Design and Implementation of a Web-GIS for the management of road infrastructure in Zimbabwe

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ABSTRACT

Road asset mapping has the potential of reducing: costs in keeping all assets data, time-consuming activities like retrieving asset attribute from large files, risks associated with losing all the data by using Geographic Information Systems (GIS). Traditional road data has been stored in the form of hard copy maps showing the different road infrastructure. The World Wide Web (WWW), has revolutionized the provision, dissemination, and data access to people in different geographical locations. Web-GIS based applications have gained popularity because their low cost, ease of use and availability to a large population – that is anyone with a web-browser. Through browsers, web-GIS based applications can display a map with useful information. The design and development of an interactive web-GIS based digital road infrastructure management tool not only allows users to visualize the road infrastructure content but also help in decision making. It makes use of open source GIS tools, PostgreSQL and PostGIS (to manage spatial and non-spatial data), Geoserver (to connect the database to the client mapping application) and Apache Tomcat (to build and deploy the application). The maps are published through Geoserver with their associated information using JavaScript libraries (Open Layers and Geoext). Further spatial analysis (attribute queries) can be done online. Results show that a web-GIS was developed that manages road asset infrastructure like road signs, bridges, animal grids, rest areas. A user can query precise assets they want to visualize for instance damaged bridges. HoweGIS:here is still need to further improve the application for instance allowing user to put complaints about damaged road assets. Thus, the development of the application will help decision makers as well as other users to utilize the information for the benefit of the country.

Keywords: *Geodatabase, web-GIS, geovisualisation*

1. Introduction

Roads as a means of transport make a crucial contribution to economic development and growth and are important for social services, businesses and the welfare of citizens of a country (De Zoysa, Keppitiyagama, Seneviratne, & Shihan, 2007). Road infrastructure provides the transport backbone to most of the business activities in any country(Burningham & Stankevich, 2005). In Sub-Saharan Africa, road transport is the dominant mode of transport which carries close to 90 percent of the region`s passengers (Ehebrecht, Heinrichs, & Lenz, 2018).Roads play an important role in our daily lives through providing a transportation network for goods and services hence understanding their spatial phenomena becomes essential for monitoring and aiding in making an informed decision and also increases efficiency in the choice of routes for transporting goods and people (Laurance, 2015). Poorly maintained roads constrain mobility, increase accident rates and human and property cost, significantly raise vehicle operating costs, and aggravate isolation, poverty, poor health and illiteracy in rural communities(Burningham & Stankevich, 2005).

In Zimbabwe, the 2018 National Budget Statement reiterated that investments in public infrastructure namely roads, aviation and rail will be prioritized. Over the last decade, Government's interventions in the transport sector have been focused on enhancing accessibility and promoting regional trade and investment particularly through the promotion of private sector participation. The services sector has consistently contributed the largest share to GDP – 65% as of 2017. The sector comprises of transportation and communications, tourism, financial services, and electricity that have sharply deteriorated over time (Zimbabwe Infrastructure Report, 2019). Zimbabwe has a responsibility as a Member State of SADC to assist in developing adequate transport networks that support socioeconomic growth in the region. Road transportation remains the mode of choice. In 2016 and 2017, 87% of visitor arrivals were by road; visitor arrivals by air in contrast only contributed 13% of arrivals into Zimbabwe. The Ministry of Transport and Infrastructural Development is responsible for road construction, maintenance and upgrading. For road mapping and record-keeping the department of roads use paper documentation to record crucial information such as road safety audits, ordinary road maintenance inspections and black spot interventions. Record keeping is an important source of data that assist the government to make timely, relevant and informed decisions hence contribute to sustainable socio-economic development (Short, 2014). Considering that Zimbabwe is one of the developing countries, where high economic growth can be translated to the expansion of infrastructure, including new road networks its map products struggle to maintain relevance given the rapid pace of development (Ogunsola & Aboyade, 2005). The existing road datasets become outdated rapidly so they lose their relevance. Therefore, the existing datasets should be updated continuously and that can be done efficiently by using digital mapping methods.

The A2 highway which connects Harare and Nyamapanda road dataset can be obtained by ground surveying and delineating roads and by extracting the road networks from satellite imagery (Christophe & Inglada, 2007). Ground surveying is conducted by using devices such as receivers for the Global Positioning System (GPS). Road network extraction from the satellite imagery can be classified as a manual, semiautomated or fully automated process (Bakhtiari, Abdollahi, & Rezaeian, 2017). Manual extraction involves a trained human operator delineating roads from remotely sensed imagery, while semi-automated extraction requires some human input to guide a set of automated processes and finally, the automated extraction process requires no human input for instance the AVREE(Automated Road Geometry Vectors Extraction Engine) which is an automatic road geometry extraction system (Wang, Hassan, El-Sheimy, & Lavigne, 2008). The road dataset was previously collected by the road department and it was kept as a hard-copy and there was the need for data extraction from the documents, then data cleaning to filter and remove errors also. Digital tools for storing road assets together with their locational data are needed. The tools should further allow for the geovisualisation of this data and the corresponding use of queries to search for desired information.

2. Methods and Materials

2.1. Study Area

This study focuses on the A2 highway located within Mashonaland east province and stretches from Harare to Nyamapanda. The A2 highway is part of the regional trunk road network linking Zimbabwe to the rest of the SADC and Comesa regions through Mozambique. The A2 Highway (R4 Highway) is a primary road in Zimbabwe running from Harare to Nyamapanda at the border with Mozambique and it is 238 km long. This is a busy entry point used by people travelling by road between South Africa, Malawi, Zimbabwe, and Mozambique. It is also popularly known as a mango and tomato supplier to *Mbare Musika* the largest green market in Harare and Zimbabwe. The following figure below shows the study area – the A2 highway length of Harare to Nyamapanda.

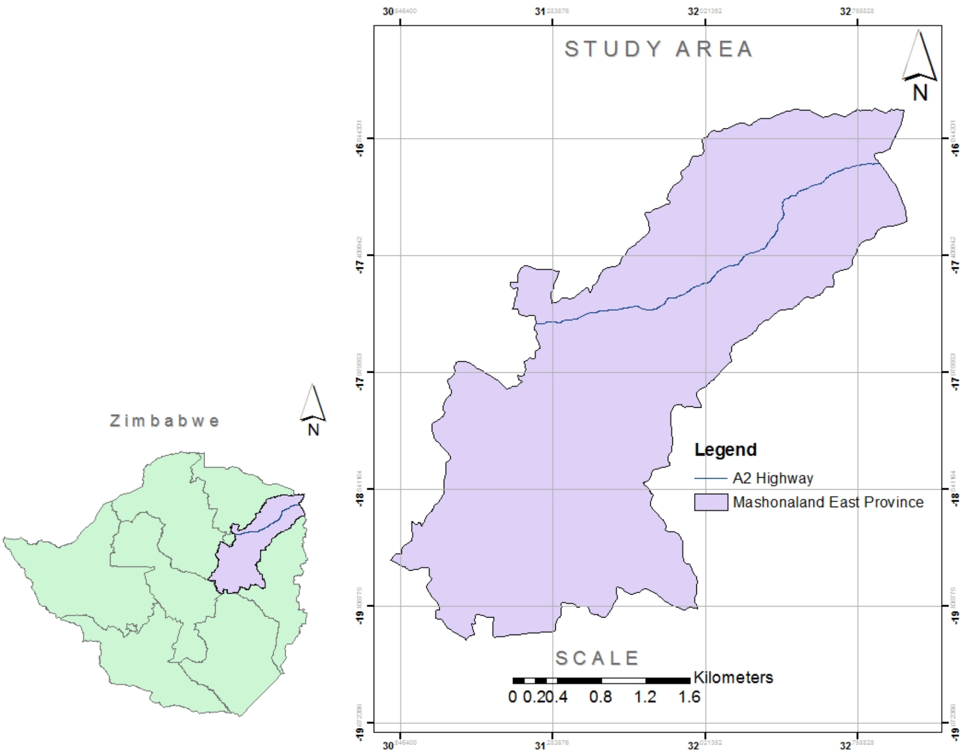

Figure 1: the A2 highway stretch of Harare to Nyamapanda.

2.2. Overview of Methodology

A web map of road assets was created to improve the efficiency of managing road infrastructure. The data was collected from the road department and it was cleaned and loaded in the PostgreSQL database. The data was then published on Geoserver as layers. Geoext was used to create the map panels and WMS to transfer layers to the Geoext panel. The flow chart in figure 2summarizes the methodology used.

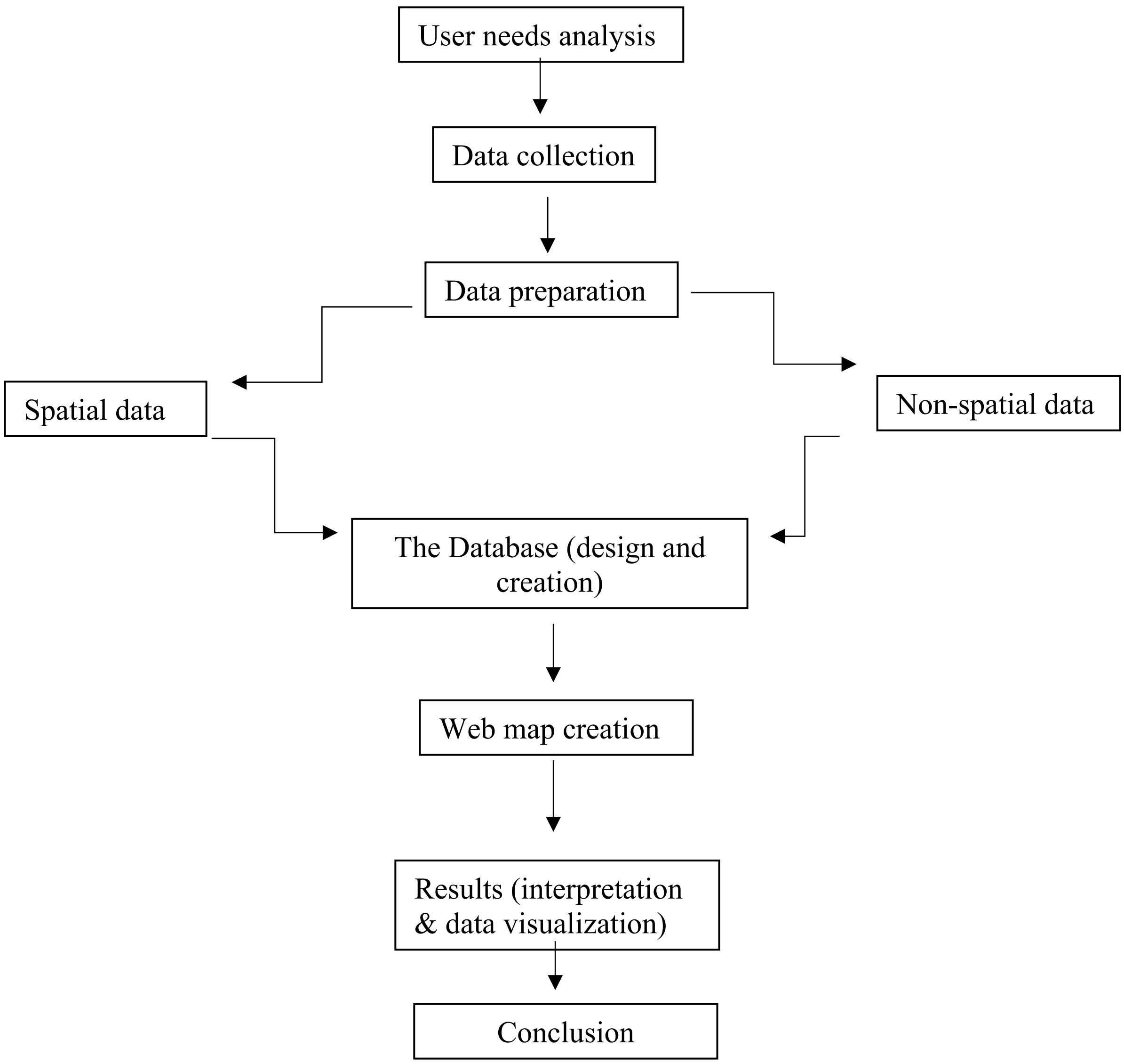

Figure 2: Summary of the methodology

2.2.1. Data Collection and Preparation

The advancements of open source technologies has given momentum to the development of web-based GIS applications(Kamiński et al., 2009). Servers like Geoserver provides easy to use tools for publishing GIS data as Open Geospatial Consortium (OGC) web services format in the web environment. The tools and technologies used in the development of the road assets web application included, PostgreSQL/ PostGIS, Apache Tomcat, Geoserver, Geoext and JavaScript.The data collection process involved the identification of data that was required for database creation and design followed by actual data extraction. The road assets considered were signages, animal grids, bridges, culverts, shelverts and junctions within the A2 highway. The data used in the creation of the database include map data (spatial data depicting the location of each asset) and attribute data (non-spatial data describing the physical characteristics of each asset). The data was acquired from the Department's database of road assets which was in paper document form and each asset was entered in Microsoft Excel in tables, and a CSV was created which was imported to QGIS for map plotting which aided in data cleaning. Data cleaning was done to detect and correct inaccurate records from the database to improve data quality (Calabrese, 2018).

2.2.2. The Database (Design and Creation)

Services of geographic information on the internet should have simple ways of managing spatial and non-spatial data. The use of database systems like Object-Relational Database Management Systems deals with spatial data characteristics effectively of which in most cases these systems are open-source (Harrington, 2009). PostgreSQL is one of the object-relational database management systems (ORDBMS) that can be used to store and analyze spatial data and it is open-source. PostgreSQL supports various data types and has a powerful indexing mechanism(Makris et al., 2021). The management of the database was made simpler by pgAdmin which is a graphical front-end administration tool for PostgreSQL. Storing of spatial data is made simple by the use of spatial extensions and these were developed and standardized by the Open Geo Consortium which is a Global Resource for Geospatial Information and Standards(Makris et al., 2021). PostGIS adds a spatial aspect to the PostgreSQL server, and the server becomes eligible to be used as a backend spatial database for geographic information systems (GIS). It adds special geometry data types and spatial function to the PostgreSQL object-relational database(Makris et al., 2021).

2.2.3. Database and Web map creation

The main objective of this research was to map and graphically display the A2 highway road assets on the Web. This involved the creation of a database in PostgreSQL/PostGIS relational database of the A2 highway assets from which the signages, junction, bridges, box culverts, shelverts, animal grids, bus stops and laybys were included. A database was created for the above-mentioned layers, which stores the important information about their condition for decision making, future planning and analysis. Once the datasets were in the database, the next step was to include them as layers in Geoserver. Since geospatial data has no intrinsic visual component styling has to be done to get the layers visualized(Duarte et al., 2021). Styling specifies colour, thickness, and other visible attributes used to render data on a map.After publishing the layers on Geoserver, the next step was to display the map on Geoext which is a JavaScript library that provides the groundwork for creating rich web mapping applications. It is Open Source and it combines the GIS functionality of Open Layers with the user interface of the ExtJS library provided by Sencha (Knörchen, Ketzler, & Schneider, 2015).A spatial database for road assets was designed and implemented using PostGIS as an extension of the PostgreSQL server, then the data was published on Geoserver. On Geoserver, layer styles were changed to allow easy interpretation of the output layers. The Web Mapping Service (WMS), Web Feature Service (WFS) and Web Coverage Service (WCS) work together to provide image files that can be used as base maps, vector files like points, polylines, and polygons to represent assets (Brovelli, Fahl, Minghini, & Molinari, 2016). The Apache Tomcat 9 was used to deploy the Java Servlets and JSPs. A web archive file was built and was dropped in the deploy directory in Tomcat. Then the GeoExt was used which is a JavaScript toolkit that produced this project's application based on ExtJS and Open Layers. Figure 3 below shows the general system architecture**.** Web-GIS is a combination of Web and Geographic Information Systems (Fu & Ph, 2012). Web-GIS is exploited for the geovisualisation of geographic data in the form of web maps. According to (Gong, Geng, & Chen, 2015) the Web and Internet have allowed direct and near real-time access to information without regard for physical access.

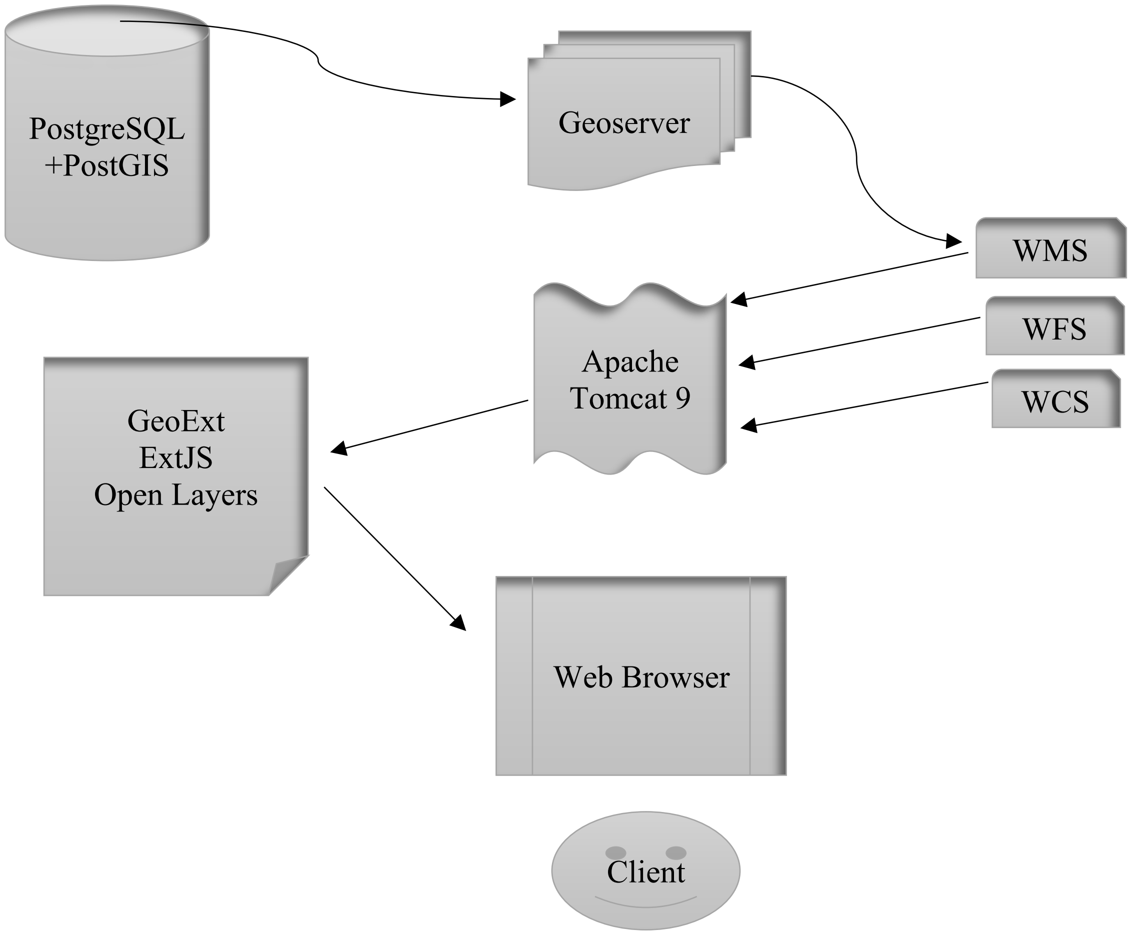

Figure 3: The general system architecture

3. Results

A web-GIS application for road assets management was realized. The graphic user interface of the web-GIS is shown in the figure 4 below with the map panel containing layers of road assets in the A2 highway.

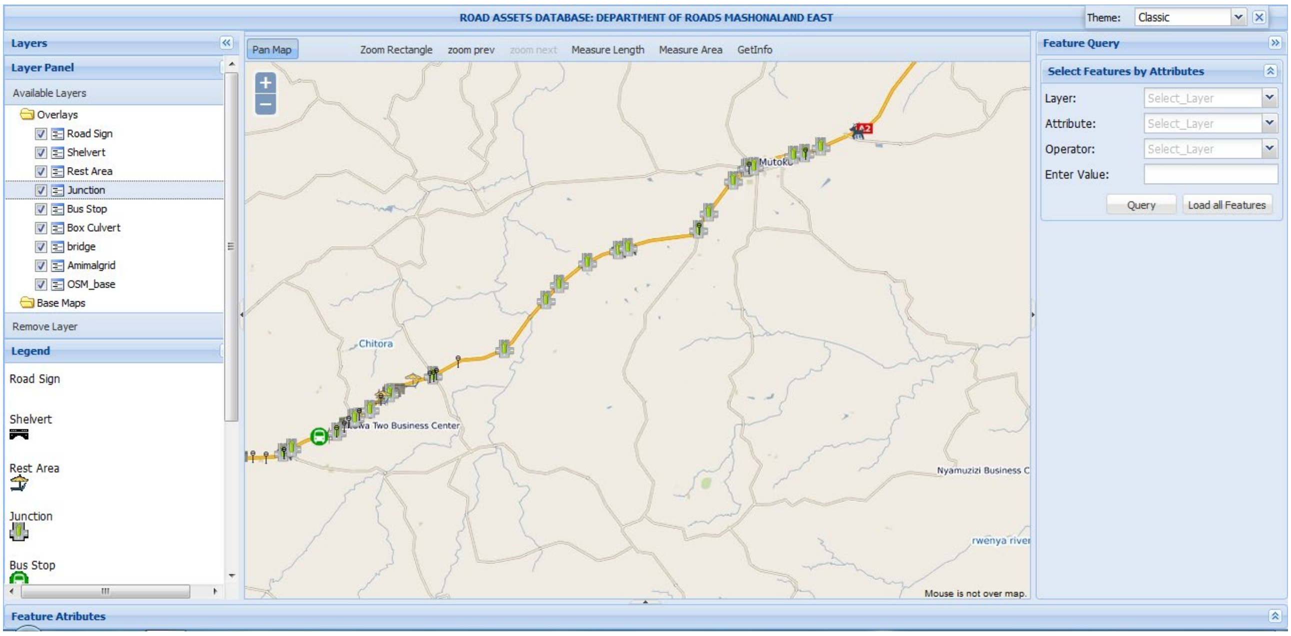

Figure 2: The web GIS with the application panel.

The important features included in the Web-GIS are as follows:

Legend, which shows the meaning of symbols used on maps displayed in the viewport. The legend appears every time a spatial data layer on the left panel in enabled via check boxes.

Map layers, is a menu list of assets in the road database that appear on the left side. The list is organized as a tree layout of folders. The folders are added in order of the registered layer name so they appear organized. They are labelled with the name of the asset they represent as shown in figure 5 below.

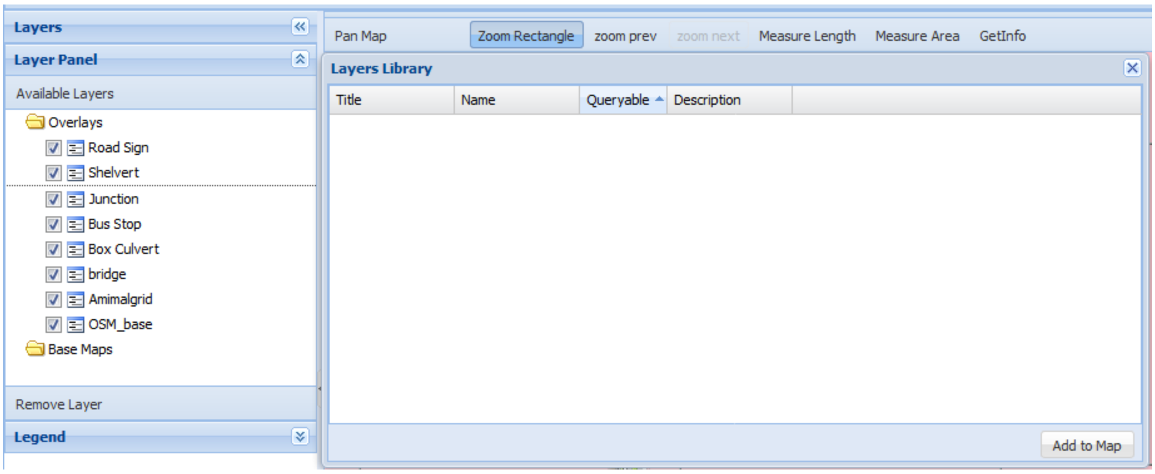

Figure 3: Shows the layers panel which is arranged in tree layout of folders and files.

Tools, represents the map navigation, which are features used on navigating the map such as zoom rectangle (as shown in figure 6 below),zoom in, zoom out, zoom previous, zoom next and pan map to change the scale of the map.

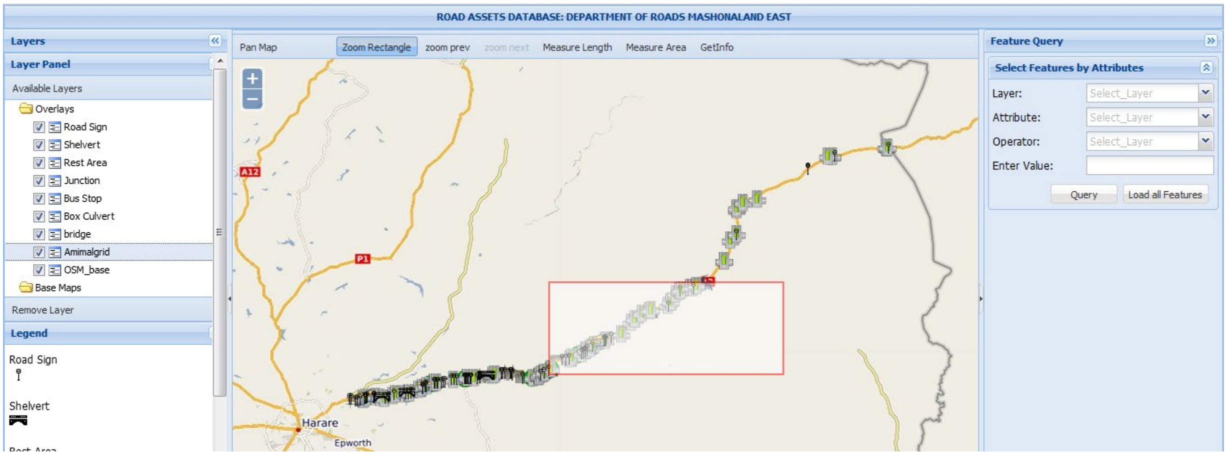

Figure 4: Zoom triangle in use to zoom to the drawn rectangle extent.

Measure length, allows the user to measure the distance from the location of an asset to the desired place for instance the nearest camp belonging to the Department of roads. Figure 7 below shows a sample result of distance calculation performed on the web-GIS map

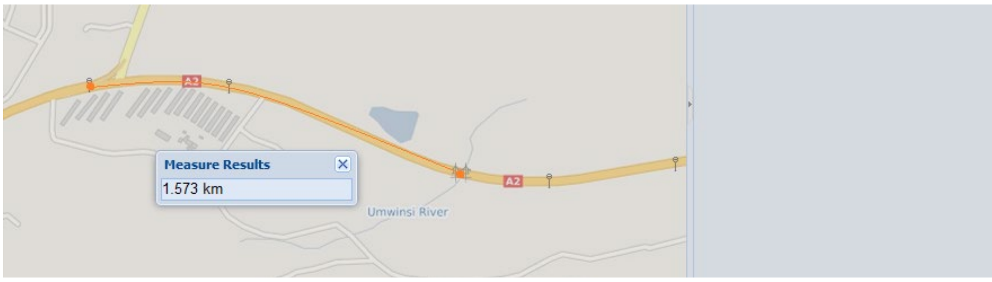

Figure 5: Measure distance function result.

Query tool, the multi-attribute tool helps the user to analyze and query the assets of the road along with their attributes. A result of the query to display all damaged signages is shown in figure 8.

Feature Atributes

attribute	y	x	chainage(k	sign categ	condition	satcc comp	comment
Signage	-17.65758017	31.69938146		Informative sign	Damaged		Derestriction
Signage	-17.59363067	31.92297396		Informative sign	Damaged	No	Missing Mutoko ...
Signage	-17.59020985	31.92667223		Danger warning	Damaged	No	Curve ahead sign
Signage	-17.58496601	31.93449767		Danger warning	Damaged	No	Curve ahead sign

Figure 6: The result of running the query to display all damaged signages.

The following diagram in figure 9 shows all the queries that can be run to analyse the road assets. These can be run in the same way shown in figure 10 below which displays the query panel.

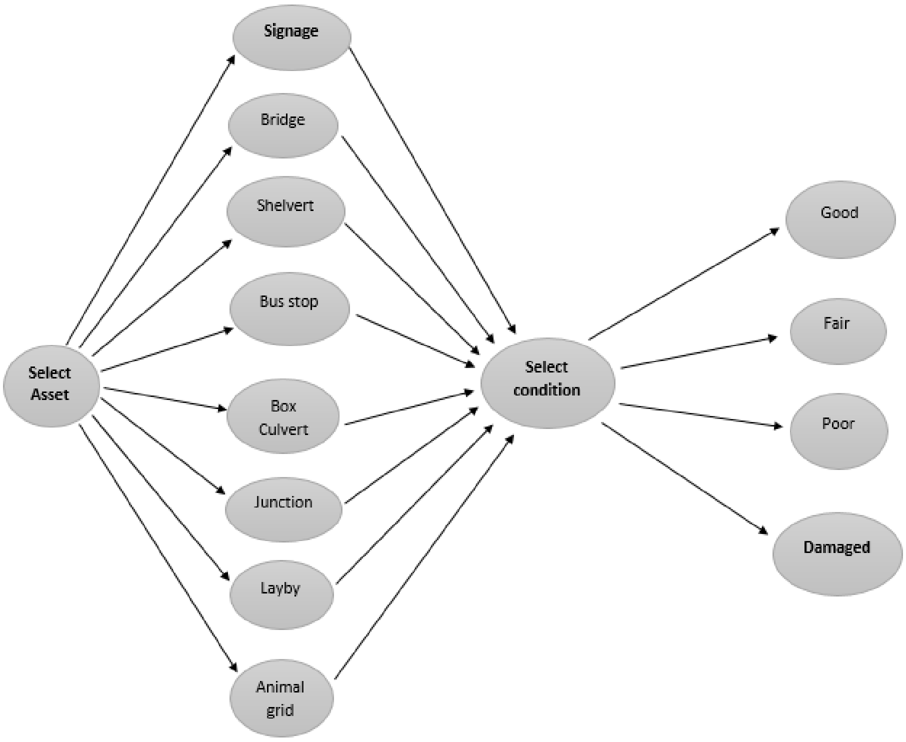

Figure 7: Queries that can be run in the query panel for analysing road assets.

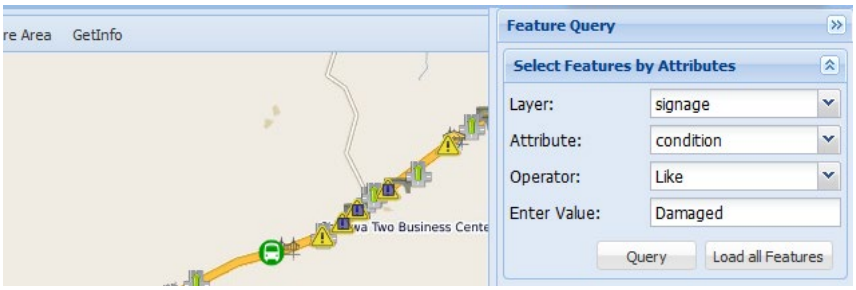

Figure 8: The query panel.

3.1. Validation

The same portion of the road length measurement in figure 7, 1.573km was done in QGIS. The following figure 10 below shows the same portion of the road measured using another GIS software QGIS giving a similar result.

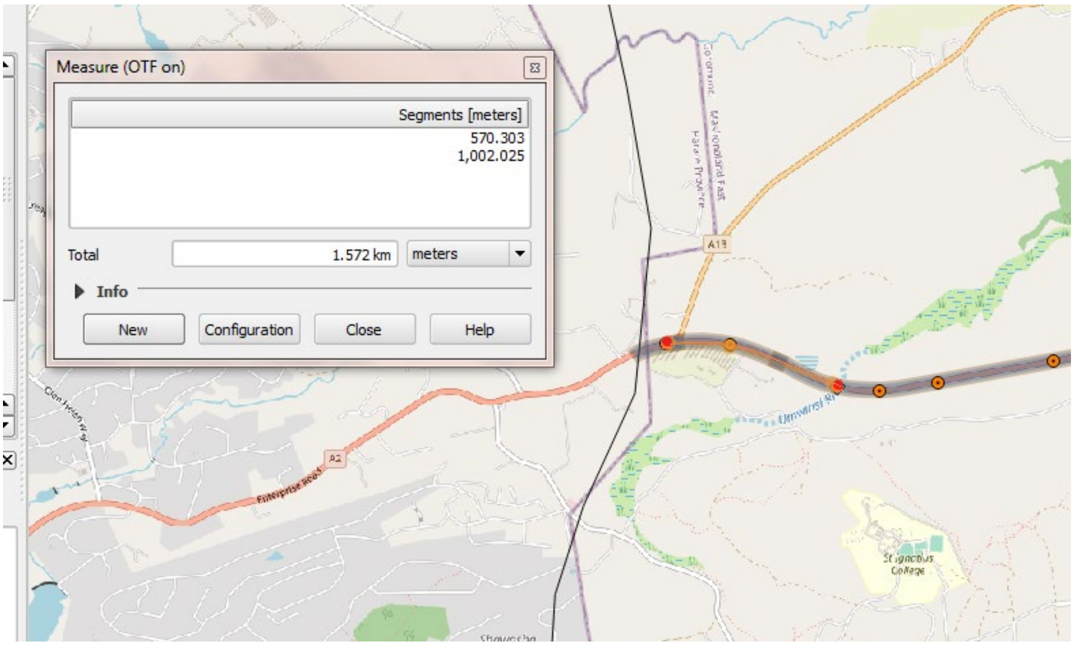

Figure 10: Length calculation using QGIS

4. Discussion

Data management, visualization and decision making were improved significantly by the customized GIS solutios. The open-source web application has been developed and demonstrated. Previous software used on projects before are costly and licensed like ESRI ArcIMS and ArcSDE. The ArcSDE 8 Bundle (including License for 1 Server) cost USD10,000 and ArcIMS Standard Edition Server/CPU License cost USD7,500(Esri, 2012). In this research, open-source software freely available online was used. This helps in reducing the cost of the project whether implemented on a small or large scale.

The web application will help in identifying faulty road signs, bridges, laybys and junctions quickly for efficient road management and aiding in decision making. From the present development, many authors conclude that this is an attempt to develop a web application for spatial planning in the field of asset management, however, there are still scopes of future advancement in what the system is capable of doing, by adding some advanced functions and modules for instance lodging user`s complaints and tracking the registered complaints. This project provided a practical web-GIS framework combined with the latest web services technology and open source frameworks. Spatial data services were developed to access and publish spatial data. The web-GIS application was developed for the visualization and analysis of road assets. The application is useful for planning, maintenance and improvement of information standard and decision-making processes, still there is scope for future advancement in what the system can do by adding some analytical modules in account to the decision making process for asset management.

5. Conclusion

A web-GIS was developed to manage road asset infrastructure like road signs, bridges, animal grids, rest areas etc. The web-GIS has enabled the visualization of scattered data into a single platform, filter assets according to their conditions and visualize them, measure the distance from any asset to the nearest department camp. Ajwaliya argued that web GIS can be used for planning, maintenance, and improvement of information standard and decision making processes (Ajwaliya, Patel, & Sharma, 2017). Hence this research allows policy-makers and decision-makers from developing countries like Zimbabwe to use cost effective solution for road management. The application was developed using open-source and free software which makes it attractive to budget conscious countries like Zimbabwe. Moreso the application is able to achieve the desired function however the aesthetics are not as attractive compared to those offered by commercial software like the ArcGIS Online and Web AppBuilder and mapbox(Bernasconi & Grandi, 2021)

The authors declare no conflict of interest.

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