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TÍTULO: DEVELOPMENT OF A SYSTEM FOR THE MANAGEMENT AND EVALUATION OF UTILITY NETWORKS THROUGH A UNIFIED SPATIAL DATABASE

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Abstract

Utility networks are essential for modern society, providing vital services such as gas, electricity, telecommunications, and water. However, their importance carries the risk of potentially devastating accidents. Understanding the dangers and causes of failures is crucial for developing preventive measures. This project aims to design an integrated system using open-source tools to leverage the capabilities of GIS, data analysis and visualization, and web development. The goal is to promote collaboration and data sharing among stakeholders to reduce the risk of accidents and ensure safer and more efficient management of public utility infrastructures.

Keywords: GIS, Utility systems, Spatial data, topographic survey.

Resumen

Las redes de servicios públicos son esenciales para la sociedad moderna, ya que proporcionan servicios vitales como gas, electricidad, telecomunicaciones y agua. Sin embargo, su importancia conlleva el riesgo de accidentes potencialmente devastadores. Comprender los peligros y las causas de las fallas es crucial para desarrollar medidas preventivas. Este proyecto tiene como objetivo diseñar un sistema integrado utilizando herramientas de código abierto para aprovechar las capacidades de los SIG, el análisis y la visualización de datos, y el desarrollo web. El objetivo es promover la colaboración y el intercambio de datos entre las partes interesadas para reducir el riesgo de accidentes y asegurar una gestión más segura y eficiente de las infraestructuras de servicios públicos.

Palabras clave: SIG, sistemas de servicios públicos, datos espaciales, levantamiento topográfico.

Dedication

"It is with sincere gratitude and warm consideration that I dedicate this work"

To my father ALI

Thank you for being my father, my hero. Thank you for supporting me and believing in me.

May this work be a tribute to your presence.

To my mother SALWA

Your care and kindness go beyond any limits, no word is strong enough to thank you and express my gratitude for giving me happiness.

To my brother Heni

Thank you for your support. I wish you all a bright future, full of happiness

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ABBREVIATIONS LIST

2D	2 Dimensional
3D	3 Dimensional
CSV	Comma-Separated Values
CHM	Canopy Height Model
DEM	Digital Elevation Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
TopoJSON	Topological JavaScript Object Notation
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPR	Ground Penetrating Radar
GPS	Global Positioning System
LIDAR	Light Detection and Ranging
PPK	Post Processed Kinematic
RTK	Real Time Kinematic
SRID	Spatial Reference System Identifier
UJA	University of Jaén
UTM	Universal Transverse Mercator
NAD	North American Datum
GRS	Geodetic Reference System
EPSG	European Petroleum Survey Group

GENERAL INTRODUCTION

In contemporary urban environment, effective utility systems management plays a pivotal role in ensuring cities sustainability, security and resilience. As the world quickly urbanizes and adopts the concept of smart cities, there is a growing need for creative solutions and inventive strategies to handle and manage critical infrastructure systems. The difficulties brought on by aging infrastructure, population increase and climate change impacts further intensify this demand.

Urban infrastructure is primarily supported by utility networks, encompassing vital services such as sewage systems, water supply, gas, electricity and telecommunication. Ensuring their uninterrupted operation is vital to promote community wellbeing, preserve public health and sustain economic activities. However, traditional utility network management methods often fail to effectively address the interdependencies and complexity present in contemporary metropolitan areas.

This study seeks to address the gap in effective utility infrastructure management by developing a comprehensive system that integrates Geographic Information System (GIS) technology with advanced programming techniques. This research, undertaken as a final degree project in the Department of Cartographic Engineering, Geodesy, and Photogrammetry at Jaén University, provides a thorough examination of utility system components, methodologies for data acquisition and management, and the analysis of utility infrastructure accidents. The project aims to produce several key deliverables: a detailed data dictionary, a robust spatial database, and a sophisticated GIS platform specifically designed for managing utility data. Furthermore, it will introduce various tools for ensuring data quality, create a dynamic dashboard for enhanced management capabilities, and develop a web mapping application to visualize underground infrastructure.

In this report, we analyze the project's context, problems, and objectives. We start with a detailed system design phase, identifying critical requirements and outlining the system's architecture and functionality. Next, we delve into the implementation phase, examining each step, proposing various approaches, and justifying the best fit for our needs. We'll go over every stage of the project in detail offering technical explanation of each technology's operation and integration.

This deep understanding will not only establish a profound grasp of the system but also will open the door for future improvements, innovations, and developments in utility network management.

CHAPTER I:

PROJECT FRAMEWORK

I. Introduction

The purpose of this introductory chapter is to provide a general context for this work. The first part is dedicated to define the project's problematic and outline its objectives. We will also introduce the chosen study area for this project which is Coquitlam city, an urban zone in the southwest of Canada, and discuss the spatial data used to test the system's functionality. Finally, a full section will be devoted to the system design phase, covering requirements, functionality, and system architecture.

II. Justification

This section provides a justification for the choice of the project, outlining its importance and the reasoning behind its selection.

II.1. Accident occurring in utility systems

The most frequent incidents involving utility network globally are:

II.1.1. Electrical failures

Electrical failure such as electrical cable raptures can cause devastating fires or power outages people’s safety at serious danger. A single spark from faulty equipment can quickly escalate into a destructive blaze that puts lives in peril and causes intensive damage. Furthermore, power outages disrupt daily activities and have an impact on emergency services, businesses and healthcare facilities. This emphasizes how important to maintain a reliable electrical infrastructure.

II.1.2. Gas leaks

Gas leaks happen when gas escape from pipelines, conduits or storage tanks into surrounding environment, regardless of the cause whether by corroded pipeline or accidental damage during construction, these leaks present a grave danger leading to explosion with catastrophic consequences.

II.1.3. Water main ruptures

The term “water main ruptures” describe the braking or bursting of underground pipelines that supply’s drinking water to homes, residences, commercial buildings and other structures leading to widespread flooding interrupting vital services and resulting in substantial property damage. Repairing the damage caused by a burst water main is costly and time consuming.

II.2. Common causes of utility systems-related accidents

In this section, we will thoroughly discuss the most common causes of accidents occurring within utility infrastructure.

II.2.1. Excavation damage during construction projects

One of the most frequent causes of utility network accident is excavation damages that accrue during building operations. There may be gas leaks, water main breaks, or electrical risks if subsurface utility lines are not precisely located and marked before digging starts. It's imperative to implement effective strategies to locate underground networks to ensure safe excavation practices and minimize the possibility of accidents occurring during construction activities.

II.2.2. Natural disasters

Natural catastrophes such as hurricanes, storms, floods, and earthquakes pose a serious risk to utility infrastructure integrity. These events frequently lead to electrical fires, gas leaks, and burst water mains, which impede recovery attempts and cause intensive damage. One of the main obstacles to respond promptly to such disasters is the lack of accurate and thorough data about the location and connection of utility networks in impacted areas. Inadequate and Insufficient data not only causes a delay in responding quickly but it also makes it more difficult to coordinate recovery efforts, prolonging the restauration of the infrastructure and so delaying the return of vital services.

II.2.3. Equipment failure

Equipment failure within utility networks due to aged infrastructure and poor maintenance, components like electrical cables, transformers and water mains deteriorate with time, raising the possibility of breakdowns. This can lead to various negative consequences, including water main raptures, electrical fires and gas leaks, all of which could endanger public safety and interrupt vital services. However, having reliable and precise data about utility networks can make maintenance easier and allow the proactive mitigation of these risks.

II.3. Real world cases

Here, we present real-world cases of accidents within utility systems to understand the implications and challenges faced.

II.3.1. Electrical incident resulting in arc flash in Bidwill, Sydney, Australia (24 July 2018)

A 31-year-old man was working on excavation projects, covering a shallow hole with concrete, and he was using an electrical hammer drill. The work was being done next to high-voltage (11 kv) and low-voltage (LV) cables, all of which were live at the time. When the worker struck the 11kv cable, there was an arc flare. His face and upper torso were severely burned. Over 13,600 homes were affected, with power restored to the majority of homes soon after the incident. A generator was used to provide electricity to the remaining houses while the broken 11kV cable was being fixed (figure 1). [20]

SafeWork NSW, NSW Ambulance, NSW Police Force and the Independent Pricing and Regulatory Tribunal (electricity supply regulator), handled the incident. The worker was conveyed to hospital and is receiving medical attention for the injuries he received. [20]

Figure 1: Trench excavation site where works were being undertaken **[20]**

II.3.2. Wednesbury flood, Wednesbury, Sandwell, England (27 April 2018)

A water main was accidently broken by a contractor operating on mechanical digger, resulting in flooding that destroyed houses and submerged cars (figure 2). Here are the devastating outcomes of the accident:

- Water levels reached 3m (9.8ft) after a 2m (6.5ft) hole was made in the pipe at about 10:30 BST on Thursday.
- Water supplies were lost for about two hours.

- Ten cars were left submerged in the road and fire service divers were sent to the scene.
- Three schools remained shut on Friday (Christ Church School, Moorlands Primary School and Joseph Turner Primary School).
- The firm isolated the power supply at the local sub-station as a precautionary measure in case floodwater reached it. [21]

Figure 2: Wednesbury flood **[21]**

II.3.3. Fire optic line cut during construction in south Dickinson, North Dakota, United States

Hundreds of customers were impacted by a fiber optic cable cut during construction in south Dickinson (figure 3), North Dakota, United States on Wednesday night. The telecommunication company suffered damages exceeding $40,000.c According to Consolidated Chief Operating Officer Brian Personne, two significant fiber-optic were cut. According to city engineer Craig Kubas, the cut was made by Western Municipal Construction, Inc., which is under contract with the city of Dickinson and is working on the Broadway project. It was found that the cut was accidental he stated. For nearly all of southwest Dickinson, the outage impacted phone lines, cable TV, and the Internet between approximately 4 p.m. on Wednesday and 1 a.m. on Thursday. An estimated 550 homes and commercial buildings, including those on Villard Street, were impacted, according to Personne. [22]

Figure 3 : Fire optic line cut during construction in south Dickinson **[22]**

III. Problem definition

Utility system management poses a critical challenge across the world, due to a number of interlinked factors. Among these are the lack of comprehensive data, the complexities of utility system infrastructures, the difficulties in identifying and mapping old utility networks, and the significant financial investments required to acquire and maintain the necessary data handling equipment and software. Failure to effectively manage these utility infrastructures contributes significantly to the occurrence of numerous incidents including electricity outages, gas leaks, and floods caused by water main ruptures, which pose threats to public safety and disrupt vital services. Addressing these challenges necessitates proactive efforts and the adoption of new technology to improve utility system management. These measures are critical not just for mitigating risks, but also for guaranteeing operational resilience and safeguarding societal well-being.

IV. Objectives

To gain a comprehensive understanding of the project's objectives, we have structured them into two main sections: general objectives and specific objectives.

IV.1. General objectives

Defining the project’s general objectives is crucial to give a broad overview and a comprehensive picture of the primary goals and expectations driving our study and development efforts. Which also highlight the project’s ’importance within utility network management.

Major general objectives are:

- Encourage the adoption of cutting-edge technologies like GIS, Photogrammetry, Data analysis, web and mobile development that can improve the administration and security of underground facilities.
- Sign agreements on data sharing between several entities to promote open communication and enhance decision-making.
- Encouraging Better Interaction and Teamwork by establishing online platforms and apps where stakeholders may interact, share data, and instantly coordinate actions.
- Urge all parties involved to work together to develop and carry out utility network projects. Collaboration make work easier and help preventing conflicts like overlapping construction activities that could harm already-existing networks.
- Create thorough emergency response plans that specify what should be done in case of an accident. These plans should specify channels of communications, resource allocation, clear roles and duties.

IV.2. Specific objectives

Here, we provide specific, measurable and attainable goals that directly contribute to the final achievement of the project’s general objectives. These goals act as concrete targets and milestones that direct our work and make it possible to track our progress efficiently.

- Architecture design of the system (requirements, components, data…).
- Data dictionary creation.
- Design of a unified spatial database that integrates multiple types of utility networks (Water, Sanitary, Drainage, Gas and telecommunications).
- Building the GIS: Implementation and data insertion.
- Assure data quality control.
- Build an analytics dashboard that summarizes relevant data and allows for faster and better decision making.
- Development of a Web mapping application allowing interactive visualization of buried utility networks.

V. Selection of Geographic Study Area and Data for System Testing

To evaluate our system's functionality, which includes storage, analysis, and visualization, we require spatial utility system data specifically from an urban area due to the complexity of urban infrastructure. For this purpose, we have selected the utility systems data of Coquitlam city. Coquitlam has an Open Data portal that provides a variety of data in several formats, including water, gas, communication, and drainage utilities. Additionally, their website includes LIDAR data and Orthophotos of the city, which will be essential for our testing and development procedures.

V.1. Choice of geographical area of study

Coquitlam is one of the largest cities of British Columbia, Canada, located on the lower mainland about 20 miles east of Vancouver's city center. Coquitlam is regarded one of the best developed residential areas in the Vancouver metropolitan region, having outstanding schools, parks, hospitals, shopping, and other amenities. Coquitlam city has 13 communities: central Coquitlam, ranch park, City Centre, Westwood plateau, Austin heights, Cape horn, Maillard Ville, Cariboo/Burquitlam, eagle ridge, Hockaday Nestor, Mayfair/pacific reach, river heights, and northeast Coquitlam [1]. This designed location map gives a more accurate representation of the study area's geographical positioning.

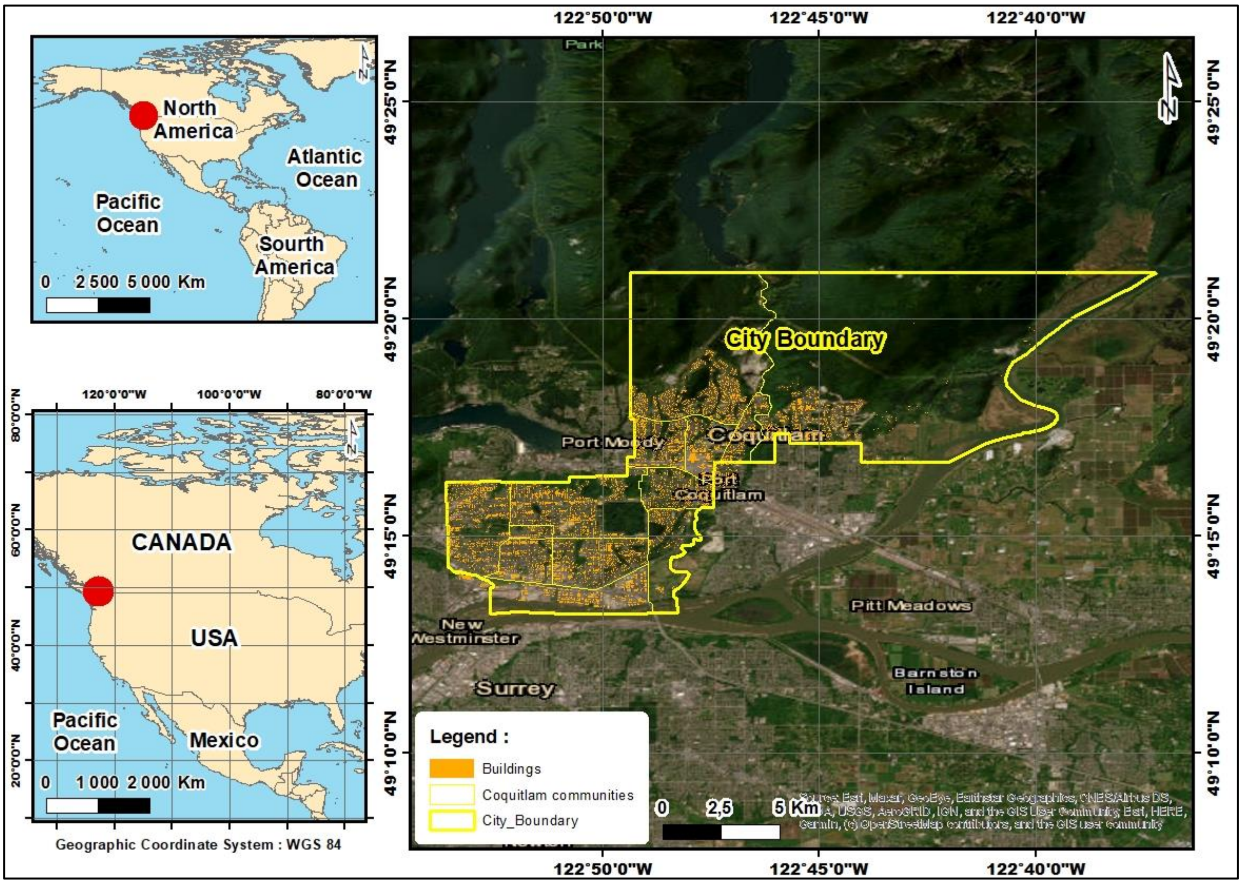

Figure 4: Geographical location of the study area.

This informative table presents geographic information about Coquitlam.

Table 1: Geographic information of Coquitlam city [1]

Country	Canada
Latitude	49.283764
Longitude	-122.793205
DMS Lat	49° 17' 1.5504" N
DMS Long	122° 47' 35.5380" W
UTM Easting	515,039.39
UTM Northing	5,459,021.83
Category	Cities
Country Code	CA
Zoom Level	13

We present the land use map of Coquitlam city (obtained from ArcGIS Hub) in the annex document, which depicts the extent of urbanization as well as various components of the city, such as residential areas, commercial zones, industrial sectors, transportation networks, agricultural lands, and more. This map substantiates our selection of the study area, highlighting its status as a thoroughly urbanized zone with diverse land use categories. Additionally, it underscores the presence of a complex underground infrastructure, which is critical for our research.

V.2. Used data to test the system's functionality

To verify the system's functionality for this project, we will use SHP and CAD data of Coquitlam's utilities system. Additionally, we require orthophotos and LIDAR data. We obtained this data from “Coquitlam's spatial data catalog”. This catalog provides a wide range of high-quality data that is critical for our testing objectives. This dataset includes:

- Topographic and aerial photography base maps
- Property Information
- Utilities include water, sanitation, drainage, communication, and transportation networks.
- Park locations, amenities, trails, and facilities.
- Designated land use and zoning
- Development permit zones and subdivision activities
- Environmental features, waterways, and SPEA mapping
- Rights of way, covenants, and easements.

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- **Orthophotos**

These orthophotos, produced in 2020 with a precision of 7.5 cm, are critical for understanding the topography of Coquitlam, including trees, roads, and buildings. They also allow for the display of some surface features of utility systems, such as manholes, water hydrants, and electric poles. This orthophoto serves as a highly valuable background interface for visualizing utility systems, especially since basemaps sometimes lack accuracy. As a result, we will get the most precise representation of the topography and the locations of utility components (figure 5).

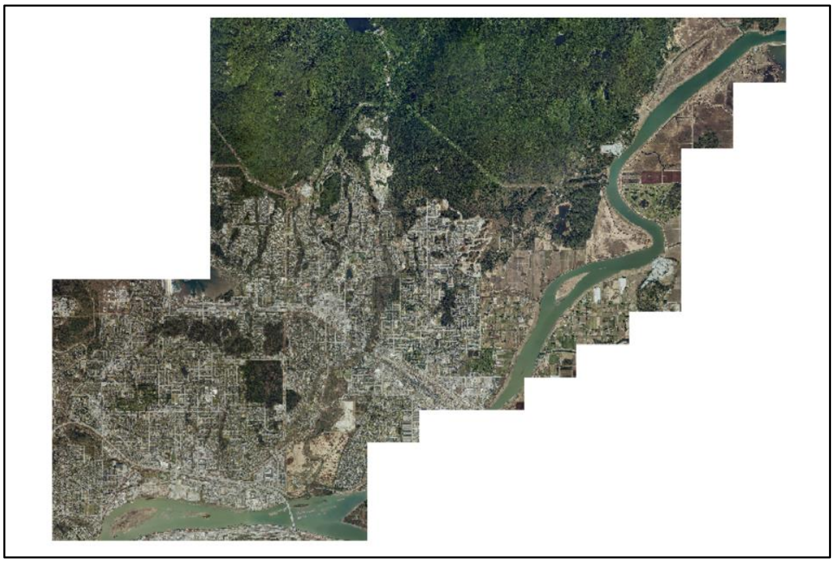


Figure 5 : Orthophoto of the city of Coquitlam [2]

- **LiDAR data**

LiDAR data is extremely important for creating 3D terrain models and provides the most accurate altimetric reference for altitude calculations (figure 6).

Figure 6 : LiDAR data for the city of Coquitlam [2]

- **DWG data**

DWG files (figure 7) are typically the primary format for utility system spatial data, collected through topographic surveys using total station and GPS equipment during installations, or through ground-penetrating radar (GPR) for existing utilities. This data is highly precise and valuable data, but it is also costly, as these topographic acquisition methods generally entail high expenses.

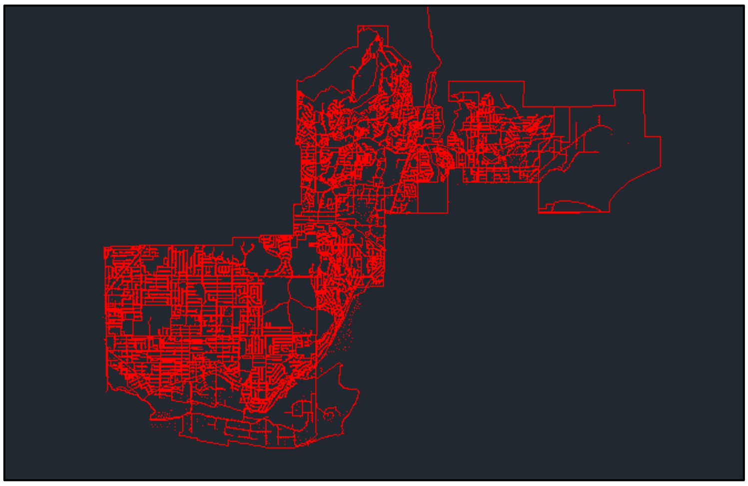


Figure 7 : DWG data of the water utilities in the city of Coquitlam **[2]**

- **Vector data**

Our spatial primary data may be vector data with attribute information ready for usage and testing in our system (example depicted in Figure 8), saving us the time it takes to convert data from DWG formats to vector data, as well as add and fill out the appropriate attributes.

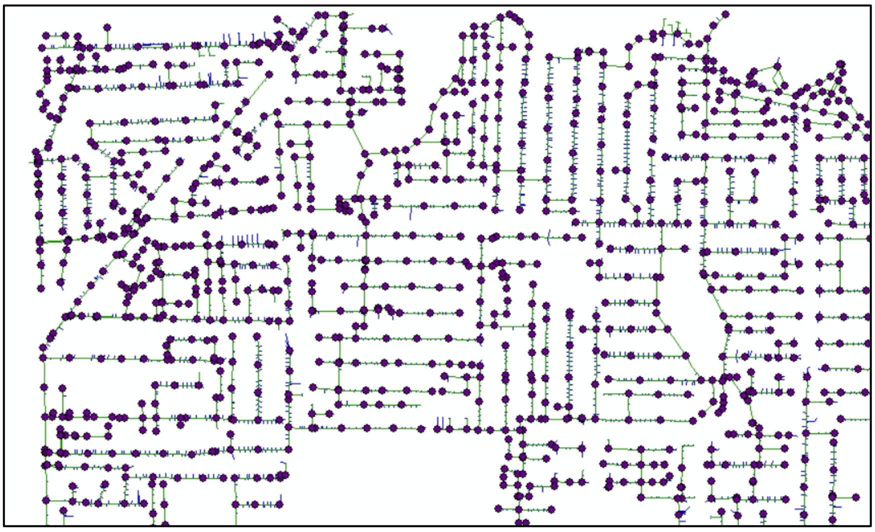


Figure 8 : SHP data of the sanitary utilities in the city of Coquitlam **[2]**

VI. System Design

In this part, we will design our system by defining its requirements, illustrating the system architecture and functionality with diagrams, and justifying our choice of tools and software to meet these requirements. Additionally, we will provide an activity diagram for system implementation, which will serve as a guideline and roadmap for the subsequent chapters. Finally, we will develop a spatial data dictionary to support our database infrastructure.

VI.1. Requirement

Three main categories of requirements can be used to classify requirements in system design: functional requirements, non-functional requirements, and extended requirements. Each form of requirement has a distinct function in driving the development process. To guarantee that a system is designed to accomplish its intended goals and operates efficiently, it is essential to comprehend and define its needs. [3]

VI.1.1. Functional Requirements

Functional requirements are the precise actions or activities that a system must carry out. Functional requirements answer the question “What does the system do?", They specify how the system ought to act in certain circumstances and in reaction to certain inputs.

System design and development are based on functional requirements, which are commonly articulated as use cases or user stories. In order to guarantee that the system fulfills its intended function and provides users with the anticipated functionality, defining these functional requirements is crucial. [3]

To enhance the comprehension of functional requirement, we present the following diagram:

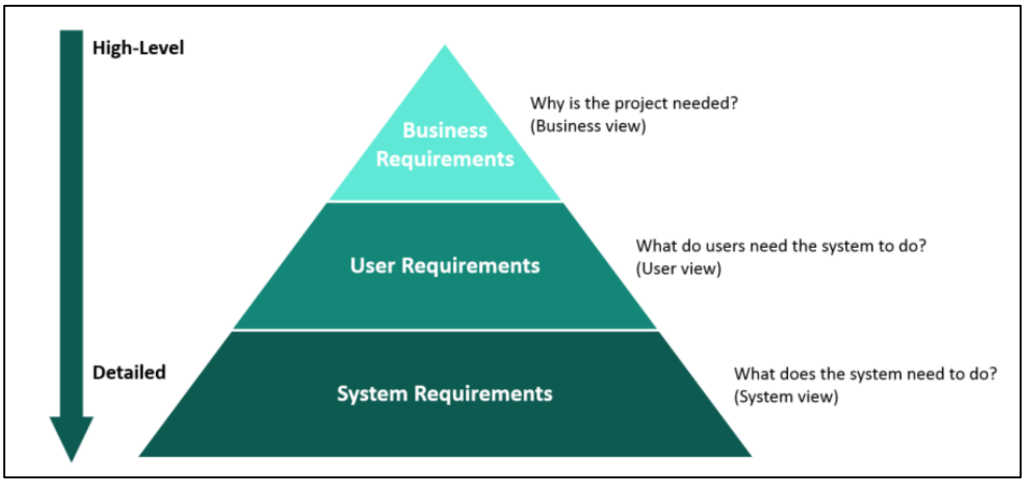


Figure 9 : Requirements Hierarchy **[4]**

- In our case in order to respond to the question of why the project is required, it is critical to recognize the urgent need for the implementation of strong techniques and strategies that efficiently oversee and manage the security of subterranean facilities. These measures are essential in order to minimize the potential consequences of accidents inside utility systems.

- To meet user requirements, it’s necessary to offer two visual tools that enable utility system analysis and visualization enhancing management capabilities, and facilitating well-informed decision-making. Since many commercial choices are too expensive, these tools need to be reasonably priced.
- User view: What does the system need to do?

The primary functions of the system are:

- **Data storage:** Make effective use of data structures like files, packages, and tables to store and manage data.
- **Data Access and retrieval:** Including query processing, for accessing and obtaining data from storage.
- **Quality Control:** ensures the integrity, accuracy and quality of spatial data through quality control and data governance.
- **Data Processing and Analysis:** Apply a variety of analytical techniques to the data, such as spatial statistical analysis.
- **Data Visualization:** This component creates visual representations of the data like dashboards and interactive web maps.

VI.1.2. Non-functional requirements

Non-functional requirements answer the question “how a system should perform?". Non-functional requirements outline the constraints or quality criteria that the system must satisfy. Rather of defining the functions the system does, they specify how effectively the system does them. In our project maintaining such elements is essential:

- **Performance:** The chosen software and tools must provide quick data queries along with efficient handling of massive amounts of spatial data.
- **Interoperability:** The chosen software and tools should support OGC protocols, which will allow the system to handle a variety of critical geographic data formats such as SHP, KML, Geojson, and others, allowing it to be flexible and interoperable with several applications and platforms.
- **Security:** Utility system data refers to private and government information that must be kept secure against unwanted access. Strong security procedures ensure the confidentiality and safety of this sensitive information.
- **Usability:** The system should be designed for easy use, allowing users to manipulate and interact with it without requiring specialized training or courses.

VI.1.3. Extended requirements

Extended system requirements include a larger range of variables and considerations that may not fall precisely into the functional or non-functional requirement categories. [3]

For our system we are going to prioritize those extended requirements:

- **Legal and Compliance:** It is crucial to make sure that the system meets the regulatory requirements of the industry and that any software utilized is properly licensed. This avoids legal problems, assures compliance and build reliability with clients or users.
- **Budget Constraints:** Making cost-effective decisions while conserving the required quality and performance is crucial when designing the system to make sure that we don't exceed the estimated project budget. This involves carefully selecting free or low-cost tools and software that can efficiently do the essential activities, hence reducing costs without sacrificing quality.

VI.2. Use Case Diagram for Utility Management System

A UML use case diagram is a fundamental document in system / software design and development that captures critical system requirements and functionality. This diagram's use cases highlight the anticipated interactions between actors (users or other systems) and the system itself, with a focus on what the system should do rather than how these actions will be implemented technically. This abstraction enables both textual and visual representation, such as diagrams, to describe the system's behavior from the user's perspective. By detailing all observable system behaviors comprehensively, use case modeling facilitates effective communication and design, emphasizing clarity and understanding of system functionalities in user terms. Notably, a use case diagram is succinct, illustrating links between use cases, actors, and the system rather than digging into procedural details or task execution sequences inside each use case scenario. [5]

We designed a use case diagram to help us understand the system requirements, functionality, and user communications better. The following illustration (Figure 10) clarifies user interactions, allowing us to better understand their demands and the system dynamics.

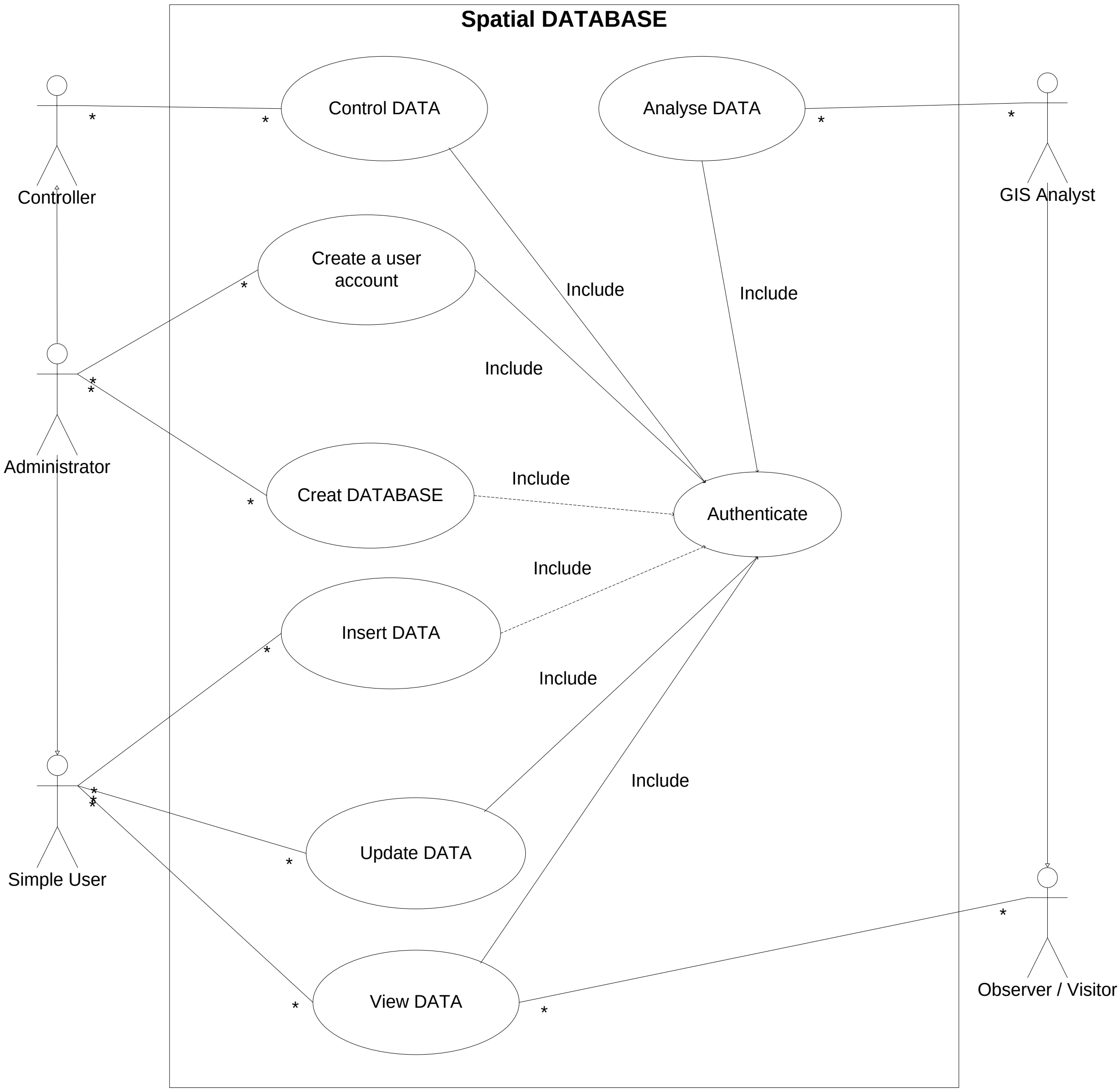


Figure 10 : Use Case Diagram for Utility Management System

VI.3. System Architecture diagram

The system architecture diagram is an abstract, basic, and generic representation of the system's component architecture. It gives a brief overview of the system's element structure in order to assist in component-component interactions and system functionality. A well-defined system architecture allows us to focus on system development and avoid long-term problems with integration and operational issues. [6]

The selection of system components should align closely with the detailed system requirements outlined in previous sections. This architecture diagram (figure 11) pertains specifically to our proposed system for managing utility systems.

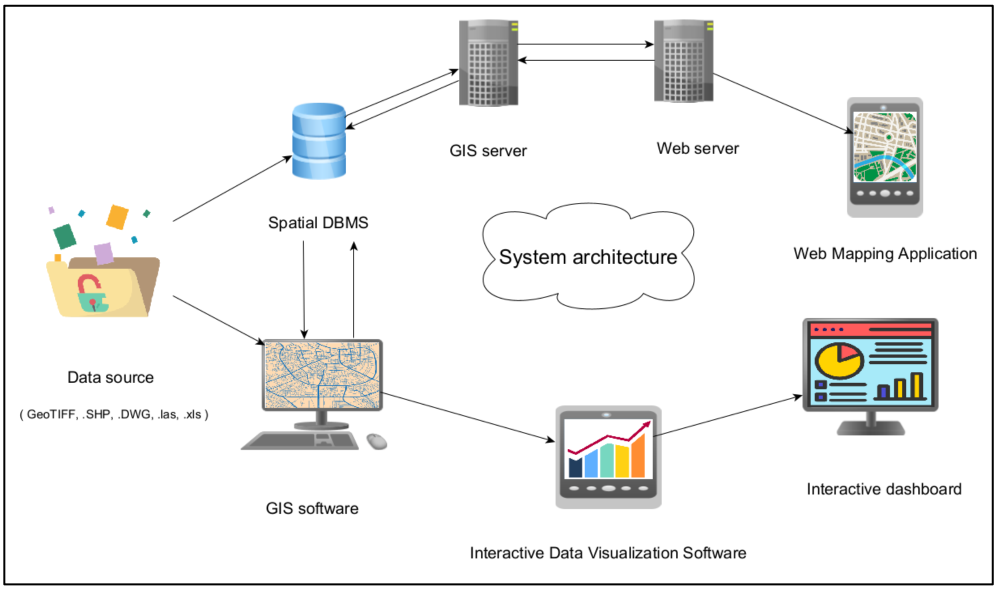


Figure 11 : System Architecture diagram

VI.4. Choice of the tools and software

The table below describes the tools and software chosen for our system, aligning with the specified system architecture, meeting all discussed requirements and desired functionalities. These technologies, being open-source and free, are selected to efficiently achieve our objectives and intended activities while maintaining quality standards and lowering expenses.

Table 2: Tools and software

Tools and software	Logo	Definition
QGIS		QGIS (previously known Quantum GIS) is a free and open-source desktop Geographical Information System (GIS) program that allows users to analyze and edit spatial data, as well as create and export graphical maps. QGIS supports raster and vector layers, as well as several geographic data formats. [7]
WhiteboxTools	WhiteboxTools	Whitebox, developed by the University of Guelph, is geospatial data analysis software that includes over 550 tools. It features extensive parallel computing, no need for additional libraries, compatibility with scripting environments, and easy integration with other GIS

Tools and software	Logo	Definition
		software. The Whitebox Toolset Extension enhances its capabilities further. [8]
PostgreSQL		PostgreSQL is a robust, open-source object-relational database system that leverages and extends the SQL language while also providing numerous capabilities for safely storing and scaling the most complex data demands. [9]
GeoServer		GeoServer is a popular open-source server for publishing and managing geospatial data at scale. It supports a wide range of input formats to generate maps, perform analysis, and share content online through APIs that adhere to OGC, ISO TC 211, and community standards. [10]
Open layer		OpenLayers makes it easy to add dynamic maps to web pages, displaying map tiles, vector data, and markers from any source. It is a free, open-source JavaScript library released under the 2-clause BSD License that promotes the usage of geographic information. [11]
Node.js		Node.js is a free, open-source, cross-platform JavaScript runtime environment that enables developers to build servers, web applications, command line tools, and scripts. [12]
Bootstrap		Bootstrap is a free, open-source front-end framework for building websites and web applications. It supports responsive, mobile-first development by offering a set of syntax for creating templates. [13]
Power BI Desktop		Power BI is a suite of software services, applications, and connections that work together to transform disparate sources of data into coherent, visually engaging, and interactive insights. [14]

VI.5. System Implementation Methodology: An Activity Diagram Approach

An activity diagram is a kind of UML flowchart that illustrates how one activity flows into another to represent a system's workflow. It describes what ought to occur inside the represented system, capturing the dynamic elements of a system. Activity diagrams are helpful in use case diagrams and business process modeling because they help visualize complicated processes. They show every step in an activity, their order, and the data flow from one step to the next. Actions, decision nodes, control flows, a start node, and an end node are important components. Activity diagrams give stakeholders a clear picture of how a system operates by outlining the process from beginning to end, facilitating understanding and analysis. [15]

- **Activity Diagram of System Implementation**

The Activity Diagram below (figure 12) depicts the System Implementation process, outlining each step required in completing the project.

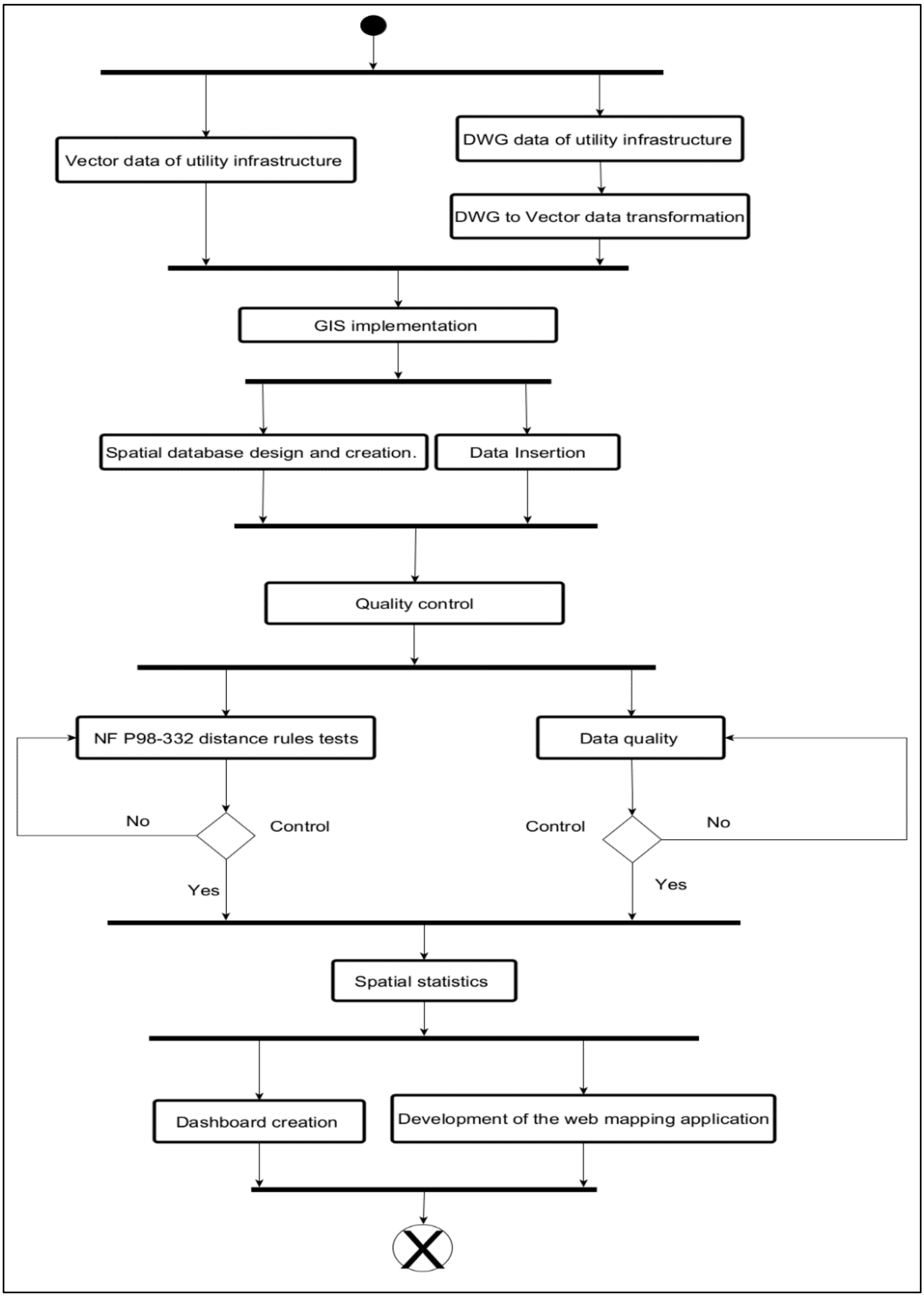


Figure 12: Activity Diagram of System Implementation

VI.6. Data Dictionary

A Data Dictionary is a collection of names, definitions, and characteristics of data elements utilized or recorded in a database, information system, or research project. It offers guidelines on interpretation, acceptable interpretations, and representation in addition to describing the aims and meanings of data items within the framework of a project. Metadata on data items is also provided via a data dictionary. The scope, properties, and application and usage guidelines of data items may all be defined with the help of the metadata that is provided in a data dictionary. [16]

- **Arc Node data model for Coquitlam's utility systems**

This data dictionary provides a comprehensive description of the tables and their properties in the Arc Node data model for the utility systems. This Model is based on two core tables: Arc and Node. These two fundamental tables serve as the model's foundation, with additional tables in the database inheriting from them to maintain a hierarchical and well-organized structure. This data dictionary defines the basic components of numerous utility systems, including water, electric, gas, and drainage utilities. It was developed to correspond with Coquitlam's utility system as published on the Coquitlam Open Data Portal, in accordance with the portal's terms of use.

The data dictionary document is encompassed within the annexed document accompanying this report.

- **Themes Covered in the Data Dictionary**

This data dictionary is divided into themes, each representing a specific type of utility system. Each theme is made up of tables with attributes defined by specific type and value. These tables relate to various components of the utility system, such as water main, water pump station, valves and hydrants.

Table 3: Themes Covered in the Data Dictionary

Theme name	Description
Water utility network	Represent the infrastructure for distributing potable water to homes and businesses.
Drainage utility network	Represent the infrastructure for transporting and managing rainwater and surface runoff.
Sanitary utility network	Represent the infrastructure responsible for collecting and transporting waste water from homes and businesses.
Communication Networks	Represent all infrastructure component related to telecommunication like fiber optic cables and communication boxes.

Methane utility networks	Represent the infrastructure responsible for transporting, managing and distributing methane to homes and businesses.

- **Reference system**

We used the same reference system of the primary data downloaded from Coquitlam's spatial data catalog.

Table 4: Reference system

Coordinate System:	**NAD 1983 UTM Zone 10N**
Projection:	Transverse Mercator
EPSG Code:	26910
Spheroid:	GRS 1980
Datum:	D North American 1983
False Easting:	500000,0
False Northing:	0,0
Central Meridian:	-123,0
Scale Factor:	0,9996
Latitude Of Origin:	0,0
Linear Unit:	Meter
Geographic Coordinate System:	GCS_North_American_1983

- **Content: Tables, Descriptions, and relationships**

All components of the utility system are presented with tables, attributes, geometric details, and topological consistency. For example, the data dictionary describes the 'Sanitary Pump Stations' element as follows:

❖ **Sanitary Pump Stations**

- Description: Sanitary Pump station is used in gravity sewer system to lift or pump waste water from a lower elevation to a higher elevation.
- Topological consistency: One Sanitary Pump Stations pumps waste water to multiple sanitary mains.
- Name of the table: SU_PUMPS
- Geometry**:** Point.
- Inheritance: Inherit **“**NODE**”**.

Table 5: Sanitary Pump Stations table

Attribute Name	Description	Data type	Source
SU_PUMPS_ID	Unique identifier for the GIS	Serial	GIS
ELEVATION	Elevation of sanitary pump stations.	Real	Utility company

Attribute Name	Description	Data type	Source
RIM_ELEV	The RIM elevation is the elevation of the top edge of the structure.	Real	Utility company
INV_ELEV	The invert elevation is the elevation of the structure s' bottom.	Real	Utility company
ALARM_TYPE	Type of the alarm system installed in each sanitary pump stations.	Character varying	Utility company
ADDRESS	Street address	Character varying	Utility company

VII. Conclusion

In summary, this chapter introduces the host organization at Jaen University, defines the project’s problem statement and objectives, and presents Coquitlam city as the study area. It also thoroughly outlines the steps involved in system design. This sets the stage for a detailed exploration of the project's state of the art in the subsequent chapter.

CHAPTER II:

STATE OF THE ART

I. Introduction

In this "State of the Art" chapter, we will explore utility systems and underground infrastructure, including common accidents within these systems, methods of data acquisition and management, and key terms related to utility networks. This chapter will provide a foundation for the subsequent chapter.

II. Underground Utility

Underground utilities refer to any public utility infrastructure that is built beneath the earth surface. Underground utilities include electric cables, telecommunications and data cables, water mains and sewer pipes, and gas and oil pipelines. These utility lines are frequently a lifeline for human society, allowing a town to function correctly. They are often built beneath the ground for convenience, safety, and aesthetic purposes (figure 13). [17]

Underground utility infrastructure is normally built and managed by the respective public utility companies. These suppliers are in charge of guaranteeing the safe and effective supply of critical services such as power, water, gas, and telecommunications. Before beginning any development projects, utility companies must acquire permission from local officials. This approval procedure is critical to ensuring that the planned utility installation follows rules and fits within the allocated right-of-way.

The right-of-way is a legal privilege granted by the local government that permits utility providers to utilize a certain area of public property for infrastructural purposes. This guarantees that services are appropriately installed without interfering with other public or private property. The permission process includes careful preparation, collaboration with numerous local offices, and, in certain cases, public discussions to address community concerns. By following these rules, utility companies contribute to the orderly development of metropolitan areas and reduce the possibility of disputes or disturbances during construction. Underground utilities are often installed using traditional excavation methods, however trenchless installation alternatives are becoming increasingly popular. Conventional excavation methods pose several dangers to construction workers, including tight spaces, engulfment, electrocution, and unstable pits. They also occupy a great amount of space and produce significant surface disturbance. [17]

Trenchless methods, on the other hand, are less disruptive, and many governments and municipalities are adopting them for underground utility installation. Horizontal directional drilling has swiftly gained popularity due to its remote steering capability, decreased human labor requirements, and low environmental effect. [17]

Underground utilities are a crucial aspect of contemporary life, helping companies and houses run efficiently. Maintaining these utilities is critical to avoiding interruptions in daily living. As metropolitan populations have grown, there has been a huge increase in demand for utility connections with increased capacity.

One of the most difficult issues in metropolitan settings is placing new utility lines alongside old infrastructure. In congested cities, this work becomes considerably more difficult due to limited space and the necessity to avoid damaging the densely packed web of present utility lines. Careful preparation and inventive solutions are necessary to properly manage this complex process. [18]

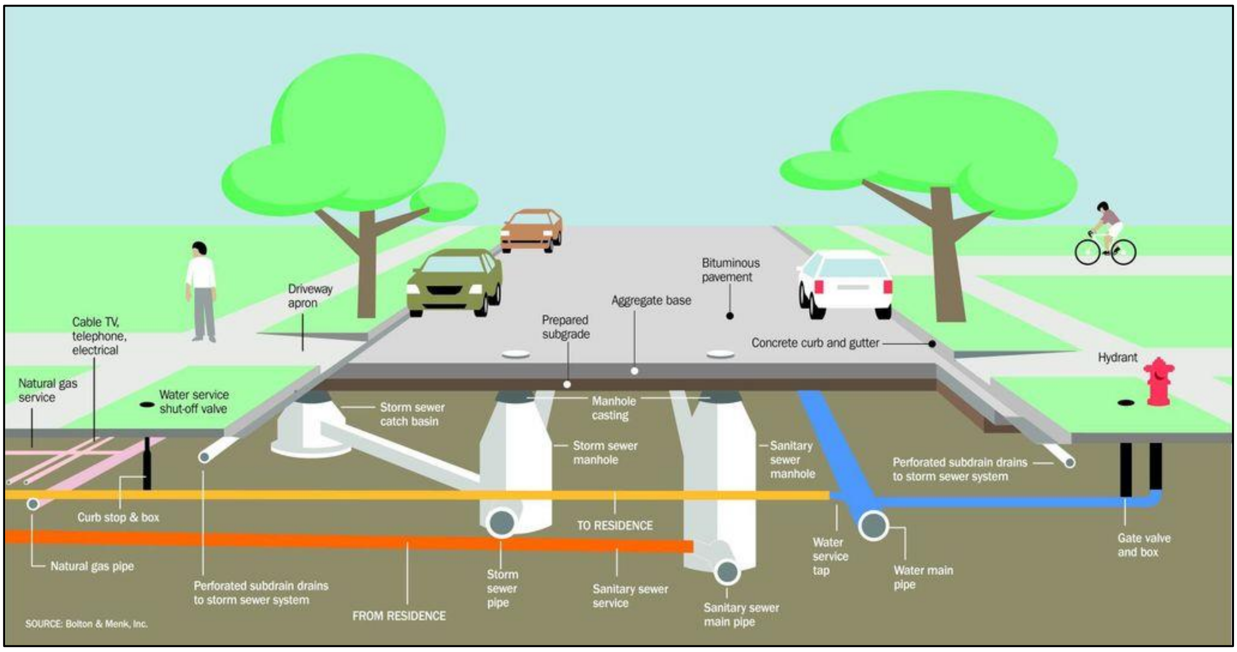


Figure 13 : Underground Utilities **[19]**

III. Utility systems data acquisition methods

Utility systems data acquisition relies on high-precision land surveying equipment, including total stations, GPS devices, and GEORADAR. In this section, we will discuss these methods.

III.1. Total station and GPS equipment

Advanced land surveying technology such as total stations and GPS equipment are used to collect a variety of utility system data, including information on storm manholes, water mains, electricity cables and water hydrants, etc.

Figure 14 : Pipeline Survey **[23]**

Using GNSS RTK for utility systems data acquisition (figure 14) offers significant benefits, primarily due to the heightened accuracy it provides. GNSS RTK enhances utility mapping by applying real-time corrections to GNSS data, enabling surveyors and mapping professionals to achieve sub-centimeter precision. This degree of precision is critical for preventing costly and time-consuming mistakes, such as accidently severing a gas line or excavating in the incorrect place. For example, a utility company in Texas used GNSS RTK technology to map their subterranean assets, resulting in a 30% reduction in excavation costs owing to improved mapping accuracy. Similarly, a city in Canada employed handheld GNSS RTK devices to map its subsurface infrastructure. RTK's accuracy enabled them to locate and document previously unknown assets, allowing for more informed infrastructure management and planning choices. [24]

Figure 15 : Sewer system asset mapping **[25]**

These technologies are critical during installation, maintenance, and other construction operations for utility systems projects because they allow for pinpointing the exact locations of all components in underground utilities.

III.2. GEORADAR

Ground penetrating radar (GPR) is a geophysical location technique that employs radio waves to acquire pictures under the ground's surface with a minimally intrusive manner. GPR (example in figure 18) is widely utilized in environmental science, civil engineering, archeological research, and other precise subsurface studies. It may be utilized to record subsurface characteristics like studying and investigating the depth of bedrock, water table, soil and sediment thickness (which involves beneath freshwater bodies), buried stream courses, and bedrock cavities and cracks. Other uses include utility network mapping so technicians can locate the position of subsurface utility networks with no disturbance the earth like (pipelines, water or gas ducts and electrical or fiber optic cables) and also buried garbage, mapping landfill and trench borders, and mapping polluted groundwater. [26]

Figure 16 : Ground penetrating radar (GPR) **[26]**

III.3. Operating principles of GPR systems

To gather data, the GEORADAR employs a transmitter antenna to broadcast high-frequency, pulsed electromagnetic waves (usually between 10 MHz and 1,000 MHz (some commercial systems may reach 7000 MHz) into the ground. The wave extends and descends until it encounters a buried item or barrier like geologic units with differing electromagnetic characteristics. Part of the wave energy can reflect or disperse back to the surface, but some of it just move below. The reflected wave to the surface reaches the receiving antenna that will be responsible of capturing the reflected energy s' amplitude and the wave s' arrival time on a data recording device. [26]

The Operating principles of GPR systems are illustrated in the following figure.

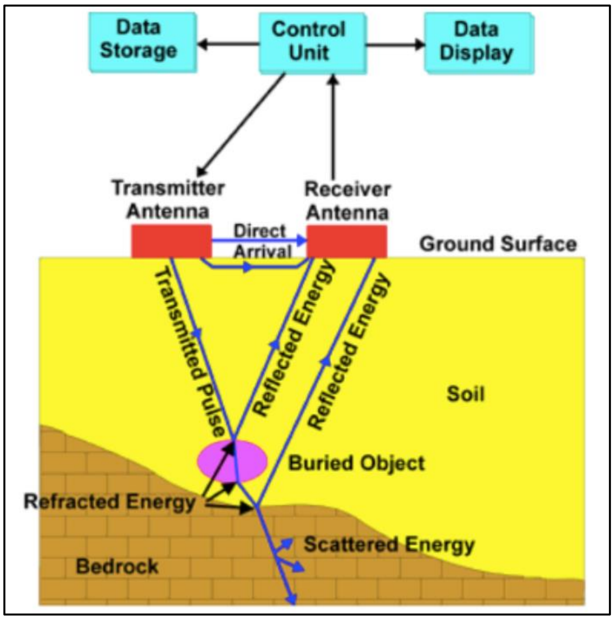


Figure 17 : Operating principles of GPR systems **[26]**

Electromagnetic waves propagate with a velocity defined mostly by the object 's electrical permittivity. The electromagnetic wave s' velocity (Speed) varies between objects with various electrical permittivity, therefore a signal passing through two materials having different permittivity over the same distance would reach its destination at different times. The measured transit time in nanoseconds 'ns' (where 1 ns=10-9 s) corresponds to amount of time that a wave takes to travel from the transmitter antenna to reach the receiving antenna, this time interval is proportional to the depth of the buried item. [26]

For an electromagnetic wave propagating in the air the velocity is 0.3 m/ns.

The equation to calculate the velocity of the material is:

$$V = C / \sqrt{\varepsilon r} \text{ [26]}$$

Where:

V: The material's velocity (m/ns).

C: represents the speed of light in a vacuum (3 x 108 m/s).

εr: represents the relative dielectric permittivity.

The permittivity of earth materials is always larger than that of air. The travel time of a wave in a substance other than air is necessarily above 3.3 ns/m. The depth of the target layer may be determined based on this velocity using the following equation:

$$D = CT / 2\sqrt{\varepsilon r} = VmT / 2 \text{ [26]}$$

Vm: The material's velocity (m/ns).

C: stands for the speed of light in a vacuum (3 x 108 m/s).

εr: is the dielectric constant, represent the relative electrical permittivity.

T: represents the two-way transit (travel) time in nanoseconds.

Table 6: Electromagnetic properties of materials **[26]**

Material	Relative Permittivity	Wave Velocities (m/Ns)	Conductivity (mS/m)
Air	1	0.3	0
Sea water	80	0.01	3,000
Fresh water	80	0.033	0.5
Sand (dry)	3-5	0.15	0.01
Sand (wet)	20-30	0.06	0.1-1
Ice	3-4	0.16	0.01
Granite	4-6	0.13	0.01-1
Limestone	4-8	0.12	0.5-2
Clays	5-40	0.06	2-1,000
Silts	5-30	0.07	1-100

III.4. Challenges and limitation of GPR

The primary challenges of GPR systems that we will be discussing include the exorbitant costs of equipment and the limitations for data acquisition posed by soil composition and moisture levels.

- **Exorbitant costs**

Ground Penetrating Radar (GPR) requires expensive hardware and software. For example, a bigger, wheeled GPR instrument required to locate a sewage line buried three feet into the earth can cost between $14,000 and $100,000, with an average monthly rental cost of $400 to $1,750. Furthermore, a full mission of utility network mapping frequently necessitates the use of both GPR and electromagnetic (EM) locating equipment, with an EM locator costing between $800 and $5,000 to acquire and $700 to $1,500 to rent on a monthly basis.

Furthermore, the specialists who operate these devices require particular training to guarantee that their tasks are completed securely and properly. The intricacy and variety of equipment demand the use of competent individuals who understand the complexities of both GPR and EM technologies.

The total cost to acquire utility network mapping ground penetrating radar and complementary tools can reach $65,000 including training. [27]

- **Soil Composition and Moisture Levels**

Soil type may be the most important geophysical element influencing ground penetrating radar restrictions. Clay and other highly conductive soils exhibit considerable signal attenuation. This significantly reduces the effective penetration depth of a specific GPR antenna frequency.

We are frequently inquired, "How deep can your GPR detect?" This is determined by the antenna used for a certain application. For lower frequency antenna, like 80MHz antenna, they have a high potential penetration (40m) but for high frequency, such as 750MHz, will be significantly lower (3.5 meters). The trade-off is that lower frequency antennas have lesser resolution. In practical terms, this means that you will only detect bigger targets at depth.

Any particular frequency will have an effective depth range that it can function within. This, however, is predicated on ideal conditions, similar to the mpg statistics provided by automobile manufacturers. The real penetration depth value is dictated by site factors, particularly soil type, and is frequently impossible to establish prior to the study.

The presence of moisture in soil has a significant impact on GPR surveys. High moisture content, particularly in saturated soils, dramatically reduces GPR signal strength by increasing soil conductivity, which absorbs and dissipates radar energy. This attenuation can totally eliminate reflections from the data, rendering subsurface things like pipes and wires opaque to the user. As a result, things that would normally be identified may not appear on the GPR data, creating a considerable obstacle for accurate subsurface studies. Effective survey planning, including scheduling and soil testing, is critical for reducing the influence of moisture and improving the dependability of GPR data. [28]

IV. Software for Utility Systems Data Management

ESRI provides a GIS solution for managing the spatial data of utility systems. In this section, we will discuss this solution.

IV.1. ArcGIS Utility Network extension presentation

ESRI's Utility Network (figure 18) is an advanced extension to the ArcGIS platform that is specifically designed for modeling, analyzing, and managing utility and infrastructure networks, such as electricity distribution, water, gas, telecommunications, and sewage systems. It is the primary component with which users interact while managing such networks, offering a complete framework for modeling utility systems such as electric, gas, water, stormwater, wastewater, and telecommunications. It is intended to simulate all system components, including wires, pipelines, valves, zones, devices, and circuits, allowing the incorporation of real-world behavior into the network characteristics being modeled. [29]

Figure 18 : ArcGIS Utility Network **[29]**

IV.2. ArcGIS Utility Network extension capabilities

A utility network is available wherever it is required, from mobile devices in the field to desktop computers in operations centers, providing seamless integration and administration of utility systems. This accessibility improves operating efficiency and accuracy, making it a very useful tool for managing large utility and infrastructure networks. [30]

These are the main advantages of a utility network:

- **Use a high-performance model that is scalable to huge utilities.**

A utility network is intended for rapid information distribution across huge datasets. The fundamental data models are designed to be as efficient as possible, with a limited number of feature classes and fewer sluggish relationship queries. Each utility network feature class comes with a built-in categorization system that employs attribute domains and subtypes. This enables a fine-grained representation of each utility feature. A utility network is designed to move quickly between network components that are connected or tied to structural features. [30]

- **Model all component of the utility system**

A utility network may be used to simulate all of the key components of a utility system. This includes modest elements like electrical fuses or little water valves, which nonetheless have an influence on resource flow. Both significant and minor utility features can be described in a data model and included into device components as required. The scalability of a utility network allows for precise modeling of all aspects of the utility, from small yet vital components to enormous assemblies of devices. [30]

- **Comprehensive view of the network**

A utility network provides a comprehensive view of the network, which is critical for understanding and operating a complex and dynamic utility system. It offers a variety of alternatives for investigating system assets and connections. The map view provides an overview of the utility, with customizable layer visibility that reveals more details as you zoom in closer. The amount of information presented may be adjusted by showing or hiding objects within containers such as stations, yards, cabinets, and vaults. Furthermore, the diagram view shows a schematic representation of the utility features, which improves knowledge of the system. [30]

- **Allow advanced analysis of the network.**

A utility network is a set of subnetworks through which a resource moves at any given time. These subnetworks are dynamic, meaning they may be changed by opening and closing devices like switches and valves. A utility network defines the start points of a subnetwork by using the resource's sources, and then traces down to the subnetwork's endpoints (or sinks) to determine its complete extent. When a switch or valve is replaced, the size of the subnetwork is recalculated. Device categories are also specified to enable more extensive tracing analysis (figure 19). [30]

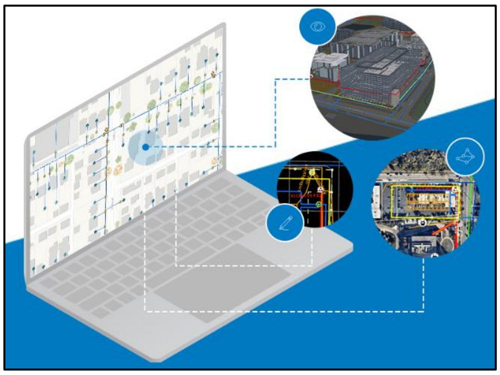


Figure 19 : Underground utilities visualization and analysis **[29]**

IV.3. ArcGIS Utility Network pricing

The ArcGIS Utility Network is not free, it is actually an extension of ArcGIS Pro (figure 20), so in order to use this extension with it’s all advanced tool to manage complex infrastructure system the user must get or pay the necessary license to use ArcGIS Pro. ArcGIS Pro provides numerous license options based on user needs and the company size.

Figure 20 : ArcGIS Pro **[31]**

The following are the three types of licenses available for purchase:

- **GIS Professional Basic**

  - Use ArcGIS Pro to map, view, analyze, and manage your data.
  - Integrate 3D, CAD, images, and other data into a single map.
  - Use ArcGIS Online and ArcGIS Living Atlas to connect people and data globally. [31]

- **GIS Professional Standard**

- All features available to GIS Professional Basic users.
- Capable of modifying data and geodatabases with many users.
- Capable of automating quality control processes, including workflow management. [31]

- **GIS Professional Advanced**

- The GIS Professional user type standard includes everything.
- Proficient in GIS data analysis, modeling, and high-end cartography.
- Robust data and database management capabilities. [31]

After obtaining the ArcGIS Pro license, the user additionally must purchase the Utility Network license. The Utility Network license itself is available in several formats, and the cost varies depending on the user's demands and the project requirement. The utility network extension can be deployed in two different ways. The geodatabase type used to store a utility network determines the deployment type.

- **Enterprise deployment**

Enterprise deployment is the principal deployment strategy for a utility network that uses an enterprise geodatabase. This services-based design supports multiuser editing and utility network sharing across all platforms (desktop, mobile, and online). [30]

- **Single-user deployment**

Single-user deployment is an alternative deployment strategy for a utility network maintained in a file or mobile geodatabase. Read-only actions allow concurrent access, while editing activities are confined to a single user. [30]

V. NF P98-332 standard

The NF P98-332 standard is a French standard that covers the techniques and constraints involved in establishing a new network near an existing network or vegetation, as well as the establishment of plants near an existing network in built-up areas and outside built-up areas, when work to open excavations, backfill, and repair is required for network installation or maintenance. [32]

The NF P98-332 standard specifies the distances between underground utilities, the proximity of buried networks to plants, and the color code for identifying and staking these networks. This standard specifies the minimum distances that must be maintained between several types of subterranean networks, such as water, electricity, gas, and telecommunications, in order to minimize interference and provide safe access for maintenance. Furthermore, it limits the proximity of these networks to vegetation and other natural features in order to prevent harm and guarantee that plants do not interfere with infrastructure. [32]

Here are some regulations of the NF P98-332 standard [33]:

- The network plan must favor installation beneath the sidewalk and allow for the installation of PE tubes in bending up to a minimum radius of curve of 30 times the tube's exterior diameter.
- The connecting path, for its part, must be as straight as feasible and perpendicular to the network pipe.

- In line with standard NF P 98-332, a minimum distance of 0.20 m must be maintained between generators and other ground constructions (both parallel and crossing).
- If the levels and locations of other works are not established or guaranteed, the installation of PE tubes will be delayed.
- The ideal strategy is to position the networks next to one other in a horizontal layer. Network overlays must be treated as exceptional circumstances.
- This text is extracted from the NF P98-332 standard document, which can be found in the annex to this report, describes the required distance between buried networks and trees: “The networks must be placed up to a minimum distance of 1.50 m from trees measured at 1 m above the ground, it is necessary to take measures specific conditions to be defined in advance with the owner or manager of the trees to avoid deterioration of the networks by the roots and the dieback of the plants, for example the implementation of systems to divert or redirect the roots.” [32].
-

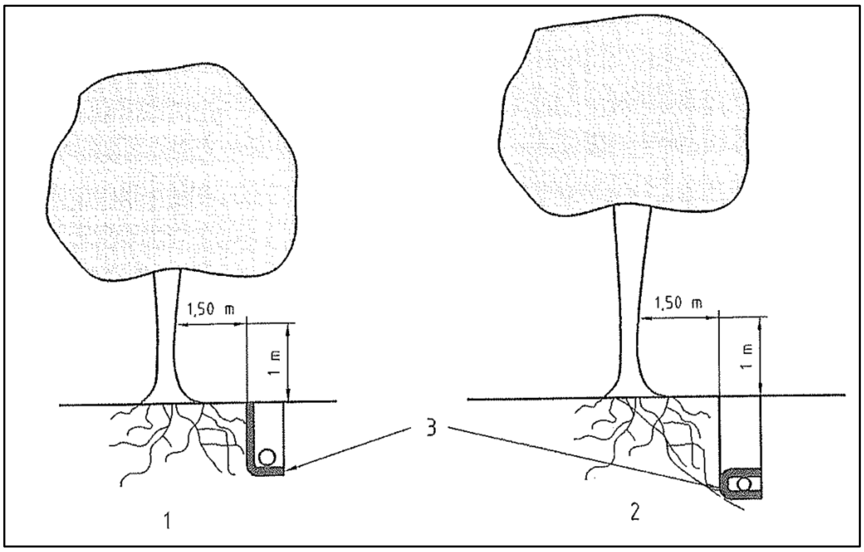


Figure 21 : Distance Between Buried Networks and Trees **[32]**

- It is illegal to cut roots with diameters bigger than five cm.
- The networks must be separated by at least twenty cm.
- In addition, a warning device should be installed at a height of twenty to thirty centimeters above the wires and pipelines.
- The device's color is standardized using the color codes for subterranean networks. [32]

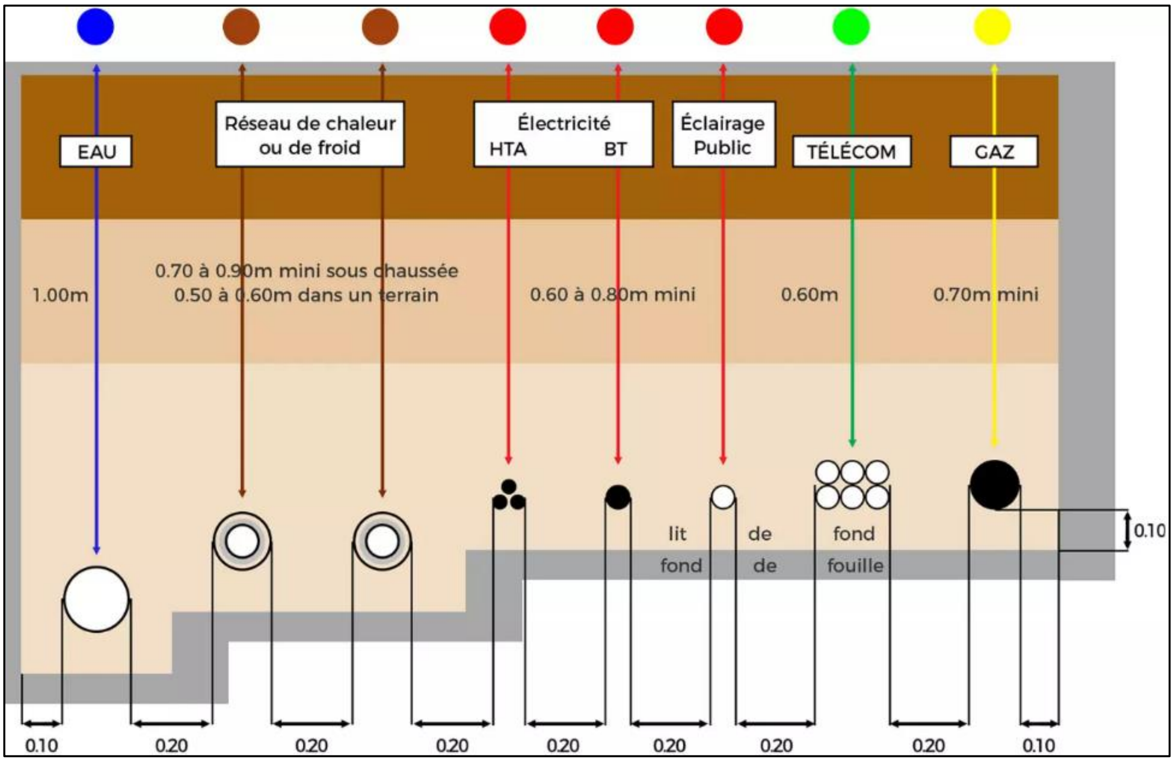


Figure 22 : Distance rules between buried networks **[33]**

The Color code (Figure 23) reserves the red color for electricity, yellow for gas, green for telecommunications, blue for potable water, brown for wastewater, and orange for heating networks. This color-coding method enables workers to readily identify the sorts of networks during excavation and maintenance, improving safety and efficiency. The NF P98-332 standard is critical for coordinating public services, enhancing construction safety, and reducing environmental impact. [33]

NATURE OF NETWORKS	COLOR OF MARKING	
BT, HTA or HTB electricity, lighting; Traffic lights and road signs		Red
Fuel gas (transport or distribution) and Hydrocarbons		YELLOW
Chemical products		Orange
Potable water		Blue
Sanitation and Pluvial		Brown
Heating and air conditioning		Purple
Telecommunications; Traffic lights and TBT road signs		Green

Figure 23 : Color codes for buried networks **[33]**

VI. Client-Side Web Mapping Pros and Cons

Client-side solutions for web mapping make it easier to build an online mapping application. This solution eliminates the requirement for a separate GIS server, such as GeoServer or MapServer, as well as advanced web programming expertise. The term "client-side" means the end user's device and the web browser or software that runs on it. This refers to the user's computer, smartphone or any other device that uses the online web mapping application and processes the data locally.

The QGIS2WEB plugin is one of the most effective client-side solutions for web mapping. With a few clicks, GIS specialist can quickly build dynamic web maps by exporting full QGIS projects, including layers, styles, and symbologies, directly to the web. This approach eliminates the need for spending time on transforming data into web-compatible formats and developing a full-stack web application from scratch. Furthermore, QGIS2WEB supports popular JavaScript libraries such as OpenLayers, Mapbox GL JS, and Leaflet. These libraries make it easier to display geographic data on web sites while also providing crucial customization options for maps. They include powerful tools such as measurement tools, layer search functionalities, layer lists, address search capabilities, pop-up displays, and hover highlighting. This allows users to quickly and easily build interactive online web mapping apps.

VII. Conclusion

In conclusion, the "State of the Art" chapter has provided a comprehensive overview of utility systems, emphasizing methods of data acquisition, management strategies, associated costs, and key terminologies. It has also highlighted the significant risks posed by accidents within these systems, which can have profound implications for human safety, community well-being, and environmental sustainability.

CHAPTER III:

SYSTEM IMPLEMENTATION AND DATA PROCESSING

I. Introduction

The system implementation phase of this project includes the completion of each important stage in the geospatial data cycle (Figure 24).

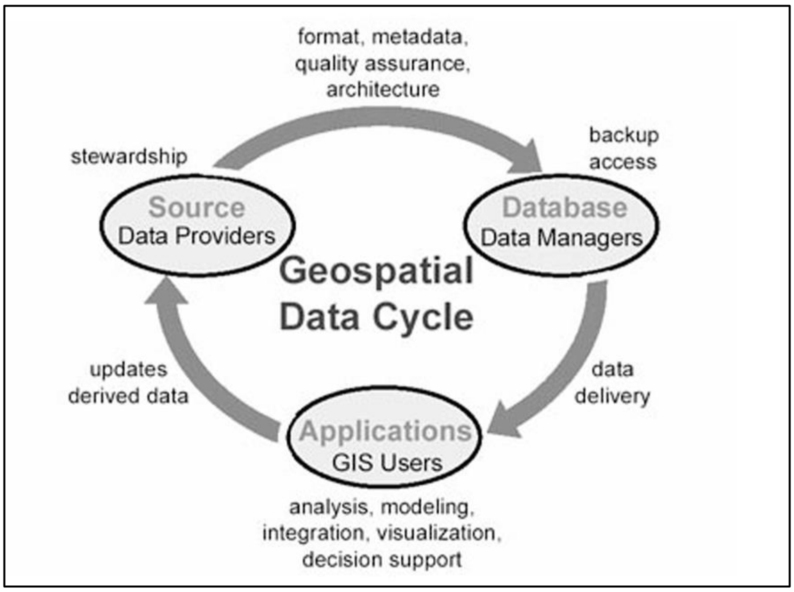


Figure 24 : Geospatial data cycle **[34]**

This section will go into depth about each phase, starting with the design and creation of the spatial database. Following this, we will be looking at GIS implementation and data entry methods to provide a reliable and well-populated database. Rigorous quality control techniques will next be used, including developing a QGIS plugin, to ensure data completeness, and then we will use the French standard for buried networks, the "NF P98-332 distance rules," to detect danger zones that could pose future accident risks in Coquitlam by analyzing distances between utility networks and between trees and underground infrastructure. Once the data quality control and distance rules have been tested, we will run spatial statistics and develop a comprehensive dashboard that will provide stakeholders with fascinating visualizations and useful information critical for utility management.

Finally, we will develop a web mapping application designed to visually represent underground utilities. This web mapping application will be extremely useful for field technicians, land surveyors, utility workers, and construction firms in identifying and locating subsurface utilities in order to avoid accidents and assure safety during construction, excavation, and maintenance operations. Each of these steps is critical for developing a complete system that store, manipulate, evaluate, manage and visualize spatial utility data.

II. Spatial database design and creation

We start by creating a PostgreSQL database named “Coquitlam_infrastructure” that will be responsible for keeping all our tables; next, we should add the spatial extension PostGIS (figure 25) to be able to utilize the “geometry” data type to store spatial data (Polygon, point and lines) and apply numerous spatial joins, queries, and analysis.

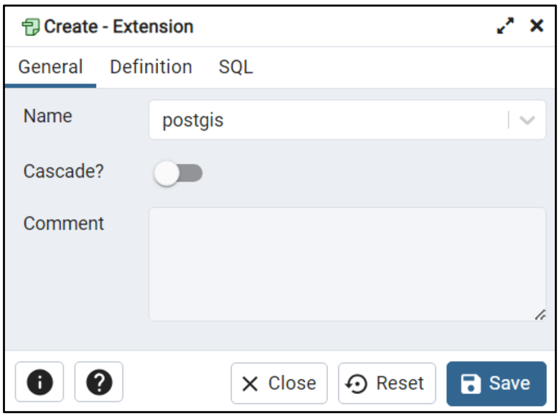


Figure 25 : Spatial extension PostGIS

- **ERD diagram**

Using the PostgreSQL's ERD tool, we can carefully create a visual representation of our database structure. This method starts by adding all of the tables provided in the data dictionary, then sets attributes and their data types for each table (figure 26).

Then by creating Primary and foreign keys we can establish relationships between tables to ensure the integrity of our spatial data.

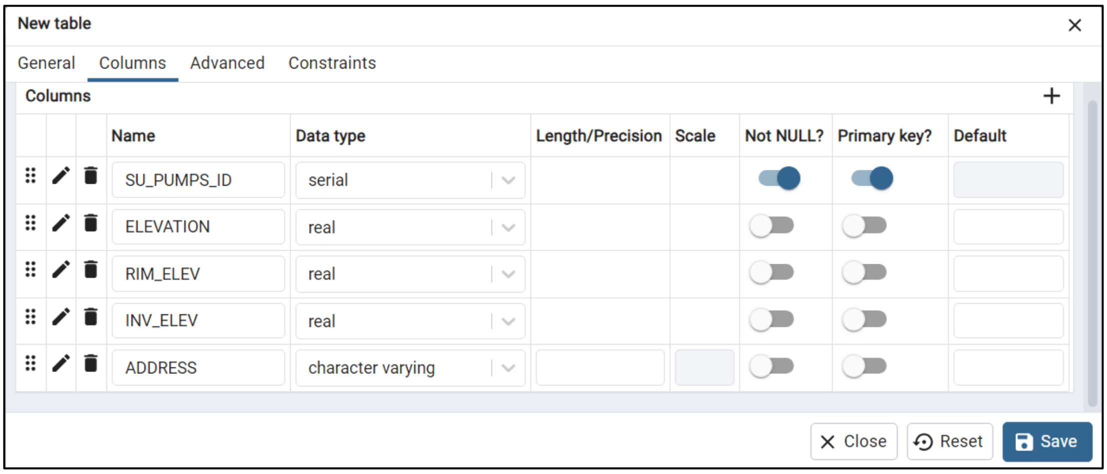


Figure 26 : Table creation

In addition to giving us a fantastic visual representation of the database's architecture, the ERD diagram acts as a guide to guarantee that all of the elements included in the data dictionary are appropriately represented.

Here is our final **ERD diagram**:

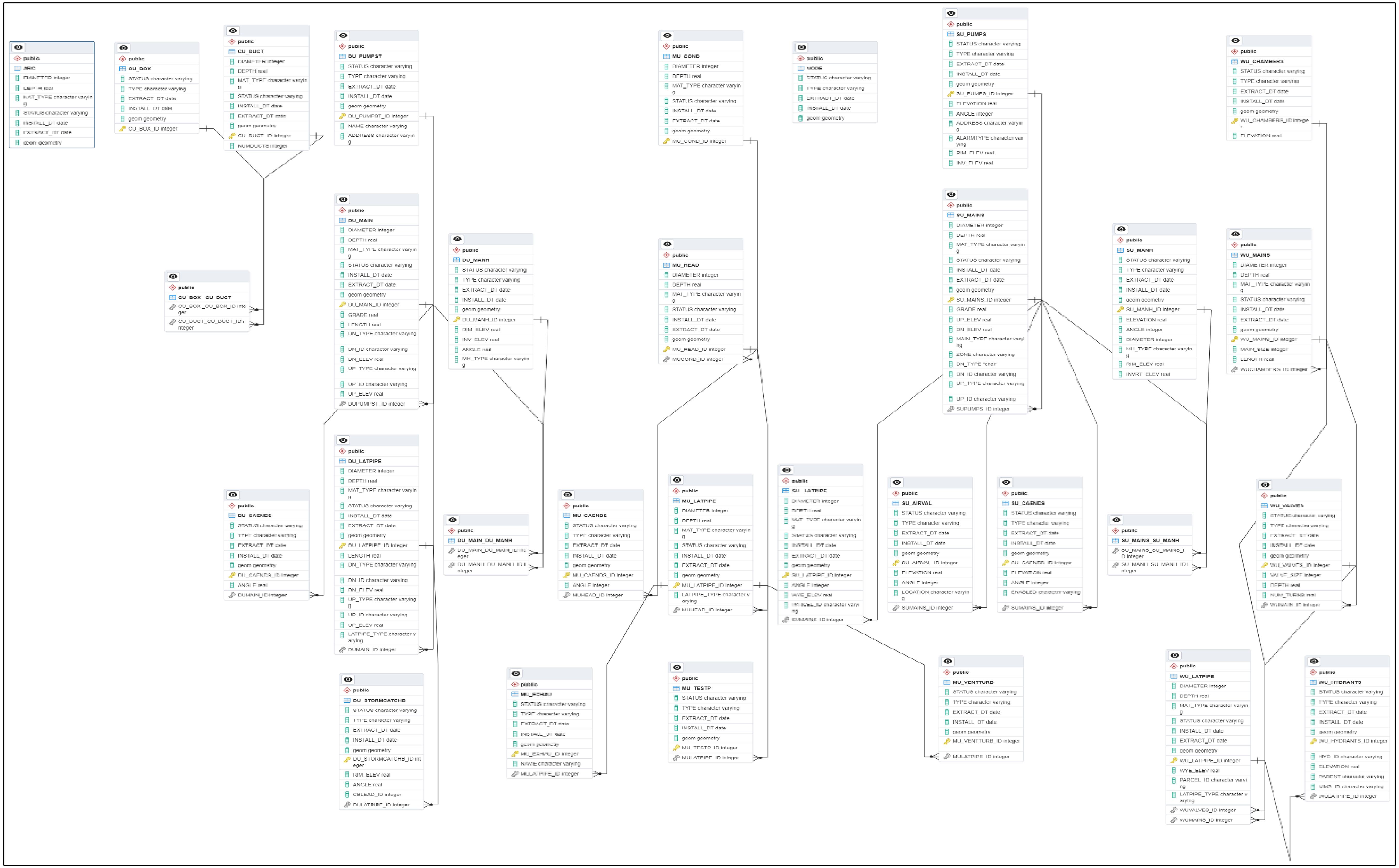


Figure 27 : ERD Diagram

The Entity-Relationship Diagram (ERD) (Figure 27) can be found in the annexed documents accompanying this project.

- **Table creation**

Once our ERD diagram has been created, we select the "Generate SQL" option. The SQL code (as shown in figures 28 and 29) created by this step will be then executed to create all of the physical tables in the database, along with their associated attributes and relationships.

```
CREATE TABLE IF NOT EXISTS public."ARC"
(
    "DIAMETER" integer,
    "DEPTH" real,
    "MAT_TYPE" character varying,
    "STATUS" character varying,
    "INSTALL_DT" date,
    "EXTRACT_DT" date,
    geom geometry
);

CREATE TABLE IF NOT EXISTS public."NODE"
(
    "STATUS" character varying,
    "TYPE" character varying,
    "EXTRACT_DT" date,
    "INSTALL_DT" date,
    geom geometry
);
```

Figure 28 : SQL code to create the ARC, NODE tables.

```
CREATE TABLE IF NOT EXISTS public."SU_PUMPS"
(
    "SU_PUMPS_ID" serial NOT NULL,
    "ELEVATION" real,
    "ANGLE" integer,
    "ADDRESS" character varying,
    "ALARMTYPE" character varying,
    "RIM_ELEV" real,
    "INV_ELEV" real,
    PRIMARY KEY ("SU_PUMPS_ID")
)inherits ("NODE");

CREATE TABLE IF NOT EXISTS public."SU_ LATPIPE"
(
    "SU_LATPIPE_ID" serial NOT NULL,
    "ANGLE" integer,
    "WYE_ELEV" real,
    "PARCEL_ID" character varying,
    "SUMAINS_ID" serial,
    PRIMARY KEY ("SU_LATPIPE_ID")
)inherits ("ARC");
```

Figure 29 : SQL code to create the SU_PUMS, SU_LATPIPE tables.

This is our spatial database thoroughly developed (figure 30), with all relevant tables, each containing attributes defined with appropriate data types. These tables will then be accessed using QGIS and filled with the necessary data. This methodical approach guarantees smooth integration and effective data handling within our GIS system.

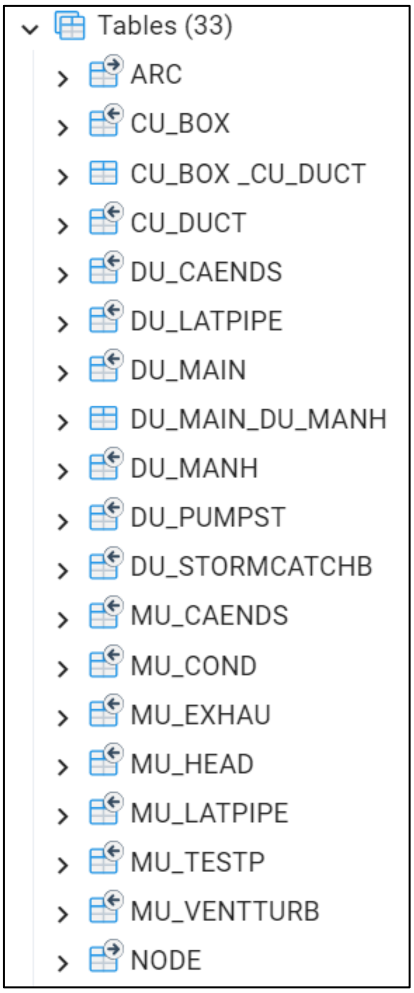


Figure 30 : Empty tables created in the database.

III. GIS implementation

The GIS implementation step entails configuring the PostGIS database and QGIS connection for effective data integration and population. We will discuss various scenarios for the data insertion step, taking into account factors such as project budget, timeframe, available resources (including personnel and equipment), required level of precision, and desired data quality. After evaluating these scenarios, we will choose the most suitable one and provide a justification for our choice.

III.1. PostGIS database and QGIS connection

QGIS is one of the best GIS software for entering spatial data into a PostGIS database. Connecting QGIS to the PostGIS database, is a simple operation that requires only five pieces of information:

- The host: The host information is the IP address of the server that hosts the PostgreSQL database, in our case we are running our database on our local machine so we set the host information as “localhost”.
- Port: It’s a number that allow PostgreSQL to establish connection with client application, so the client side (In our case the client is QGIS) can interact with the database server, 5432 is the default value of PostgreSQL's port.
- Username: Name of the user.
- Password: Databases provide a lot of security by requiring the user to log in via a credential password, it’s the PostgreSQL user password that was specified during the PostgreSQL installation through PGAdmin.
- Database: Name of the database.

So, all we need to do here is open the Data Source Manager and create this new PostGIS connection (as shown in Figures 31).

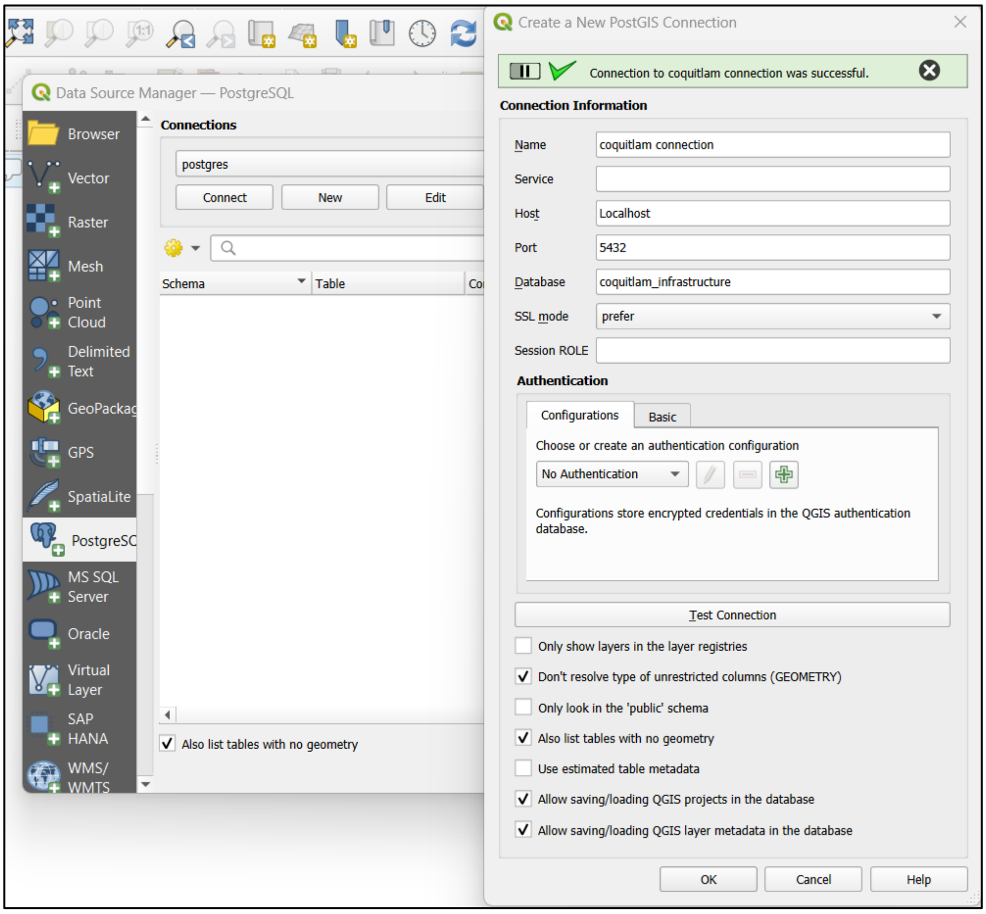


Figure 31 : PostGIS database and QGIS connection.

The key advantage of the connection between QGIS and the PostGIS database is that any data edits made in QGIS are automatically reflected in the PostGIS database system.

Once we've established the connection, all of the empty tables in our PostGIS database will appear. We can simply add the proper geometry to the table by filling out the geometry attribute, and we can also add the appropriate reference system by entering the SRID (figure 32).

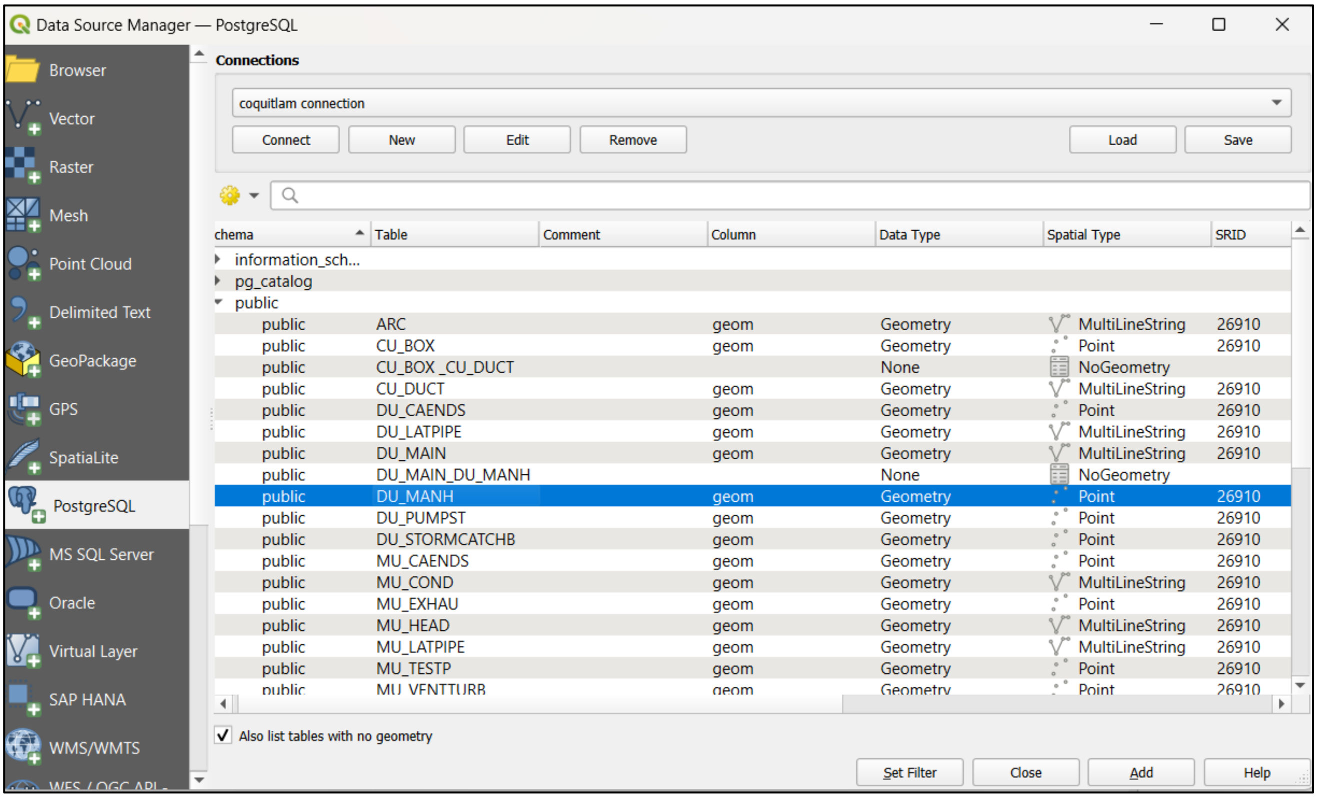


Figure 32 : Empty tables of the PostGIS database.

III.2. Data insertion

In our GIS system, data entry is the most critical stage. The approach employed is determined by a number of factors, including the project's objectives, the primary data source, project timeframe, and budget. We will go over all of the scenarios and justify each option, as well as highlight the limits of each strategy.

III.2.1. Copy / paste feature approach

- **First scenario: Primary data source is vector data**

If the primary data source is vector data edited and generated from another data model or without a data model, to integrate it in our spatial data model, we can easily use the copy-paste feature tool in QGIS. This tool allows us to select all features (figure 33) from a data source layer and paste them, along with their attribute data, into our spatial empty table in the PostGIS database.

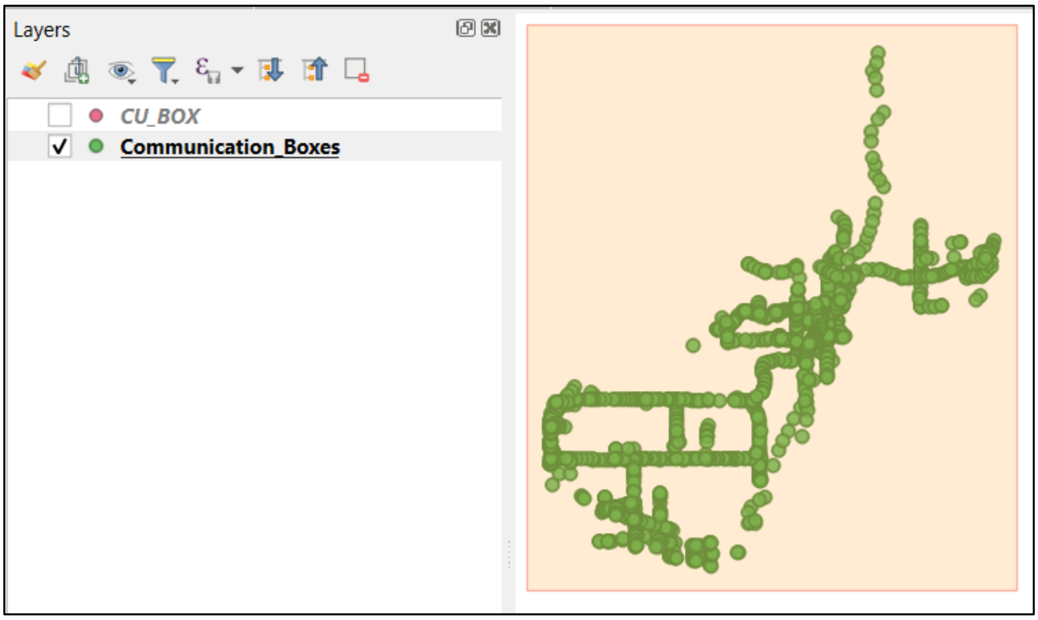
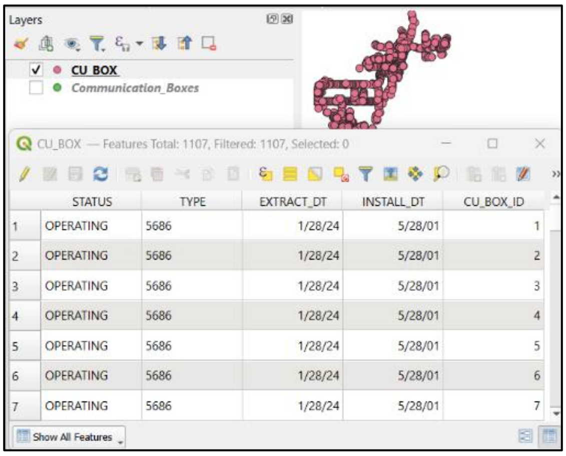
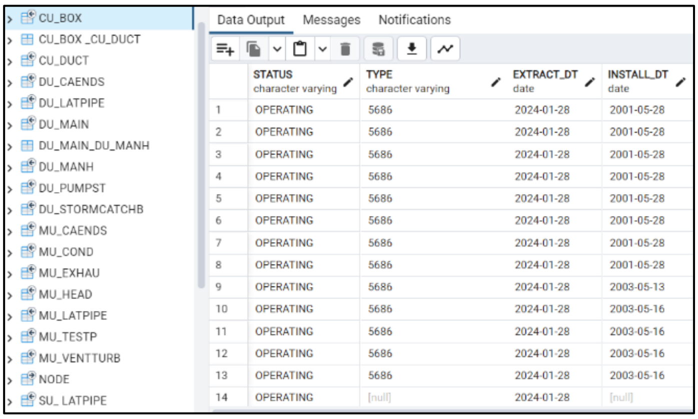


Figure 33 : Selected features.

We need to activate editing mode on the layer where we'll paste the features. After pasting, we click save and turn off the editing mode. And we can see here that we have 1107 features copied with attribute data in our spatial layer in QGIS, as well as that any changes made to the spatial layer in QGIS are reflected in the PostGIS database thanks to the PostgreSQL, QGIS connection (as illustrated in Figures 34 and 35).



	STATUS	TYPE	EXTRACT_DT	INSTALL_DT	CU_BOX_ID
1	OPERATING	5686	1/28/24	5/28/01	1
2	OPERATING	5686	1/28/24	5/28/01	2
3	OPERATING	5686	1/28/24	5/28/01	3
4	OPERATING	5686	1/28/24	5/28/01	4
5	OPERATING	5686	1/28/24	5/28/01	5
6	OPERATING	5686	1/28/24	5/28/01	6
7	OPERATING	5686	1/28/24	5/28/01	7



	STATUS character varying	TYPE character varying	EXTRACT_DT date	INSTALL_DT date
1	OPERATING	5686	2024-01-28	2001-05-28
2	OPERATING	5686	2024-01-28	2001-05-28
3	OPERATING	5686	2024-01-28	2001-05-28
4	OPERATING	5686	2024-01-28	2001-05-28
5	OPERATING	5686	2024-01-28	2001-05-28
6	OPERATING	5686	2024-01-28	2001-05-28
7	OPERATING	5686	2024-01-28	2001-05-28
8	OPERATING	5686	2024-01-28	2001-05-28
9	OPERATING	5686	2024-01-28	2003-05-13
10	OPERATING	5686	2024-01-28	2003-05-16
11	OPERATING	5686	2024-01-28	2003-05-16
12	OPERATING	5686	2024-01-28	2003-05-16
13	OPERATING	5686	2024-01-28	2003-05-16
14	OPERATING	[null]	2024-01-28	[null]

Figure 34 : Copied feature in QGIS layer **Figure 35 :** Data inserted in the PostGIS database.

- **Second scenario: Primary data source is DWG data**

When the primary data source is DWG (AutoCAD drawing) files obtained during a land surveying operation utilizing a total station, GPS equipment, or GPR, the method will include transforming the DWG data into vector data, followed by a copy-paste feature technique in QGIS. This approach will only copy the spatial features in our PostGIS database, leaving the attribute data to be entered manually or joined with an Excel file if it is available.

- **DWG to SHP transformation**

We start by importing our DWG data into QGIS and selecting the "Merge layers" option. It's important to set our reference system correctly before clicking OK to complete the import process.

The data is then added and classed according to its geometric properties as lines, polylines, text (no geometry), and points (figure 36).

Figure 36 : DWG data imported.

Once imported, we will convert this DWG data to SHP format so that we can transfer spatial features into our PostGIS database tables. To do this, we will right-click on the DWG layer, pick "Export," and export it as an ESRI Shapefile (as shown in the figure 37).

Figure 37 : ESRI shapefile generated.

Next, using the “Select by Expression” tool of QGIS (figure 38) we will categorize the data based on “layer” field values. Each layer value represents an individual component of the utility system, such as water mains or water lateral pipe.

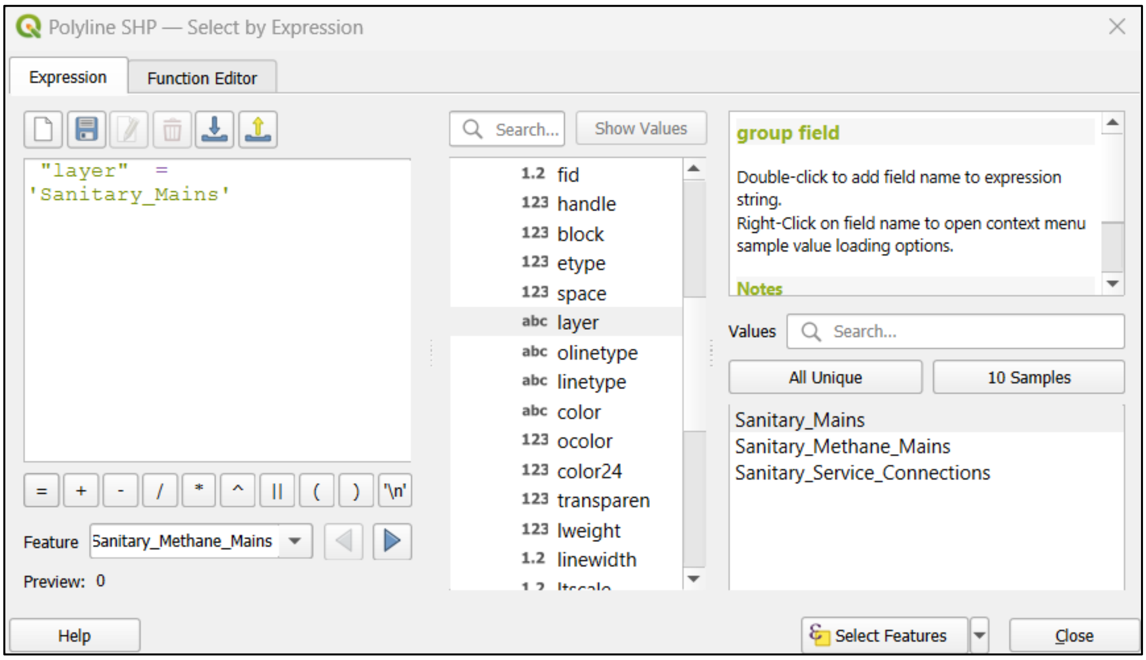


Figure 38 : Data classification.

For every layer value, we select the right features, then copy / paste them into our PostGIS database table using the “Paste Features” icon (as demonstrated in the figure 39).

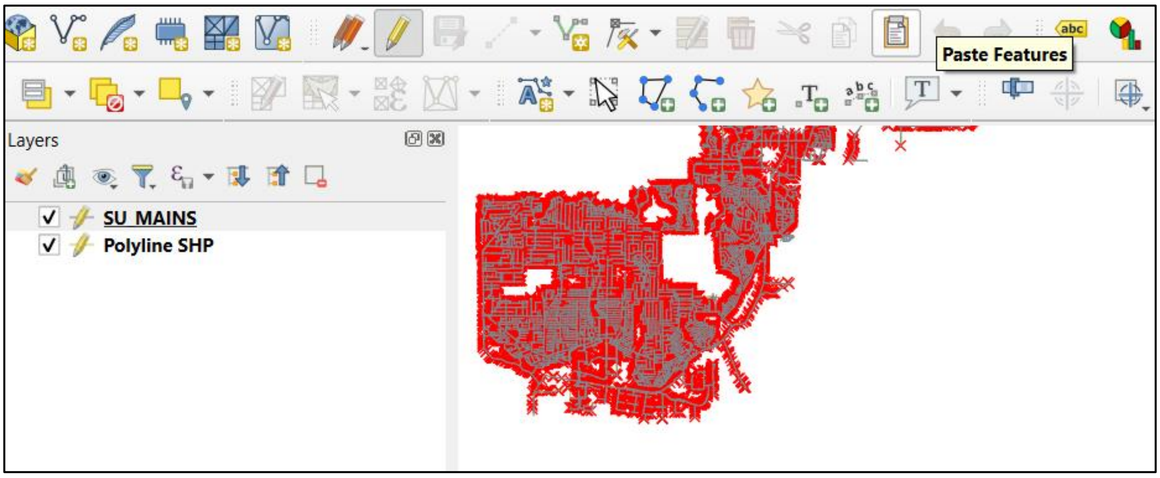


Figure 39 : Copy paste process.

This step is repeated for each layer value, ensuring that all utility system components are fully integrated into the PostGIS database. While this procedure seems simple and straightforward, it has both significant benefits and limitations.

If we choose to work with this copy/paste approach in QGIS, we need to use a spatial data model without table associations "relationships", This means that the spatial database model should initially consist just of tables and their attributes, this is because QGIS will not be able to fill the foreign key attributes of each table with a copy-paste approach, which will result in errors.

To maintain data integrity, we can establish relationships between tables after the data has been added, allowing us to run informational data queries.

To establish a relationship between tables, we have to make sure that the primary and foreign key attribute types have the same type "serial". This is important since QGIS only accepts this option when connecting to PostgreSQL. This is an example of establishing a relationship between the sanitary mains table and the sanitary capped ends table (figure 40).

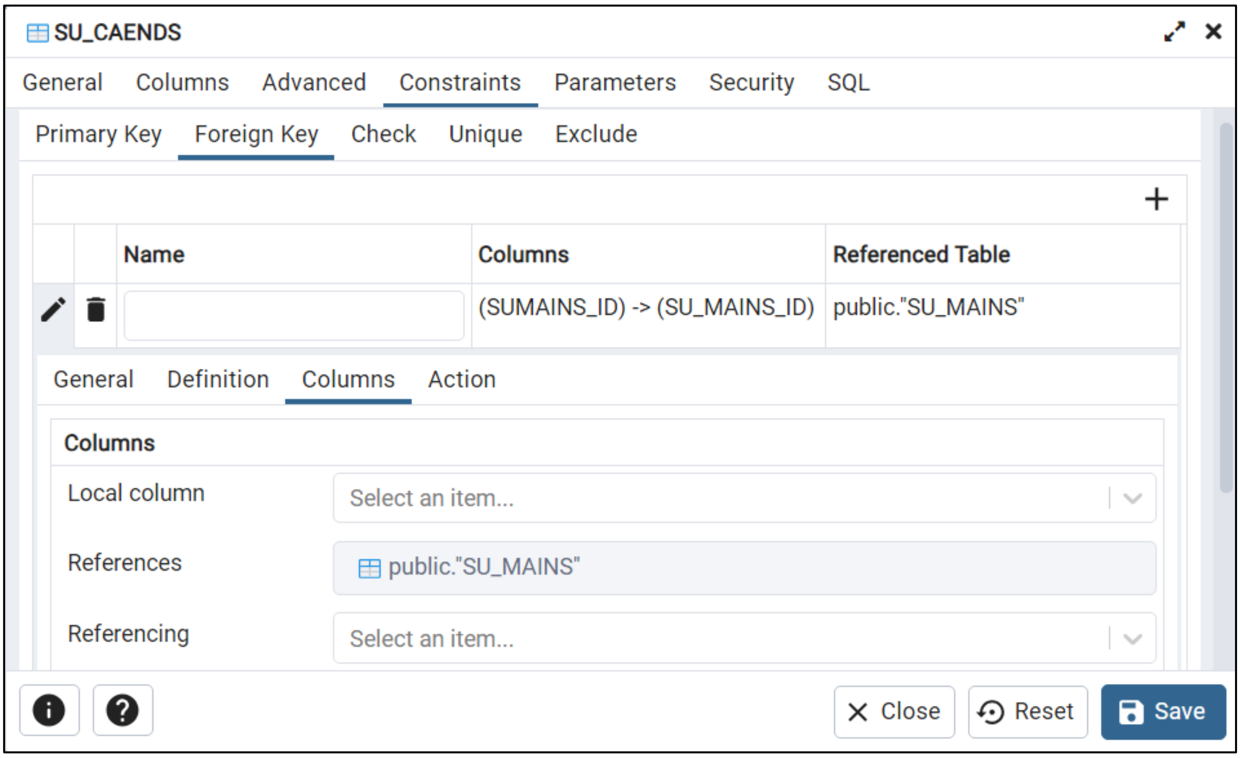
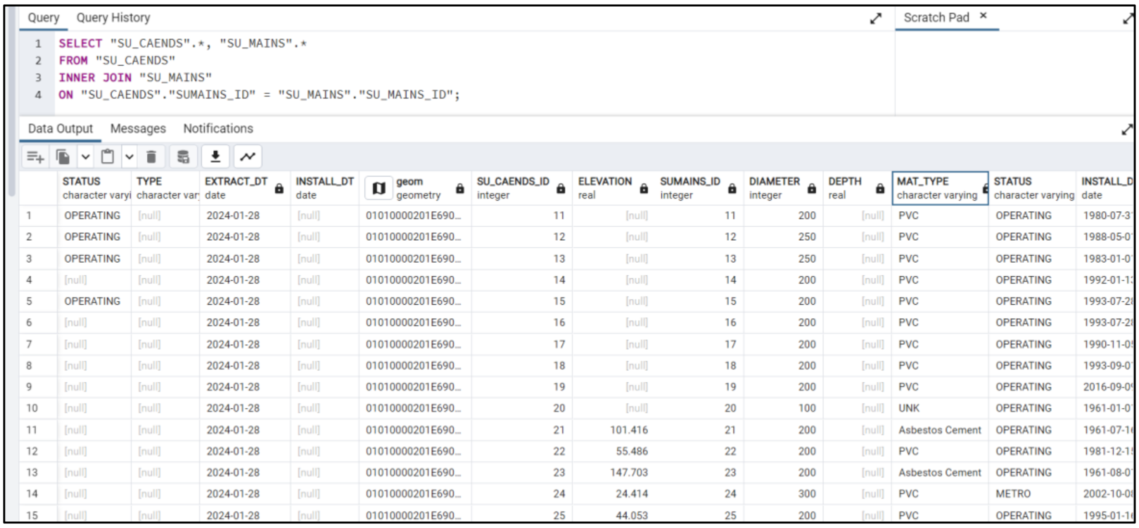


Figure 40 : Creating Foreign key constraint.

We can now access data from both the sanitary mains and sanitary capped end tables by utilizing JOIN syntax in multi-table queries (figure 41). This enables us to combine relevant data from different tables based on common fields: primary keys and foreign keys, resulting in full insights on sanitary infrastructure data.



	STATUS character varyi	TYPE character var	EXTRACT_DT date	INSTALL_DT date	geom geometry	SU_CAENDS_ID integer	ELEVATION real	SUMAINS_ID integer	DIAMETER integer	DEPTH real	MAT_TYPE character varying	STATUS character varying	INSTALL_D date
1	OPERATING	[null]	2024-01-28	[null]	01010000201E690...	11	[null]	11	200	[null]	PVC	OPERATING	1980-07-3
2	OPERATING	[null]	2024-01-28	[null]	01010000201E690...	12	[null]	12	250	[null]	PVC	OPERATING	1988-05-0
3	OPERATING	[null]	2024-01-28	[null]	01010000201E690...	13	[null]	13	250	[null]	PVC	OPERATING	1983-01-0
4	[null]	[null]	2024-01-28	[null]	01010000201E690...	14	[null]	14	200	[null]	PVC	OPERATING	1992-01-1
5	OPERATING	[null]	2024-01-28	[null]	01010000201E690...	15	[null]	15	200	[null]	PVC	OPERATING	1993-07-2
6	[null]	[null]	2024-01-28	[null]	01010000201E690...	16	[null]	16	200	[null]	PVC	OPERATING	1993-07-2
7	[null]	[null]	2024-01-28	[null]	01010000201E690...	17	[null]	17	200	[null]	PVC	OPERATING	1990-11-0
8	[null]	[null]	2024-01-28	[null]	01010000201E690...	18	[null]	18	200	[null]	PVC	OPERATING	1993-09-0
9	[null]	[null]	2024-01-28	[null]	01010000201E690...	19	[null]	19	200	[null]	PVC	OPERATING	2016-09-0
10	[null]	[null]	2024-01-28	[null]	01010000201E690...	20	[null]	20	100	[null]	UNK	OPERATING	1961-01-0
11	[null]	[null]	2024-01-28	[null]	01010000201E690...	21	101.416	21	200	[null]	Asbestos Cement	OPERATING	1961-07-1
12	[null]	[null]	2024-01-28	[null]	01010000201E690...	22	55.486	22	200	[null]	PVC	OPERATING	1981-12-1
13	[null]	[null]	2024-01-28	[null]	01010000201E690...	23	147.703	23	200	[null]	Asbestos Cement	OPERATING	1961-08-0
14	[null]	[null]	2024-01-28	[null]	01010000201E690...	24	24.414	24	300	[null]	PVC	METRO	2002-10-0
15	[null]	[null]	2024-01-28	[null]	01010000201E690...	25	44.053	25	200	[null]	PVC	OPERATING	1995-01-1

Figure 41 : Multi-table query.

One last thing to mention is that the effectiveness of this strategy depends primarily on the quality of the primary data source. This approach will be effective if the data was collected and entered correctly with spatial and attribute data. The GIS implementation procedure will be quick, resulting in rapid deployment and timely results, and the project will have low costs since a full team of technicians is not needed for manual data editing and entry.

In our case, since the primary source of data is ESRI shapefiles modeled and vectorized in an ESRI spatial model, we used this method to create the final GIS for Coquitlam's utility systems, (as illustrated in the figure 42).

Figure 42 : Utility system of Coquitlam city.

Other methods for GIS implementation and data insertion will be addressed in the next sections.

III.2.2. Orthophoto-Based Feature Extraction

Orthophoto offer high-definition imagery with centimeter-level precision, allowing for exact measurements and analysis. As a result, they may be used to extract and edit some surface infrastructure element of utility systems such as electric poles, storm catch basins, water hydrants, and manholes.

Here are two figures (Figure 43 and figure 44) that demonstrate how to extract urban and utility system features from orthophotos using QGIS editing tools.

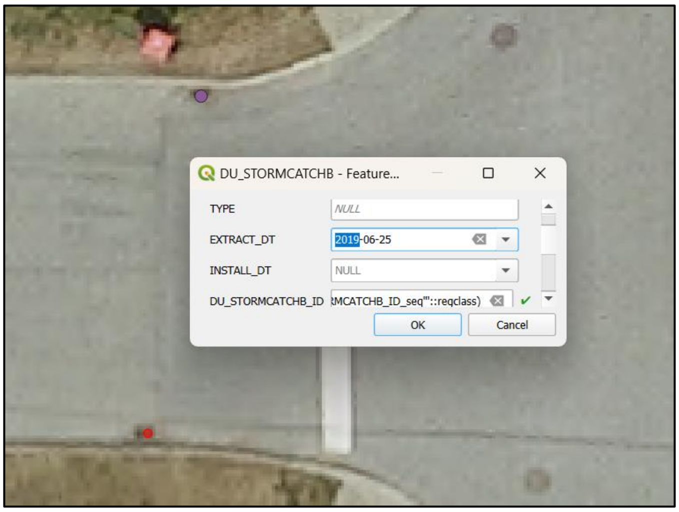


Figure 43 : Storm catch basin feature creation.

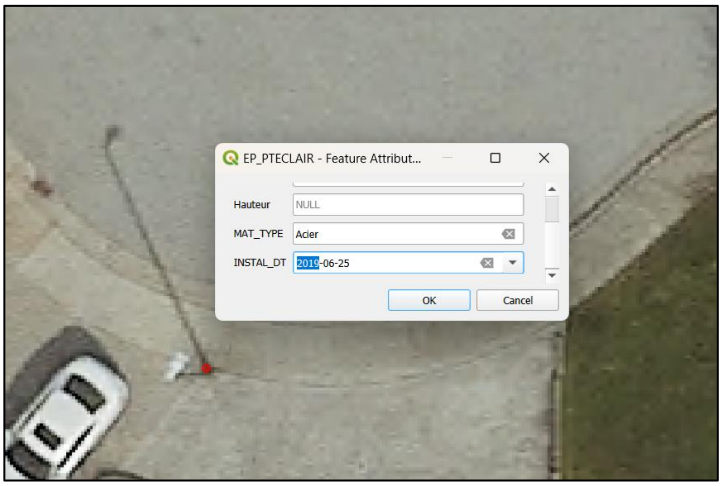


Figure 44 : Lighting pole feature creation.

This strategy is only effective on surface elements and does not function well with underground utility component. It is useful for collecting spatial features but not for entering attribute data, which is usually obtained during fieldwork. Even with surface elements, the technique may be limited if components are concealed by blur or shadows.

III.2.3. GIS Data Collection Using QField

QField is a professional mobile program that enables you modify QGIS projects on a variety of mobile devices, including data collectors, phones, and tablets. QField supports feature digitizing, attribute editing, attribute search, and custom forms using QGIS. It is an open-source mobile data collecting solution for Android, iOS, and macOS developed by the QGIS team. [35]

Figure 45 : QField.

To utilize QField for collecting data, we firstly should install the QField. Then we setup our project by adding and setting up the essential layers. We then add a backdrop map, ideally orthophotos for utility system data collecting due to their accuracy. Following that, we create a QField package that contains our QGIS project and data for usage with QField. We load this package into our mobile device and begin fieldwork. Once data collection is complete, we synchronize the data from QField with our QGIS project to update and analyze the acquired information. [35]

When we talk about spatial utility system data, we refer to precision and accuracy. To achieve this with QField, several acquisition methods may now be paired with it to collect features from the terrain with centimeter-level precision, capture photos if necessary and record attribute data. One of the most efficient methods for acquisition and data insertion is to use QField with a GNSS RTK receiver. These may now be linked together to collect accurate data directly in our GIS (figure 46).

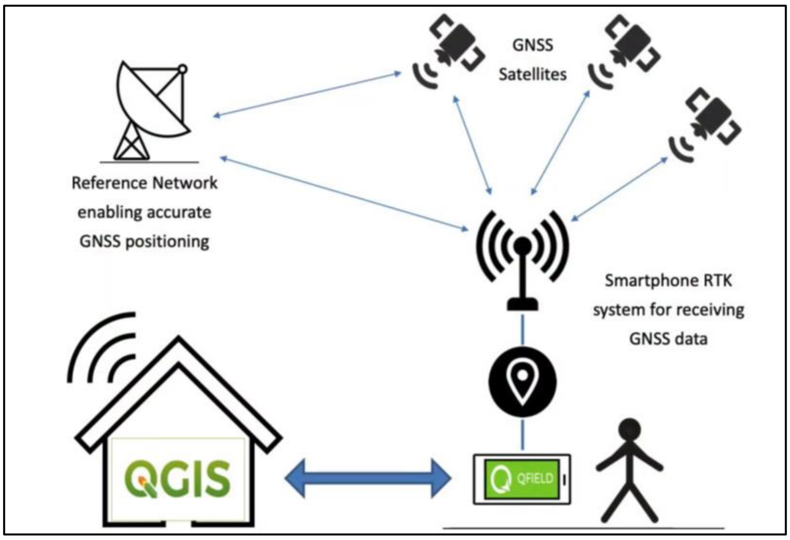


Figure 46 : Field Data Collection with QField and GNSS RTK receiver **[36]**

We can clearly see the high level of precision that can be attained with this method (figure 47). This screenshot from the "Centimeter accuracy GPS" site shares their experience collecting field data using QField and a GNSS RTK receiver, illustrating the level of precision possible with this technology.

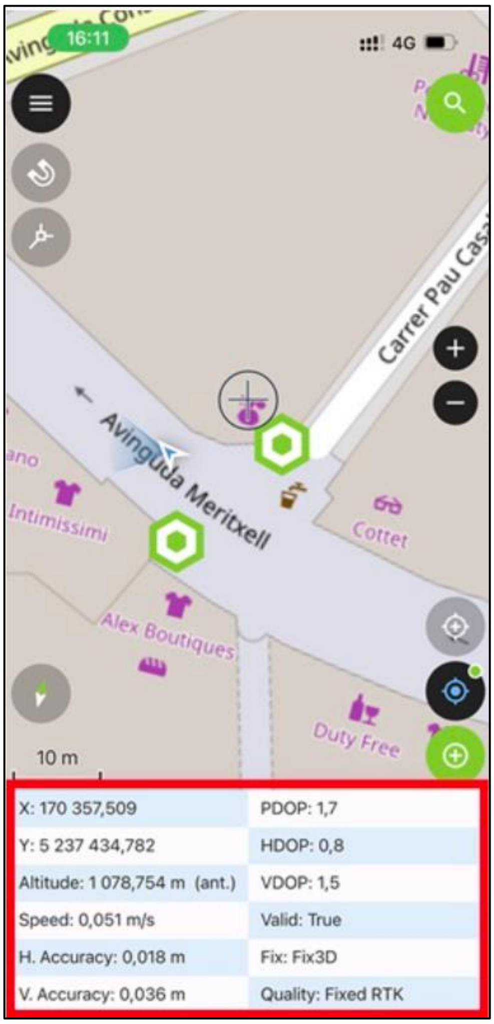


Figure 47 : Precision Field Data Collection with QField and GNSS RTK **[37]**

This approach of feature collection, creation and attribute data insertion at the same time using the QField, GNSS RTK receiver combination is very useful since it ensures spatial precision and precise entry of attribute data such as INSTALL_DT, TYPE, TECH_NAME, and ELEV.

It is practicable to start from scratch by integrating our spatial data model " the PostGIS database", followed by a straightforward and simple editing process. This technique offers maximum data accuracy and robustness, making it ideal for utility system projects at all stages, including installation, maintenance, and surveying.

The main disadvantage is the initial investment required to purchase field surveying equipment: GNSS receivers; however, the software components for data collecting, QField and QGIS, are free and open-source software, alleviating worries about extra expenditures.

III.2.4. Adding Metadata

Spatial metadata, often known as geographic metadata, refers to metadata specifically applicable to geographic data and information. This metadata can be saved alongside geospatial data, whether in vector or raster format, or documented separately. There are various standards for geospatial metadata, including those developed by the International Organization for Standardization (ISO) and the Federal Geographic Data Committee (FGDC). [38]

After we've inserted data, we need to add metadata to each layer in our spatial database to include details such as dataset type, owner, contact information, CRS (Coordinate Reference System), map extent, altitudes, and more (as demonstrated in figure 48).

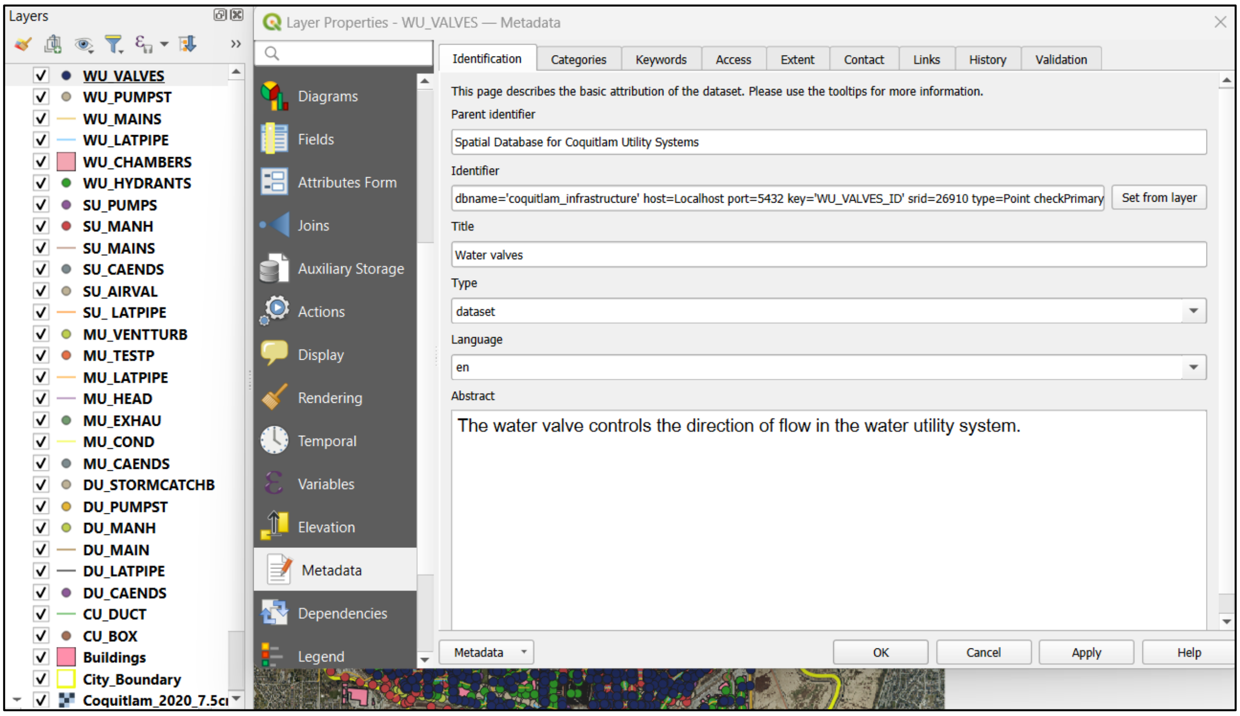


Figure 48: Layer properties_Metadata

III.2.5. Conclusion

All methods of data insertion have their utility, being advantageous in certain situations but limiting in others. The choice among them is determined by a number of factors, including the project budget, timeframe, available resources (including personnel and equipment), needed level of precision, and desired data quality. It is critical to recognize that the three ways may all be used in a single project since we might have multiple formats of primary data sources, and each data source type requires a certain methodology to work with. Furthermore, the needed level of accuracy for particular features might vary depending on the project specification document provided by the client. Depending on the precision given, we can use the right approaches to achieve the needed level of precision for various features

IV. Quality control (Data quality and "NF P98-332" distance rules tests)

In this quality control section, we will focus on data quality, emphasizing logical consistency, spatial accuracy, and completeness. We'll introduce QGIS tools to ensure spatial data integrity and develop a custom QGIS plugin for data completeness. Additionally, using the French "NF P98-332 distance rules" for buried networks, we will identify danger zones in Coquitlam by analyzing distances between utility networks and trees with underground infrastructure.

IV.1. Data quality

In the Arc-node spatial data model for utility networks, the relationship between MultiLineString and Point feature types can be characterized as follows: a Point may serve as a junction between two lines, an endpoint of a line, or an intersection point. Typically, in utility spatial data, a Point should be geometrically linked to a line. The presence of a separate line or an isolated Point is generally considered an error. Based on these criteria, it is critical to determine the most effective QGIS algorithms for detecting errors in utility system layers.

We will concentrate on three primary aspects of data quality: Logical consistency, Spatial accuracy and completeness of data.

IV.1.1. Logical consistency and spatial accuracy

The following figure clearly illustrates the connectivity between sanitary main features and sanitary manholes, as previously mentioned in the data dictionary for the topological consistency between the two layers. No manhole can be disconnected from a main, and no main can be disconnected from a manhole.

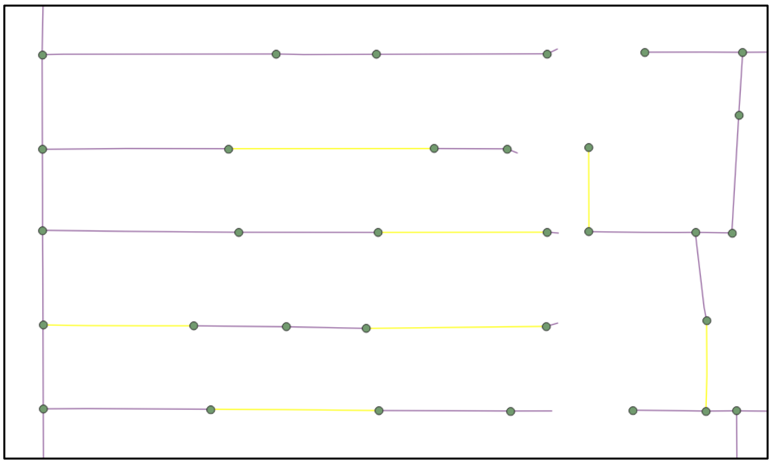


Figure 49 : Connectivity between sanitary main features and sanitary manholes.

One of the best tools in QGIS to detect errors like "**isolated points**" or "**isolated lines**" is "Select by Location" with the condition set to "Disjoint." (Figure 50), we will apply this to the main/manhole case and explore the results.

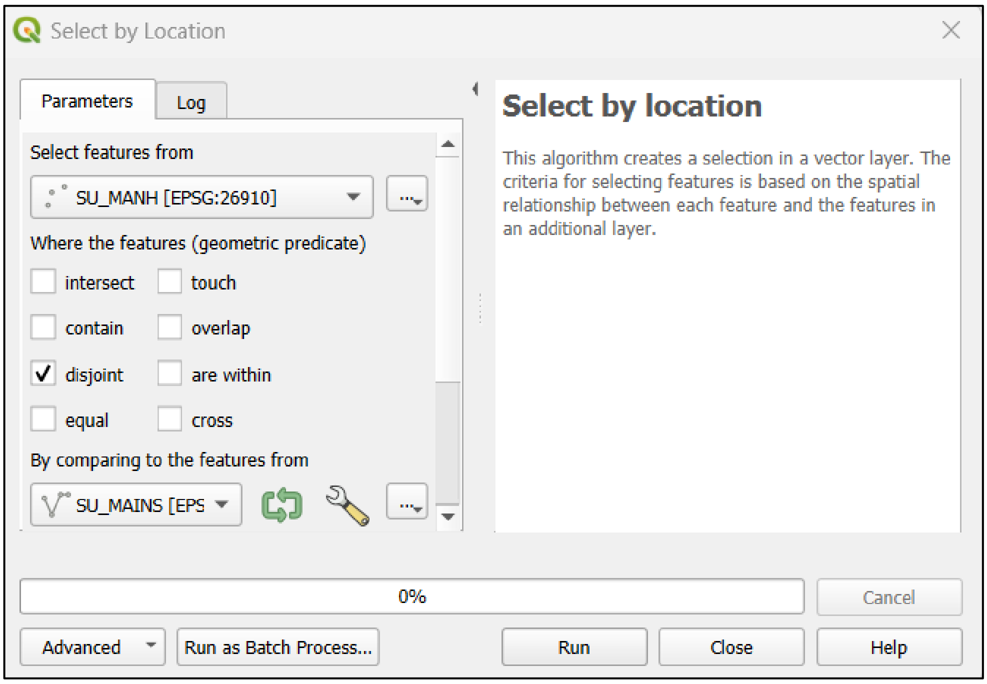
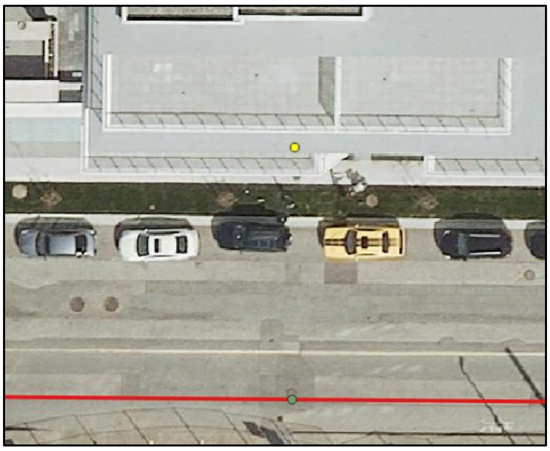


Figure 50 : Select by location.

Now that we have detected all isolated manholes, we can clearly see in the orthophotos that these locations are highly unlikely to be the actual positions of manholes (e.g., we can't have a manhole on the roof of a house, (Figure 51). Therefore, these erroneous points should be deleted.



→

Figure 51: Error Detected - Manhole Located on Roof of a House.

Figure 52: Error Corrected - Erroneous Manhole Point Deleted.

To correct these errors, it is essential to refer back to the original data sources, such as DWG files, historical topographic survey maps, and planning documents. Furthermore, orthophotos can serve as vital tools for visual verification. If we can't obtain the necessary details from these sources, we should even go to the field to verify the information.

We can apply the same process to identify isolated mains and pipelines (figure 53) that are not linked to manholes or located in inappropriate locations.

Figure 53: Error Detected – Isolated main.

Here, we observe (Figure 56) a main that exists but is not connected to the manhole. The manhole is clearly visible in the Orthophoto, so we simply need to update our sanitary main table by adding it as a new point feature.

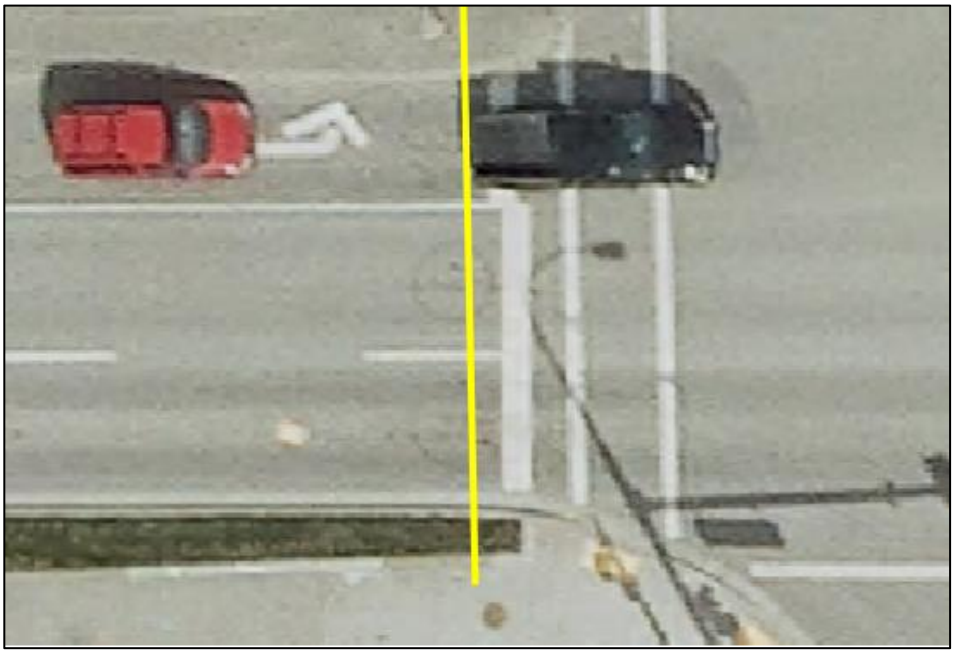


Figure 54: Missing manhole detection.

Snapping errors are also common where a point feature (such as a manhole, communication boxes) is located just adjacent to a line feature (such as a main, cable, or pipeline). In such cases, the point feature is often more geometrically exact since it is defined by a single specific set of coordinates that accurately mark its location. During land surveying, this exact position is accurately documented with high precision, making the point feature a reliable reference. So, representing it as a point feature on a map corresponds exactly to its real-world position.

In contrast, a line feature, such as a main or pipeline, is created in CAD or GIS software by connecting several points also acquired during land surveys. This method inherently introduces more potential for error because the accuracy of the line depends on the accuracy of multiple points and the precision with which they are connected.

In utility networks When point/MultiLineString features need to be snapped, such as snapping a main line to a manhole, using the point feature "the manhole" as a reference guarantee a high level of precision. To get maximum accuracy, we should pull the line from its end vertex and snap it to the point.

This can be achieved using QGIS's Snapping toolbar (figure 55), which facilitates precise connection of features.

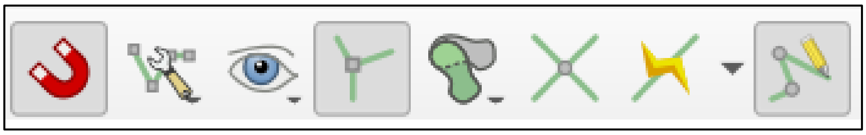


Figure 55: Snapping toolbar.

These two figures (figure 56 and 57) illustrate a snapping error before and after correction.

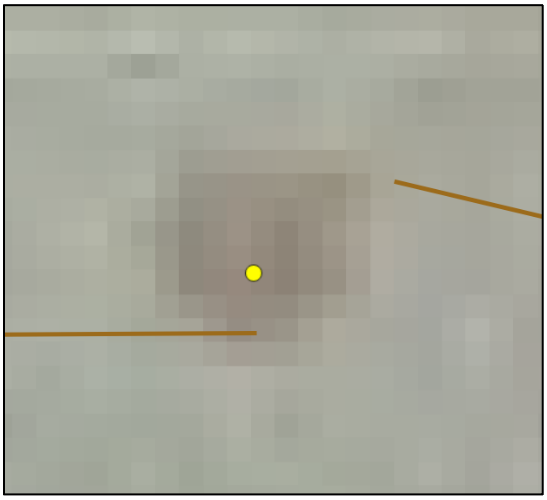


Figure 56: Snapping error after correction.

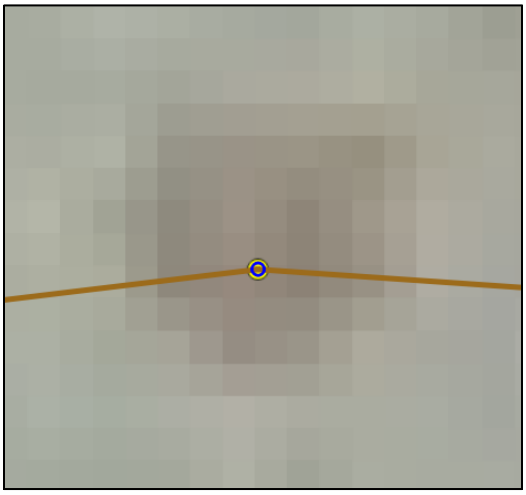


Figure 57: Snapping error before correction.

By using these approaches and tools, we can ensure the logical consistency and spatial accuracy of our data.

IV.1.2. Data completeness

To ensure data completeness, it's essential to identify all unedited features required in our spatial database, and then integrate them. We propose developing a QGIS plugin that can be highly beneficial, especially for Sanitary and Drainage Utility systems. This plugin's main goal is to detect intersection points between line vector and assess whether visible point feature such as manholes or hydrants are present at these junctions. By utilizing Orthophotos as a visual guide, we can easily detect and identify any previously unrecorded features.

The implementation process starts with the installation of the "QGIS Plugin Builder" tool, after installation, the next steps involve opening the tool, creating a new plugin project, and configuring parameters such as Class name, Plugin names, and Author information., Finally, the plugin project files are placed in a specific directory. (Figure 58).

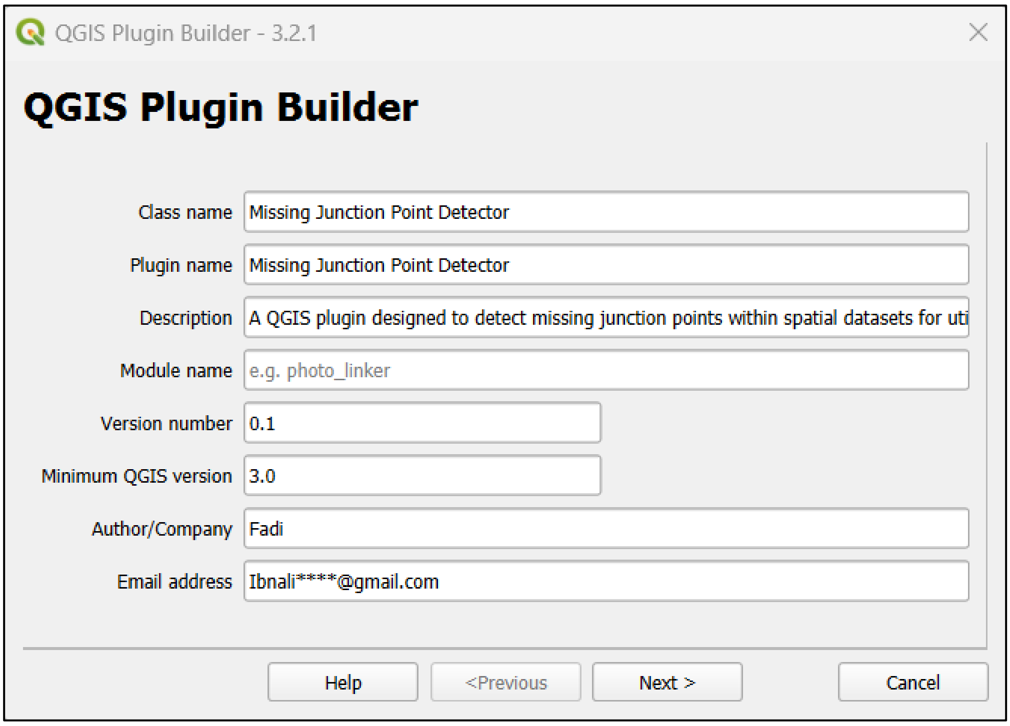


Figure 58: QGIS Plugin Builder

Next, we launch Qt Designer and use the .UI file to design the plugin interface, including inputs and outputs (as demonstrated in figure 61).

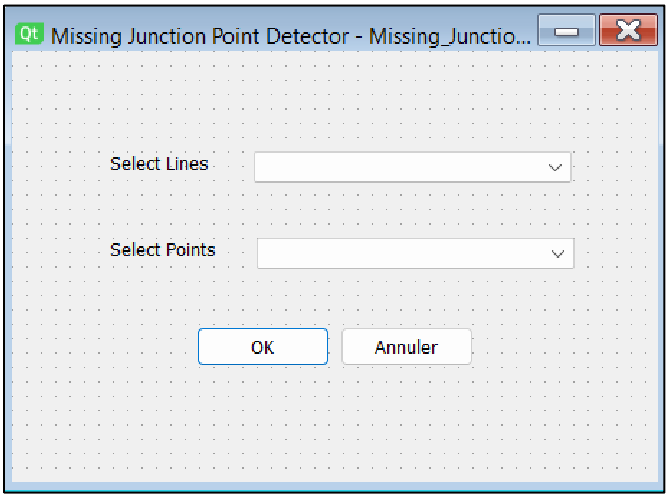


Figure 59: Designing the Plugin Interface Using Qt Designer

The plugin integrates two essential QGIS algorithms: "Line Intersection" from the Vector Analysis tool, which generates points where lines intersect, and "Extract by Location" with the "Disjoint" condition, which identifies and extracts non-overlapping points.

Python scripts that correspond to these algorithms are copied as Python commands and configured within the .py file to align with the plugin's functionality. This is the final QGIS Plugin, which includes all of the necessary functions and features for its intended use. (Figure 59)

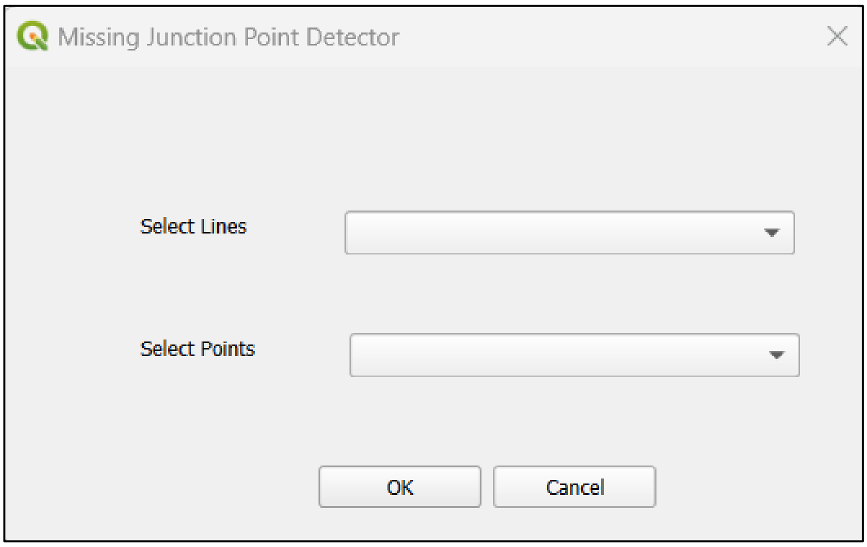


Figure 60: Missing Junction Point Detector

The following figure illustrates the result of executing the Plugin on sanitary manholes and mains dataset to identify points where there are likely unrecorded manholes, these points should then be visually inspected and examined against Orthophotos to ensure that no manholes were overlooked during the field data collecting or GIS editing processes.

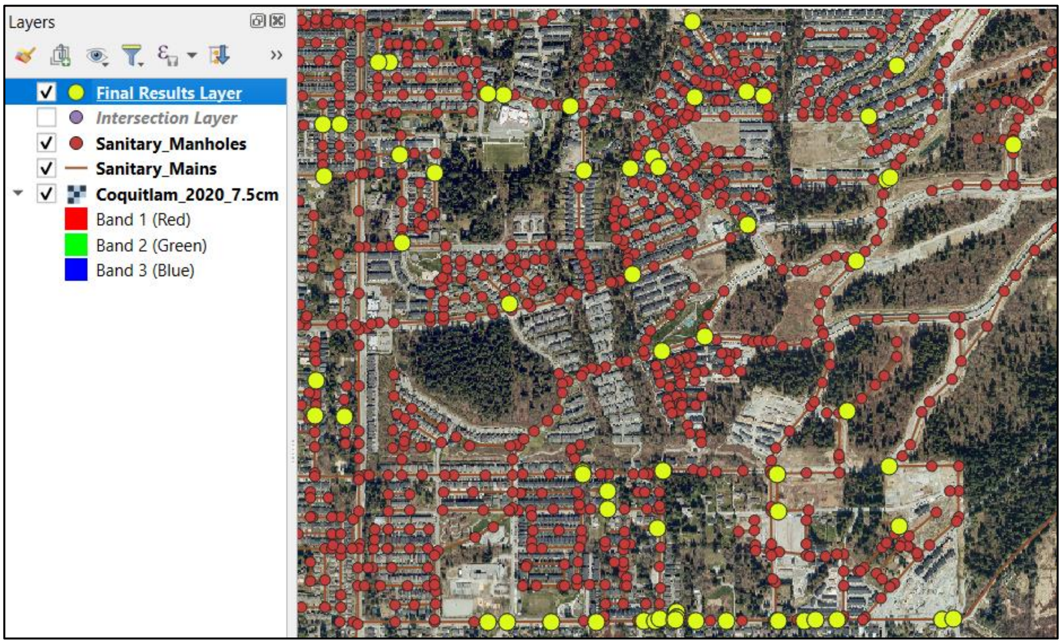


Figure 61: Plugin Output

The following two figures demonstrate the plugin's ability to pinpoint intersections of sanitary mains where manholes may have been overlooked during the GIS editing process or land surveying work. These generated points highlight areas that require further inspection and validation. These visualizations showcase the plugin's effectiveness in ensuring the completeness and accuracy of the sanitary utility database.

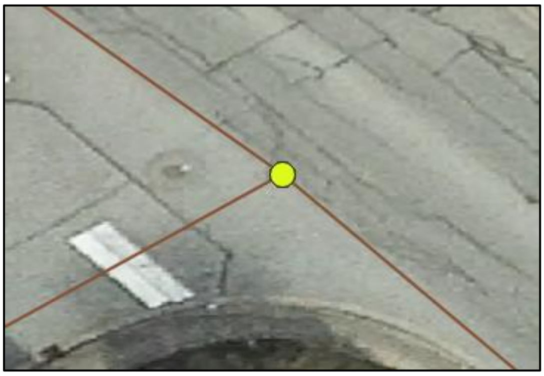


Figure 62: Detection of Unrecorded Manholes at Intersection Points.

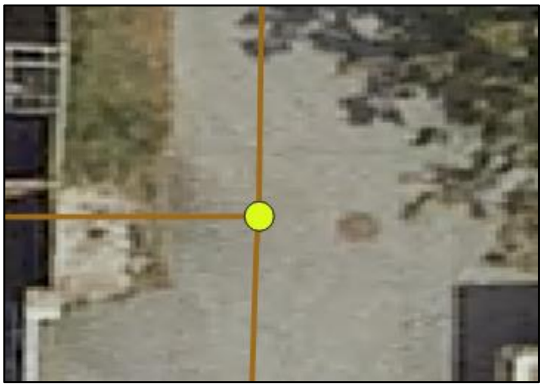


Figure 63: Visualization of Likely Unrecorded Manholes in Sanitary Network.

Before moving further with the tests to assess adherence to distance criteria, it is crucial to rigorously apply all the tools presented in this section and ensure that our spatial database is both complete and accurate, reflecting the existing conditions of the underground infrastructure. This thorough preparation will ensure that the subsequent analysis is based on reliable, accurate and exact data.

IV.2. NF P98-332 distance rules tests

In the “NF P98-332 distance rules tests” section, our focus will be on assessing the distance between buried utility networks and trees. We will identify all trees located at an improper distance from buried infrastructure (less than 1.5 meters). Additionally, we will detect buried utility networks that are situated at an inappropriate planar distance from each other (less than 20 centimeters). The NF P98-332 standard distance rules are thoroughly discussed in the state-of-the-art section.

IV.2.1. Distance Between Buried Networks and Trees

To detect trees at an improper distance from buried infrastructure (less than 1.5 meters), we will first calculate the height of the trees and classify them to extract those over 1 meter tall for our distance tests. Creating a Digital Surface Model (DSM) and a Digital Terrain Model (DTM) is essential for precise height calculations.

The Digital Terrain Model product represents the elevation of the ground, whereas the Digital Surface Model product represents the elevation of the highest surfaces at that point (as shown in the figure 64). [39].

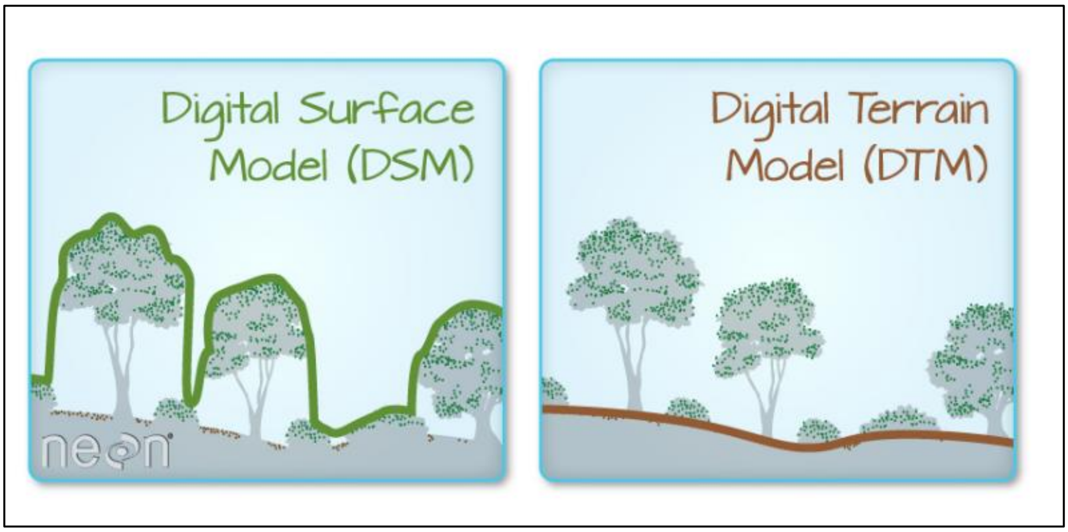


Figure 64 : DSM and DTM **[39]**

The Canopy Height Model (CHM) (figure 65) is calculated as the difference between the Digital Surface Model (DSM) and the Digital Terrain Model (DTM), expressed as CHM = DSM – DTM. This model calculates the heights of objects on Earth's surface, such as trees and buildings. By subtracting the ground elevation (DTM) from the surface elevation (DSM), the CHM precisely depicts the height of the canopy or any objects above ground. [39]

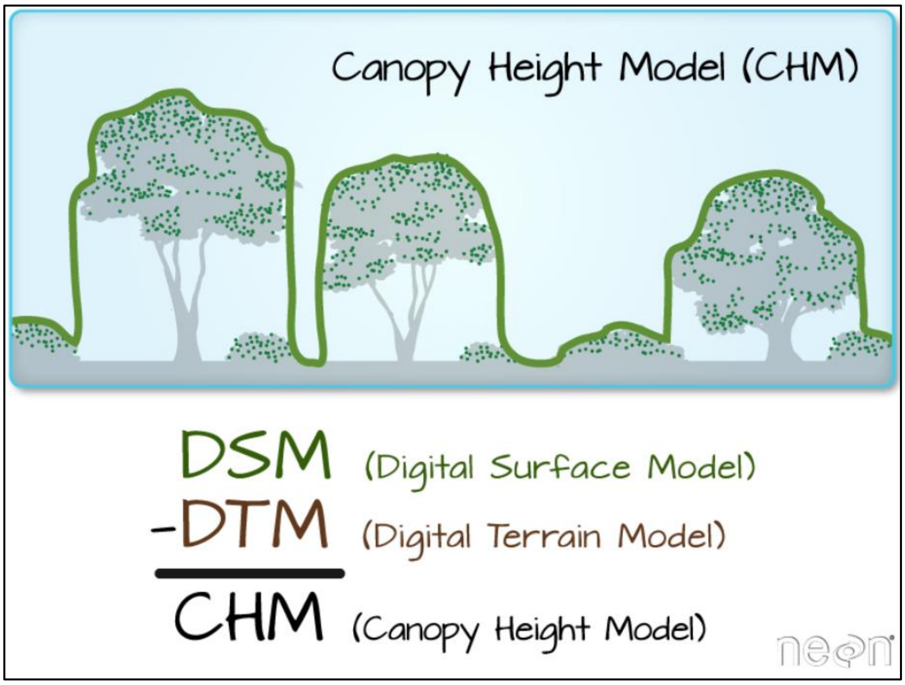


Figure 65: Canopy Height Model **[39]**

Using this principle, we will calculate tree heights using the appropriate tools in QGIS. The following activity diagram outlines the workflow.

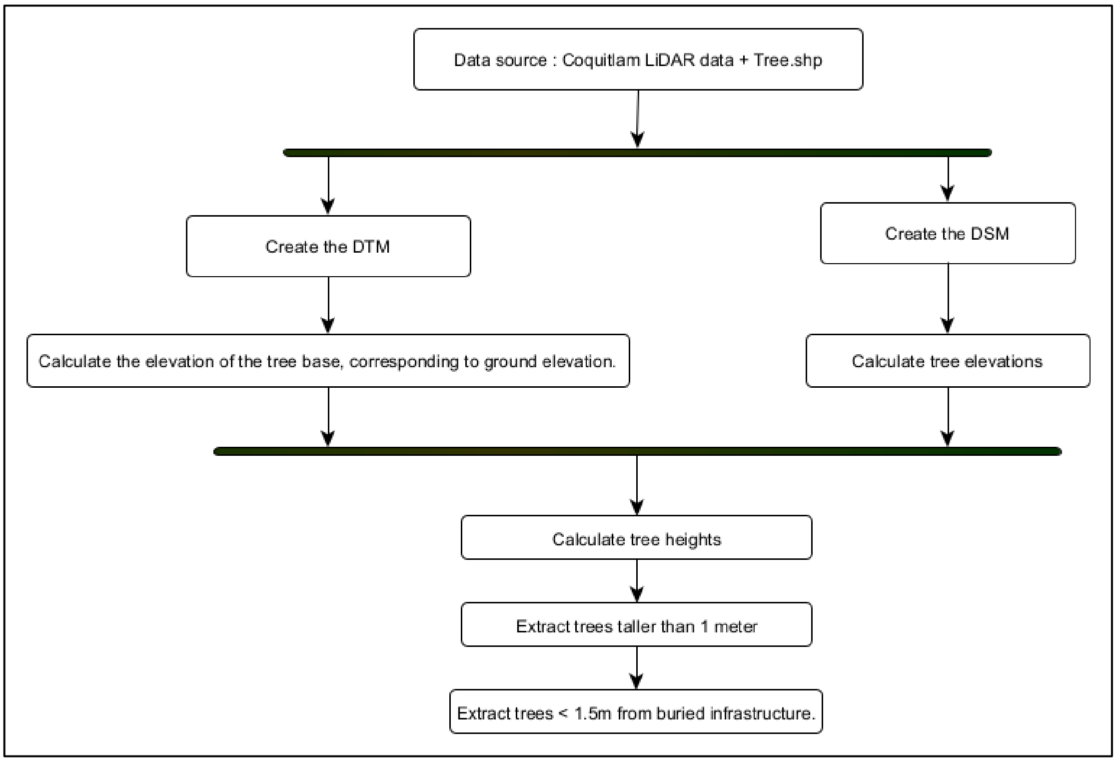


Figure 66: Workflow Activity Diagram

We installed and configured the **"WhiteboxTools"** software package, enabling us to utilize the "lidarDigitalSurfaceModel" tool for generating a Digital Surface Model (DSM) from classified LIDAR data (figure 67).

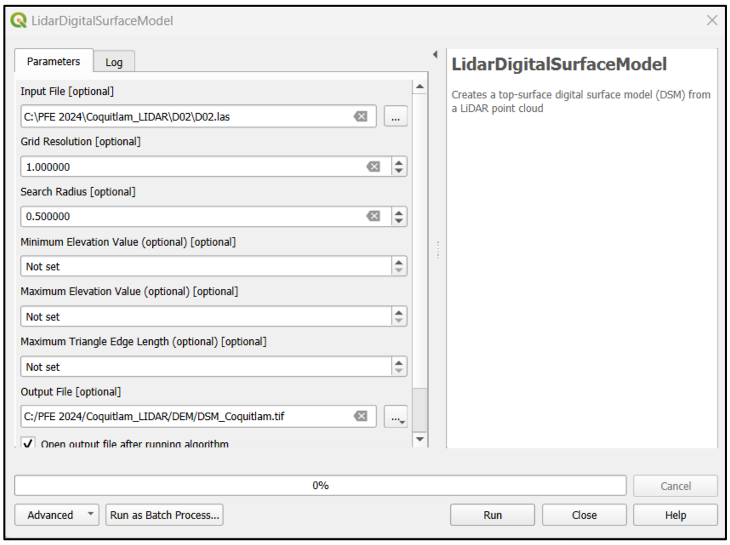


Figure 67 : Lidar Digital Surface Model.

The figure below shows how we superimposed the tree layer onto the generated DSM raster, effectively capturing all features on the Earth's surface with precision.

Figure 68: The tree layer overlaid on the generated DSM raster.

Using the "Drape (set Z value from raster)" tool in QGIS, we will assign elevation values from our raster dataset (DSM) to our vector points (trees) (figure 69).

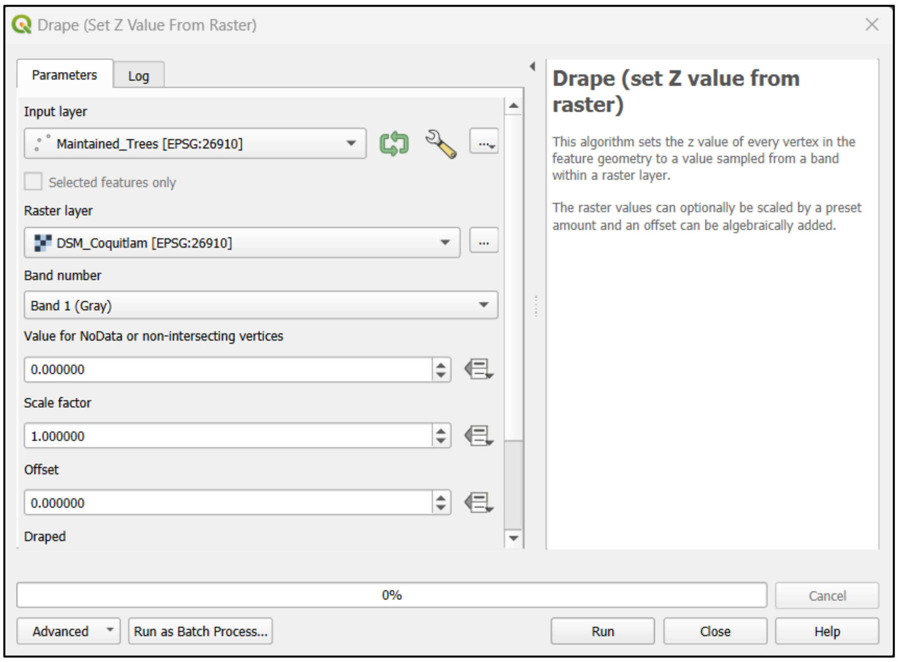
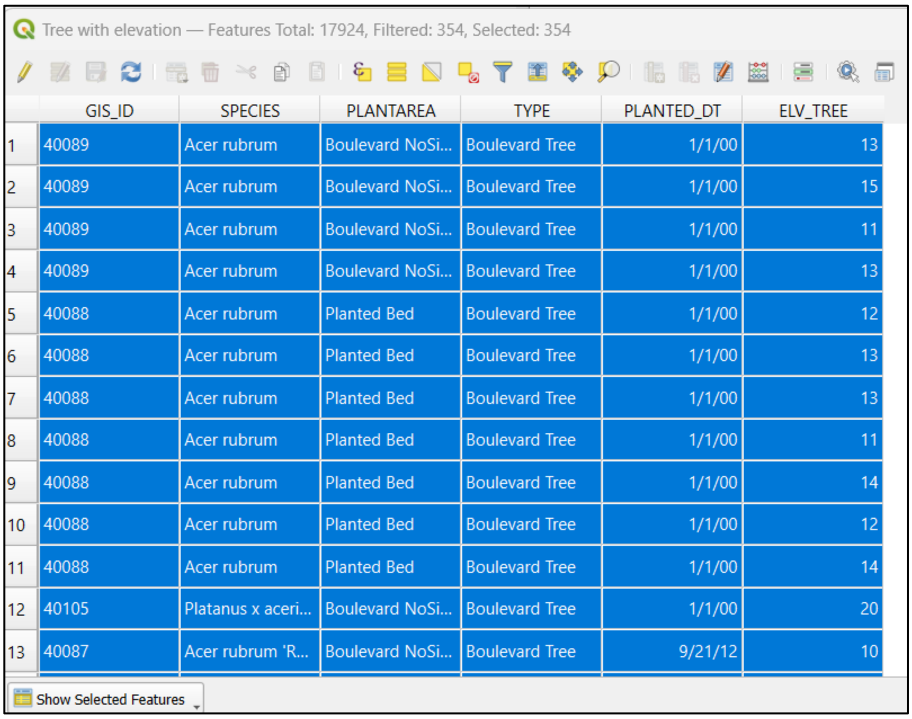


Figure 69 : Drape (set Z value from raster).

To add the ELV_TREE column for tree elevation in the attribute table, we need to enable editing mode, click on the field calculator, and use the “Z($geometry)” function. This will generate the elevation column, (as illustrated in the figure 70).



Tree with elevation — Features Total: 17924, Filtered: 354, Selected: 354

	GIS_ID	SPECIES	PLANTAREA	TYPE	PLANTED_DT	ELV_TREE
1	40089	Acer rubrum	Boulevard NoSi...	Boulevard Tree	1/1/00	13
2	40089	Acer rubrum	Boulevard NoSi...	Boulevard Tree	1/1/00	15
3	40089	Acer rubrum	Boulevard NoSi...	Boulevard Tree	1/1/00	11
4	40089	Acer rubrum	Boulevard NoSi...	Boulevard Tree	1/1/00	13
5	40088	Acer rubrum	Planted Bed	Boulevard Tree	1/1/00	12
6	40088	Acer rubrum	Planted Bed	Boulevard Tree	1/1/00	13
7	40088	Acer rubrum	Planted Bed	Boulevard Tree	1/1/00	13
8	40088	Acer rubrum	Planted Bed	Boulevard Tree	1/1/00	11
9	40088	Acer rubrum	Planted Bed	Boulevard Tree	1/1/00	14
10	40088	Acer rubrum	Planted Bed	Boulevard Tree	1/1/00	12
11	40088	Acer rubrum	Planted Bed	Boulevard Tree	1/1/00	14
12	40105	Platanus x aceri...	Boulevard NoSi...	Boulevard Tree	1/1/00	20
13	40087	Acer rubrum 'R...	Boulevard NoSi...	Boulevard Tree	9/21/12	10

Show Selected Features

Figure 70 : ELV_TREE column

Now it's time to generate the DTM. To achieve the most accurate results, we need to filter our classified LIDAR data using the “Filter” tool and export only the ground point cloud (figure 71).

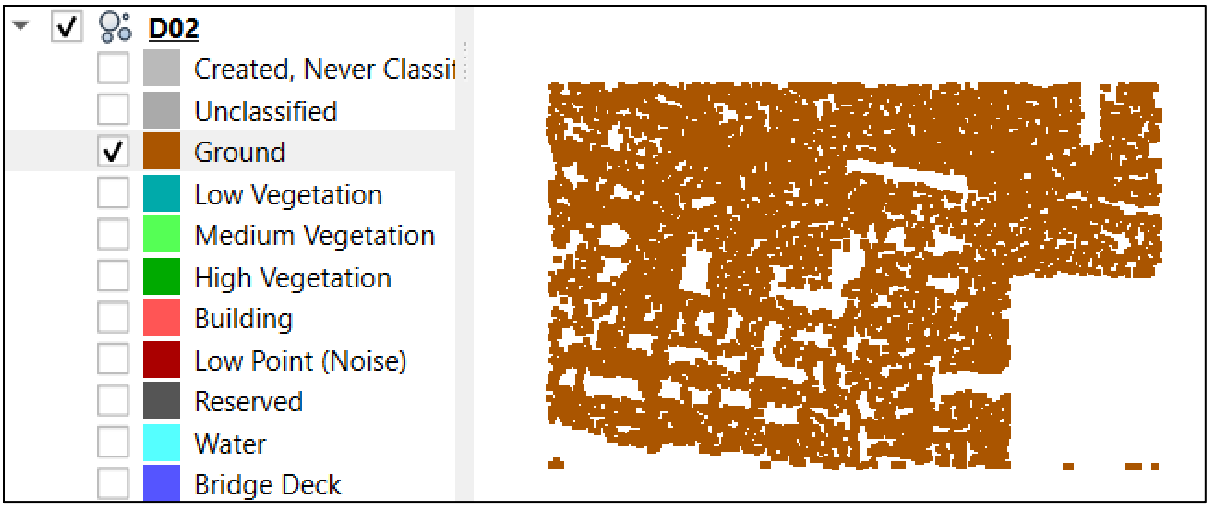


Figure 71 : Ground class.

Next, we will employ the "Export to Raster (Using Triangulation)" algorithm. This method enables us to convert the ground class into a regularly gridded raster by interpolating between points using triangulation (figure 72).

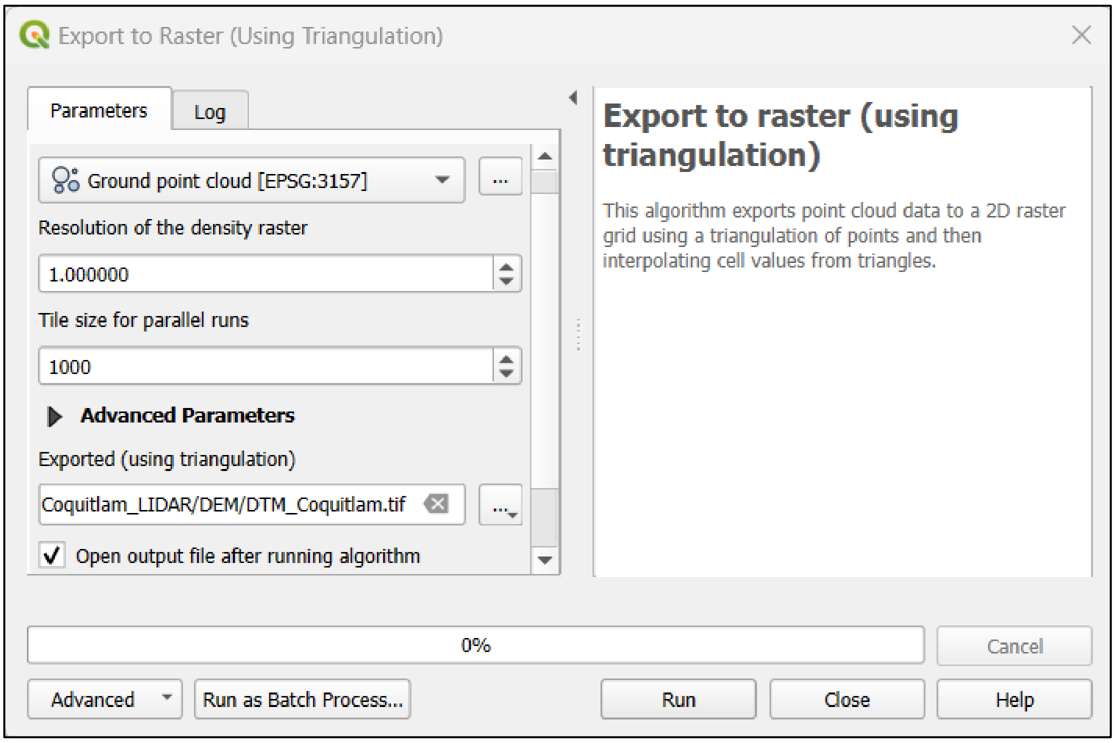


Figure 72 : Export to Raster (Using Triangulation).

This process allows us to achieve the most realistic representation of our terrain. The resulting DTM is displayed in the HILLSHADE style.

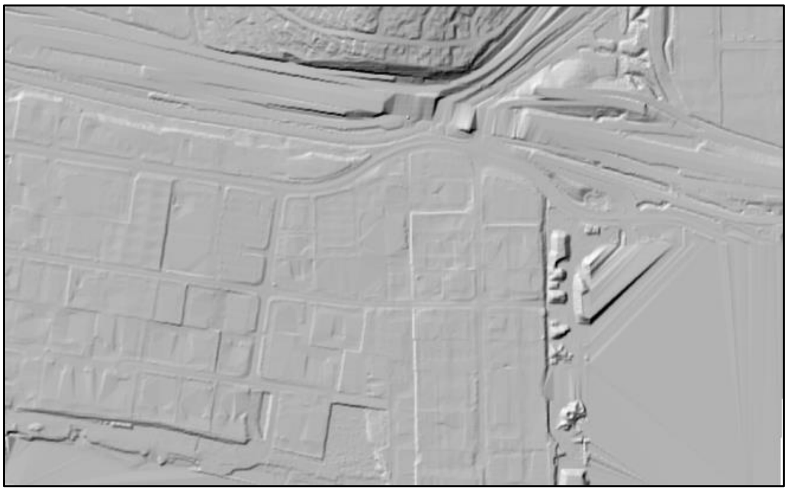
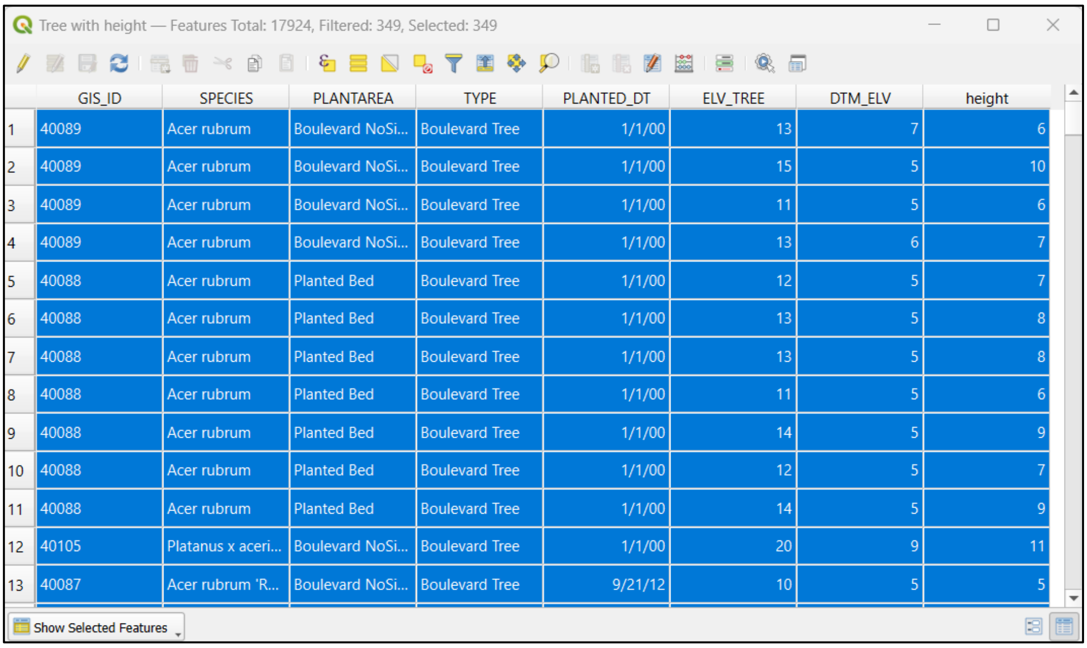


Figure 73 : Digital Terrain Model.

Now, using the same process as before with the "Drape (set Z value from raster)" tool, we will assign elevation values from our DTM raster to the tree points. This will calculate the elevation at the base of each tree, corresponding to the ground elevation. We then add a column called DTM_ELV using the "Z($geometry)" function.

The height value is calculated using the formula: height = ELV_TREE - DTM_ELV. The next figure displays the results of this process.


Tree with height — Features Total: 17924, Filtered: 349, Selected: 349

	GIS_ID	SPECIES	PLANTAREA	TYPE	PLANTED_DT	ELV_TREE	DTM_ELV	height
1	40089	Acer rubrum	Boulevard NoSi...	Boulevard Tree	1/1/00	13	7	6
2	40089	Acer rubrum	Boulevard NoSi...	Boulevard Tree	1/1/00	15	5	10
3	40089	Acer rubrum	Boulevard NoSi...	Boulevard Tree	1/1/00	11	5	6
4	40089	Acer rubrum	Boulevard NoSi...	Boulevard Tree	1/1/00	13	6	7
5	40088	Acer rubrum	Planted Bed	Boulevard Tree	1/1/00	12	5	7
6	40088	Acer rubrum	Planted Bed	Boulevard Tree	1/1/00	13	5	8
7	40088	Acer rubrum	Planted Bed	Boulevard Tree	1/1/00	13	5	8
8	40088	Acer rubrum	Planted Bed	Boulevard Tree	1/1/00	11	5	6
9	40088	Acer rubrum	Planted Bed	Boulevard Tree	1/1/00	14	5	9
10	40088	Acer rubrum	Planted Bed	Boulevard Tree	1/1/00	12	5	7
11	40088	Acer rubrum	Planted Bed	Boulevard Tree	1/1/00	14	5	9
12	40105	Platanus x aceri...	Boulevard NoSi...	Boulevard Tree	1/1/00	20	9	11
13	40087	Acer rubrum 'R...	Boulevard NoSi...	Boulevard Tree	9/21/12	10	5	5

Show Selected Features

Figure 74: Tree Height Measurement.

We can now extract all trees with a height above 1 meter by setting an appropriate expression in the field calculator and exporting them to a new shapefile. Next, we will use the "Select within Distance" tool to test the planar distance between trees and utility conduits, mains, and cables (figure 75).

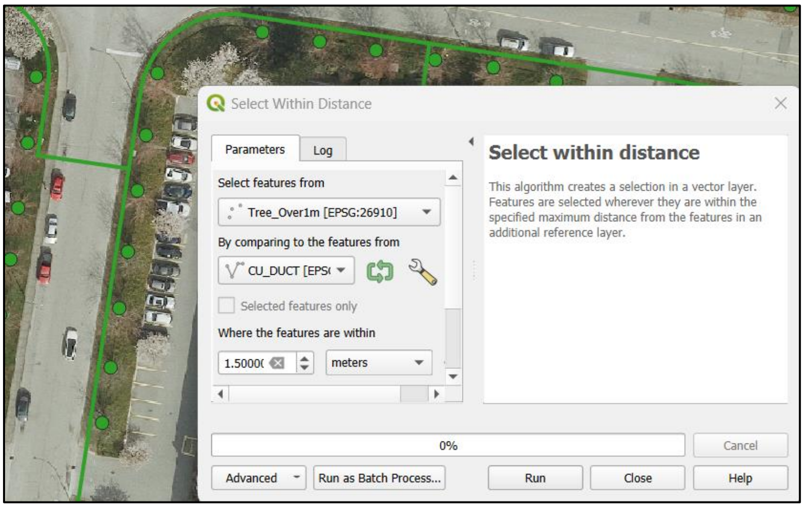


Figure 75 : Select within Distance.

This process will allow us to detect all trees within a 1.5-meter distance that may pose a danger to the utility systems, as their roots can deteriorate networks and complicate maintenance operations.

The results after execution are illustrated in the following figure.

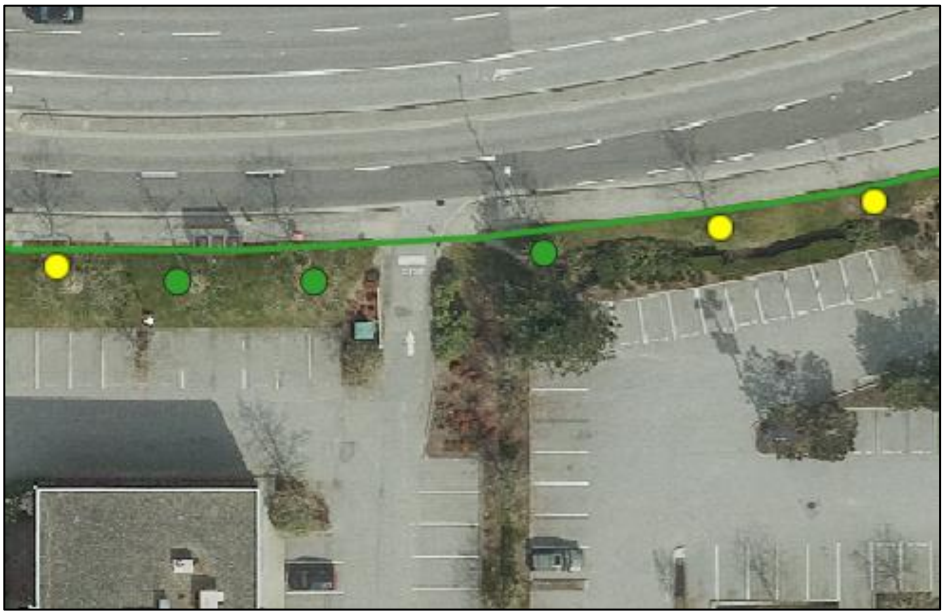


Figure 76 : Detected trees.

The identified trees can be exported in various geospatial formats and visualized on web maps and dashboards. This information can then be shared with authorities and stakeholders such as Ministries of Land Planning or municipal offices. This allows these entities to be informed about potential risks posed by trees and take proactive measures accordingly.

IV.2.2. Distance between buried utility networks

Calculating planar distances between various utility system networks (pipelines, ducts, mains, and cables) using GIS tools and software is highly challenging due to the complexity and interconnected nature of these networks, as depicted in the following figure.

Figure 77: Complex Utility Networks in Urban Areas.

One approach that can be beneficial yet has limitations is to selectively compare pairs of buried networks, such as “water mains and methane mains”. We can employ the "Select within distance" tool to identify features within the first input layer that are within 20 cm of the second input line layer (figure 78).

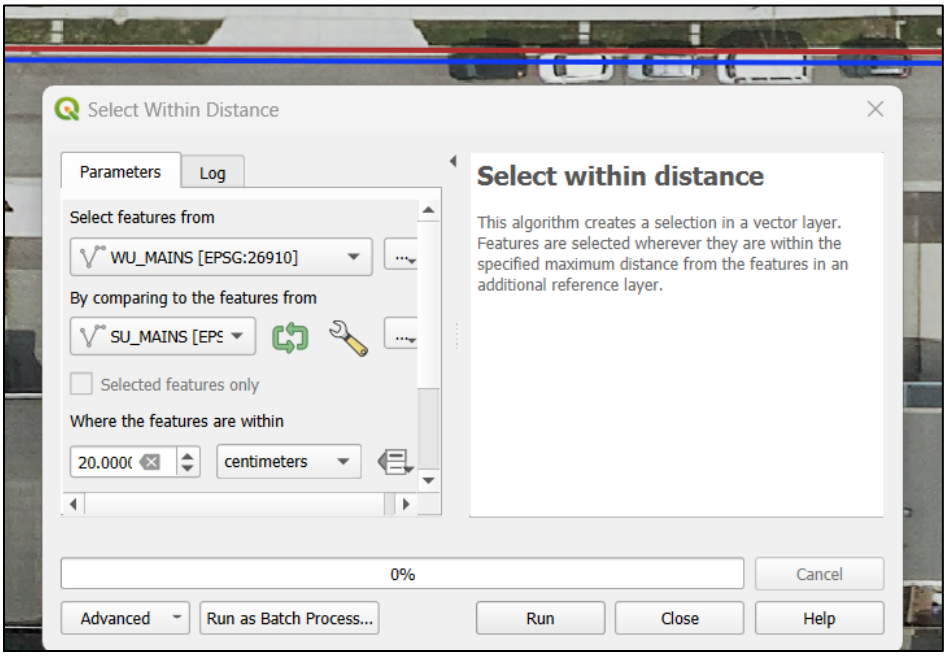


Figure 78 : Select within distance.

This tool effectively selects all networks with less than 20 cm of parallel distance, as illustrated in the figure.

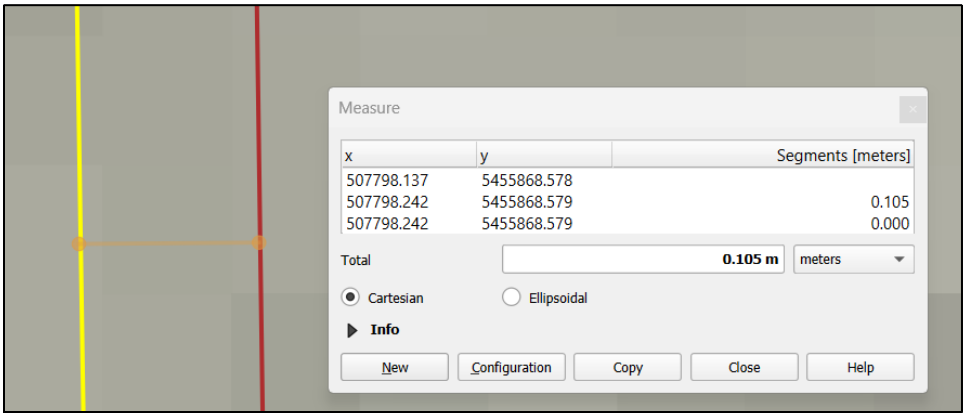


Figure 79: Parallel distance verification with measure tool.

One drawback of this approach is that the algorithm may select line features where intersections exist, potentially complicating data interpretation. Therefore, careful visual inspection and filtering of the data become necessary to distinguish between close proximity selections (less than 20 cm) and intersection selections. This task is challenging due to the complex nature of these utility network dataset.

To address this, we propose creating a point shapefile named "Danger" to pinpoint zones where two ducts or mains are dangerously close. These close proximities pose risks to both human safety and the environment, potentially leading to accidents in the future. By identifying and mapping these zones, stakeholders can be informed and engaged in discussions to make informed decisions and install preventive measure. This approach facilitates proactive risk management and enhances decision-making processes regarding utility network safety.

V. Spatial statistics and Dashboard creation

Our aim is to create an analytics dashboard to identify decommissioned devices within the utility systems of Coquitlam City. This dashboard will enable stakeholders to monitor the status of infrastructure systems and make informed decisions. To achieve this, we need to gather data and perform spatial statistics to count the number of decommissioned devices, such as manholes and hydrants, within all communities in Coquitlam City.

- **Calculating the number of decommissioned devices in utility system per community**

We need to filter the data before counting the decommissioned devices in each community. Using the "Select by Expression" tool in QGIS, we will select layers with the attribute "STATUS" value equal to "Decommissioned." We will then export all selected features to a new ESRI shapefile. The following figure illustrates this process using the drainage manhole layer "DU_MANH."

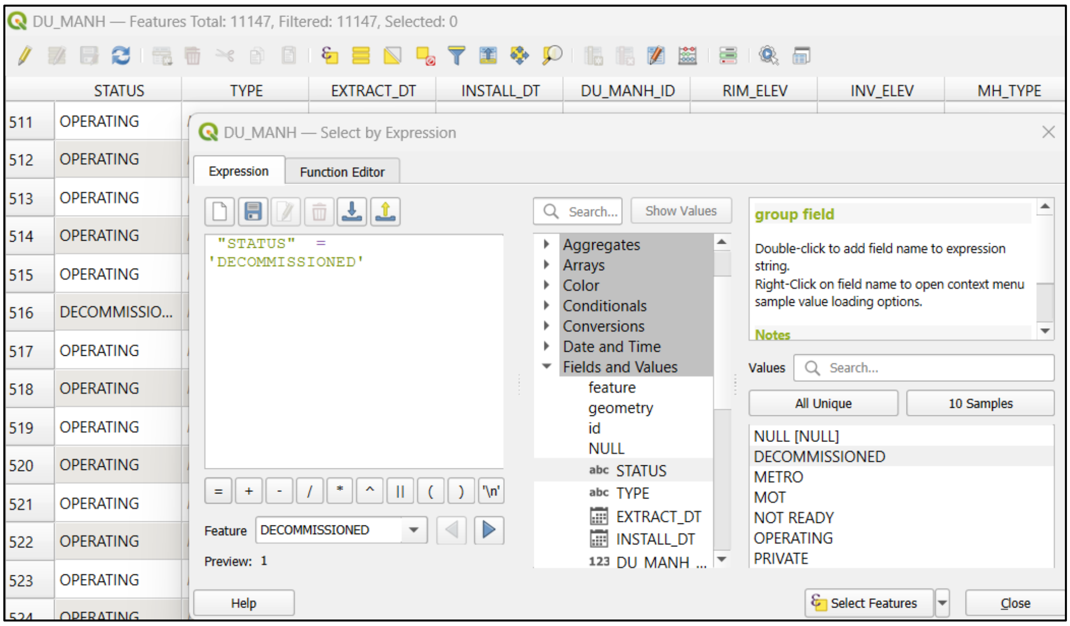


Figure 80 : Select by expression.

The figure below demonstrates how we superimposed the decommissioned storm catch basins layer onto the Coquitlam community profile boundaries, ensuring both layers are in the same coordinate system. This allows for accurate spatial analysis.

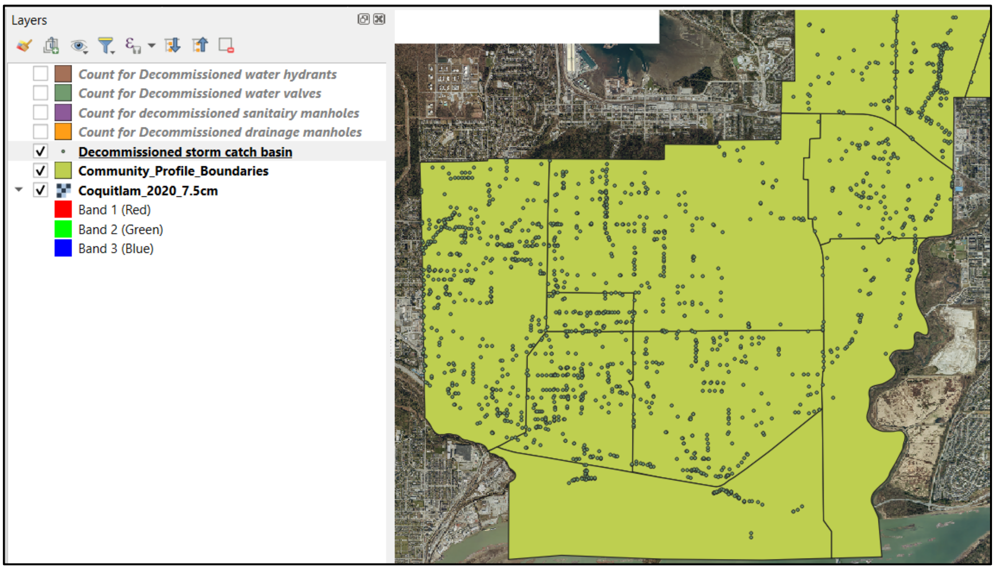


Figure 81: Decommissioned storm catch basins.

We will utilize the vector analysis tool "Count points in polygon" in QGIS to tally the point features within each polygon feature of a layer. This tool facilitates the process of determining how many points fall within each polygon (figure 82).

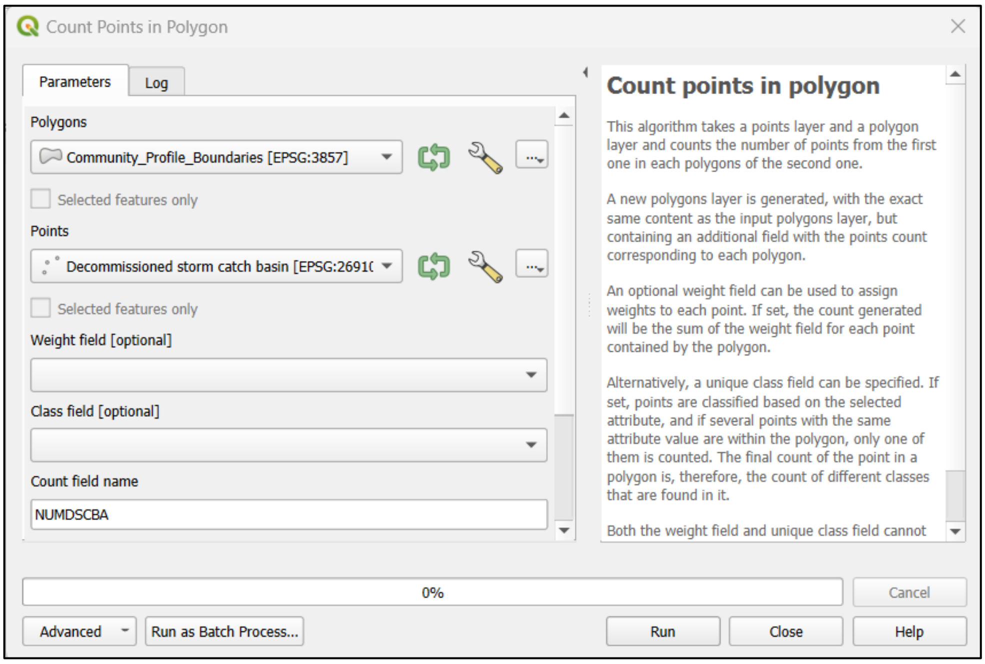
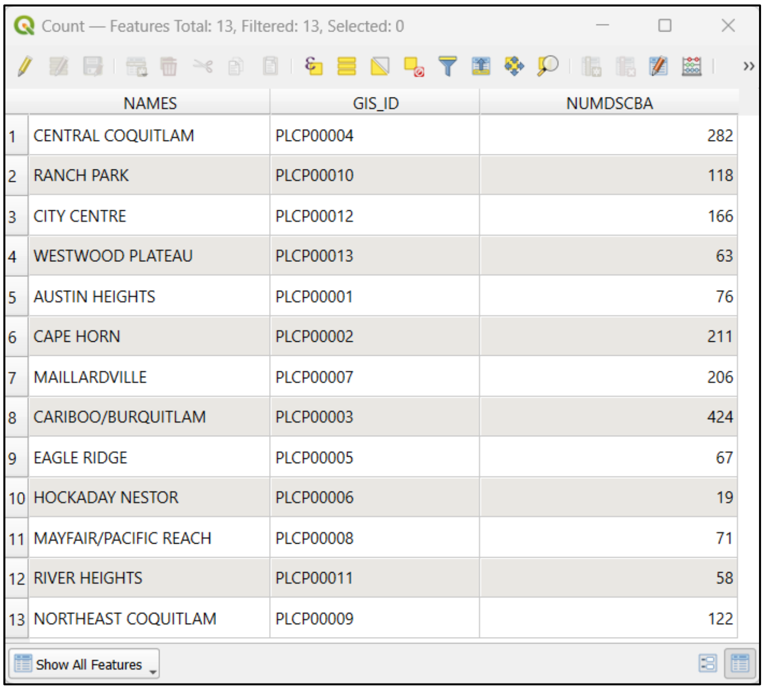


Figure 82: Count points in polygon.

The following figure illustrates the output of this process: a new column is generated to indicate the number of point features inside each Coquitlam community.



	NAMES	GIS_ID	NUMDSCBA
1	CENTRAL COQUITLAM	PLCP00004	282
2	RANCH PARK	PLCP00010	118
3	CITY CENTRE	PLCP00012	166
4	WESTWOOD PLATEAU	PLCP00013	63
5	AUSTIN HEIGHTS	PLCP00001	76
6	CAPE HORN	PLCP00002	211
7	MAILLARDVILLE	PLCP00007	206
8	CARIBOO/BURQUITLAM	PLCP00003	424
9	EAGLE RIDGE	PLCP00005	67
10	HOCKADAY NESTOR	PLCP00006	19
11	MAYFAIR/PACIFIC REACH	PLCP00008	71
12	RIVER HEIGHTS	PLCP00011	58
13	NORTHEAST COQUITLAM	PLCP00009	122

Figure 83: Count.

We will apply this process to multiple devices in our utility system, recording the number of out-of-service components. Afterward, we will perform calculations to generate a CSV file that provides detailed counts of utility devices within each community (figure 84).

A1 | NAMES

	A	B	C	D	E	F	G	H	I
1	NAMES	GIS_ID	DSMANH	DDMANH	DWHYD	DWVALVE	DSTCATB	Area	TOT_DECOM
2	CENTRAL COQUITLAM	PLCP00004	4	21	25	141	282	9144908	473
3	RANCH PARK	PLCP00010	2	4	10	71	118	3066091	205
4	CITY CENTRE	PLCP00012	2	8	4	27	166	2830458	207
5	WESTWOOD PLATEAU	PLCP00013	0	7	1	17	63	23110712	88
6	AUSTIN HEIGHTS	PLCP00001	1	13	4	35	76	662287	129
7	CAPE HORN	PLCP00002	3	10	8	68	211	4957551	300
8	MAILLARDVILLE	PLCP00007	5	15	12	70	206	2774431	308
9	CARIBOO/BURQUITLAM	PLCP00003	22	51	42	234	424	6444196	773
10	EAGLE RIDGE	PLCP00005	1	7	7	35	67	3082360	117
11	HOCKADAY NESTOR	PLCP00006	0	1	4	27	19	1945013	51
12	MAYFAIR/PACIFIC REACH	PLCP00008	5	5	14	34	71	6005055	129
13	RIVER HEIGHTS	PLCP00011	0	13	7	2	58	4504115	80
14	NORTHEAST COQUITLAM	PLCP00009	7	37	22	165	122	61012064	353
15									

Figure 84: CSV file.

Now that our data is prepared, we can load it into Power BI for visualization and analysis. This will allow us to gather insights and convey our findings more effectively.

To incorporate the community boundaries layer into our Power BI Dashboard, it is essential to convert its format to TopoJSON, which is Power BI-compatible. This conversion process is simple: we need to upload our shapefile (SHP) into mapshaper (figure 85), a free and open-source editor capable of performing various geospatial operations, including file format conversion. The following two figures illustrate this process.

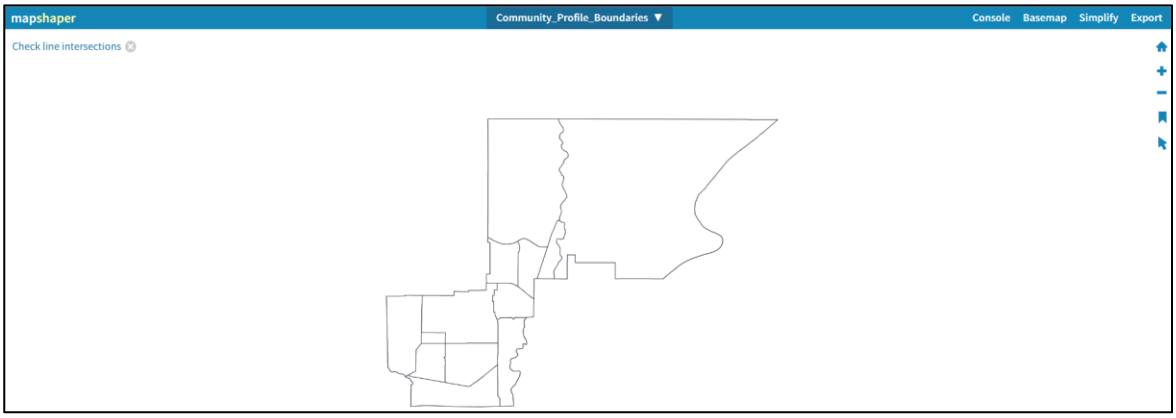


Figure 85: Mapshaper.

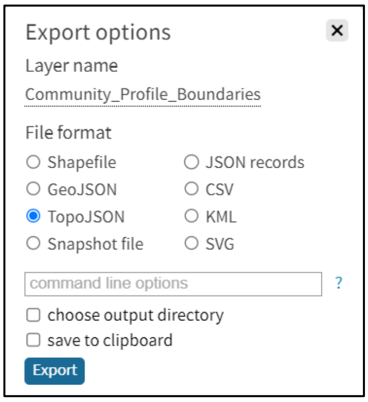


Figure 86: Conversion of Shapefile (SHP) to TopoJSON using Mapshaper.

We loaded our dataset into Power BI and structured it for analysis. Using various data visualization tools, we extracted meaningful insights regarding the total number of decommissioned devices within each community. This data was represented on a map to provide a clear geographical overview.

Additionally, we employed several useful tools of Power BI, such as the "Grouped Bar Chart," to illustrate the distribution of decommissioned utility devices per community. For detailed information on the area of each community, we used a Pie Chart, and for population data, we utilized the "Card" tool. The figure below showcases our final Power BI dashboard, which contains all of the insights and visualizations derived from our comprehensive data analysis.

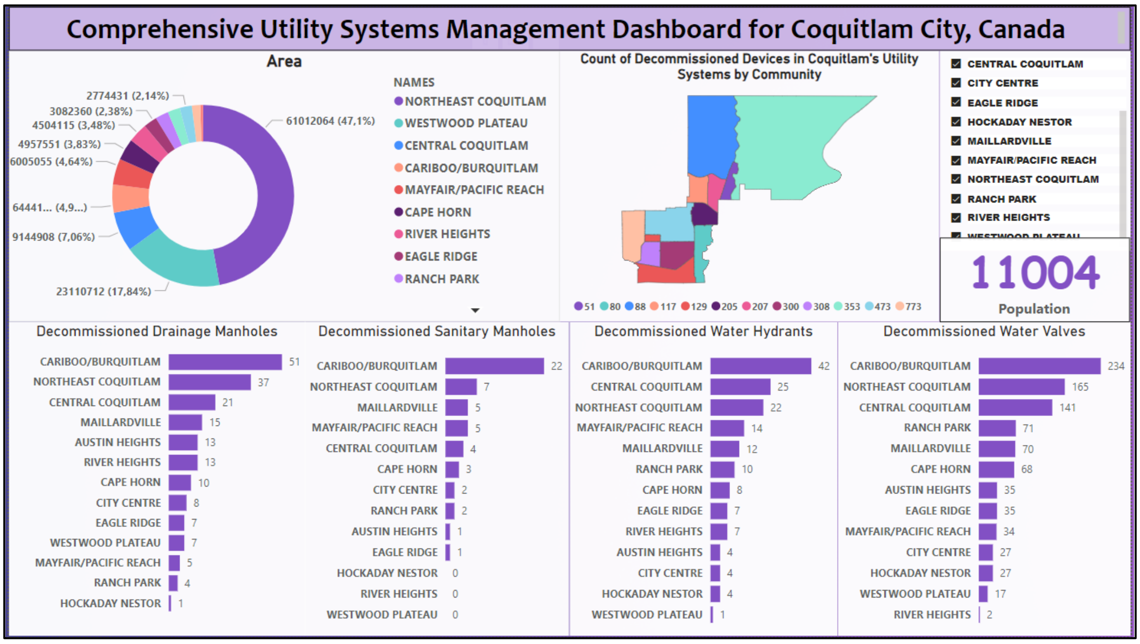


Figure 87: Comprehensive Utility Systems Management Dashboard for Coquitlam City, Canada.

The Power BI dashboard provides a dynamic experience, allowing users to engage with the data interactively. For example, selecting the Northeast Coquitlam region on the map visual will show data exclusively for that region and will highlight related data in other visuals, such as bar charts and Pie chart. Increasing the depth and clarity of the insights offered (as shown in figure 88).

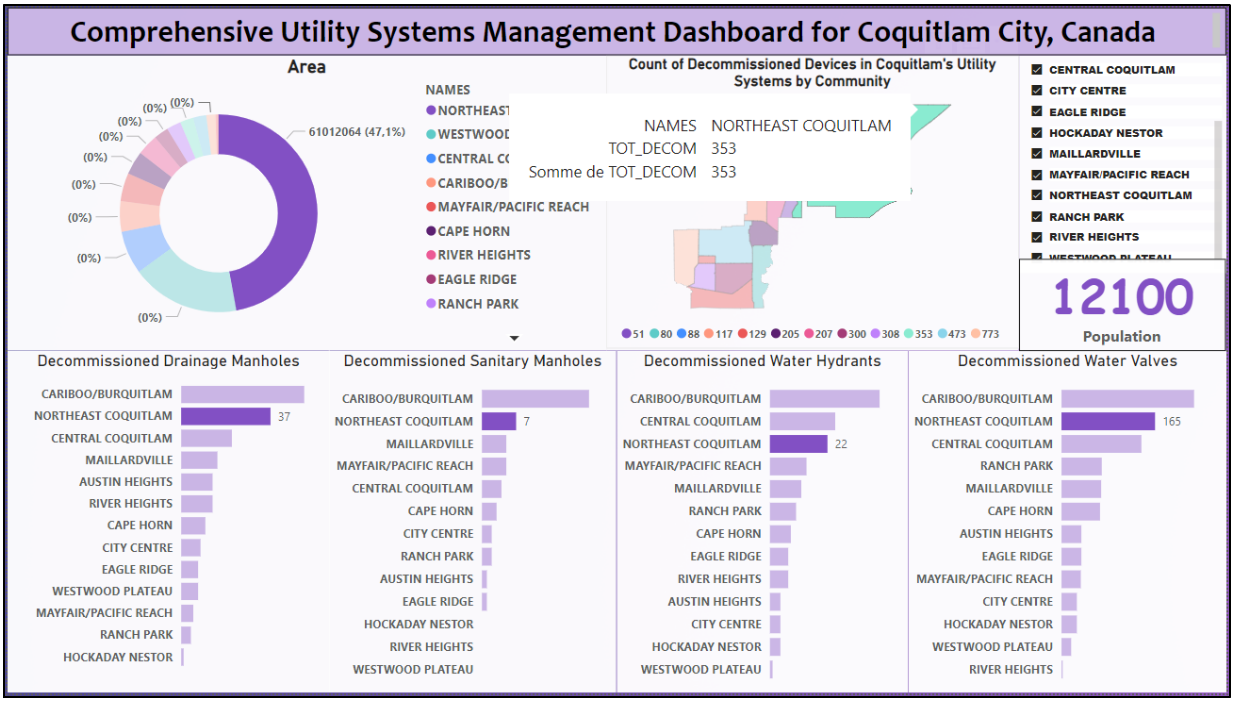


Figure 88: Interactive selection and filtering.

Using GIS technologies might be difficult for many stakeholders and decision-makers lacking a background in spatial analysis. However, a dashboard may help to clarify complicated data by offering detailed statistics and insights.

This allows them to gain a deep understanding and thorough awareness of the current state of the underground infrastructure for utility systems, anticipate potential future issues with out-of-service devices, and make informed decisions regarding budget allocation for maintenance and repair work.

VI. Development of web mapping application

Web mapping is the process of viewing, analyzing, and sharing a map-based visual representation of geospatial data via the internet. Geospatial mapping may be accessed online via a web browser interface thanks to web mapping. There are instances where web mapping is referred to as web GIS (Geographic Information System). Its flexibility in terms of accessibility and ease of use in terms of interacting with location data is a major factor in its appeal. This makes it possible for people other than GIS specialists to utilize mapping applications. [40]

VI.1. QGIS2WEB Plugin

As seen in the image below, we first prepared our QGIS project, making sure it had all of the necessary layers, styles, and symbols. We then accessed the QGIS2WEB plugin, which was installed from the QGIS plugin repository and customized the export settings by specifying the layers to incorporate into our web mapping application. We opted to utilize the Leaflet library for its user-friendly interface and ease of use.

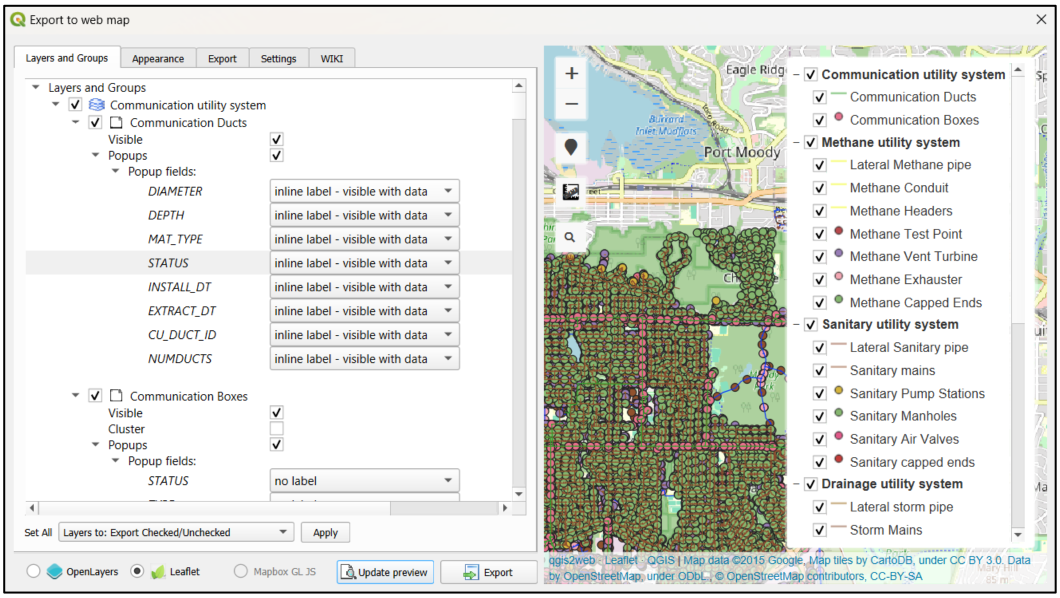


Figure 89 : Creating a Web Map Using QGIS2Web.

Here is our final QGIS2WEB web map, which includes a layer switcher tool that automatically list the layers to choose from, a measure tool for calculating distances, and a geolocate user tool for locating the user present position (figure 90).

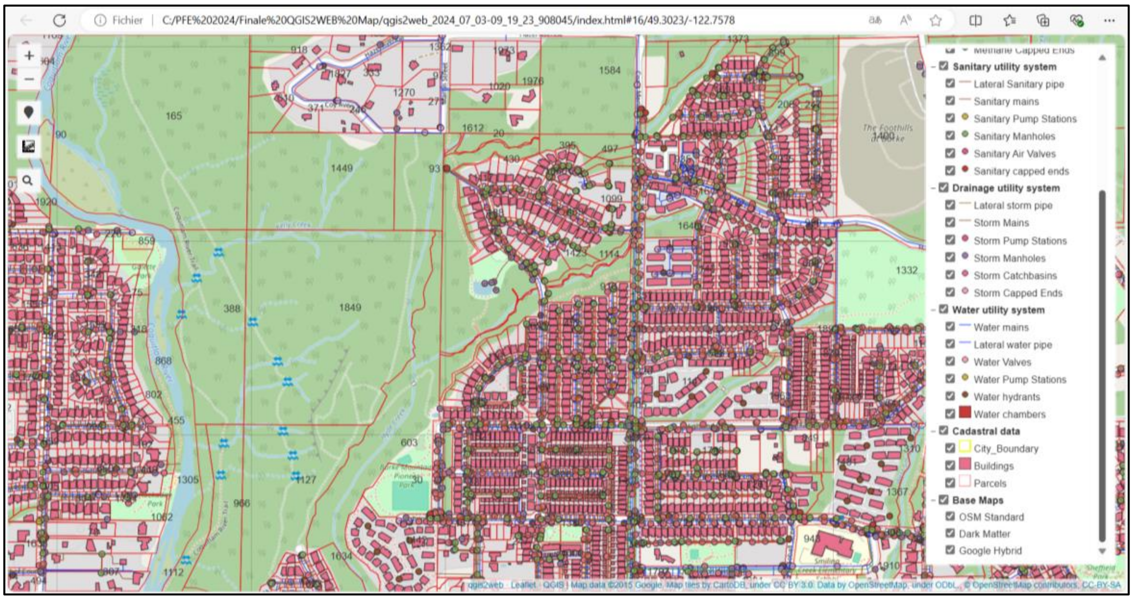


Figure 90 : QGIS2WEB web map.

Although the QGIS2WEB plugin makes it easier to create online web mapping apps, it has several limitations. It mostly confines users to the capabilities provided by the QGIS plugin itself. Furthermore, a significant drawback arising from its client-side architecture is its inefficacy to handle huge datasets, which is especially visible when dealing with utility network data classified as such. The high number of features significantly slows down the rendering process, resulting in a bad user experience. As a result, it is critical to consider developing an innovative solution to overcome these limitations.

VI.2. Advantage of using Server-side over Client-side Web Mapping

In client-side web mapping, the map content and application are downloaded together. The majority of data processing processes are executed on the client side. All interactivity, including panning, zooming, and clicking on map features, occurs on the client side also, making it independent of the Internet connection. However, performance is dependent on the browser's capabilities, and the amount of data that can be handled is limited by the client's device. [41]

In server-side web mapping, each interaction requires communication with the server, making all interactivity dependent on an Internet connection. This approach ensures that performance is browser-independent and allows the system to handle huge amounts of data and integrate distributed data sources efficiently. [41]

VI.3. Server-side Solutions for Web Mapping

The figure below illustrates the system architecture for a Server-side web mapping application.

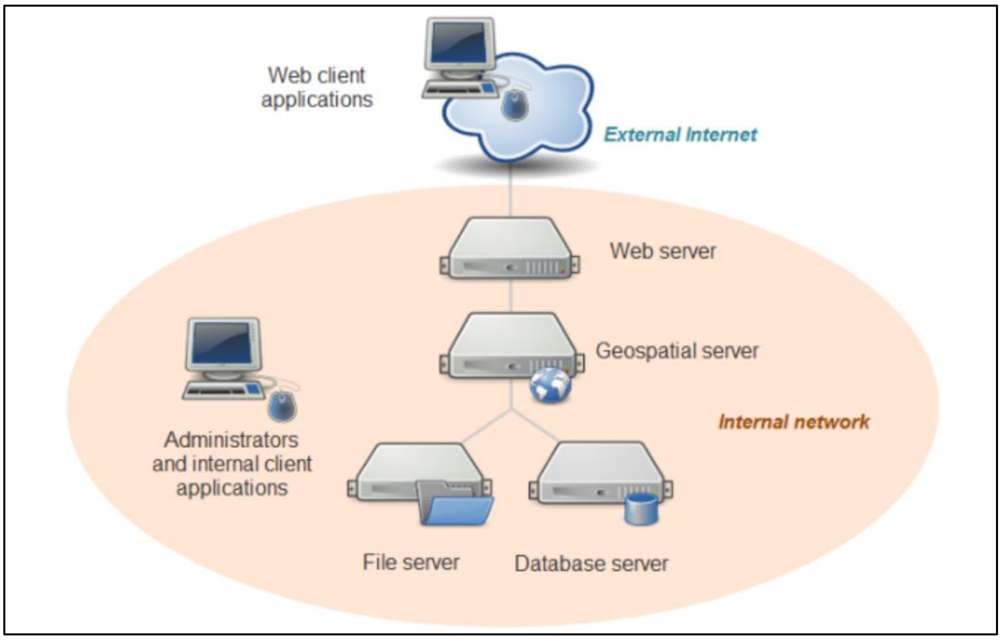


Figure 91 : System architecture for web mapping [42]

Server-side web mapping involves a remote server (web map server) generating the map content instead of the client browser. When a user interacts with the web map, it sends a request to the map server. The server processes this request and prepares the map content, and sends it back to the user's browser for display. This method leverages the server's resources for rendering complex maps, ensuring that even users with less capable devices can access detailed and dynamic map content. [41]

VI.4. Publishing Layers from PostGIS via GeoServer

Publishing layers from PostGIS using GeoServer allows for dynamic creation of maps from spatially referenced data. GeoServer connects to PostGIS to access and publish spatial tables as map layers. It supports a variety of OGC protocols, including WMS (Web Map Service) for displaying maps as images (e.g., GIF, PNG) and WFS (Web Feature Service) for vector formats (e.g., KML and GML). [43]

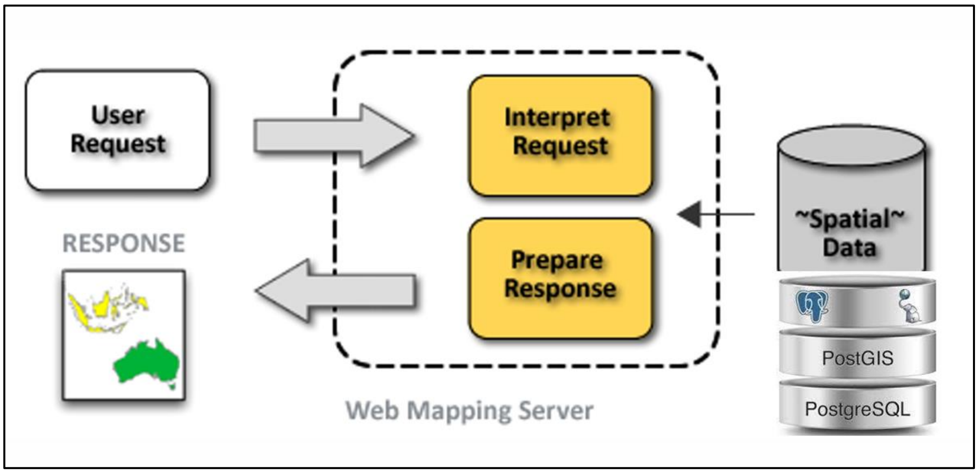


Figure 92: Workflow Diagram for Web Mapping Server **[44]**

We will use the WMS protocol from GeoServer to visualize spatial features through the web map. The figure below shows how the WMS (Web Map Service) protocol works, specifically how it generates map images from spatial data.

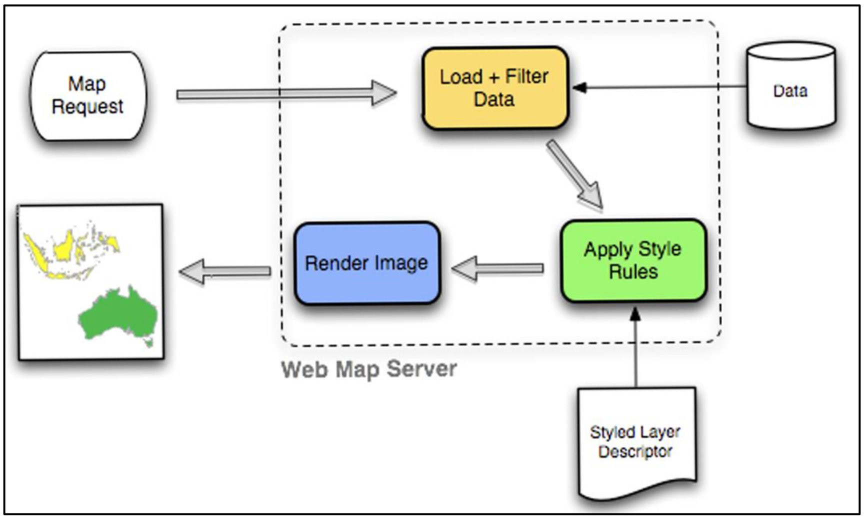


Figure 93: A diagram illustrating the process of how a WMS converts data into a map image **[43]**

The process is simple: the client sends a request to the map server, which generates and delivers an image based on the parameters entered. The WMS can create an image from a variety of sources, including vector data, raster data, or a combination of the two. [43]

To publish our PostGIS layers using GeoServer, we first create a new workspace that serve as a container for grouping our layers. Once the workspace is set up, we create a new store and pick "PostGIS database" as the vector data source. We then define the database connection parameters, which include the host, port, database name, username, and password to enable the addition of our database tables (figure 94).

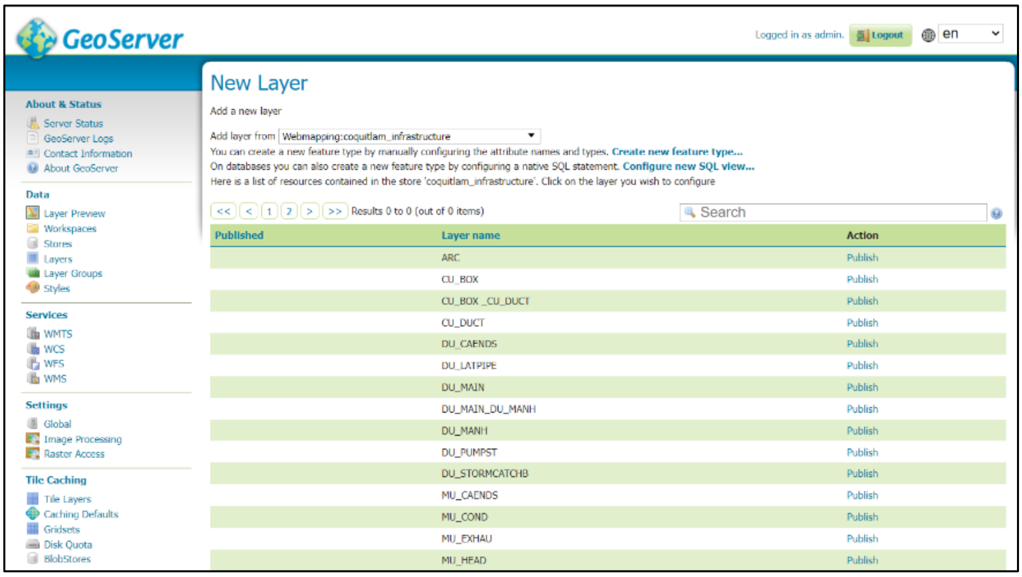


Figure 94: Layer Added to GeoServer

After loading the store and adding the tables, we can proceed with creating a new layer. We choose the appropriate layer and set the publishing parameters, then calculate the layer's bounding boxes using the "Compute from data" and "Compute from native bounds" links.

This is our communication boxes layer, published as shown in the following figure.

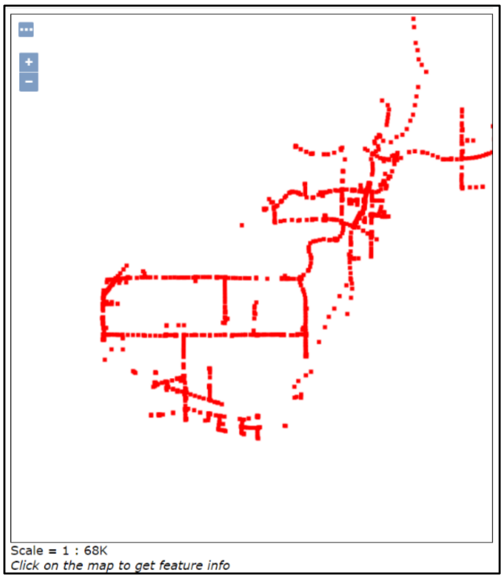


Figure 95: Layer published

The PostGIS layers are published with GeoServer 's default style. To show custom styles like colors, thicknesses, and labels, we must specify them in QGIS and export them as SLD files. These SLD files, saved as.XML, may then be imported into GeoServer to set the required styles for the published layers.

VI.5. Website Development Process

The initial step involves preparing our web development environment. We started by installing **Visual Studio Code**, which serves as our code editor, followed by the installation of **Node.js**. We next created a directory for our project by choosing a folder to hold the application components. Then we initialized our project by creating a **Package.json** file, which contains the project metadata (name, version, description, etc.), configuration settings, and helps manage the dependencies and libraries needed for our project.

The next step is to install the **OpenLayers** library, which is required for designing interactive tools that improve the user experience. Additionally, we included **Bootstrap** by including its CSS and JS files, which are required for constructing the application's frontend.

Next, we build an **HTML file** that will serve as the basis for all of the pieces in our web mapping application, as well as a **CSS file** to style them. These files are connected to the **JavaScript file**, which contains all published layers, such as utility system layers and cadastral layers (buildings and parcels), via GeoServer using the **WMS protocol**. This configuration enables us to access and show these layers over the internet. We added an **OpenStreetMap layer** that will be our background map.

The JavaScript file also contains all of the function code for OpenLayers tools, which is required for an interactive experience. This allows users, such as field technicians or land surveyors, to easily navigate between layers during fieldwork operations such as excavation, maintenance, or construction work. The following figure illustrate the final developed web map.

Figure 96: Final Developed Web Map Displaying Coquitlam Underground Infrastructure

We implemented a layer switcher tool that allows easy switching between layers and a mouse position tool that displays latitude and longitude values. Additionally, we developed two measurement tools, displayed on the interface's navbar, for measuring distances and areas, which are essential for fieldwork, as shown in the next two figures.

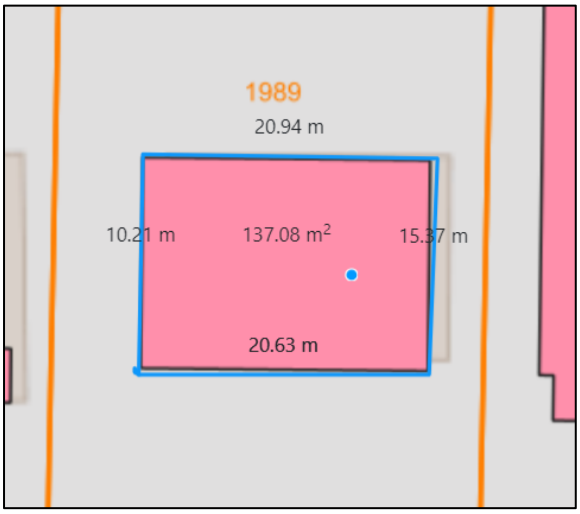


Figure 97: Area measurement tool

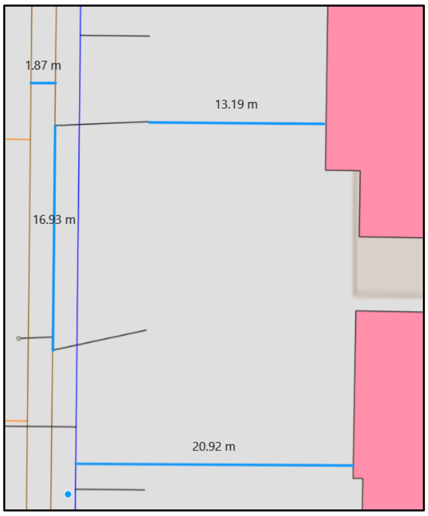


Figure 98: Distance measurement tool

VII. Conclusion

In conclusion, this chapter covered: the creation of a robust spatial database for utility management, GIS implementation, data entry, quality control, and the use of French distance rules to identify risk zones. We developed a comprehensive dashboard and a web mapping application, which now aid field technicians, land surveyors, utility workers, and construction firms in safely managing and visualizing subsurface infrastructure. Each step was essential in building an effective system for handling spatial utility data.

GENERAL CONCLUSION

In this project, we explored the significance of utility systems in daily human activities, the economy, and future development. We highlighted the potential impacts of accidents related to utility systems and the importance of implementing measures to properly manage our infrastructure. We proposed and developed a comprehensive system composed entirely of free and open-source tools and software that can be integrated to store, manipulate, manage, control, and visualize data related to utility systems.

We chose Coquitlam, Canada, as our study area due to its urban environment and complex infrastructure. Additionally, Coquitlam's Open Data portal supplied us with a wide range of spatial data types and formats needed for testing our system.

Our process began with carefully designing the system by specifying requirements (functional, non-functional, and extended requirements), functionalities, and the system's architecture. We developed a data dictionary to guide our spatial data model, which is an Arc Node data model composed of points and line features, chosen to adapt to the nature of utility networks. This data dictionary defines all components of the utility networks as spatial elements, presented with tables, attributes, specified geometries, and topological consistency that should be maintained between features.

We then proceeded to the system implementation phase, where we designed and created our spatial database in PostgreSQL using the spatial extension PostGIS. For the data insertion part, we presented various approaches, each advantageous in certain situations but limiting in others, depending on factors such as data source, level of precision, and project objectives. We justified our choice of the data insertion approach used.

After data insertion and spatial layer creation, we focused on data quality, emphasizing three essential parameters: logical consistency, spatial accuracy, and completeness. We demonstrated various QGIS tools useful for ensuring spatial data integrity. To guarantee data completeness, we developed our own tool, a QGIS plugin, which detects possible missing junction points representing visible features like "manholes" in utility networks.

Using the French standard for buried networks, the "NF P98-332 distance rules," we detected danger zones that could pose future accident risks in Coquitlam by analyzing distances between utility networks and between trees and underground infrastructure.

Additionally, we performed spatial statistics to count the number of decommissioned devices, such as manholes and hydrants, within all communities in Coquitlam. The valuable data obtained from these statistics was used to create an analytics dashboard, enabling stakeholders to monitor infrastructure status and make informed decisions.

The final component of our system is a web mapping application. In our report, we examined various methods for visualizing utility networks data. We found that QGIS2WEB, a client-side solution, struggles with large-scale data due to client-side processing limitations. To enhance interactivity and user experience, we proposed developing a full-stack web mapping application using a web map server. We hope this web mapping application will help field technicians, land surveyors, and construction companies locate and visualize utility infrastructure like pipes, mains, and cables, thus avoiding damage and preventing accidents.

In conclusion, we utilized modern technologies such as GIS, data analysis, and web development to develop our system. We aim to encourage all parties involved in utility system management to work together and collaborate in developing and carrying out utility network projects. We advocate for agreements on data sharing between various entities to promote open communication and enhance decision-making. We believe this developed system will facilitate collaboration, ease work processes, and help prevent conflicts, such as overlapping construction activities that could damage existing networks.

It is important to note that many other modern technologies, such as BIM, IoT, AI, and digital twins, can further improve the management of underground infrastructure. Is it possible to see a future where the perfect use of these technologies creates a smart infrastructure that entirely prevents utility network-related accidents?

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