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GIS in Water Supply Network Maintenance in Tarkwa, South Western Ghana

Michael Soakodan Aduah, Saviour Mantey and Naa Dedei Tagoe
Department of Geomatic Engineering, University of Mines and Technology,
P.O. Box 237, Tarkwa, Ghana

Abstract: Developing systems to manage and maintain water supply networks is an important aspect of the operations of water companies. This study uses GIS to investigate the water supply network of a section of Tarkwa Municipality in South Western Ghana. The objective is to create a geodatabase that supports improved operations and performance and to determine costs of asset replacement. Digital maps of the study area were re-projected to the WGS84 UTM Zone 30 North projection. Analogue maps of the mains and lateral pipelines were scanned and geo-referenced to this projection. The pipelines and valves were then manually digitized, their attribute tables created and a geodatabase model developed. The analysis indicates that more than half of the network is over-aged. Also of the 11 km of pipelines, more than 76% was laid in 1975 and 1978. AC and PVC pipes laid in 1975 and 1978 comprise 29 and 47% respectively while the rest of the study area is covered by AC and PVC pipes laid in 1987. This study also observed that the length of AC pipes have consistently reduced since 1975. The study has further demonstrated the suitability of GIS techniques in studying water distribution networks. The system developed three scenarios that can support the design of long term expansion and replacement action plans. The study also provides detailed spatially referenced information on pipelines and the associated cost of replacement as they reach the designed lifespan.

Key words: Digital maps, geodatabase, Ghana, GIS, pipelines, Tarkwa

INTRODUCTION

Water distribution systems have existed since the Minoans constructed the first piped water conveyance system (Zhang, 2006). Currently, water distribution systems effectively serve municipalities of all sizes worldwide. A water supply network consists of engineered hydrologic and hydraulic mechanisms (Anonymous, 2005). These include water resources, pumps, treatment plants, reservoirs, pipes and their accessories (Babovic *et al.*, 2002; Chin, 2006) and other equipment for operation and management. One of the major challenges in water supply is the provision and management of the pipe network and the associated assets. Effective functioning of these assets is necessary for distributing water continuously and efficiently. Therefore effective asset management in the water supply sector is vital for providing uninterrupted services. However, water supply assets are mostly buried underground and can only be accessed after excavation (Babovic *et al.*, 2002). Thus it is complicated to ascertain the status of these assets and has often led to unplanned disruption of services when systems abruptly breakdown. Often major excavations are done to replace or repair broken water assets disrupting transportation and smooth conduct of business in urban areas.

Maintaining or replacing water supply assets is expensive. Developing systems to manage and maintain existing networks effectively is therefore a crucial aspect of the operations of water companies. In this regard, systems have been developed to track the state of underground water supply assets to support management and operations. These systems are mostly statistical and modeling schemes (Ambrose *et al*., 2010; Babovic *et al.*, 2002). They lack spatial analytical capabilities and require a lot of data to be effective (Brussels, 2005).The location of water supply assets is vital to its effective management. To be able to excavate and replace a damaged pipe the exact route and depths are required. This has the advantage of preventing waste of resources when buried pipes can be traced. Geographical Information Systems (GIS), with extensive spatial analytical capabilities have become widely applied in the infrastructure sector since its introduction in the 1960s. GIS is applied in four sections of the water infrastructure sector: asset management, distribution management, customer and outage management (Brussels, 2005). It is ideal to manage infrastructure by integrating all the information systems within these sections. However, lack of data is often a serious limitation. Consequently, a GIS application in the operations and maintenance section of water utilities is a first stage approach to integration and optimization of all sections of water supply systems.

Corresponding Author: Michael Soakodan Aduah, Department of Geomatic Engineering, University of Mines and Technology, P.O. Box 237, Tarkwa, Ghana, Tel.: +233 249 447799

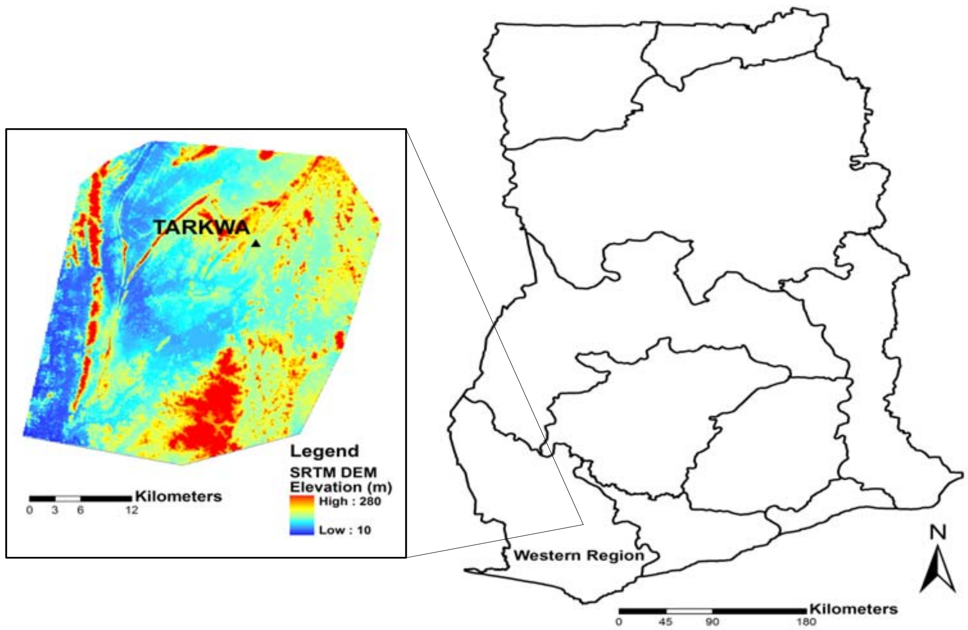

Fig. 1: Map of Ghana showing the location of the study area

GIS is further applied in the entire lifespan of water supply systems from planning to implementation, operation and maintenance to replacement (Brussels, 2005). This is because GIS provides a variety of support in asset inventory (Keeping record of pipes, valves, fittings, hydrants and meters together with their characteristics and status); determining and prioritizing repair and replacement works; and closing valves to redirect water flow. Moreover, service continuity can be ensured by limiting repair and maintenance time through spatial scenario modeling, locating areas affected by particular problem and informing affected parties. Through GIS, the direction of flows can be established to find upstream and downstream of points to optimize water pressure so as to identify an isolated part of a network. Though many countries are advancing in the use of GIS in management and operation of their water supply systems, the technology is currently under utilized in Ghana. Hence, it is essential to create systems that motivate the use of GIS in managing water systems. The adoption of such a system has the potential to improve the quality of service.

In this study, the water supply network in a section of Tarkwa (Fig. 1) is investigated with GIS functionalities. This is to create a geodatabase that supports improved operational performance and to determine the replacement costs as at 2010 as well as use Cartographic tools for effective display of the pipe network information.

Study area: The study was carried out in Tarkwa Municipality (Fig. 1) in the Western Region of Ghana. Tarkwa is located on latitude 5º North and longitude 2º West, approximately 89 km north of Takoradi, the Western Regional capital. The study area falls within the equatorial zone with a mean annual rainfall ranging from 1500 to 1933 mm and a mean relative humidity of 70 to 90%. Daily temperature ranges between 20 and 40ºC (Akabzaa and Darimani, 2001). Tarkwa is surrounded by tropical rainforests and shrubs and it is between two long ranges of hills considered the two limbs of a gold mountain with an average elevation of 300 m above sea level (Akabzaa and Darimani, 2001). The mountains provide the water catchment for many rivers and streams in the area including Bonsa River which is the main source of water for the township. The Ghana Water Company Limited (GWCL) treats water from the Bonsa River and pumps it through their mains to the town.

According to the 1994 Ghana population census, population of Tarkwa district (formerly Wassa West) was 260,000 with an estimated growth rate of 3.0% (Akabzaa and Darimani, 2001). About 70% of the population resided in Tarkwa, where population growth is above the national average of 3.1%. This has been attributed to migration of people in search of mining sector jobs (Akabzaa and Darimani, 2001). Tarkwa is therefore characterized by high population growth. The population has outstripped many municipal services especially safe

Table 1: HDPE distribution mains (Bill of Quantities as at 2008)

Outside diameter (mm)	Unit rate per meter in euros (Pipe cost, excavation and backfilling cost)
32	5.06
40	5.62
50	6.49
63	7.91
90	9.38
110	12.02
125	14.22
140	16.86
160	22.05
180	26.07
200	30.08
225	37.01

GWCL contractor

drinking water. For instance, Kuma and Ewusi (2009) observed that many people do not have access to regular supply of piped water, a situation that has led to rampant sinking of water wells. It is anticipated that the water supply will continue being insufficient owing to the rapidly increasing population that is supported by the boom in gold production.

MATERIALS AND METHODS

Materials: Data for the study includes shapefiles of roads, contour lines and cultural features obtained from Survey of Ghana digital maps. Analogue map of main and lateral pipelines, pipe replacement costs (Table 1) and attributes information of the pipelines were obtained from the GWCL. Valve and hydrant location points were surveyed with handheld GPS instrument in March 2010.

Methods: The methods used for this study included development of a geodatabase, building geometric network and carrying out spatial and attribute queries in GIS. Also map layouts were generated from the spatial analysis and graph plotted using attribute data. The study was conducted in March 2010 using methods discussed in the sections below.

Geodatabase design: The acquired digital maps were assigned the Ghana War Office projection and re-projected to the WGS84 Universal Transverse Mercator (UTM) Zone 30 North projection. This was to enable accurate overlaying of spatial data obtained from other sources. The analogue pipelines map was scanned and geo-referenced to the digital road map. The pipelines were then manually digitized as lines and valves as points and their attribute tables created.

In spatial databases, subtypes define the range of valid properties for a feature and quicken data entry and validation while domains are used to restrict the range of values that can be used in a subtype. These include the data type (e.g., integer, double, text) or a data group (e.g., a list with specific properties). Subtypes and domains are properties of the Environmental Systems Research Institute (ESRI) geodatabase and allow fields in different tables to be used in a geodatabase. It is necessary to model subtypes and domains in any spatial database systems so as to ensure database integrity. In Table 2, the subtypes and domains used for this study are presented. In order to build a sound geometric network model for the pipeline, subtypes and domains were created for each feature class. The feature classes with available data are the pipelines, valves and hydrants. Fittings data was not available and were not included in the geometric water network. However, the feature class, tertiary lines (supply lines to consumers) were included though its spatial data was unavailable. This is to allow logical editing whenever the data becomes available.

Table 2: Subtypes and domains

Codes/Fields	Line material	Line type	Domains
1	PVC	Main	Main line material, Main line size
2	AC	Lateral	Lateral line material, Laterallinesize
3	-		Tertiary Tertiary line material, Tertiary line size

Database validation: Database validation was performed to ensure that all features within the network model were properly connected had the correct set of subtypes and domains and all the privileges associated with data editing were adhered to. The developed spatial database was therefore tested to ascertain its validity. Firstly, all network features were selected, set to edit mode and validation performed using the edit tool in ArcGIS. This showed that all the features were valid to participate in the network model. Also several pipe lines of type main, lateral and tertiary were added and their attributes checked. This was to ensure that the subtypes and domain properties were properly setup.

Water pipeline analysis: Water pipeline network maintenance is one of the main activities that water companies execute to ensure continuous supply of water. The costs of providing and maintaining these assets is significantly high. Therefore it is crucial that the network elements are critically analyzed to provide quality information that would lead to effective management. One of the most important pieces of information needed is the type of pipes, their location, current status and the costs to replace or repair. It is reported that repair of pipes with diameter less than 18 inches is uneconomic (Muzibira, 2003). Muzibira (2003) found that there is not enough working space for repair equipment and the costs of repairing such pipes almost equals that of replacement.

Therefore, in this study replacement was chosen over repairs. The reasons are that the study area had a maximum pipe diameter of 8 inches, the pipes were over-aged and a larger percentage of the network was built with AC pipes. The replacement of pipe lines is a major part of investment in ensuring efficiency of water distribution systems. Therefore the focus of this study is the replacement of pipes based on a variety of criteria.

Table 3: Pipe material characteristics

Material	Design life time (years)
Asbestos Cement (AC)	30
Cast Iron (CI)	50
Ductile Cast Iron (DUC)	60
Poly Ethylene (PE)	30
Poly Vinyl Chloride (PVC)	25
Steel (ST)	60

Brussels *et al.* (2004)

Firstly, the pipelines for replacement were obtained by selecting all pipes that are aged more than their designed life span and those made of Asbestos Cement (AC). In the study area only two material types are present; AC and PVC with designed lifespan of 30 and 25 years respectively (Table 3). Pipes like any other infrastructure should be repaired or replaced as they reach their designed lifespan. This is because pipes start to degrade and failure probabilities increases leading to possible contamination of domestic water. AC pipes have also been found to contribute to polluting drinking water when it reaches its life span as it release fibres into the water (Brussels, 2004). The health risks involved in using worn out AC pipes are therefore high.

HDPE pipes were also used for the study because they have numerous advantages over PVC and other pipe materials (Anonymous, 2011). Many water companies prefer replacing old pipes with HDPE. The replacement costs of pipes in this study were estimated by multiplying the cost of constructing a new HDPE pipe per meter by the required length of selected pipes to be replaced per scenario. In order to provide the opportunity to select the best option so as to utilize financial resources efficiently, several scenarios were analyzed to arrive at the pipelines that need replacement. The total financial requirements and other factors per scenario would then be the consideration for selecting any scenario.

RESULTS

Analysis of the pipeline network database indicates that more than half of the Tarkwa network is over aged and require replacement (Table 4). Of the over 11 km of pipeline studied, more than 76 % was laid between 1975 and 1978 (Fig. 3). AC and PVC pipes laid in 1975 and 1978 comprise 29 and 47%, respectively while the rest of the study area is covered by AC and PVC pipes laid in 1987 (Table 4). From Fig. 2 and 3, it can be observed that the length of AC pipes laid since 1975 has reduced consistently. This could be as a result of the shift towards usage of PVC pipes worldwide due to the health risks associated with old AC pipes.

Table 4: Pipe material and year of construction

Year	Pipe type	Length (m)
1975	AC	2413.856
1978	AC	897.374
1987	AC	656.582
1975	PVC	2595.222
1978	PVC	2736.054
1987	PVC	1974.067

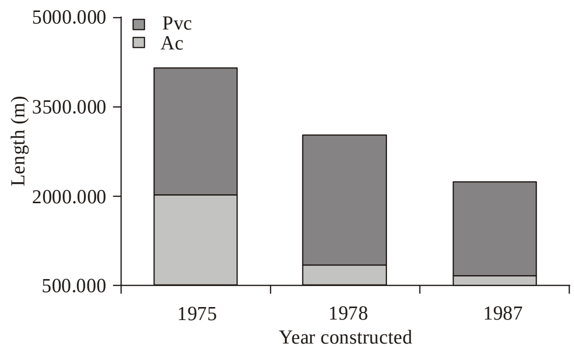

Fig. 2: Graph of pipe material and year of construction

Pipe replacement: The pipes to be preplaced were selected based on three scenarios discussed below.

Scenario one, replacing all pipes: This scenario is based on the assumption that all pipelines would have to be replaced at some point in the future. In this regard the total cost is needed to support effective planning of replacement activities. In Table 5, the length of pipe material to be replaced per suburb is presented. Also the costs to replace all the pipes are included as a guide on prioritization. It can be observed from Table 5 that over 3 km of pipeline made of PVC was laid in the Cyanide area while about 2.4 km of AC pipes were found in Nzemaline. These two areas comprise almost 50% of pipeline network in Tarkwa and therefore should be a priority in any replacement activities. However, the pipelines in Nzemaline are made of AC (Fig. 4 and Table 5) and should be of a higher priority when replacement is been planned. The total replacement cost is estimated at 279,606.76 Euros.

Scenario two, all AC pipes and PVC pipes (aged more than 25 years): In this scenario it is expected that all AC pipes will have to be replaced while all PVC pipes aged more than their design life should also be replaced. In Table 6 the pipes lines that meet this criterion is presented. It can be observed that a total of 9.3 km pipe

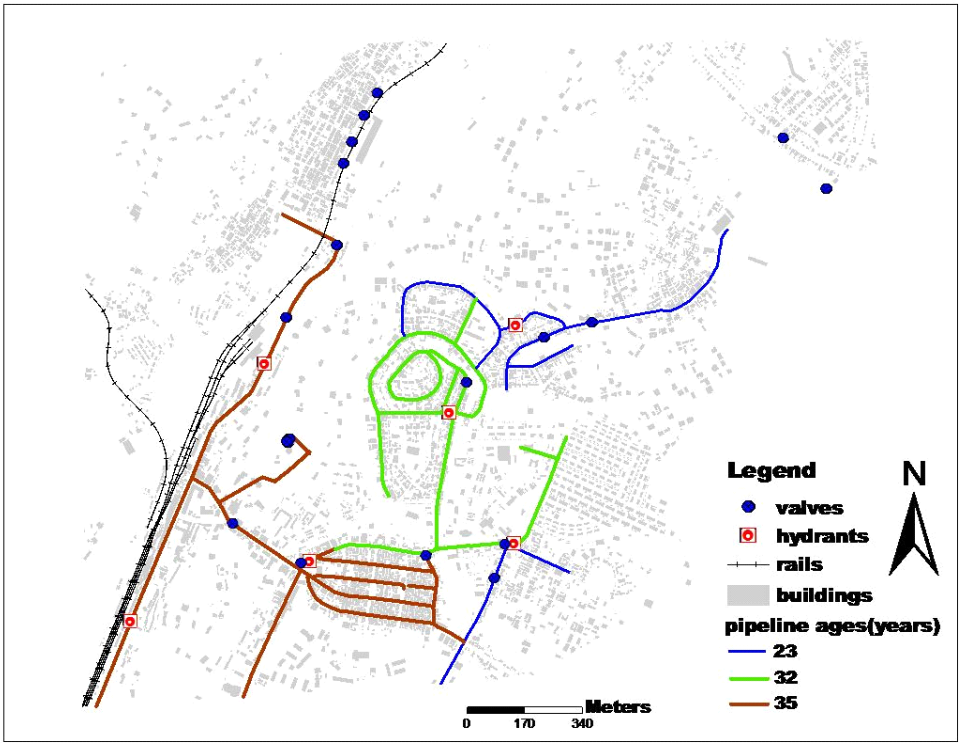

Fig. 3: Map of pipeline ages

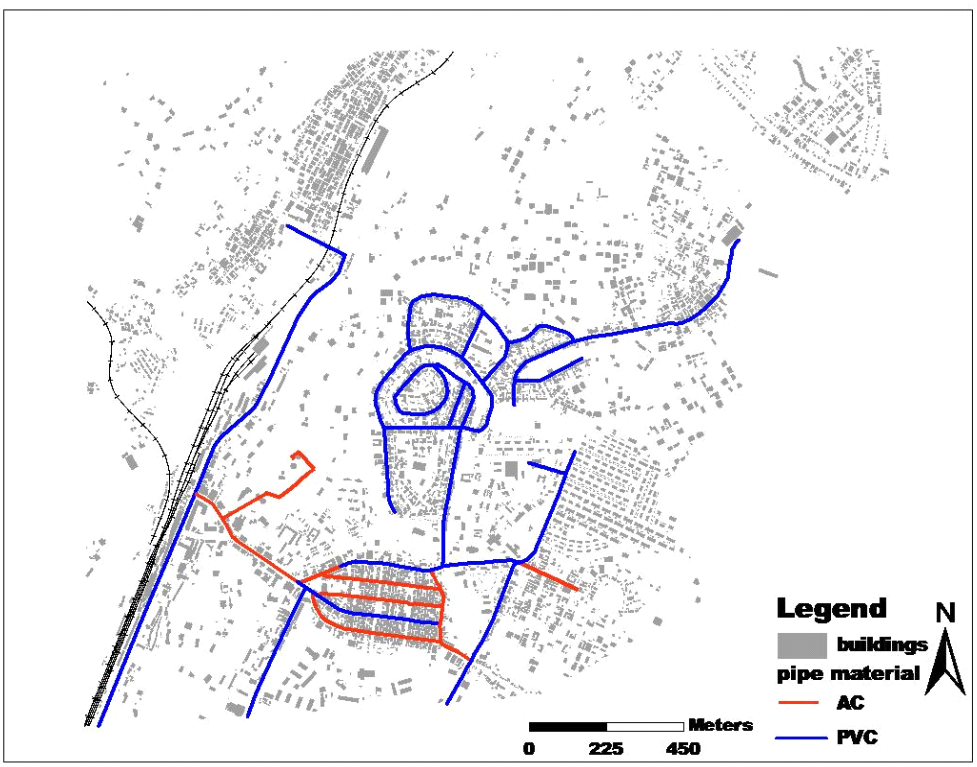

Fig. 4: Map of pipeline materials

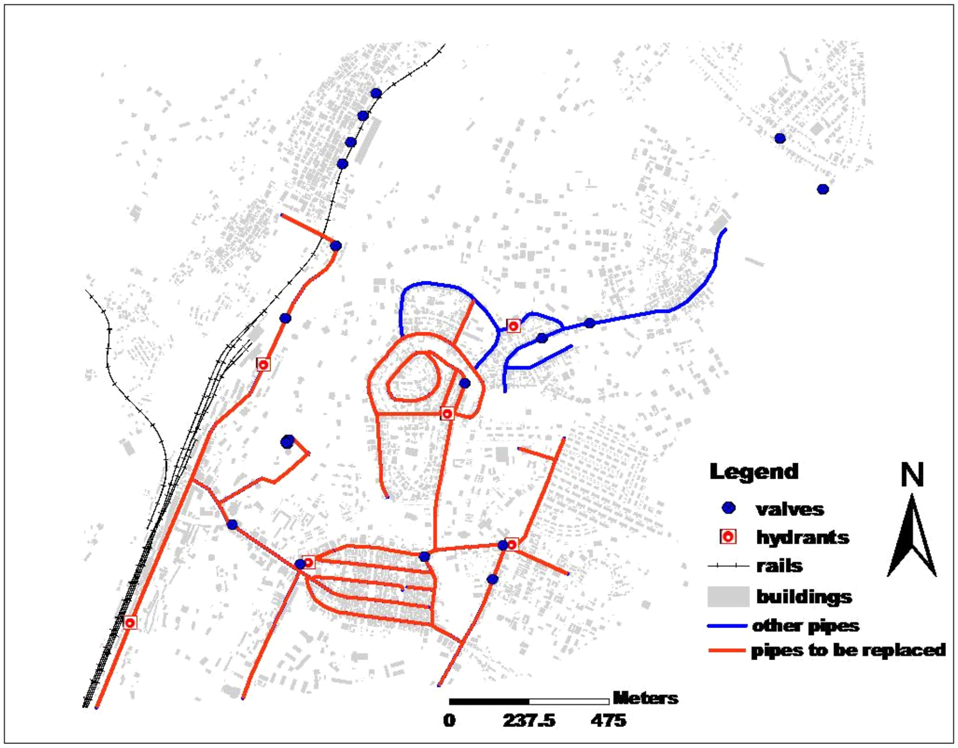

Fig. 5: Map of pipelines to be replaced (scenario two)

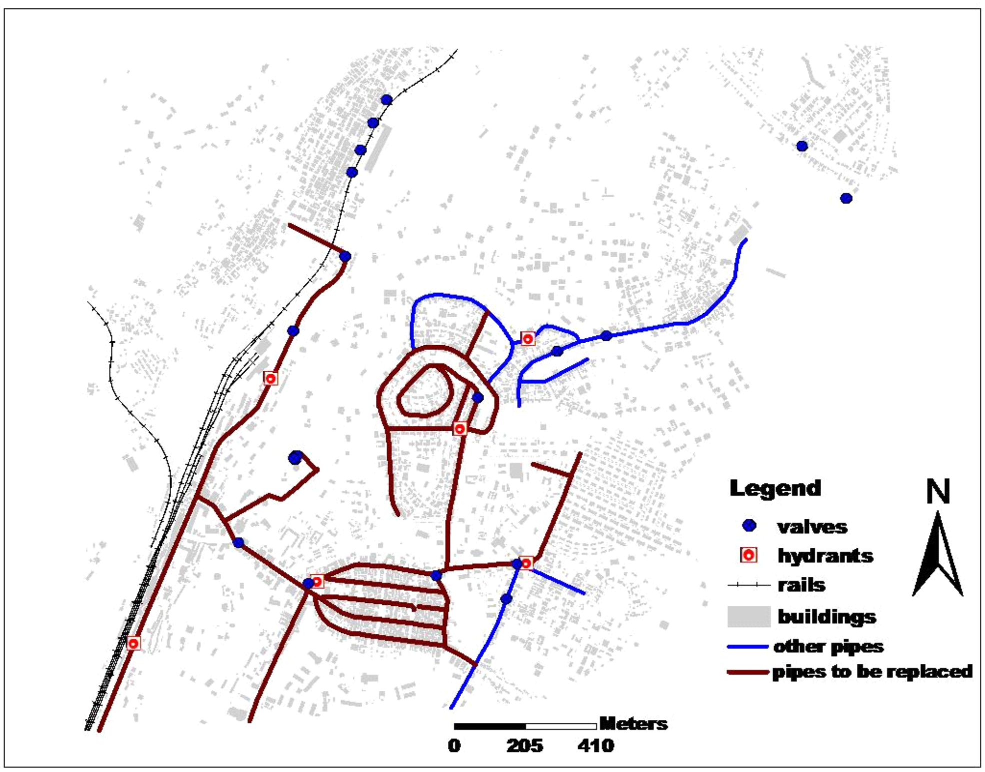

Fig. 6: Map of pipelines to be replaced (scenario three)

Table 5: Pipe replacement cost in suburbs

Suburb	Pipe type	Pipe length (m)	Replacement cost (Euro)
Cyanide	PVC	3095.337	52650.28
Cyanide (Reservoir)	AC	100.546	3721.20
Hospital	AC	897.374	39574.19
Kwabedu	PVC	1351.153	16240.86
Nzemaline	AC	2433.168	51081.62
Post office	AC	2152.441	73645.21
Railway Quarters	PVC	115.860	1392.64
Zongo	AC	656.582	27578.00
Cyanide	AC	470.293	13722.74

Table 6: Total replacement cost (scenario two)

Pipe material	Pipe length (m)	Replacement cost (Euro)
AC	3967.812	96731.36
PVC	5331.275	117012.76

Table 7: Total replacement cost (scenario three)

Pipe material	Total length(m)	Replacement cost (Euro)
AC	3311.230	79347.70
PVC	5331.275	117012.62

lines would have to be replaced and the total cost is estimated at 213,744.12 Euros. Since more than 50% of these pipes are PVC, which have less health risks, it would be imperative to start replacing the AC pipes per suburb (Table 5 and Fig. 4). In Fig. 5, a map showing all pipelines under this scenario is presented.

Scenario three, AC and PVC pipes aged more than design lifespan: In this scenario, replacement is solely based on pipe age. All pipelines with age more than their design life span are to be replaced irrespective of pipe material. Table 7 shows that the cost to execute this scenario is over 79,000 and 117,000 Euros for AC and PVC pipes respectively. The cost of this scenario is 8.1% lower than scenario two. However, in scenario two, all AC pipes will be replaced making it a better choice in terms of health. In (Fig. 6), a map of the pipelines to be replaced is presented. The replacement activities covers almost all the study area. Therefore pipes of diameters 4, 6 and 8 inches will need replacement.

DISCUSSION

Replacement or maintenance of water supply assets is based on asset performance. Ideally water assets should be replaced if the cost of maintenance exceeds replacement (Ambrose *et al.*, 2010). Factors such as pipe diameter, customer perceptions and water quality also play a part in making this decision. A replacement ensures that system performance is optimized. However, there exist a plethora of scenarios with different cost and technical implications. The three scenarios in this study provide different opportunities and challenges.

In scenario one, all pipe lines would require replacement considering that most of them are already past their design lifespan. The cost of executing this scenario is the highest in terms of financial and capital resources, inconvenience to the public through disruption of transport routes and water supply to consumers during replacement activities. This scenario though ideal in ensuring the most efficient service, it would be challenging to execute under these circumstances. In scenario two, pipe line replacement is based on age of PVCs and a replacement for all AC pipes due to the associated health risks. In this scenario the aged PVC pipes consisting of mains and laterals form more than 50% of pipes to be replaced. Hence it would be beneficial in terms of health to start the replacement with AC pipes. Furthermore, a third scenario is developed, where pipe replacement is primarily based on their design lifespan. This scenario is the most ideal in the infrastructure industry since all projects are expected to provide optimum service for a specific period of time and be replaced after that. The scenario ensures that only pipes that are classified as aged are replaced. The estimated cost of executing this scenario is 8.1% lower than scenario two.

It is expected that executing any of the scenarios would cause some inconvenience to the public during construction. Therefore in applying a particular replacement scenario, the costs should not be the only consideration. To avoid inconveniencing the public, a gradual approach to adopting a scenario would be effective. Here the replacement activities should be scheduled for one suburb at a time, starting with densely populated areas. In a particular suburb further prioritization could be carried out. For instance, all pipes made of AC can be replaced, then replacement of 4 inches PVC pipes and finally replacement of all 6 inches PVC pipes. In this way disruption of service and inconvenience to the public would be minimized.

Efficient infrastructure operation depends on the application of long term planning and maintenance strategies. Since replacement and maintenance activities largely depend on availability of funds, it is imperative that future costs are currently ascertained for effective financial planning. The cost to replace or maintain the pipe network in future can be computed by planning a yearly replacement schedule using the database developed. Therefore funds could be secured in advance for any replacement activity on a continuous basis. This would ensure that pipe network maintenance is continuous rather than an instantaneous activity.

CONCLUSION

This study has demonstrated the suitability of GIS geodatabase techniques for studying water distribution networks. The system developed can support the design of a long term expansion and replacement action plans for the GWCL. The system provides detailed spatial information on pipelines and the associated costs to replace them. It also provides spatially referenced information to support scheduling work and possible identification of affected parties or consumers during any replacement activity. However, data such as pipe condition, pipe failure records, population of suburbs and customer information if available would further improve prioritization of these activities.

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