GIS-Based Pipeline Route Mapping for Water Distribution in Obafemi Awolowo University, Ile-Ife, Nigeria

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Abstract

Pipelines transport water, natural gas, crude oil, and finished petroleum products over long distances within countries and across borders to meet energy needs. And as the planning of water distribution system is carried out through complicated and repeated manual process, research have tried to improve those processes through the better tools of geographic information systems. This study modelled the suitable and least-cost pathway for pipeline route selection and also determined and mapped the optimal pipeline route for water distribution in Obafemi Awolowo University Ile-Ife using GIS techniques. Topographic map and the pipeline network map of the existing pipeline network were acquired. A Digital Elevation Model (DEM) was derived from the contours of the topographic map and a slope model over the area was derived from the DEM. The multi-spectral satellite imagery of IKONOS (2010) with 0.6 metres resolution of the area was obtained. Data collected were analysed using Spatial and Utility Network analysis. It was observed that the existing water pipeline network did not cover the existing facilities in the University. And that areas within the University experienced acute water supply shortages. Furthermore, the suitability and least-cost pathway pipeline siting model generated four segments as optimum route for water distribution from the treatment plant to the reservoirs likewise from the reservoirs to the various demand points in the community. The study concluded that the present water distribution network was not adequate to meet the water demand and that geospatial technique generated a better distribution route to ensure efficient water distribution network system in the community.

Introduction

Water is a basic human right. Without it societies wither and people die (Joanne, 2000). Much of the ill-health which affects humanity, especially in the developing countries can be traced to lack of safe and wholesome water supply, that is, water that is easily accessible, adequate in quantity, free from contamination, safe and readily available throughout the year. There can be no state of positive health and well-being without safe water (Aderibigbe, et al, 2008). Man needs water for drinking, cooking, bathing, sewage disposal, irrigation for agriculture, industrial uses and for recreational purposes amongst many other uses. A study in 1990 estimated that more than 1 billion people in developing countries lacked access to safe drinking water (WHO, 1995). Washing hands after defaecation and before
preparing food is of particular importance in reducing disease transmission, but without abundant water in or near homes, hygiene becomes difficult or impossible (Park, 2002; Aderibigbe, et al, 2008).

Many cities and municipalities are facing steady population increases and community growth which, as a result, exerts greater strain on these cities’ resources. Inevitably, urban infrastructure has had to compensate for this growth and accommodate for the needs of the community (Cross et al, 2007). Affordable municipal water strategies are necessary to meet the growing urban demand. Some of these strategies include large-scale projects that involve pumping water through a series of pipelines spanning large tracts of land and requiring an extensive infrastructure of reservoirs and pumping stations. Indeed, siting the route of a pipeline is a crucial component that will later influence its design, construction and maintenance which will then determine some of the environmental impacts (Marshall and Ruben, 1983). Cross et al (2007) noted that it is important that these environmental consequences of pipeline construction are clearly defined and understood to better assess the effectiveness and drawbacks of its construction.

The Obafemi Awolowo University (OAU) is a community faced with the same water distribution problem as any urban centre. The population of both staff and students in OAU Ile-Ife have increased over time but the facilities for water distribution remain as it were. The population of both staff and students has increased from about 11,000 in 1976 to over 16,000 in 1982 and to over 36,000 in 2010 excluding other users who directly or indirectly offer services on the campus.

A consistent water shortage which has been observed by university community members in the recent past is due to insufficient and poorly-located infrastructures in terms of pipelines and pumping stations. This evolved question such as: How is the existing water distribution pipeline network in OAU? What are the major problems facing the pipeline network? Is the existing network meeting the population demand? How best can the water distribution network be piped? One identifiable factor of irregular water flow to different demand points on campus is the current pipeline route network, which was designed manually then. The present planning and practice for pipeline system is time consuming and laborious. The recent available technology of GIS has been found to be helpful in pipeline route selection for efficient water distribution. Since the current pipeline was laid over 48 years ago coupled with increasing water demand as a result of increased population, there is a need for an upgrade of the pipeline network and thus a better route selection that will ensure regular and uninterrupted supply to all demand points is required.

For pipeline route siting, GIS is used since it is capable of organizing and objectively selecting the most suitable route based on innumerable sets of data (Luettinger and Clark, 2005). Manual pipeline route planning uses available maps, surveys and experience and is seriously constrained due to lack of updated data and quantitative approach. This is inadequate for complex terrains and long routes. Remote sensing (RS) and GIS method on the contrary uses updated maps from latest RS data, integrates thematic cost (resistance/ impedance) layers in GIS environment and computes all possible routes with associated costs or impedances (Dubey, 2000). This study developed a system that can determine the optimal route for effective water distribution which can help in the monitoring of the route for easy maintenance, repairs and expansion in OAU.

Study Area

In terms of its spatial extent, the Obafemi Awolowo University, Ile-Ife, Osun State, Campus covers over 9,000 hectares of land. The University is divided basically into 3 zones: Residential, Academic and Communal. Topographically, the nature of Ife shows that areas surrounding the university are hilly with many steep slopes ranging from a 6 to 12% incline. Also, conspicuous within the university area are inselbergs which form the highest topographical points on the campus. The general elevation of Ife area is over 240m and drained by Rivers Shasha, Awosun, Amuta and the Opa which bounds the University.
campus along the North East and which the University heavily rely on for its daily water consumption through the Opa Dam project (University of Ife Master Plan, 1981). Figures 1 and 2 shows the study area.

Figure 1. Ile-Ife in its Regional setting

Figure 2. O.A.U. Campus
Theoretical Framework and Literature Review

The theoretical principles of optimal route selection rest on the optimization models such as Location-Allocation Model. Cooper (1963) formulated the location-allocation model, in which the locations of facilities and the allocation of users to facilities are determined simultaneously in such a way that the total travel cost between the users and the facilities is minimized (Ohsawa, Y., 1989). Location-allocation methods provide an approach for analysing the optimality in locational decision as well as efficiency in human spatial behaviour (Ayeni, 1979).

Location-allocation models constitute a class of combinational problems in spatial analysis. Since spatially structured combinational problems could be identified with mathematical systems whose component elements represent the most basic of spatial entities such as points, lines, regions and areas, they (combinational problems) provide a means of understanding and evaluating issues pertaining to, or arising from urban analysis and planning. Combinational problems fall into two general classes. One class deals with network or graph theoretical problems while the other deals with grouping and partitioning problems (Aguda and Ibikunle, 1997). An instance of the former class would be the development of a distributional system for basic utilities such as water, gas and electricity while that of the latter is concerning the location of a group of central facilities. As noted by Aguda and Ibikunle (1997), the common characteristics of the two classes of combinational problems arise from a consideration of efficiency and optimality in the structuring of space.

The general structure of location-allocation methods as defined by Ayeni (1979) is: given the distribution in space of a set of \( n \) points, their weights, a set of \( p \) indivisible centroids or facilities without predetermined locations; and given transportation or shipping costs, the problem is to find location for the \( p \) facilities, the allocation of each point to these facilities and the quantities to be transferred in such a way as to optimize an objective function such as the total costs of operation. According to Ayeni (1979), location-allocation method finds the optimal distribution of activities as well as an efficient system of flows or interactions between supply and demand points. Because of its worth in spatial locational decision, the location-allocation model is well suited to be adapted in the area of route/site selection for community water distribution network as it is the concern of this study.

Pierce et al (1998) in their research asserted that adequate water supply requires engineering the supply and its transmission from one area to another, keeping in mind the environmental effects of water transmission systems. Dubey (2000) in his research determined that the route of least cost between source and destination points is searched iteratively over corridors of narrowing width using network analysis approach. The cost was computed as weighted sum of material cost of pipeline, the construction cost of laying the pipeline and the access cost of approaching the route. Path analysis was used to locally optimize the route, which yields final alignment. The final route which was 51 % longer than the straight-line path had cost implications of just a fraction of percent of the straight-line cost, because the straight line passed over a hilly terrain. Zhang et al (2008) also used GIS techniques to design a system for water supply planning in Ohio.

The factors and variables that influence pipeline route selection

The identification of the factors that influence route mapping is the first step for the pipeline route mapping. Luettinger and Clarke, 2005; Ryan, 2001; Hutson, 2006 in their different studies divided the factors that influences route selection for pipeline in their analysis into two groups, cost and non-cost. Cost issues relate to the actual financial costs of the construction and maintenance of the pipeline. Non-cost issues are those that do not affect the direct cost of the pipeline, but have environmental or social consequences. The cost issues include pipeline length, land use, slope, overburden depth (depth to
bedrock) and river, road and rail line crossings while the non-cost issues include constructability, community and traffic disruptions, environmental concerns and right-of-way issues (Cross et al, 2007).

When selecting the location for a new facility, the goal is to locate it so that it supplies the greatest utility to the public in the most efficient manner possible while minimizing negative impacts to people and the natural environment. It is critical to consider not only how the land is being used by people, but also its natural characteristics. In order to accomplish this goal authorities analyze an abundance of location-based information in an attempt to determine the most suitable site to construct a new facility. GIS provides the means to standardize, automate, and explain the rationale involved in selecting the location of the new facility (Glasgow 2003).

Methodology

Maps, fieldwork and remote sensing techniques are necessary for pipeline routing, pipeline design and construction. The data required for this work was obtained from both primary and secondary sources. The primary data was collected through field observation and the use of GPS to collect the coordinates of features in the study area which was integrated into the GIS environment. The secondary data includes topographic map of 1982, geologic map, Soil map, Land-use and road maps which were used for the route selection process. Also, high resolution satellite imagery, IKONOS of 2010 with 0.6m resolution of the study area was used and analyzed in order to extract relevant geospatial data. A digital elevation model (DEM) was obtained from the topo map and a slope model over the area was derived from the DEM (see figures 3 and 4). The ArcGIS 9 program was used in this study to provide spatial information capturing, analysis, and display capabilities.

Conceptual Data Modelling

This is the representation of a human conceptualization of reality. It is the process of designing the conceptual model of data by examining the relationship between entities and the characteristics of the entities and attributes (Kufoniyi, 1998). The technique in data modelling is Entity-Relationship Diagram (ER Diagram). Figure 5 shows the ER Diagram of a Pipeline-based Information System. Dam supplies water to reservoir and the reservoirs are connected to pipeline while pipeline is laid in the soil, passes through different landuse types, is besides the road, depends on relief and it is affected by geology and water-body.

Pipeline Route Selection

Figure 6 shows a summary of the phases of activities performed in the model-builder for the pipeline route selection. The steps used to produce the best route for a new water pipeline/path are outlined. Using ArcGIS 9 Spatial Analyst Module: Classify the layers participating in the spatial analysis; Create a cost surface; Define starting and end points for each segment of the pipeline; Give standardized values to all the variables identified; Give percentage weight to the factors (see also Table 1); Perform a least-cost pathway analysis (weighted overlay).

Suitability and Least-cost pathway for pipeline route selection

Figure 7 shows the GIS model builder that conducts suitability and least-cost pathway analysis for pipeline route selection which was developed. The model calculated the best path through the landscape from the source (the treatment plant) to the destination point, taking into consideration the slope of the land, the geology, the soils, proximity to roads, the overburden depth and the type of landuse the path will cross.
Figure 3. Digital Elevation Model of Obafemi Awolowo University Ile-Ife

Figure 4. Slope Map (Derived from the DEM)
Figure 5. Entity-Relationship Diagram of a Pipeline-based Information System

Figure 6. Framework of the model (Adapted from Cross et al, 2007)
Weighted Overlay

A cost dataset was created by deciding which datasets are required, reclassifying them to a common measurement scale, weighting them, then combining them. The cost dataset identified the cost of travelling over the landscape from the source point to the destination points. For example, it is difficult to build a pipeline on steep slopes, so slope was calculated to take into consideration the slope of the land. A cost surface was prepared using the above criteria and weights. This cost layer was thereafter used as the basis of a least-cost pathway analysis.

Table 1 shows the multi-criteria evaluation (MCE) that made use of some variables (factors) which were given standardized values on a scale of 1 to 10 with 1 being no additional cost to the route and 10 being the highest additional cost to the route creation. Slope was ranked from 0 to 25 degrees, the different landuse types were scaled, road was ranked from 0 to above 50m from the road. Each dataset i.e. factors were given preferred weights. The weights here are based on the level of influence each has on the route selection as regards suitability. To find the least cost path, a direction dataset was created as an additional dataset from the Cost Distance tool (see also figure 7). A cost path analysis using the distance and direction datasets created from the Cost Distance tool was then done.
Pipeline Routing Criteria:

Table 1: Weightings of Factors for MCE

<table>
<thead>
<tr>
<th>Factor</th>
<th>Weight</th>
</tr>
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<tbody>
<tr>
<td>Slope</td>
<td>25%</td>
</tr>
<tr>
<td>Landuse</td>
<td>25%</td>
</tr>
<tr>
<td>Road</td>
<td>10%</td>
</tr>
<tr>
<td>Geology</td>
<td>15%</td>
</tr>
<tr>
<td>Overburden</td>
<td>15%</td>
</tr>
<tr>
<td>Soils</td>
<td>10%</td>
</tr>
</tbody>
</table>

* MCE Multi-Criteria Evaluation
Source: Authors’ work

Though these weights are subjective, they are based on the level of influence each factor has on the overall site and as obtained from literature such as ESRI Desktop Help and Cross et al (2007).

Results and Discussion

The existing pipeline network map (figure 8) was derived from three different scanned paper works collected from the Water Engineering Unit of the OAU, georeferenced, digitized and merged using the base map (topographic map) of the study area. The map revealed that the campus is yet to be fully covered.

Least Cost Pathway for Pipelines

A least-cost pathway analysis was performed to find the most efficient path for each segment. The least-cost pathway was conducted in four segments: the first segment runs from the treatment plant cum pumping station to the reservoir B (segment A – B) while the second segment is between the treatment plant cum pumping station and the valve junction (segment A – C). The valve junction is a point taken on the route for easy access and dissemination to other points. The third segment extends from the valve junction to reservoir A (segment C – D) and the fourth segment runs between the valve junction and the proposed reservoir which in this content is referred to as reservoir C (segment C– E). A combination of all the segments is as shown in figure 9.

Network Analysis
Network Analysis was also performed using GIS software. In order to determine and map the optimal pipeline route for water distribution, the Utility Network Analyst in ArcMap 9.3 was used.

“Find Path” of each of the reservoirs and pumping station was done to obtain the optimal pipeline distribution route from the reservoirs to the demand points (Figure 10).
Figure 8. Existing Pipeline Network Map

Figure 9. Least-cost Pathway for Pipeline to the Reservoirs
Figure 10. The optimal pipeline route for water distribution

Figure 11 shows the water pipeline distribution network in its entirety as was planned and mapped from this study comprising the main pipeline route taking the water from the treatment plant cum pumping station to the reservoirs and the other pipelines leading from the various reservoirs to the demand points. It is the complete water distribution network consisting of the pipelines, the reservoirs and treatment plant and pumping station.

Figure 11. The entire optimal pipeline route for water distribution
Conclusion

A GIS-Based pipeline route mapping for water distribution has been developed for Obafemi Awolowo University campus in this study. The planning and construction of the water distribution systems are ways to help alleviate water shortages experienced by the University Community. Pipelines and similar large scale water projects undertaken are rarely vetted through a process of environmental or social impact assessment. But this study, by incorporating both the environmental and traditional sets of criteria an optimal route was achieved using GIS. The databases generated both spatial and non spatial information which will be useful in managing the pipeline routing and water distribution through integration with Geographic Information Systems. To this end, the uses of remote sensing and GIS for planning need to be encouraged. In the database or attribute tables generated, information like length, type and uses of utilities and facilities are stored and this information can be retrieved and updated at any time needed.

Recommendation

It has been shown from the study that remote sensing and GIS are adequate and suitable for planning and mapping of water distribution routes. Safer and cheaper pipeline transportation of water resources is a major concern for the public and the Government. Having built a database that includes topography, geology and landuse from available maps and satellite imagery for the study area, additional data can also be incorporated to modify the model. So, this model should be implemented in developing our water resources and distribution system. Since the world is not stagnant and development occurs regularly, basic utilities should be checked and upgraded regularly for effective coverage.

Through the utilization of various factors, a Multi-Criteria Evaluation and a Least-cost Pathway were generated for the route in this study. A multi-criteria evaluation is essential in utility planning therefore its use should be encouraged.

References


