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Geog574
Final Project
April 22, 2024

Abstract:

This project aims to design and implement a spatial database that enhances the efficiency and effectiveness of Capital Improvement Program (CIP) planning for municipal infrastructure, focusing primarily on roads and watermains. By integrating and analyzing geospatial data, the database supports strategic decision-making in municipal infrastructure management. Key functionalities include identifying patterns of infrastructure degradation and enabling preemptive maintenance to optimize resource allocation. This report outlines the conceptual and logical database designs, the implementation of spatial data structures, and the development of queries that drive CIP decisions. Through this approach, the project demonstrates the essential role of spatial databases in advancing municipal planning and infrastructure maintenance, thereby improving community resilience and enhancing the quality of life for residents.

Introduction

Municipalities rely heavily on efficient and effective infrastructure management to ensure the quality of life and safety of their residents. Central to this management is the execution of Capital Improvement Programs (CIPs), which are strategic, long-term investment plans aimed at the construction, maintenance, and enhancement of infrastructure assets. These assets typically include roads, watermains, and other public utilities that are crucial for everyday life.

The execution of CIPs requires planning and prioritization to allocate limited resources wisely and to mitigate potential risks associated with aging infrastructure. Geospatial data is increasingly playing a pivotal role in this context, offering insights into the spatial characteristics and conditions of municipal assets. By leveraging such data, municipal engineers can make more informed decisions, prioritize improvements more effectively, and maximize the impact of investments.

Problem Statement

Despite the availability of geospatial data, many municipalities face significant challenges in integrating this data into their CIP planning processes. One major hurdle is the lack of a robust spatial database system that can efficiently manage and analyze diverse datasets related to municipal infrastructure. Specifically, municipal engineers often struggle with:

- **Data Fragmentation**: Geospatial data is frequently dispersed across various departments and formats, making it difficult to consolidate and use effectively.
- **Data Quality and Accessibility**: Inconsistent data quality and lack of easy access to up-to-date information often hinder accurate analysis and forecasting.
- **Analytical Capabilities**: The existing tools may not adequately support the spatial analyses required for effective infrastructure planning and decision-making.

The focus of this term project is to address these challenges by designing and implementing a spatial database tailored for CIP planning. This database will:

- Consolidate geospatial data related to roads and watermains, providing a unified view that facilitates more effective decision-making.
- Enhance decision-making capabilities through query functionalities and spatial analysis tools that can identify maintenance needs.
- Support dynamic CIP planning by allowing municipal engineers to simulate various scenarios and assess the potential impacts of different investment strategies.

The main objective of this project is to develop a spatial database that enhances the efficiency and effectiveness of CIP planning through improved management and analysis of geospatial data related to municipal infrastructure such as roads and watermains. This system aims to provide a platform that facilitates better decision-making and strategic planning in municipal infrastructure projects.

Model Design

The Model Design section presents the framework for the spatial database, crucial for enhancing CIP planning for municipal roads and watermains. This section outlines the conceptual model and the logical model, focusing on how the database structures data and defines relationships between key infrastructure elements.

Conceptual Model

The conceptual model serves as the foundation for a spatial database designed to support the management and analysis of municipal infrastructure, focusing on roads and watermains. The model is structured to capture not only the attributes and characteristics of the infrastructure but also the relationships and interactions between different elements. The conceptual model (*Figure 1*) was created using the online tool, ERDPlus.

Roads Entity

The Roads entity is central to the model, capturing data about the roadway system within a municipality. Attributes include *RoadID* for unique identification, *RoadName* for common naming, and *FromRoad* and *ToRoad* to denote connectivity and flow. Further attributes such as *RoadType*, *SurfaceType*, and *TrafficVolume* provide insights into the road's design and usage, while *LastMaintenanceDate* and *ConditionRating* are included for assessing the road's current condition and planning future maintenance.

Watermain Entity

Parallel to roads, the *Watermain* entity records information about the water distribution system. Each watermain is uniquely identified by *PipeID* and described by its *Material*, *Diameter*, and *InstallYear*, with *PipeLength* capturing its spatial extent. A notable feature of this entity is the *BreakFrequency* attribute, a derived value that quantifies the condition of the watermain by calculating a breaks per foot score based on the length of pipe and the related watermain breaks.

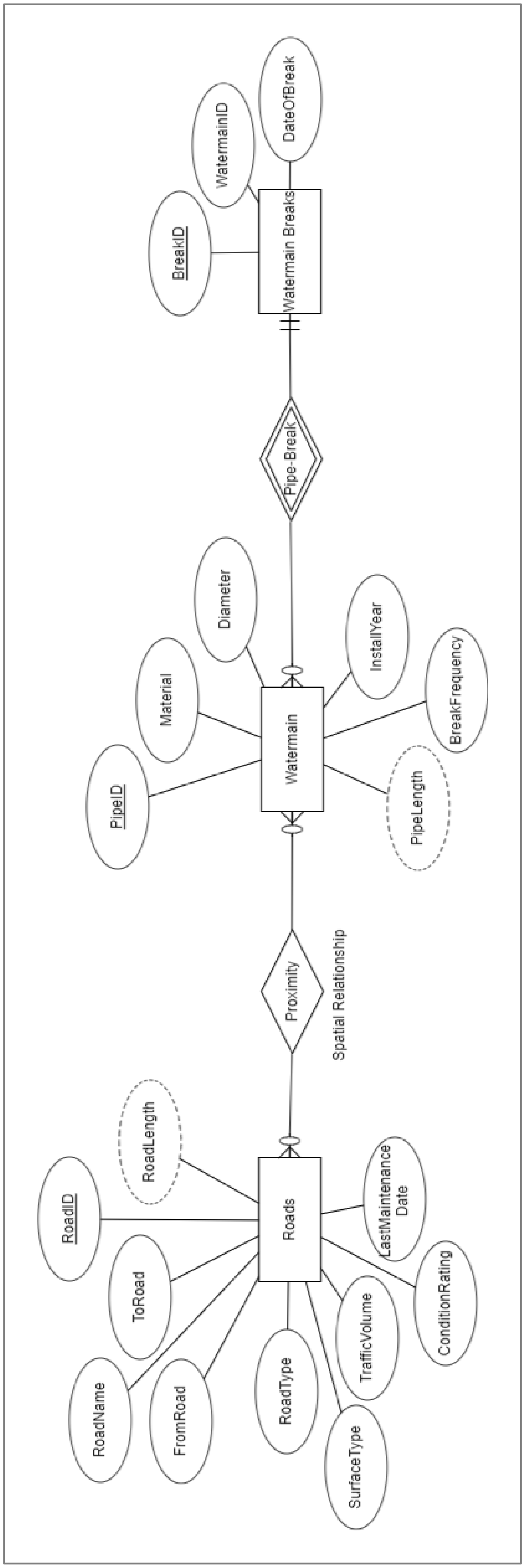

Figure 1. Conceptual Model (ERD Plus)

Watermain Breaks Entity

To understand the impact of watermain failures, the *Watermain Breaks* entity is included. It links each recorded break, identified by *BreakID*, to the affected *WatermainID* and logs the *DateOfBreak*. This data is used in analyzing break patterns and identifying potential vulnerabilities within the water distribution system. The relationship between the watermain and the watermain breaks entity is indicated by the *Pipe-Break* element. The notation indicates that watermain breaks are dependent on watermains. A break cannot exist unless there is a watermain. Additionally, there can be more than one break on a watermain, but a break cannot have more than one watermain associated with it.

Spatial Relationship

A key aspect of the conceptual model is the spatial relationship called *Proximity*, which connects the Roads and Watermain entities. This represents the physical reality of watermains often running beneath roads, necessitating a wholistic approach to infrastructure maintenance and planning. The notation used in this model indicates that the relationship is optional, meaning that there can be roads without watermains and watermains that do not run underneath a road (through a park, for example). The notation also indicates that there can be more than one watermain under a given road, and potentially, one segment of watermain may run underneath more than one road.

Logical Schema Diagram

The logical schema diagram (*Figure 2*) is part of the spatial database design process that translates the conceptual model into a practical structure for implementation. It details the tables, fields, and relationships that constitute the database, focusing on the essential geospatial objects such as roads, watermains, and their attributes, and the interconnections between them. This schema not only establishes the database's architecture, with key constraints and domain constraints ensuring data integrity, but also illustrates the spatial and nonspatial relationships crucial for the dynamic analysis of municipal infrastructure.

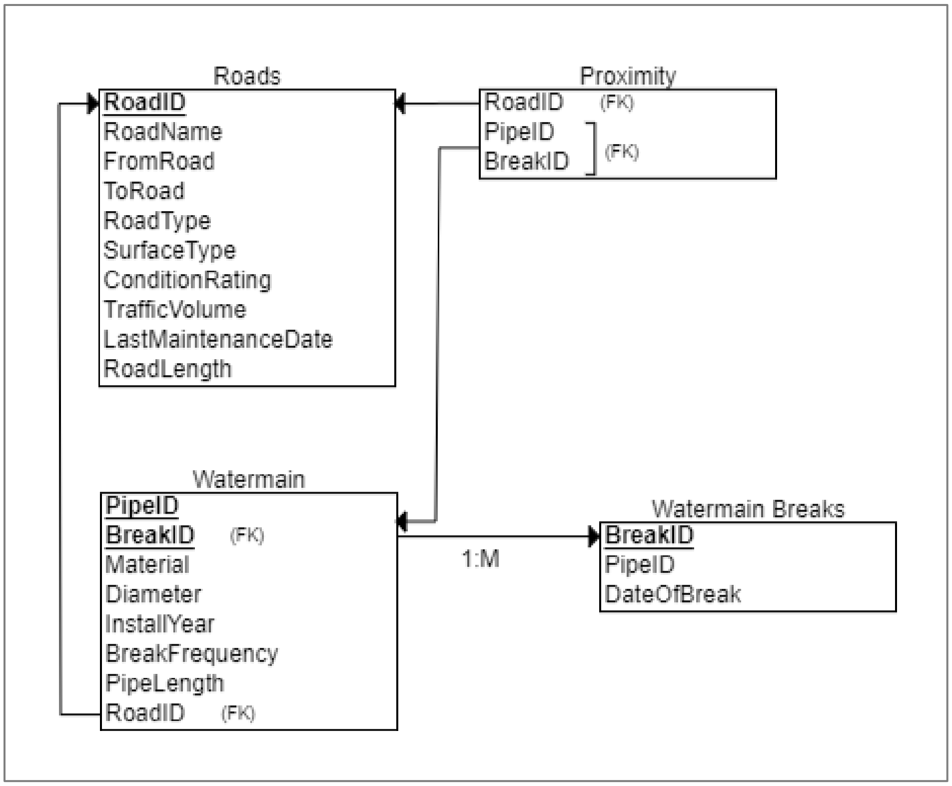

Figure 2. Logical Schema Diagram

The following tables (*Table 1, Table 2, Table 3)* catalogue the various entities and their associated attributes that are part of the spatial database. Each table specifies field names, aliases, data types, lengths, and constraints, ensuring clarity and consistency in data storage and retrieval. Additionally, provided below (*Table 4*) is a table detailing the domains for RoadType, SurfaceType, TrafficVolume, and PipeMaterial, that include descriptions and coded values, to maintain data integrity and standardize entries across the database. These tables serve as reference for the implementation and future expansion of the database.

Table 1. Roads Fields

Name	Alias	Type	Length	Constraints	Domain
RoadID	Road ID	Integer		Primary Key, Unique	
RoadName	Road Name	String	200	Not Null	
FromRoad	From Road	String	200		
ToRoad	To Road	String	200		
RoadType	Road Type	String	50	Not Null	RoadType
SurfaceType	Surface Type	String	50		SurfaceType
ConditionRating	Condition Rating	Integer			Range: 1-10
TrafficVolume	Traffic Volume	String	50		TrafficVolume
LastMaintenanceDate	Last Maintenance Date	Date			
ShapeLength	Road Length	Float			

Table 2. Watermain Fields

Name	Alias	Type	Length	Constraints	Domain
PipeID	Pipe ID	Integer		Primary Key, Unique	
Material	Material	String	50		PipeMaterial
Diameter	Diameter (in)	Float			
InstallYear	Install Year	Integer			
BreakFrequency	Break Frequency	Float		Calculated from Watermain Breaks	
RoadID	Road ID	Integer		Foreign Key	
ShapeLength	Pipe Length	Float			

Table 3. Watermain Breaks Fields

Name	Alias	Type	Length	Constraints	Domain
BreakID	Break ID	Integer		Primary Key, Unique	
PipeID	Pipe ID	Integer		Foreign Key	
DateOfBreak	Date of Break	Date		Not Null	

Table 4. Domains

Domain Name	Description	Data Type	Code	Label
RoadType	Road type categorizes roads based on their function and capacity.	String	Major	Major
			Minor	Minor
			Arterial	Arterial
			Collector	Collector
			Residential	Residential
			Service	Service
SurfaceType	Surface Type specifies material composition of a road's surface	String	Asphalt	Asphalt
			Concrete	Concrete
			Gravel	Gravel
TrafficVolume	Traffic Volume classifies roads according to the typical number of vehicles using the road over a given period of time	String	Light	Light
			Moderate	Moderate
			Heavy	Heavy
			Variable	Variable
PipeMaterial	Pipe Material details the types of materials used for watermains	String	PVC	PVC
			CI	CI
			DI	DI
			Copper	Copper
			HDPE	HDPE

Database Implementation

The Database Implementation phase began after the design of the spatial database was completed. Using ArcGIS Pro, a new project was created, including a project geodatabase to store the infrastructure data. This geodatabase includes the feature classes for Roads, Watermains, and Watermain Breaks, each populated with fields as outlined in the earlier sections of this report.

An important structural component of the database is the one-to-many (1:M) relationship class between the Watermains and Watermain Breaks. This relationship allows for effective tracking and analysis of the frequency and occurrence of breaks along the watermains, facilitating better maintenance and response strategies.

The data used to populate these feature classes comes from proprietary datasets provided by a municipal client in Wisconsin. The spatial reference for the project is NAD83 (2011) Wisconsin South US Foot to ensure geographic accuracy and compatibility with local mapping standards. This configuration provides a solid foundation for all geographic data operations and analyses within the database, supporting the City's infrastructure management and planning efforts.

Data Input

The data input phase of this project was completed by using ArcGIS Pro, where a direct connection was established with the ArcGIS Online account holding the City's authoritative GIS data. This setup facilitated a streamlined integration of real-world infrastructure data into the project database.

For the watermain data, the **Append** geoprocessing tool in ArcGIS Pro was utilized to transfer data from the City's authoritative watermain database to the local layer within the project database. Key attributes such as pipe material, diameter, and year of installation were mapped accurately from the source to the target database. The Object ID from the authoritative layer was repurposed to serve as the new Pipe ID in the project layer, ensuring consistency and traceability of the data records.

After appending the Watermain Breaks data from the authoritative layer on ArcGIS Online to the local database feature class, the next step was to create a spatial join using ArcGIS Pro. The 'closest' setting was chosen for the spatial join to effectively link each break point to the nearest watermain. Once the spatial join was completed, using the Field Calculator the PipeID field in the Watermain Breaks table was updated with the PipeID from the associated watermain. This field acts as a primary key in the Watermain table and a foreign key in the Watermain Breaks table, creating a functional relationship within the database.

Next, the frequency of breaks per foot for each watermain segment was calculated. This was achieved by first creating a summary table that counted the number of breaks for each pipe segment and then joined this table to the Watermain table. Finally, the Field Calculator was used to populate the BreakFrequency by dividing the number of breaks by the length of the pipe in feet.

Integrating the road data into the project presented a more challenging scenario due to the variety and multiple sources of available data. The City itself maintains a road dataset intended to record road maintenance activities. The Wisconsin Department of Transportation (WisDOT) provides a database that includes certified road miles for which the City is responsible, along with associated PASER ratings that assess pavement conditions. Additionally, the County GIS Department maintains a comprehensive road centerline layer that covers the entire county.

During the course of this project, it became evident that the City would greatly benefit from developing a dedicated authoritative layer for road centerlines that includes historical data on road ratings and various maintenance techniques. Such a layer would provide a consolidated view of road conditions and treatments over time, enhancing planning and decision-making processes. However, given the limited scope of this current project, it was decided to utilize the existing lines and information available from the WisDOT WISLR dataset. This dataset provides comprehensive and up-to-date road rating data, which, while not encompassing all desirable historical data, serves the immediate needs of this project effectively.

After appending data from the Wisconsin DOT's Statewide Information System for Local Roads (WISLR) into our local Roads database, it was observed that each road feature was duplicated. To address this issue and ensure data accuracy, the "Delete Identical" geoprocessing tool was utilized. This tool was configured to remove duplicates based on identical shape_lengths, which, while effective for the current project scope, acknowledges a need for future refinement to ensure precision.

Then, to link the Roads layer with the Watermain layer, a spatial join was executed using a 30-foot search radius, aligning each watermain with its nearest road. After this join, the Road ID from the Roads layer was transferred to the Watermain table using the Field Calculator, establishing a direct linkage between the two. To ensure data integrity and facilitate easier data management, the join was removed after updating the fields. Instead, a **Relate** was established based on the Road ID, connecting the Roads layer to the Watermain layer. The setup's effectiveness was confirmed in ArcGIS Pro, where selecting a road line displayed the related watermain and any associated watermain breaks within the attribute panel (*Figure 3*).

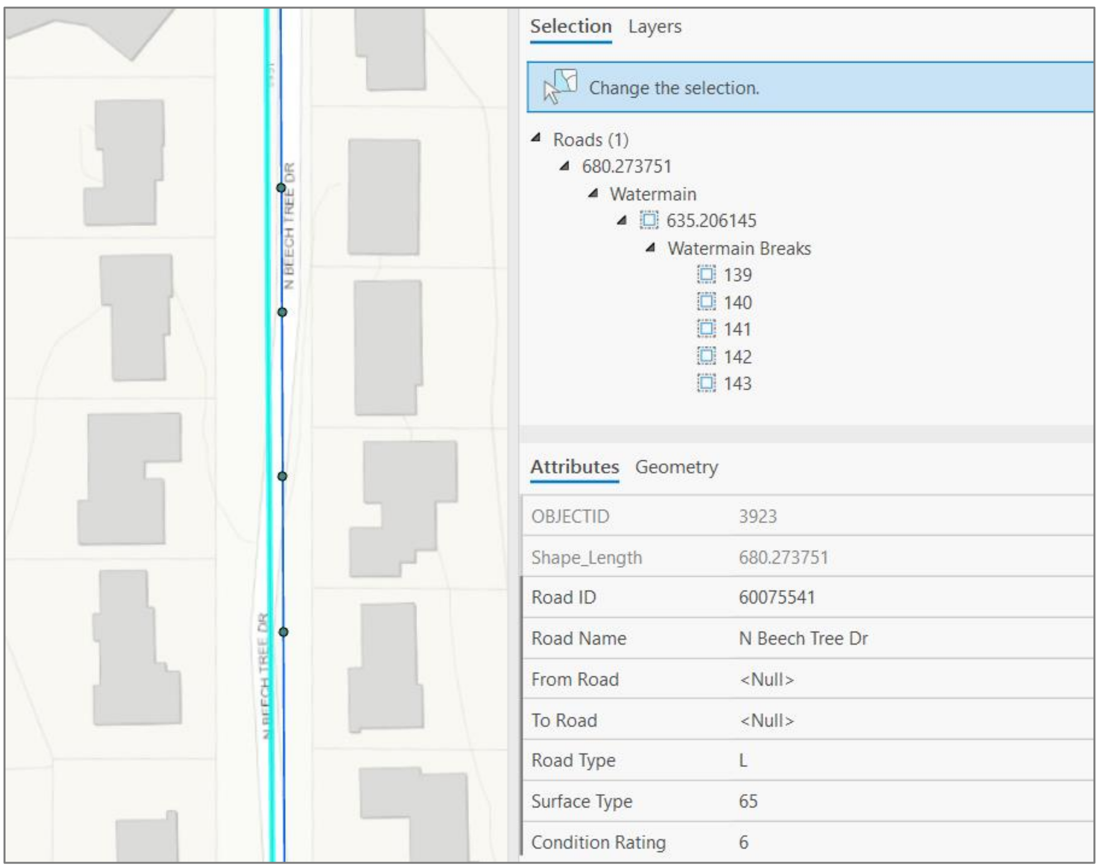

Figure 3. Road Selection in ArcGIS Pro

In concluding the data integration section, it's clear that developing a comprehensive road dataset is essential for effective infrastructure management. This project highlighted the complexities of managing overlapping jurisdictions, such as watermains beneath roads not owned by the city and watermains running through areas without roads. Additionally, situations where roads need repair but do not have associated watermains require as much consideration when planning capital improvements.

These scenarios emphasize the importance of a detailed and adaptable approach to infrastructure management within a GIS system. By ensuring accurate mapping and maintenance records for both roads and watermains, the City can better plan and allocate resources, enhancing service delivery and infrastructure sustainability.

Database Manipulations

In the final section of this report, the focus is on database manipulations that are designed to enhance infrastructure management by providing a structured approach to analyze spatial data. The goal of this project is to create a dynamic system that allows municipal engineers to better understand and prioritize infrastructure improvements. Through query design and map visualizations, questions about the City's watermain responsibilities, the aging of infrastructure, and the prioritization of maintenance efforts can be answered.

Database Query Design

Query 1: Watermain Responsibility

- Objective: Determine the total lineal feet of watermain that the City is responsible for.
- Methodology: Using ArcGIS Pro, created a bar chart that summarizes the watermain layer by calculating the length of watermain by pipe diameter (*Figure 4*).
- Outcome: 415,968 lineal feet of watermain owned and maintained by the City (415,968 / 5,280 = 78.8 miles)

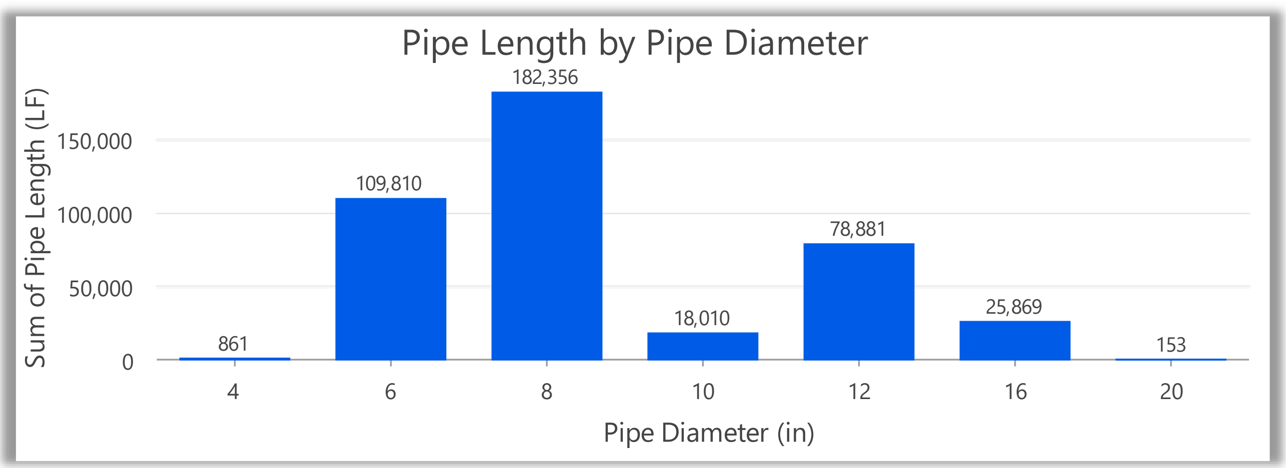

Figure 4. Pipe Length by Pipe Diameter

Query 2: Aging Infrastructure (Watermains)

- Objective: Identify the amount of watermain that was installed on or before the year 2000.
- Methodology: Using the Select by Attributes tool in ArcGIS Pro, select the watermains that have an install year entered as less than or equal to "2000" OR if the install year is null (*Figure 5*). The selected watermains were viewed in a bar chart and then exported to an excel table to better visualize the breakdown of aging watermain in the system (*Figure 6*).

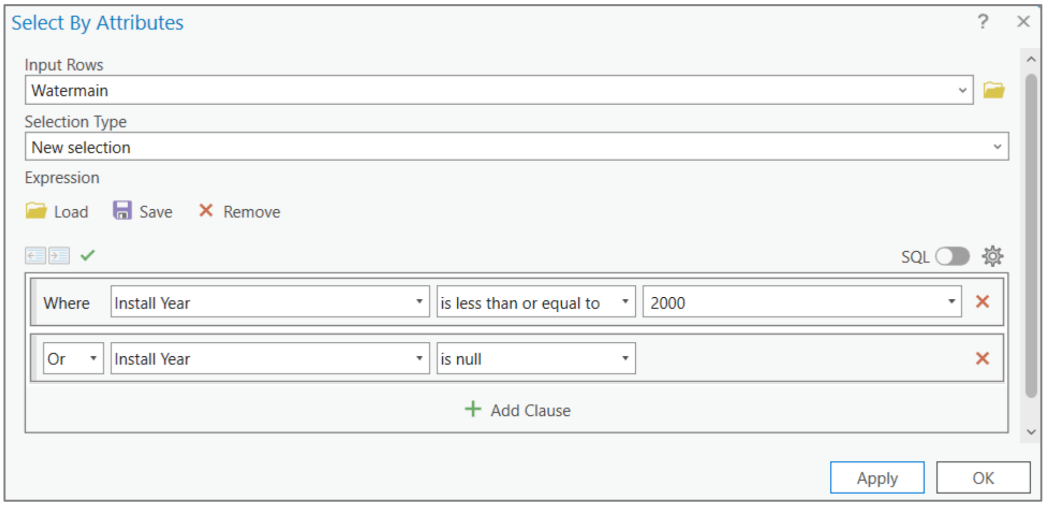

Figure 5. Query to Select Older or Unknown Age Watermains

- Outcome: The total length of watermain that was installed on or before the year 2000, is 250,879 lineal feet. Approximately, 60% of the watermain is considered aging.

Install Year	Sum of Pipe (LF)	Install Year	Sum of Pipe (LF)	Install Year	Sum of Pipe (LF)
1935	2,466	1972	4,991	1991	2,399
1957	12,687	1973	6,135	1993	2,282
1958	14,697	1974	1,445	1994	5,247
1959	3,467	1975	6,026	1995	3,818
1960	58,177	1976	456	1996	3,706
1961	36,137	1977	2,246	1997	903
1962	5,114	1978	1,277	1998	1,839
1963	6,613	1980	1,318	1999	6,253
1965	2,031	1982	1,364	2000	6,334
1966	9,718	1984	626	Unknown	2,939
1967	10,095	1985	2,796	**SubTotal**	**35,720**
1968	8,923	**SubTotal**	**28,680**		
1969	16,356				
SubTotal	**186,480**				
		Total	**250,879**		

Figure 6. Length of Watermain by Year Installed

Query 3: Roadway Responsibility

- Objective: Determine the total lineal feet of roadway that the City is responsible for.
- Methodology: Using ArcGIS Pro, the visualize statistics tool was used to summarize the sum of shape_length of the Roads layer.
- Outcome: 404,399 lineal feet of roadway owned and maintained by the City (404,399 / 5,280 = 76.6 miles)
- Observation: It is important to also note here that the Roads layer is a preliminary dataset that would require further development outside of this term project.

Query 4: Aging Infrastructure (Roads)

- Objective: Identify the length of roads that show a condition rating of 5 or less.
- Methodology: Using the Select by Attributes tool in ArcGIS Pro, select the roads that have a condition rating of 5 or less. Create a bar chart to visualize the sum of roadway by condition rating (*Figure 7*).

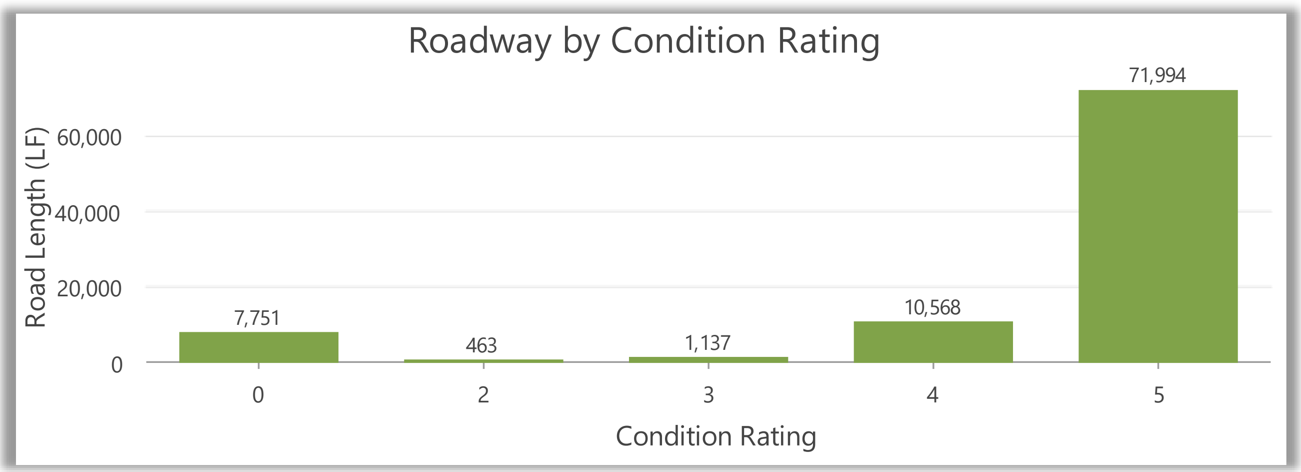

Figure 7. Roads by Condition Rating

- Outcome: 91,914 lineal feet of roadway has a condition rating of 5 or less. Approximately, 22% of the City's roads are considered in poor condition.
- Observation: The condition rating data came from the 2021 WISLR shapefile. In future development of this project, a more current rating would be required. It was also observed that there are some ratings of 0, which would also require further investigation and understanding.

Query 5: Prioritizing Infrastructure Improvements

- Objective: Identify areas where both watermain and road conditions indicate a high need for improvement, allowing for coordinated infrastructure management.
- Methodology: Define thresholds for what constitutes poor condition for both roads and watermains.

For this project, a poor road condition is a rating of 5 or less. Using ArcGIS Pro to visualize the location of poorer rated roads, the screenshot below highlights a small sample area of the City (*Figure 8*). Road names and topography have been removed as the information that this represents is proprietary and not open to the public.

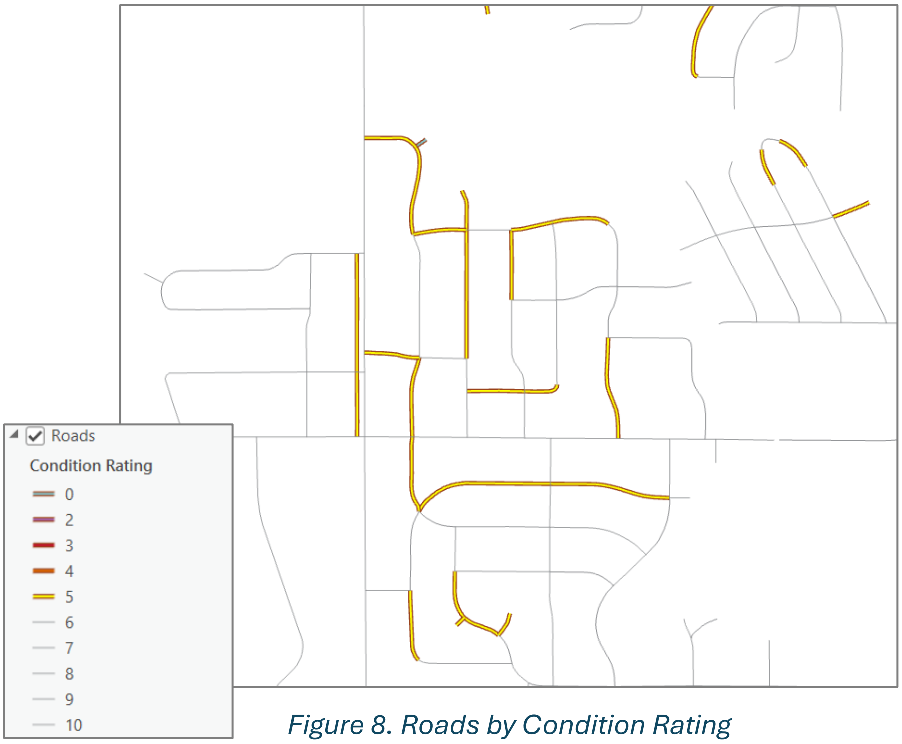

Figure 8. Roads by Condition Rating

A watermain segment that needs to be highlighted is when there are 2 or more breaks on the segment. Using ArcGIS Pro to visualize the location of watermain segments based on the number of breaks, the screenshot below highlights a small sample area of the City (*Figure 9*). Road names and topography have been removed as the information that this represents is proprietary and not open to the public.

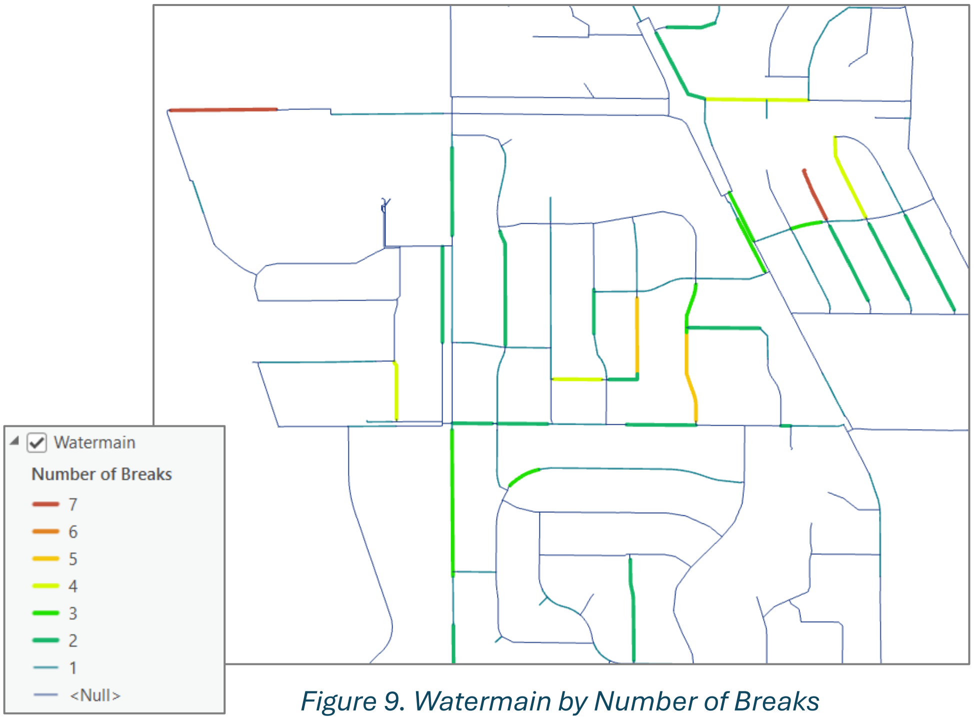

Figure 9. Watermain by Number of Breaks

Next, ArcGIS Pro was used to identify roads in need of maintenance due to their proximity to problematic watermains. All watermains with two or more breaks were selected using the **Select by Attribute** tool, highlighting potentially problematic segments. A definition query was then applied to display only roads with a condition rating of 5 or less, focusing on those in poorer condition. Using the **Select by Location** tool, road segments within 30 feet of these high-risk watermains were identified, pinpointing areas where both road and water infrastructure might require simultaneous improvements.

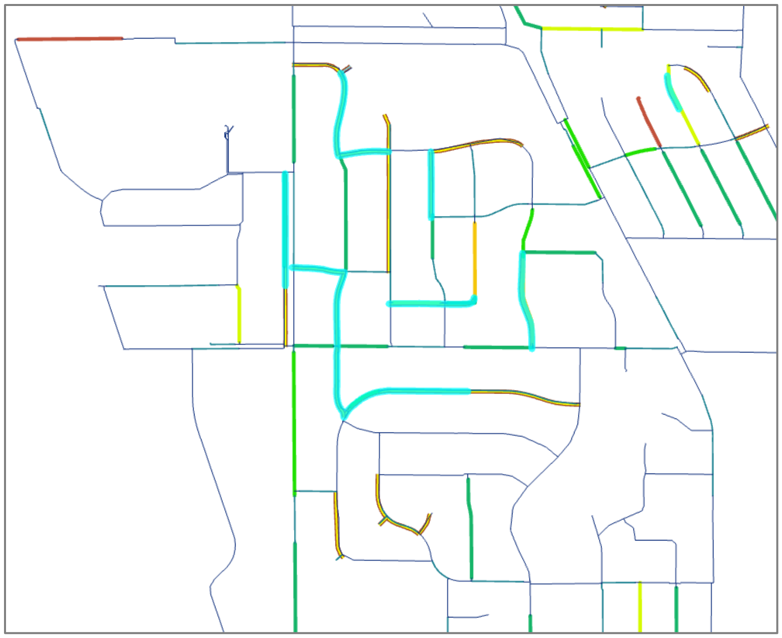

Figure 10. Sample Area Highlighting Priority Project Areas

- Outcome: Once the query was designed and implemented, roads with a poor condition rating were selected that are within 30' of a watermain that has a record of failure. In this example, 76 road segments were selected. In theory, these 76 areas would prove to be a starting point of where to prioritize infrastructure improvements in the City.

Conclusion

This report has detailed the creation and implementation of a spatial database aimed at enhancing the efficiency and effectiveness of Capital Improvement Program (CIP) planning for municipal infrastructure, particularly roads and watermains. By integrating and analyzing geospatial data, the project has established a dynamic system that enables municipal engineers to make informed decisions, prioritize necessary interventions, and optimally utilize resources. However, it is important to note that this project serves as a preliminary test and merely represents the initial phase of a more comprehensive design process that is required for full-scale implementation.

Observations and Future Considerations:

1. Expansion to Include Additional Utilities:
    a. Enhancements to the database should include the integration of other critical utilities within the right-of-way, such as fire hydrants, valves, and sanitary and storm sewer systems. This would provide a more holistic view of underground infrastructures, supporting broader planning and maintenance strategies.
2. Incorporating Up-to-Date Road Assessments:
    a. The need for the most current road condition data, such as the 2023 WISLR ratings, and the development of a consistent, authoritative road dataset that

accurately reflects current conditions and maintenance histories were identified as critical requirements.

3. Automated Updates:
    a. To ensure the database remains up-to-date, particularly regarding watermain break frequencies, development of an automated toolbox or model builder is recommended. This tool should update break frequency metrics automatically each time a new break is recorded, ensuring data relevance for ongoing CIP planning.

While the findings from this project are promising, significant additional design and development work is necessary to realize a fully operational system. This project should be viewed as a starting point, providing a framework that needs further refinement and expansion to meet the complex demands of infrastructure management. As this project progresses, further testing, feedback, and iterative improvements will be crucial in evolving the database into a robust tool for municipal planning and infrastructure maintenance.

References

Wisconsin Department of Transportation (WisDOT). (2021). WISLR Road Data. Data not publicly accessible.

Clark Dietz, Inc. (2024). Watermain Infrastructure Data. Provided for the purpose of this project. Data not publicly accessible.

Milwaukee County Land Information Office (MCLIO). (2024). Milwaukee County Street Centerlines Layer. Available at https://data-mclio.hub.arcgis.com/.