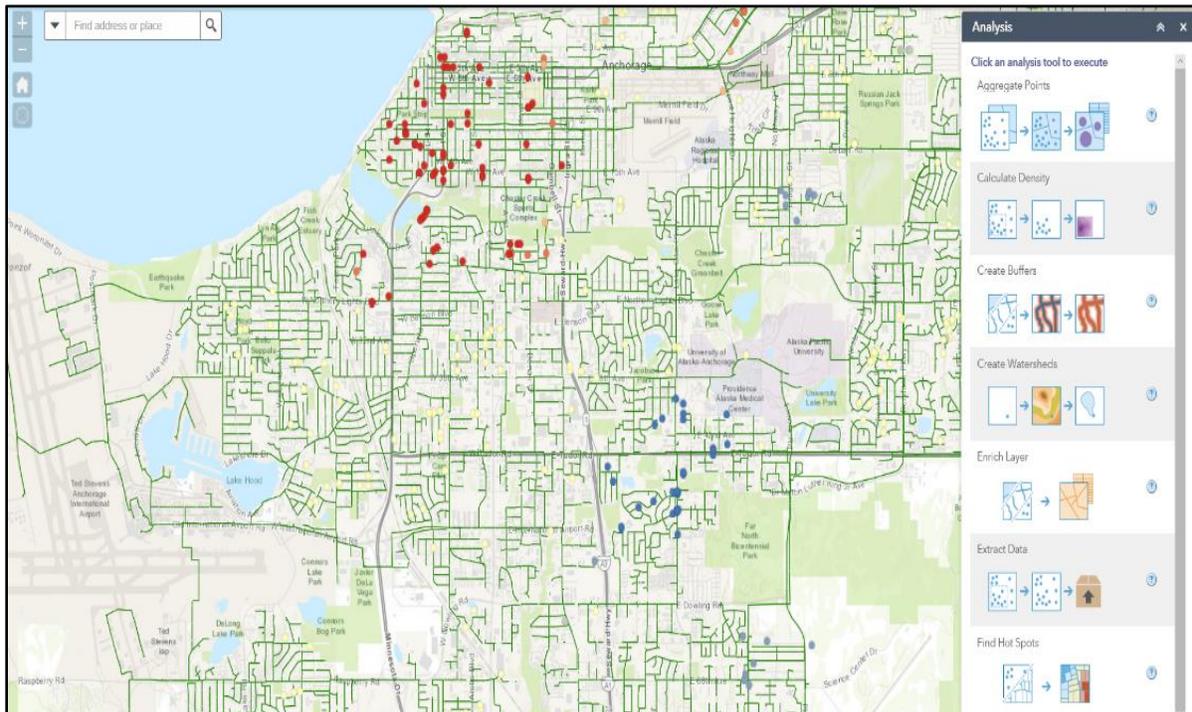


Figure 4.10 – Analysis widget capabilities and age at failure hotspot analysis

Risk rating model was developed on the excel environment and final rating was imported in the arcmap as a database table with Object ID field intact. A tabular join was performed to the pipe break point layer to match risk score with respective data point. Finally, the map document was

published on Virginia tech enterprise account as a map service through arcmap desktop. The map service was used as an input to web app builder tool and resultant application was linked to PIPEiD website for information dissemination.

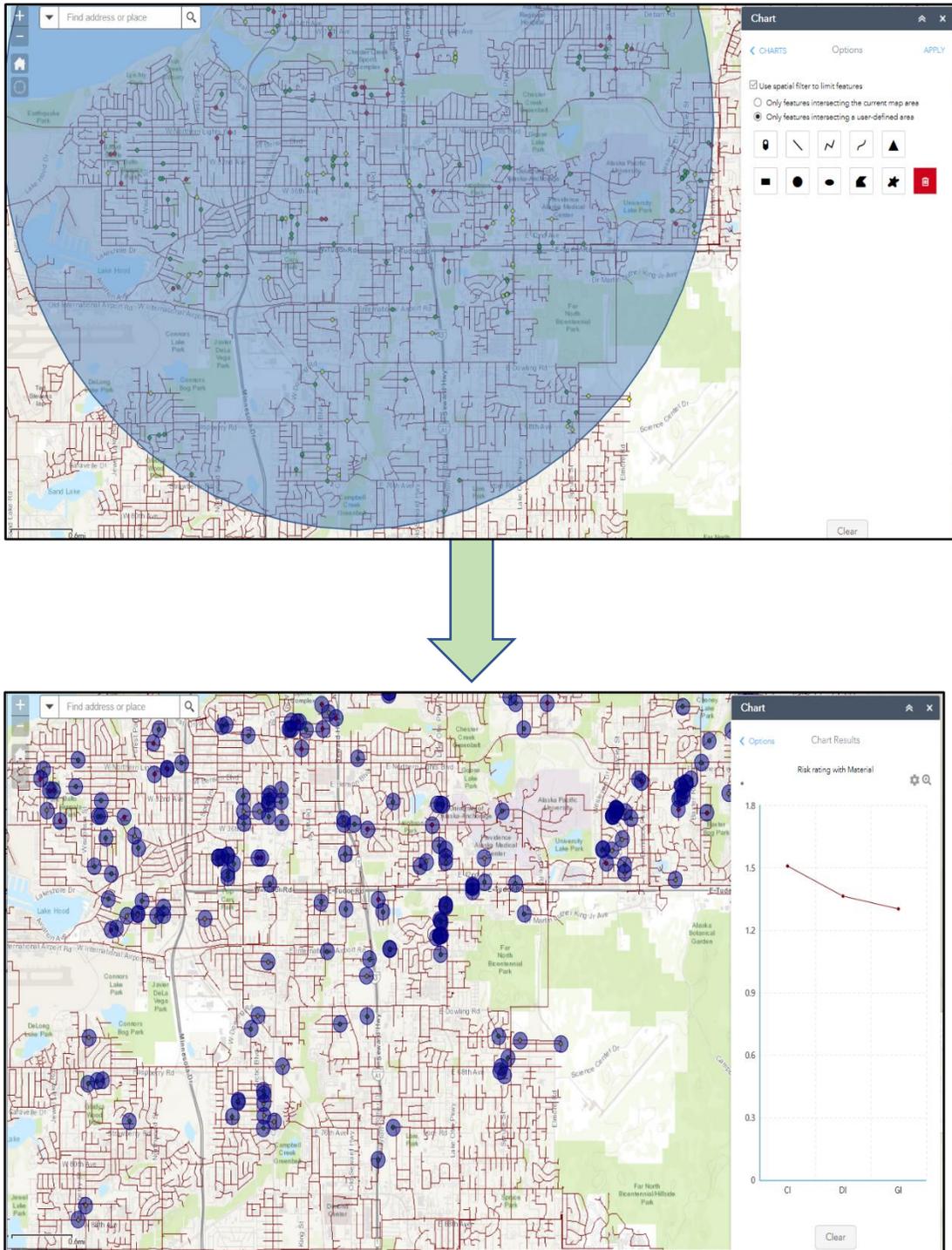


Figure 4.11 - Risk rating with material line chart populated in a user defined AOI

The risk rating values depicted of different materials in the above diagrams have no statistical backing and it just showcases the data presentation capabilities of the GIS web application. This document in no way claims to prove the validity of employed risk and performance rating models, however the implementation of models in a web application environment is elaborated in context with drinking water pipeline data visualization.

4.4.3 Utility Z

5 layers related to a Utility Z data were published online as map service capable of mapping and KML services.

- Pipe burst incidents is a point layer showing location of pipe burst locations.
- Pipe repair layer depicts all pipelines with repairs happened
- Street layer color coded with total AADT counts
- Railroad layer
- Soil layer classified according to the steel corrosion potential index

Typical layout of the application is shown in Fig 4.12. Layer, Legend, Basemap, Analysis and Select widgets are designated to specific parcels in the application interface.

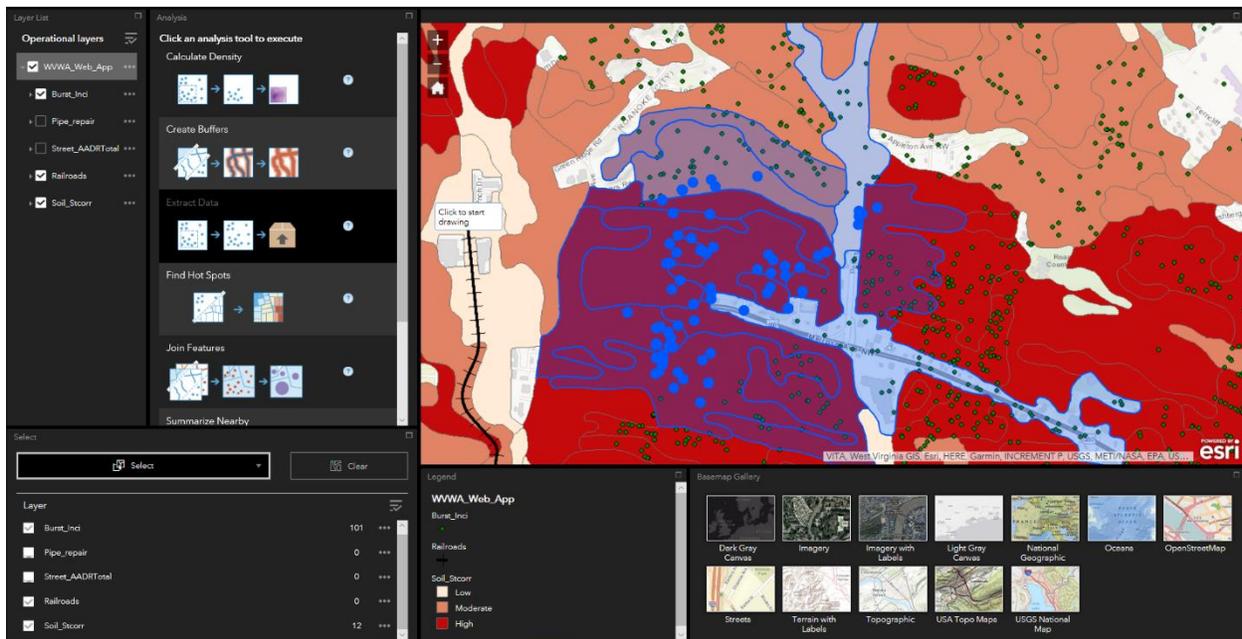


Figure 4.12 – Snapshot of GIS web app with select widget tool functionality

Select widget functionality is shown which enables the user to easily sketch an area of interest and selectable features from all the layers that fall partially within the drawn sketch are selected. Attribute values of selected features can be exported to local machine using export feature tool. The resulting table can be viewed in excel for further investigation.

Analysis widget provide multiple functionalities like ‘Summarize Within’ which results in summarizing the break points falling in a soil polygon layer. Consequently, polygons with high

break counts can be analyzed in detail. Multiple buffers can be created at the same time using ‘Create Buffer tool’, this is especially useful in analyzing pipe breaks near railway crossings to study potential stray current effects.

4.5 INFORMATION DISSEMINATION AND DECISION SUPPORT

Analysis and visualization results are distributed to respective utilities through PIPEiD platform. Individual utility hub pages are created to provide exclusivity of access to models and corresponding applications. To navigate efficiently through PIPEiD platform, utilities are divided based on their scale of operation into small, medium and large utilities. Geographical division in 5 cohorts of northern, central, southern, eastern and western states across the country is created through primary links on the website. Each menu item leads to a page containing mentioned utility scale categories.

A utility hub page provides three main services of

- Raw Data and Standardized Data download
- External data download pertaining to the respective utility
- Web Application and Modeling Platform access

Utility Hub Pages comprise of three tabs: data hub, model hub and information hub (Figure 4.13). Data hub provides information of data collection strategies and links to raw and standardized datasets. External data download link too is embedded in the data hub. Model hub provides information about nature of models employed and links to web applications for visualization. Information tab will provide the knowledge gained through analysis across diverse utility datasets with exposing the data itself.

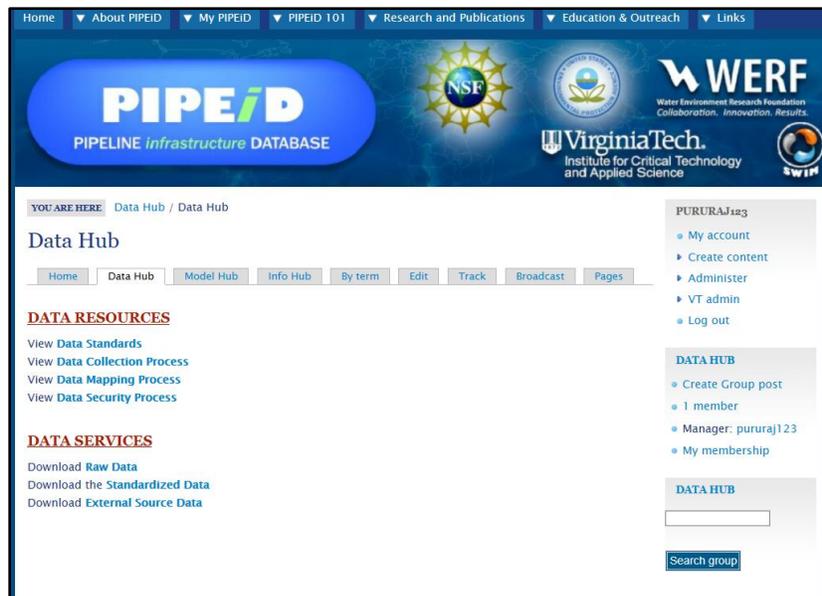


Figure 4.13 – Utility Hub Page snapshot

4.6 CONCLUSION

This manuscript elaborated on several aspects that need to be considered for developing GIS web applications using ESRI's web app builder tool. Drinking water utilities are scattered in their approach of data collection and storage. This document presented a data standardization framework for efficient query and analysis of disparate data sources. Model results are disseminated through different visualization strategies tailored towards strategic, tactical and operational level decision support requirements.

This document highlights the tools available for information visualization in a web application environment. Multiple widgets are configured, and their respective capabilities are showcased through examples of sanitized utility datasets. Techniques for collection and integration of external data through various open source platforms is highlighted which can be used by water utilities to enrich their data content. The developed applications are distributed to stakeholders via PIPEiD website which acts as a centralized and secured platform for all utilities to download, query and visualize information.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The need for effective asset management of drinking water infrastructure is underscored by the fact that water pipeline network in united states provides service to more than 320 million residents of the county. Consequently, condition assessment and risk analysis on these buried assets has gained prime importance for efficient utilization of federal and private funds. This involves supporting decision making process at various organizational levels. Data visualization is an integral aspect to extract knowledge from gathered and analyzed information. This thesis presents a visualization framework for drinking water pipelines to support comprehensive asset management practices.

Key areas of Data Standardization, Enrichment and Visualization are presented in this document with the help of sanitized utility data examples. This thesis elaborated on tools and techniques available to visualize performance and risk model output in conjunction with external data layers in a web environment. Development of a GIS based web application to enhance scalability, flexibility and dynamic data visualization is highlighted in this document. The main contributions include:

- Modifications on the centralized PIPEiD platform resulted in smooth navigation through incorporation of new site menus and links. Creation of geographical cohorts resulted in increased organization for utility hub pages.
- Developed a file geodatabase system for storing drinking water pipeline data parameters to function as a standard for data collection and storage.
- Collected external shape files related to traffic loading, soil characteristics, land cover, demographic and climate datasets for specific utility service area locations.
- Elaborated on the steps to publish content online through arcmap 10.4.1 desktop and used advanced development tools like ESRI's Web Application Builder to create web applications showcasing different widgets depicting pipeline performance and risk rating model outputs along with external data layers to support decision making.
- Introduced new tabs namely data, model and info hub under utility specific pages to help provide services of raw, standardized and external data download, web application links and generalized knowledge dissemination. This is accomplished on www.pipeid.org website.

5.2 RECOMMENDATIONS

Drinking water pipeline asset management can be made more comprehensive by incorporation of a standardized data collection and storage model. There is a need for a centralized web-based GIS centric platform for water utilities to analyze and run diverse models on sanitized datasets. A methodology to collate external data parameters that effect pipeline condition will help access the cause-effect relationships between water main failures and multiple external influencers.

The future scope of research should focus to improve developed GIS web application using –

1. ArcGIS Developer edition toolkit for web app builder that utilizes HTML/Javascript programming language. This will enable creation of custom widgets tailor made for specific utility requirements.
2. Creating a standard report template and enabling the report generation tool on the web application by publishing it as a geo-processing service on ArcGIS Desktop. This can help effectively disseminate content to diverse set of users.
3. Developing a robust thin-client based data storage protocol to minimize data loading time on the client side.
4. Upgrade the PIPE*i*D website Drupal edition to enable new modules and site tracking capabilities. This will aid in creating dynamic content on individual utility hub pages.
5. Geoprocessing capabilities on the web app builder can be explored in detail to integrate models with user-defined inputs and or fuzzy/Matlab based models. This can be done via hybrid integration of third party services where model processing is outsourced and only the results are integrated with visualization platform. Analysis software APIs can be explored to call Python scrips in the ArcMap model builder platform.

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APPENDIX A

A1-1a. Drinking Water Baseline Physical Parameters			
Parameter	Units	Source	Level
Pipe identification number	Pipe ID	Utility records	Essential
Pipe node length	Feet	Utility records; construction specification	Essential
Material type	Material Type	Utility records; construction specification; pipe sample	Essential
Design diameter	Inches	Utility records; construction specification; product standards; pipe sample	Essential
Age	Years	Utility records; construction specification	Essential
Depth	Feet	Utility records; construction specification; other testing	Essential
Location	GPS Coordinates	Utility records; construction specification	Essential
Design life	Years	Utility records; product standards	Essential
Joint type	Joint Type	Utility records; construction specification; product standards	Silver
Lining	Lining Type	Utility records; construction specification; product standards; pipe sample	Silver
Cathodic protection	Yes/No	Utility records; construction specification	Silver
Vintage	Year	Utility records; construction specification; product standards	Silver
Design wall thickness	Inches	Utility records; construction specification; product standards; pipe sample	Silver
Remaining wall thickness	Inches	Utility records; pipe sample	Silver
Installation	Year	Utility records; construction specification	Silver
External coating	Yes/No	Utility records; construction specification; product standards; pipe sample	Silver
Wire type (PCCP only)	Wire Type	Utility records; product standards	Silver
Thrust restraint	Yes/No	Utility records; construction specification; other testing	Gold
Pipe section length	Feet	Utility records; construction specification; product standards	Gold
Manufacture/class/date	Year	Utility records; construction specification	Gold

Material quality	Records	Utility records; construction specification; product standards; pipe sample	Gold
Dissimilar metals	Material Type	Utility records; construction specification	Gold
Degradation of pipe material	Records	Utility records; product standards; pipe sample; other testing	Gold
Trench width	Feet	Utility records; construction specification; other testing	Gold
Valve type	Type	Utility records; construction specification	Gold
Absorption capacity	%	Utility records; product standards; other testing	Gold

A1-1b. Drinking Water Baseline Environmental Parameters			
Parameter	Unit	Source	Level
Land cover	Feet Square	Utility records; construction specification; aerial photography; online database	Essential
Soil type	Type	Utility records; geotechnical records; other testing; online database	Essential
Water source	Records	Utility records	Essential
Dead load	Pounds	Utility records; construction specification; aerial photography	Essential
Live load	Pounds	Utility records; other testing	Essential
Climate/temperature	°F	Utility records; online database	Silver
Soil corrosivity	Level	Utility records; geotechnical records; other testing	Silver
Groundwater table	Feet	Utility records; geotechnical records; other testing; online database	Silver
Bedding condition	Records	Utility records; construction specification; other testing	Silver
Stray currents	Records	Utility records; construction specification; geotechnical records; other testing	Silver
Frost penetration	Feet	Utility records; other testing; online database	Silver
Soil moisture content	%	Utility records; geotechnical records; other testing	Silver
Flooding	Records	Utility records; aerial photography; online database	Silver
Soil pH	pH	Utility records; geotechnical records; other testing	Gold
Trench backfill	Records	Utility records; construction specification; other testing	Gold
Soil resistivity	Level, Ωm	Utility records; geotechnical records; other testing	Gold
Extreme events	Records	Utility records; online database	Gold
Non-uniform bedding	Yes/No, Records	Utility records; construction specification; other testing	Gold

Topography	Records	Utility records; construction specification; aerial photography; online database	Gold
Groundwater corrosivity	Level	Utility records; other testing	Gold
Compliance	Records	Utility records; other testing	Gold
Soil disturbance	Records	Utility records	Gold
Runoff rate	%	Utility records; other testing	Gold
Rainfall/precipitation	inches	Utility records; other testing; online database	Gold
Slope of land	%	Utility records; construction specification; aerial photography; online database	Gold
Tidal influences	Records	Utility records; aerial photography; other testing; online database	Gold
Catchment area (watershed)	Feet Square	Utility records	Gold
Seismic activity	Records	Utility records; online database	Gold
Average closeness to trees	Level	Utility records; aerial photography	Gold
Wet/dry cycles	Records	Utility records; online database	Gold
Soil sulfides	Units	Utility records; geotechnical records; other testing	Gold

A1-1c. Drinking Water Operational Data			
Parameter	Units	Source	Level
Operational pressure	Psi	Utility records; hydraulic model; other testing	Essential
Pipe renewal record	Record	Utility records	Essential
Water quality violations	Records	Utility records; other testing	Essential
Operation and maintenance practices	Records	Utility records	Essential
Consumption	gpm	Utility records	Essential
Service type	Type	Utility records; construction specification; hydraulic model	Essential
Pressure limitations	Records	Utility records; product standards	Silver
Water temperature	°F	Utility records; other testing	Silver
Water flow velocity	gpm	Utility records; hydraulic model; other testing	Silver
Pressure surges	Records	Utility records; hydraulic model	Silver
Pipe inspection record	Records	Utility records	Silver
Leakage amount	Gallons	Utility records; hydraulic model; other testing	Silver
Pressure complaints	Records	Utility records; customer complaints	Silver

Discolored water	Records	Utility records; customer complaints; other testing	Silver
Leakage allowance	%	Utility records	Silver
Water pH	pH	Utility records; other testing	Gold
Hydraulic capacity	gpm	Utility records; product standards	Gold
Backflow potential	Level	Utility records; hydraulic model	Gold
Fire flows	Level	Utility records; other testing	Gold
Water pumps	Number	Utility records; construction specification; product standards	Gold
Connection density	Number	Utility records; construction specification; hydraulic model	Gold
Service connections	Number	Utility records; construction specification; hydraulic model	Gold
Main connections	Number	Utility records; construction specification; hydraulic model	Gold
Service interruptions	Number	Utility records; customer complaints	Gold
Hydrant density	Number/100 ft	Utility records; construction specification; hydraulic model	Gold
Valve density	Number/100 ft	Utility records; construction specification; hydraulic model	Gold
Node elevation	Number/100 ft	Utility records; construction specification; hydraulic model	Gold
Node hydraulic	Number/100 ft	Utility records; construction specification; hydraulic model	Gold
Backlog of maintenance	Records	Utility records	Gold
Hydrant information	Records	Utility records; product standards	Gold
Valve information	Records	Utility records; product standards	Gold
Wire breaks (PCCP only)	Records	Utility records; other testing	Gold
Water corrosivity	Level	Utility records; other testing	Gold
Water age	Time	Utility records; hydraulic model	Gold
Presence of tuberculation	Yes/No, Level	Utility records; other testing	Gold
Water alkalinity	pH, Level	Utility records; other testing	Gold
Dissolved oxygen content	%	Utility records; other testing	Gold
Water source	Records	Utility records	Gold
Hazen-Williams C factor	Number	Utility records; hydraulic model	Gold

A1-1d. Drinking Water Financial Parameters			
Parameter	Units	Source	Level
Annual Capital Cost	\$/Year	Utility Records	Essential
Annual Maintenance Cost	\$/Year	Utility Records	Essential
Annual Repair/Rehabilitation Cost	\$/Year	Utility Records	Essential
Installed and Replacement Cost	\$	Utility Records	Silver
Annual Operational Cost	\$/Year	Utility Records	Silver
Annual Energy Cost	\$/Year	Utility Records	Silver

Depreciated Value	%	Utility Records	Gold
Benefit/Cost	Record	Utility Records	Gold

A1-1e. Drinking Water Forensic Parameters			
Parameter	Unit	Source	Level
Age	Year	Utility Records	Essential
Remaining wall thickness	Inches	Utility Records/ Forensic Inspection	Essential
Failure mechanism	Records	Utility Records/ Forensic Inspection	Essential
Failure mode	Records	Utility Records/ Forensic Inspection	Essential
Third party damage	Records	Utility Records/ Forensic Inspection	Silver
Manufacturing defects	Records	Utility Records/ Forensic Inspection	Silver
Rupture modulus	ROM	Forensic Inspection	Gold
Tensile strength	psi	Forensic Inspection	Gold
Fracture strength	psi in ^{1/2}	Forensic Inspection	Gold
Joint condition	Level, Records	Forensic Inspection	Gold
Lining condition	Level, Records	Forensic Inspection	Gold
Bedding condition	Level, Records	Forensic Inspection	Gold
Coating condition	Level, Records	Forensic Inspection	Gold
Cathodic protection condition	Level, Records	Forensic Inspection	Gold

APPENDIX B

A1-2. Drinking Water Consequence of Failure Parameters			
Parameter	Unit	Source	Level
Environmental Impact	Level 1	Utility records, expert judgment	Essential 1
Traffic Flow Impact	Level 1	Utility records, expert judgment	Essential 1
Service Disruption Impact	Level 1	Utility records, expert judgment	Essential 1
Time Impact – Length of time out of service	Level 1	Utility records, expert judgment	Essential 1
Financial Impact - carrying out the repair of pipe section	Level 1	Utility records, expert judgment	Silver
Financial Impact on Private Property	Level 1	Utility records, expert judgment	Silver
Access to Pipe	Level 1	Utility records, expert judgment	Gold
Utility Density	Level 1	Utility records, expert judgment	Gold
Type of Utility	Type	Utility records, expert judgment	Gold
Utility Pattern	Type	Utility records, expert judgment	Gold
Quality of Utility Record	Level 1	Utility records, expert judgment	Gold
Availability of Repair materials	Level 1	Utility records, expert judgment	Gold
Contaminated Soils	Level 1	Utility records, expert judgment	Gold
Other Factors	Level 1	Utility records, expert judgment	Gold

APPENDIX C

WEB APPLICATION DEVELOPMENT GUIDELINES

Model Builder environment is composed of several key elements which are being elaborated as below. Fig - C.1 depicts the composition of these essentials and their subtypes.

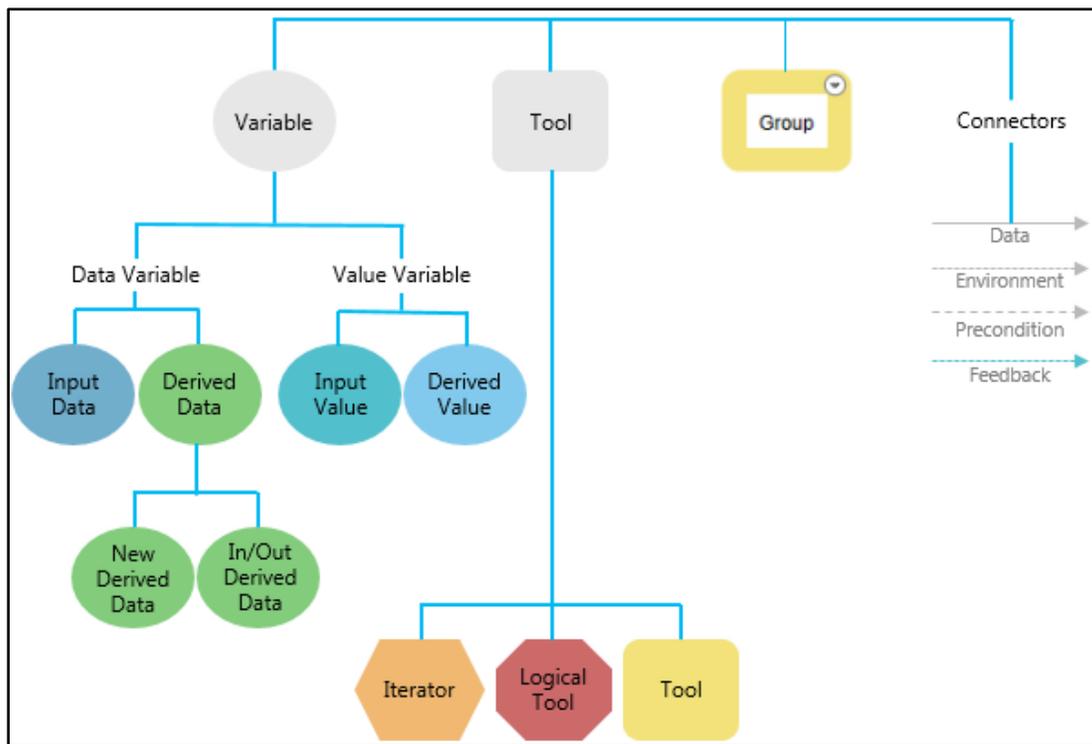


Figure C.1 - Model Builder Components

Tools in a Model

There is a multitude of inbuilt tools available in ArcMap toolbox however many times, custom tools that are defined by the user are necessary for analysis and computation purposes. These tools are created in the model builder platform provided by ArcMap and moreover can be

incorporated in the toolbox to be applied to layers in for iterative analysis purposes. Fig - C.2 provides an overview of model builder platform and tools created while analyzing utility data.

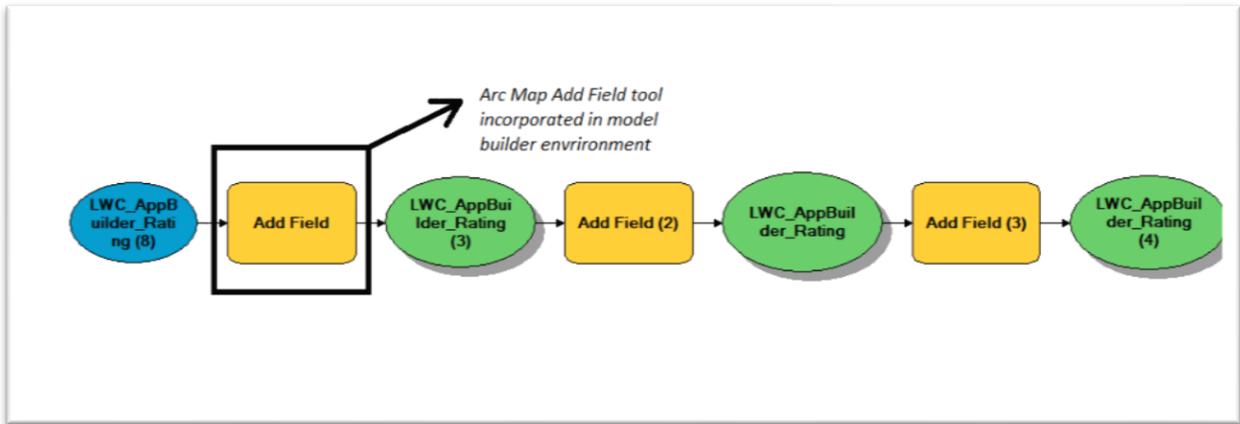


Figure C.2 – Model Builder interface and Tool incorporation

Variables in a Model

Variables are elements in the model builder platform that can store data paths or values. Data paths are referenced to specific layers or datasets that are used for analysis while data values can range from Booleans, Strings, Numbers or Environments to name a few. Fig – C.3 highlights this concept with much clarity

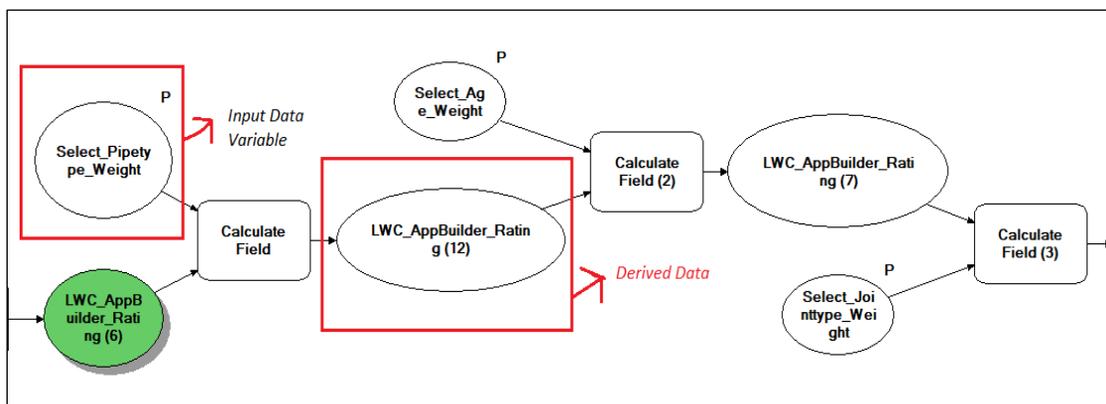


Figure C.3 – Variables in model builder for PIPEiD models

Connectors in a Model

Connectors are used to connect values and data layers together. They are essential elements in the completion of the model as data and tools interact with each other via connectors. Connectors can be categorized as data, environment, precondition, and feedback.

Labels in a Model

In addition to the variable, tool, and connector model elements, there are text label elements, which are graphic elements for explanatory text in a model. A label is not part of the processing sequence. Labels can be attached to elements or float freely in the model diagram.

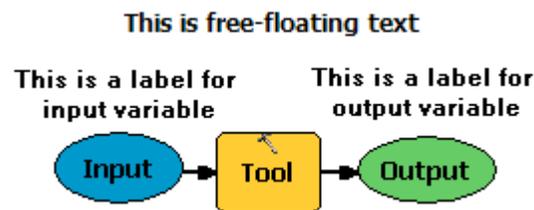


Figure C.4 - Labels

Model Execution – Local

Following are the sequential steps to be followed for executing model in a model builder environment on the local machine. These are not hardwired and have been formulated as per the experience of research team members

Creating new personal geodatabase

Creation of a new geodatabase is recommended prior to model development to ensure file path consistency and stable workspace. New personal geodatabase will acquire appropriate geometric coordinate system as deemed with for the dataset. Arc Catalog window offers the functionality of creating a new geodatabase. The process is intuitive, and a simple right-click on the catalog

window provides us with the option. Fig - C.5 below depicts this option on a sample model development phase under PIPEiD.

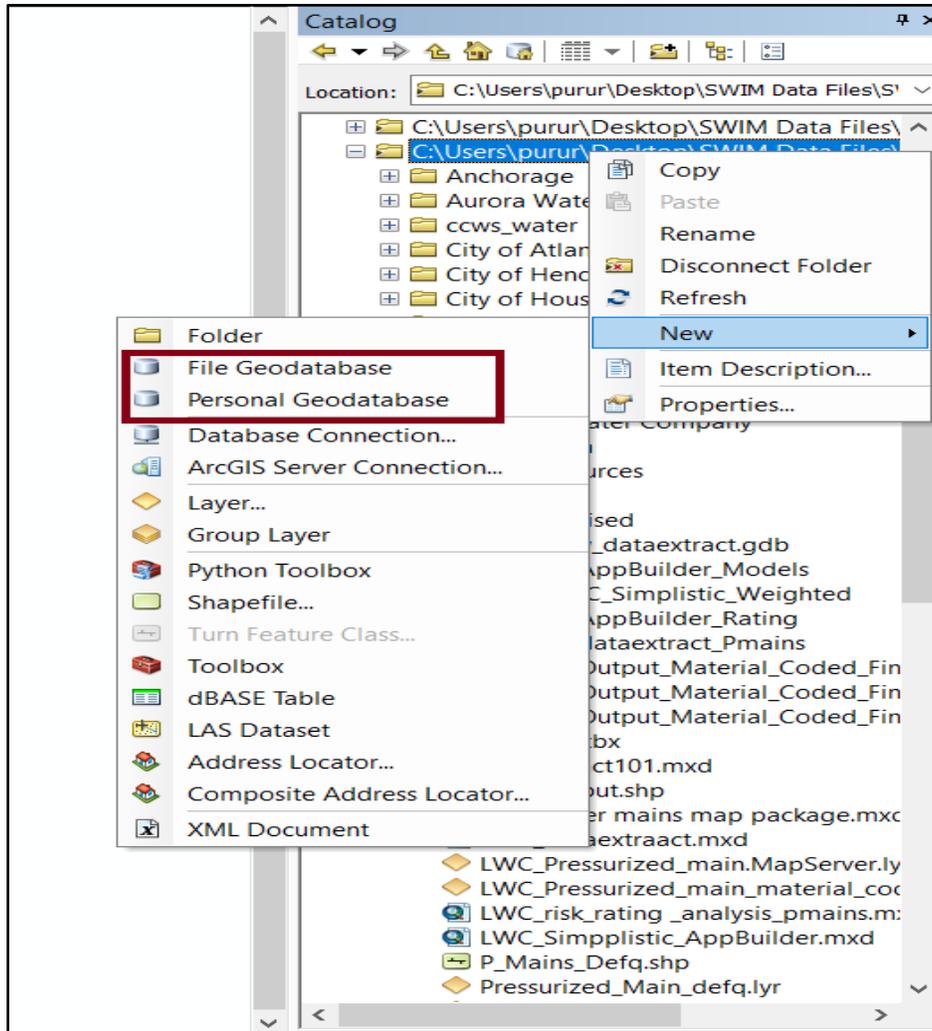


Figure C.5 – Personal Geodatabase Catalog Tree

Defining Model Parameters

This is an extremely crucial step when it comes to publishing models that are user interactive. Model parameters can be considered as user-defined inputs that help in the processing of interlinked tasks comprising the model. Weighted model for Utility A contains user-defined weights for Material, Diameter, Joint type, as build length and Age. This can be seen in the model flowchart below in Fig – C.6.

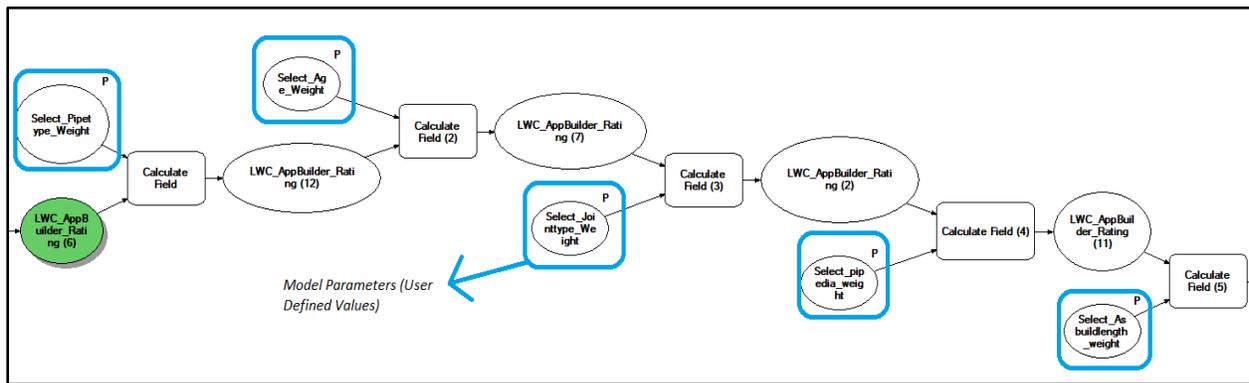


Figure C.6 – Model Parameters containing user-defined weights on PIPEiD test model

1. Errors and high priority warnings

Publishing the model through geoprocessing results window is the next step after successful completion of model development. Broken connections, inappropriate layer coordinate systems, non-coherent data types are some of the common high priority errors without which model publishing process cannot undergo.

2. Checking that data source is registered with the server
3. Checking that local machine is connected to the publishing server.
4. Service Capabilities - Weighted models, Fuzzy models or Risk rating models are geoprocessing services. In the service editor dialogue box, Mapping, Geoprocessing or KML should be ticked on as per requirements. The figure below elucidates this process
5. Publishing the service, this may take several minutes depending on the data accessed by service.
6. Noting down the unique service URL that can be accessed from service properties tab in the catalog window

Model Execution Web

Following are the sequence of steps to be completed for publishing local models to online applications. These applications can then be accessed by the intended audience for multiple purposes ranging from simple data queries to populating region specific charts to run risk rating models.

Creating an Enterprise ESRI Account

Enterprise ESRI account can be created via logging in to ESRI’s Enterprise GIS web page. The main purpose of creating an enterprise account is to exploit full-scale functionalities of Web App builder which are otherwise not available when an individual account is used. The Fig – C.7 below depicts clearly where to navigate on the website to create an enterprise account.

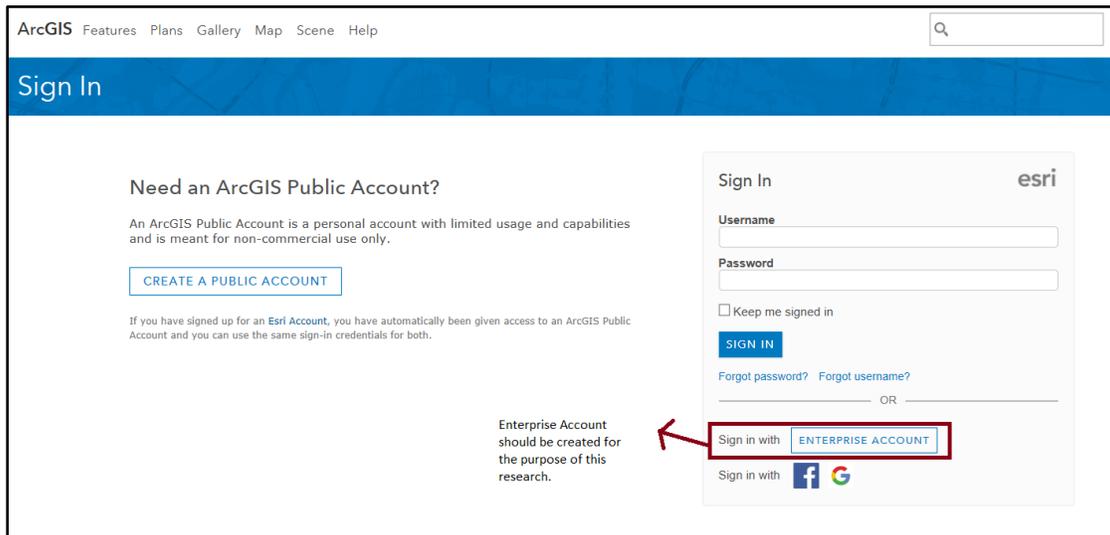


Figure C.7 - Enterprise Account Login Page ESRI Arcgis online

Publishing layers under My Content (Setting access settings to private)

Next step in the process is to publish the layers to be used in the web application on the “my content” panel on the profile homepage. ArcMap allows for publishing map services to online content. This can be accomplished directly from the software panel whereby any map can be shared as a service. The user needs to be connected to the online resources for this to work properly.

An interface of the “My Content” page is shown in the Fig – C.8 below:

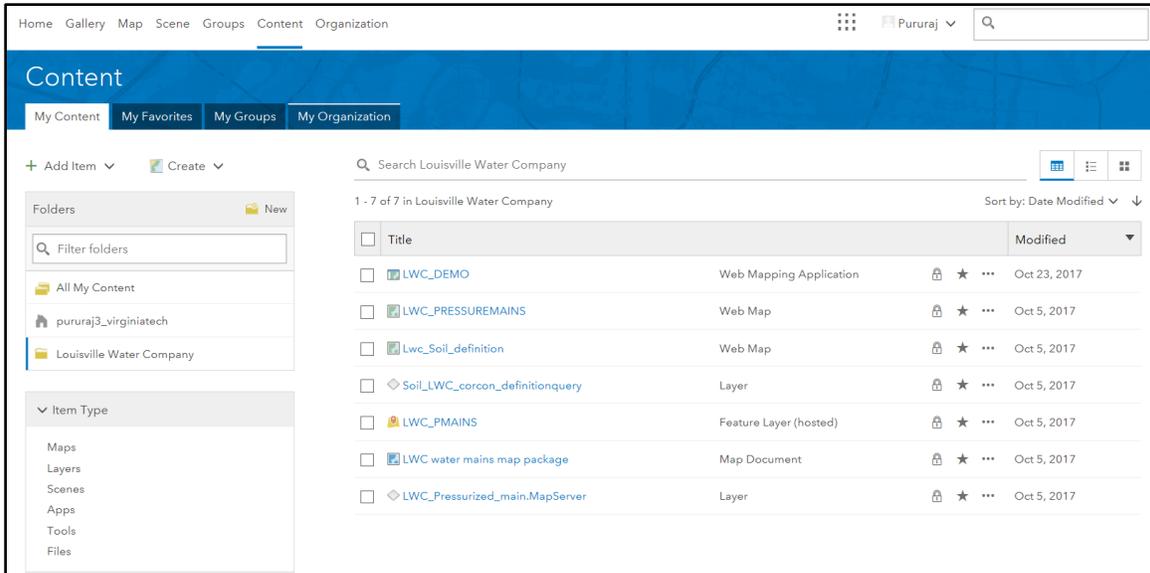


Figure C.8 - “My content” page web app builder

Creating an application through web app builder (2D)

Web application builder is the hub when the application is designed, and functionalities are added. ESRI has provided with several inbuilt themes for the applications, these can be accessed from the properties pallet of the web app builder. In addition to themes, this pallet also provides the developer access to base maps to be used for applications. A wide range of selection options is available through online base opensource base maps. The research team selected the streets and roads base map for simplicity and clarity. The widgets can also be accessed from the properties pallet as shown in the Fig – C.9 below:

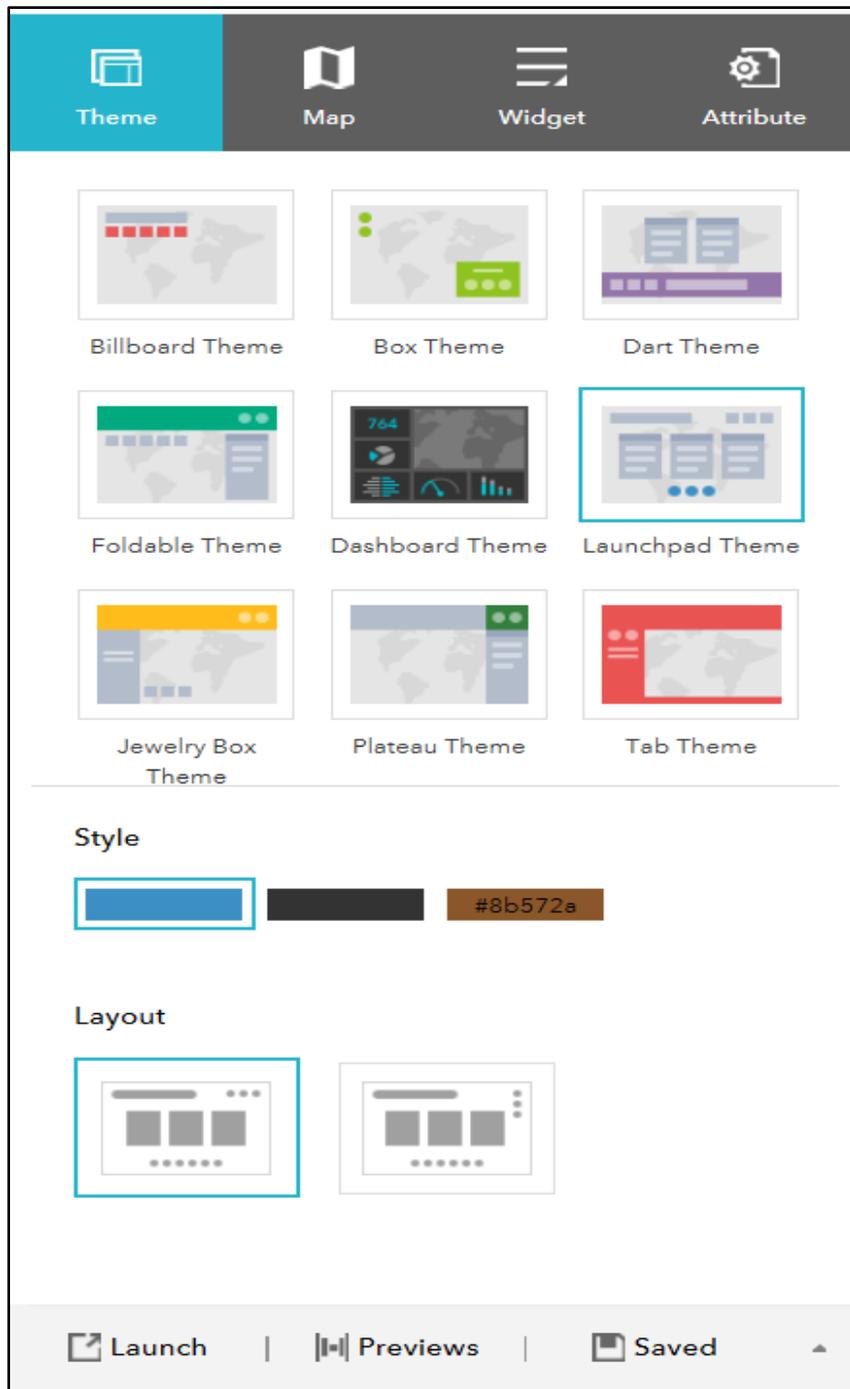


Figure C.9 – Properties Pallet Web Application Builder

Widgets

Widgets provide the functionality necessary for the application. To make the user query the data, populate charts on the data, download selected data, perform hotspot analysis on the data, cluster

analysis on the data and much more, widgets are integral to everything related with user experience on the site. The application developed by the research team currently utilizes several widgets including the Chart widget, Geoprocessing widget, layer widget to name a few.

Charts

Charts widget enable the user to select an Area of Interest (AOI) and populate attribute fields of the layers selected based on user-defined criteria. The widget also empowers users to select the type of resultant visualization. Pie charts and Bar histograms are incorporated in the application developed by the research team.

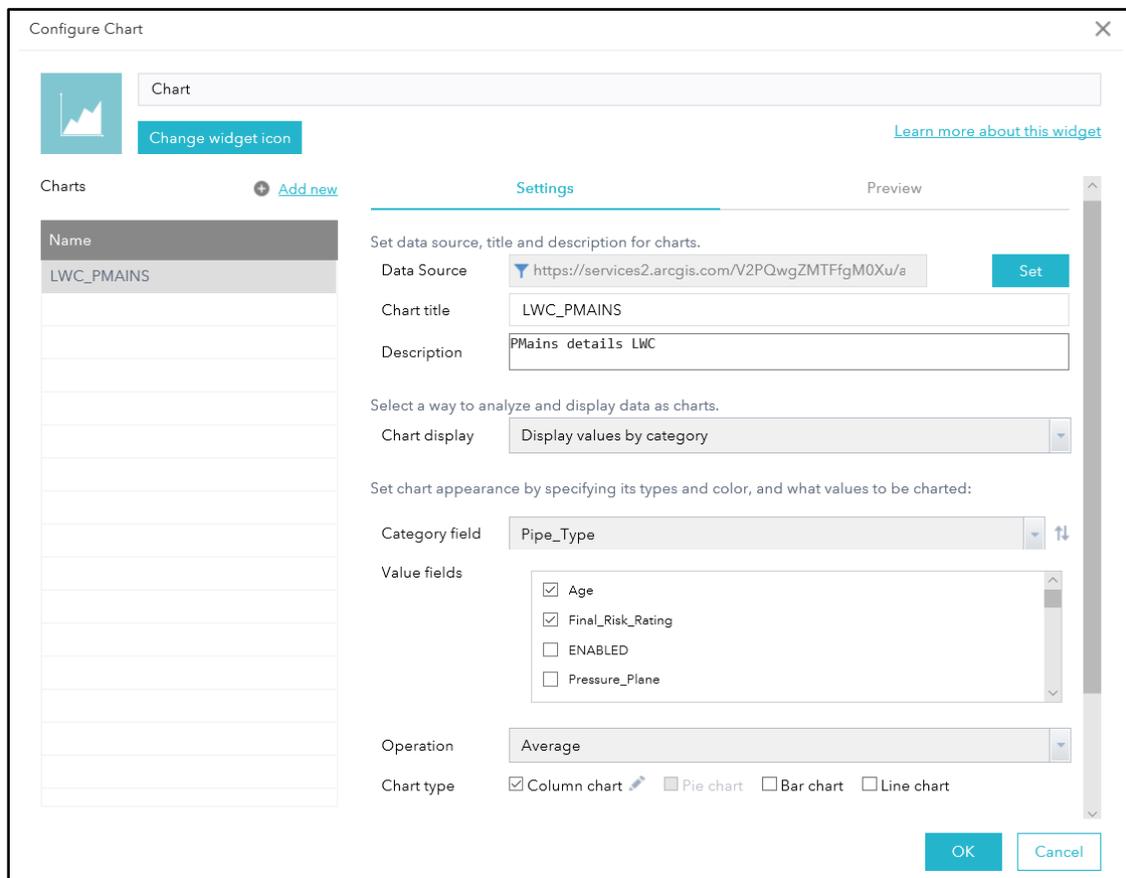


Figure C.10 – Chart Widget Configuration Page

Layers

Layers widget enable the user to manage all the layers that the application is accessing. This widget provides the functionality of turning on and off several layers based on the interest and type of visualization necessary.

Geoprocessing

This is the most important widget in the web application builder domain. Models published on the local machine are tied to the web application via Geoprocessing widget. The widget utilizes a task URL which accesses the server where the application is being hosted. All the application on PIPEiD are hosted on Virginia tech server and are subject to the two-factor authentication process.

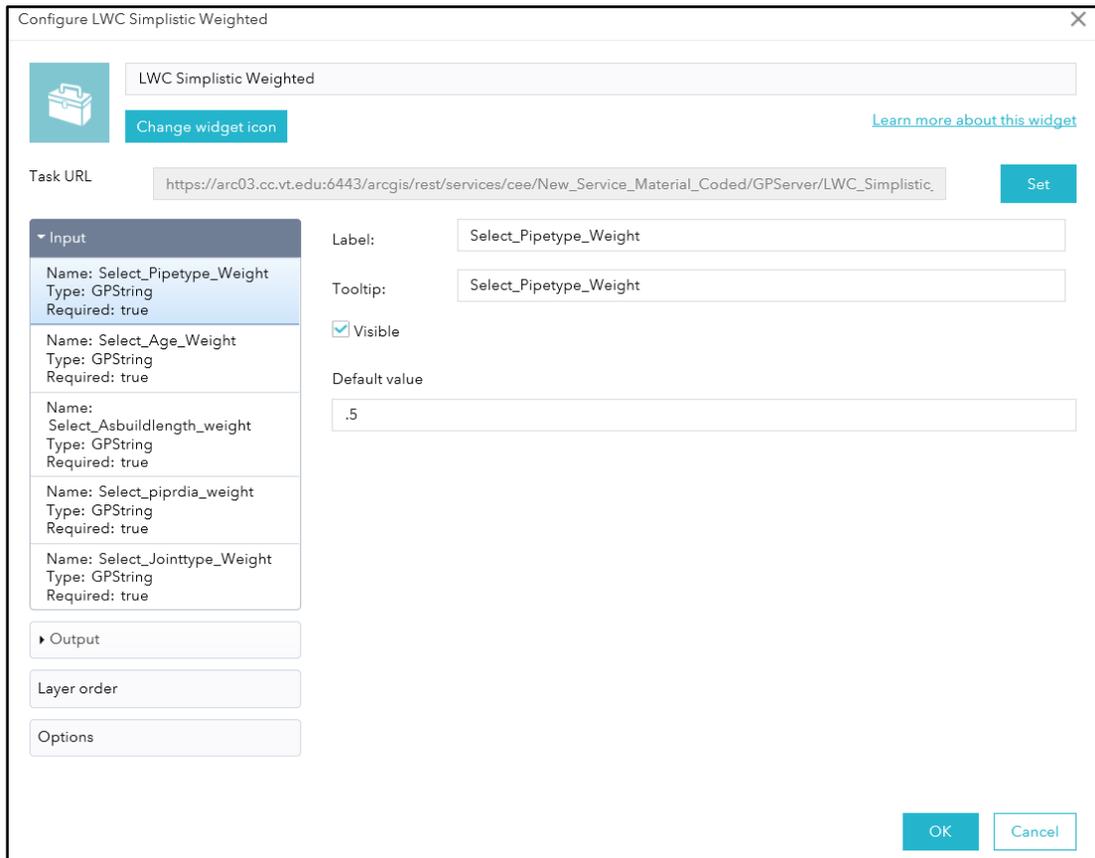


Figure C.11 – Geoprocessing widget configuration tab

