Determination of an Optimal Trunk Sewer-line Route for Kikuyu Town Using Geospatial Technologies

Stephen Kamau Wanjama[1]

Patroba Achola Odera[2]

Abstract

Sewage management is important in the development of an area. The method used should be cost effective and environmentally friendly. Traditional methods used for sewage collection in Kikuyu Town include insanitary pit latrines (used by households) and septic tanks (mostly used by industries and institutions to cater for the large volumes of sewage). The best alternative is a sewerage system that uses sewer-lines to convey sewage into a treatment works. This project seeks to replace the traditional methods currently used in Kikuyu Town with a sewerage system. Geospatial technologies are used to site a treatment plant and the main trunk sewer-line route in Kikuyu Town. A comprehensive methodology that incorporates environmental factors is adopted. These factors are weighted using the Analytic Hierarchy Process (AHP). The most crucial factor considered in this research from weighting is slope, as the sewer line is designed to flow by gravity. The objective is to have the sewer-line on sloping terrain from high to low elevation areas, where the treatment works is located. ArcGIS is used to analyse these factors to determine a feasible route for the main trunk sewer-line. This produce an optimal route that avoids forest cover and water bodies. Road crossings and rail crossings are also minimised. The proposed route utilises the existing road reserves, which help in minimising the costs while also reducing disputes that may arise due to acquisition of private land.

Key words: Trunk sewer-line, sewage, sewage treatment plant, Analytic Hierarchy Process, Geospatial technologies, Kikuyu Town

[1]Department of Geomatic Engineering and Geospatial Information Systems (GEGIS), Jomo Kenyatta University of Agriculture and Technology [2]Division of Geomatics, School of Architecture, Planning and Geomatics, University of Cape Town, Cape Town, South Africa.

Corresponding Author: patroba.odera@uct.ac.za

Introduction

A sewerage system collects wastewater and solid-waste (sewage) from households, factories and industries and conveys it using sewer pipes to a treatment works where it is treated and released back into nearby water bodies. The design of a sewerage system should ensure a comprehensive treatment of wastewater according to the limits allowable by the National Environment Management Authority (NEMA) in Kenya, the standards of the World Health Organization (WHO) and the guidelines of the World Bank Environmental Health and Safety, before releasing it into the river (Kamau, 2012). It comprises collection points of sewage from buildings, which is conveyed by sewer lines that release the waste into a sewage treatment plant.

Sewer lines are grouped into four main categories: building, lateral, branch and trunk. Building sewer lines convey sewage from buildings and drain it into the lateral sewer lines; branch sewer lines collect sewage from lateral sewer lines and drain it into the trunk sewer lines. A trunk sewer line is the main sewer line from the start node to the end node at the treatment works. Manholes are situated at every node where two sewer lines connect. They are provided for cleaning, maintenance, and repair purposes at the head of the sewer line, at the sewer line junction, at points where there is a change in sewer pipe size, slope or alignment, and at the specified intervals along a straight sewer line reach (Nagoshe *et al.*, 2014).

A sewerage system is normally designed to facilitate sewage flow by gravity to avoid prohibitive cost. Treatment works are designed at low elevation areas with generally flat terrain. A sewerage system is a better replacement for the traditional methods such as pit-latrines and septic tanks. With the rapid population growth, traditional methods of sewage collection are proving to be inefficient, hence the need for a sewerage system.

The inefficient and traditional techniques of optimal sewer-line location are based on expensive and protracted methods. These methods utilise static paper maps, which are huge and bulky. Furthermore, they are not precise and the role of all effective parameters in sewer-line location cannot be easily considered. Technical, economic and environmental concerns cannot be satisfactorily addressed using the traditional planning methods. This has in turn necessitated the search for new technological methods which consider a wide set of parameters to alleviate the limitations of traditional methods, resulting in the optimal route which is cost-effective and environmentally friendly (Abuga & Mundia, 2015).

Kikuyu Town (Figure 1) is one of the rapidly growing towns in Kenya. With the completion of the Southern By-pass, the population is set to grow even higher. Due to this, the existing methods of handling wastewater, including solid-waste by use of pit-latrines and septic tanks in Kikuyu Town, are proving inefficient. The steep rise in population has led to much pressure on the system, forcing wastewater to be drained into nearby water sources, which can lead to pollution of ground water and surface water bodies. Pit-latrines are poorly maintained, with some overflowing, and this poses a huge environmental risk in the form of soil and water pollution. The walls of pit-latrines are not well constructed, hence there is seepage into the soil which eventually leads to groundwater contamination. Such latrines are also insanitary due to the foul smell they produce by acting as breeding grounds for flies, leading to possible outbreak(s) of diseases.

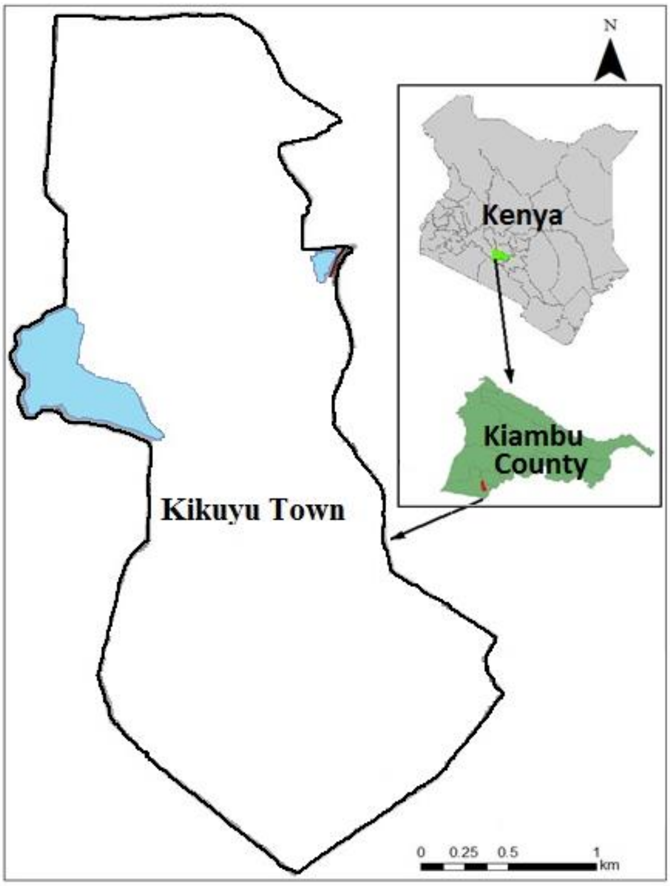

Figure 1: Study area (location of Kikuyu Town within Kiambu County is shown by the red colour)

Septic tanks pose almost similar challenges though they have less impact than pit-latrines. However, with industries using them, the effluents in these septic tanks are very harmful to the soil and upon seepage, they can contaminate ground water. The collection of sewage from these septic tanks by use of collection trucks, which are not well equipped, is another challenge with using these methods. The stench that the sewage emits during collection, coupled with leakages, pose an environmental hazard.

The use of geospatial technologies to determine optimal routes in engineering projects has been studied by several authors, e.g. Cheng & Chang, 2001(general utility route); Gipps *et al.*, 2001 (transport route); Balogun *et al.*, 2012 (oil pipeline route); Macharia & Mundia, 2014 (oil pipeline route); Abuga & Mundia, 2015 (sewage management system and sewer-line extension); Kathuo & Mubea, 2016 (water utility route). Some of the factors considered for determining the optimal route for oil pipeline, sewer-line extension and water utility are applicable in the design of a new sewer-line route, though with different weightages. This paper determines an optimal trunk sewer-line route in Kikuyu Town using geospatial technologies. This is achieved through a detailed mapping of Kikuyu Town followed by the application of a multi-criterion decision making process.

Materials and Methods

Data

A number of data sets have been considered in this study (Table 1). They include satellite image, digital elevation model (DEM), geology, soil, population and land parcels (obtained from cadastral maps). A satellite image is used to obtain details of the area either through image classification or digitization. Google earth image has also been used in this study for detail mapping. The Digital Elevation Model (DEM) provides a 3D representation of the topography. The shuttle radar topography mission (SRTM) of 30 m spatial resolution has been used in the current study. Soil data provides information about soil types in study. However, this factor (soil) is not critical in the current study because the area of study is wholly clayey.

Table 1: Data sets

Data Type	Description	Source
Satellite Image	Google earth image	Google earth application
DEM	SRTM (TIFF)	USGS Website
Geology	Rock Structure	ILRI
Soil Data	Soil type	ILRI
Population	1989, 1999 and 2009 Census	KNBS
Land Parcels	Registry Index Maps (Scanned Maps)	Survey of Kenya

Data on water supply network and electric power-lines was also used. A water supply network gives information on the underground connection of pipes transporting water from the main supply to households and industries. Underground water pipe network is important, as sewer lines should maintain a safe distance from water pipes in case of any leakage and during construction to avoid interference with the laid pipes. Electric Power Lines refer to the position of poles connecting electric cables. Electric Power Lines are important since construction of sewer lines beneath electric lines is discouraged but they can run parallel to each other.

Determination of an Optimal Sewer-line Route

The following rules were used in the routing process for the various variables. Table 2 shows the rules used in determination of the optimal route.

Table 2: Rules governing establishment of sewer-line route

Variable	Rule	Reason
Road	Route near roads and avoid road crossing	Utilize road reserves to minimize cost
Water Bodies	Route far from water bodies and avoid crossing them	Avoid contamination
Railway	Route near railway line and avoid rail crossing	Utilize rail-way reserve
Slope	Avoid high and low slopes	Enable flow by gravity
Forests	Avoid forested areas	Minimize cutting down of trees
Land Parcels	Route near parcel boundary but not within the parcels	Avoid compensation while having sewer line close to settlement

In accordance with NEMA regulations on environmental factors, the sewer-line route was designed to avoid water bodies and forested regions. Using opinion from engineers, the sewer line route was designed to use road reserves while avoiding private land, which would otherwise require compensation to those affected; compensation would not only slow down the implementation but also increase the implementation costs.

Variable Weighting

Many variables are considered in the determination of an optimal route. Not all these variables are equally important: for example, slope and protected areas have varying levels of importance. Therefore, it is vital that these variables are ranked in order of importance; this could be as simple as ranking from 1-10. However, for complex analysis a more thorough weighting is required. Analytic Hierarchy Process (AHP) is one of the most suitable weighting methods used to rank variables in optimal route determination.

AHP is one of the Multi Criteria Decision making methods that uses a quantitative technique for decision ranking, which involves making alternatives by developing a numerical score to rank each decision alternative based on how well an alternative meets the decision maker's criteria. To make comparisons, a scale of numbers is needed that indicates how many times more important or dominant one element is over another element with respect to the criterion to which they are compared (Saaty, 2008). The study used questionnaires administered to experts in engineering and the environment to determine the weights. Eight variables were considered in the questionnaire (proximity to railway line, proximity to road, proximity to water bodies, protected areas, geological setting, slope, soil type and forest). However, two variables (geological setting and soil type), were removed at the weight computation stage, because the entire area has the same soil type and geological setting, due to its small extent. The analysis was performed using Euclidean distance, cost path and weighted overlay tools in ArcGIS.

Sewage Treatment Plant

The start node was selected at an elevation of 2,011 m. This was a high elevation point to enable flow of sewage down to the treatment works. It was also determined to be close to a road reserve (Southern By-pass). The end node was a point selected on the treatment works where the trunk sewer line would drain the sewage. It was at an elevation of 1,889 m, which was the lowest elevation point on the treatment works. Figure 2 shows the location of the proposed treatment works and the start-end nodes.

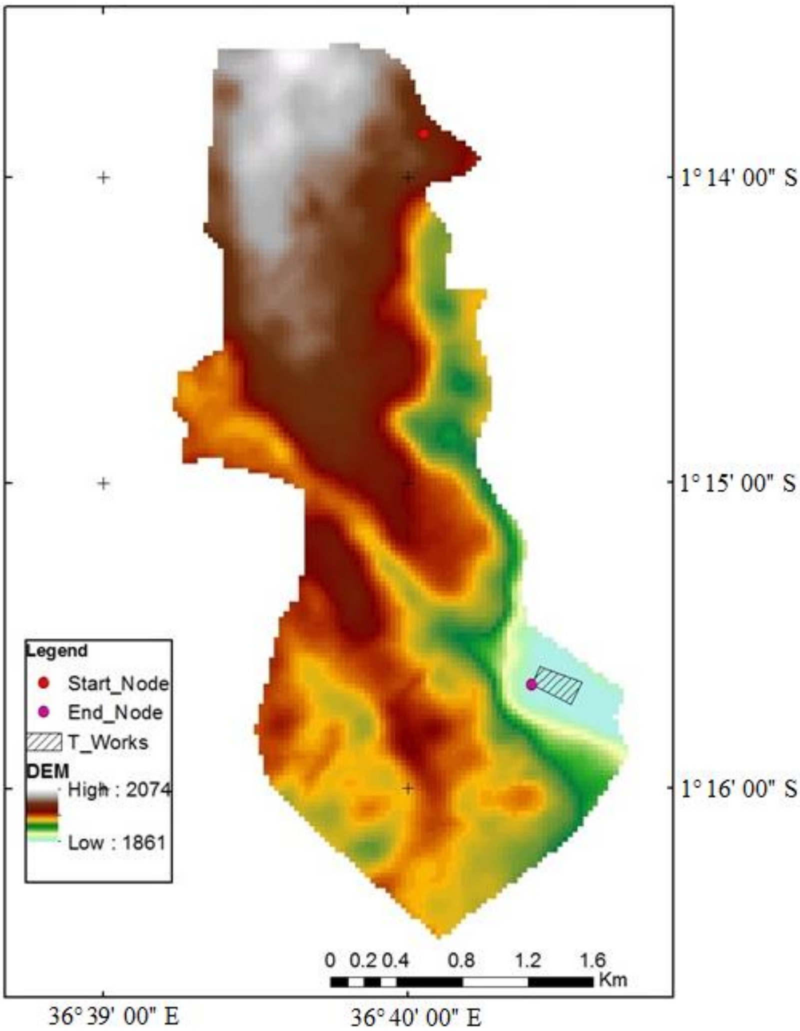

Figure 2: Proposed Treatment Works (Plant) and Nodes (units for elevation are in m)

The location for the treatment plant fulfilled the following conditions: low elevation area (the main trunk sewer line drains its contents into the treatment works, hence it has to be at a lower elevation); fairly flat slope (the proposed treatment works was located on a generally flat area to enable the slow movement of sewage as it undergoes treatment in the various ponds); proximity to a nearby water body (the proposed treatment works was located near the Nairobi river which would allow release of treated wastewater).

Results and Discussion

Optimal trunk Sewer-line Route

Questionnaires were distributed to experts to obtain the weights for ranking the variables. The questionnaires were processed to produce the weights given in Table 3. The weights obtained indicate that slope and proximity to railway-line are the most and least crucial factors respectively (among the tested variables) in the determination of the location of a trunk sewer-line.

Table 3: Weights of Variable

Variable	% Weight	Weight (scale of 0-1)
Proximity to roads	28	0.28
Proximity to rail	3	0.03
Slope	39	0.39
Forest	12	0.12
Protected Areas	8	0.08
Proximity to Water Bodies	10	0.10
Total	100	1

The weights were then used to determine the optimal trunk sewer-line route for Kikuyu Town shown in Figure 3. The length of the route was found to be 3,767.99 m. The route did not cross any water body and provided a safe distance from them, with the closest being at 224.13 m. It passed through highly suitable and suitable slope range, with only about 278.83 m (approx. 6%) passing through less suitable area.

Spatial relationship between the optimal sewer-line route and variables

The distance from water bodies was reclassified into five categories, with a value of five representing unsuitable area assigned to area under water bodies, denoted in red colour during reclassification. A value of one was assigned to the area furthest from the water bodies, representing the most suitable region. This was necessary to avoid crossing water bodies as per NEMA regulations. Figure 4a shows the effect of water bodies on the optimal sewer-line route.

Slope was reclassified, with very high and low slopes assigned high values, representing unsuitable areas. Slope as the most crucial factor in the analysis was assigned the highest weight. The optimal route passed through highly suitable and suitable slope range, with only about 278.83m passing through less suitable area. Figure 4b shows the effect of slope on the optimal route. From the DEM (Figure 5a), it is evident that the optimal route slopes gently, from high elevation areas to the low elevation areas, which would enable flow by gravity. Figure 5a shows the optimal sewer-line route overlaid on the Digital Elevation Model (DEM).

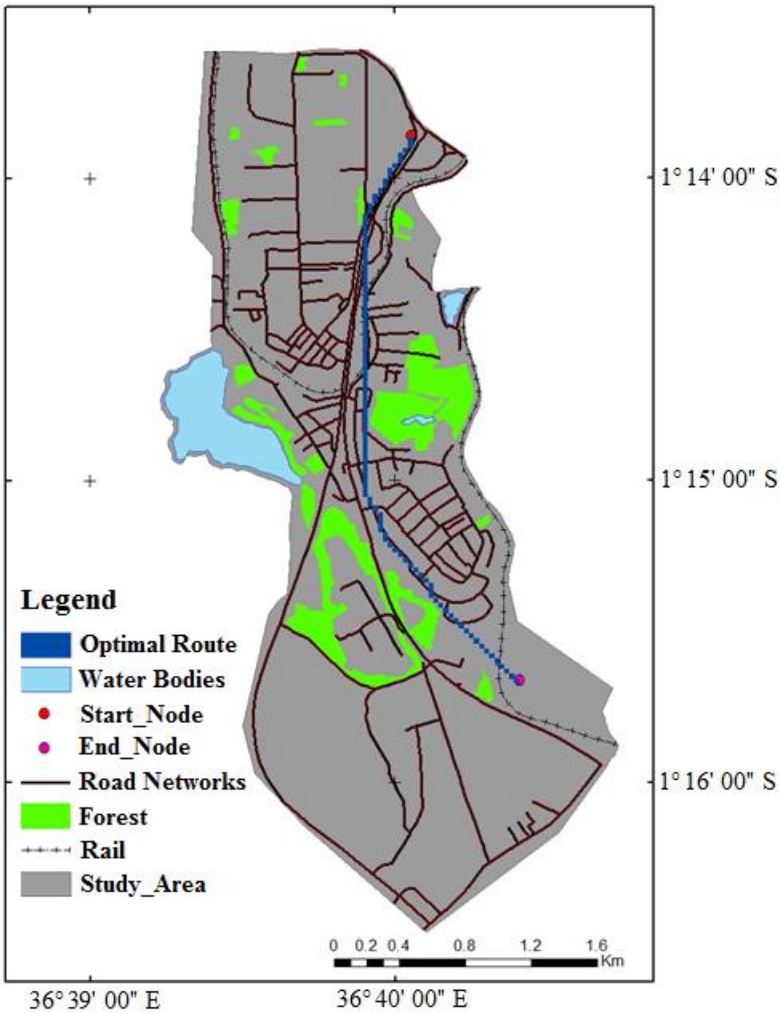

Figure 3: Optimal sewer-line route overlaid over the map of the area

Area under roads was assigned a value of five, representing unsuitable areas to avoid road crossings. A value of one was assigned to areas close to roads to enable utilisation of road reserves. The optimal route utilised road corridors, with the major part utilising the Southern By-pass corridor and other dry weather roads. There were 10 road crossings, with only one being a major road (The Southern By-Pass); the other nine were on unclassified dry weather roads. Figure 5b shows the effect of road network on the optimal trunk sewer-line route.

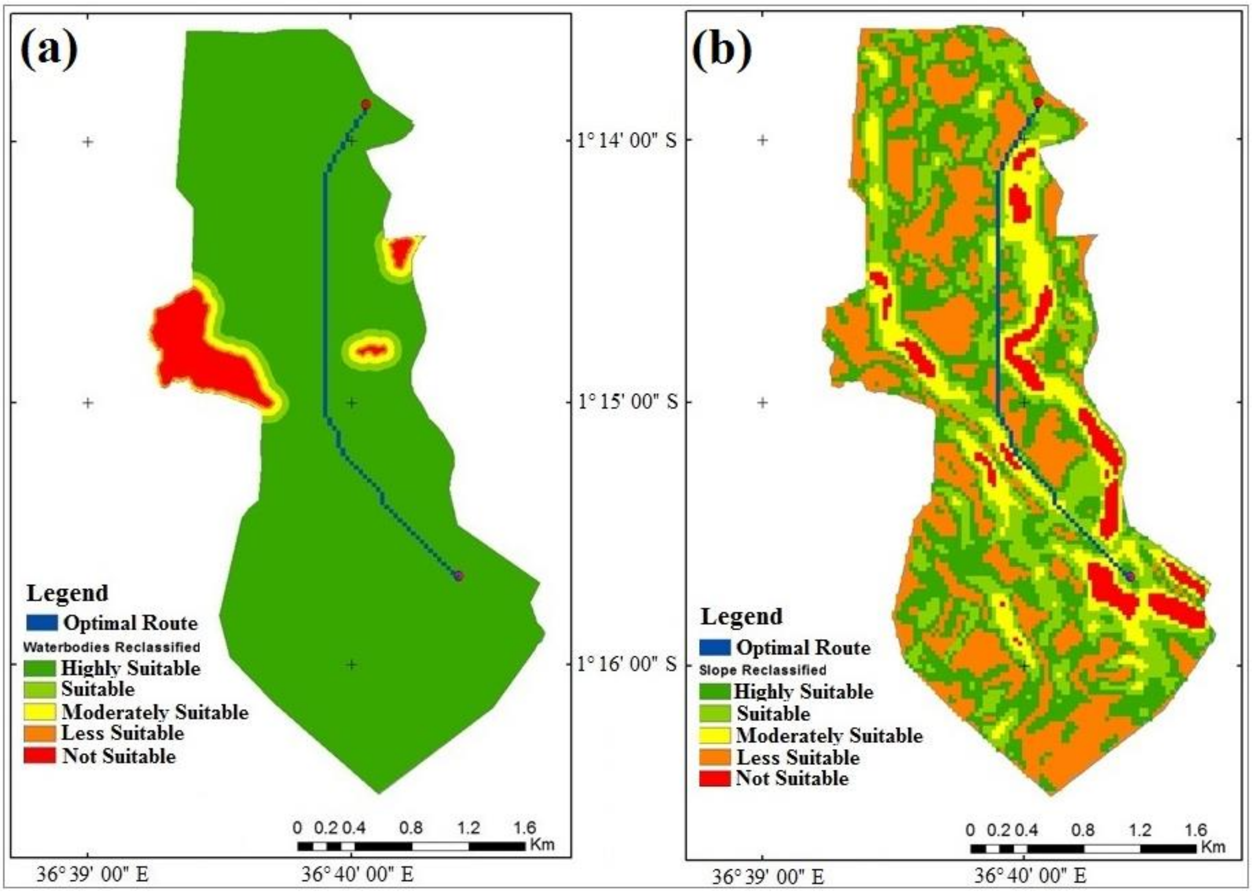

Figure 4: Effects of Water Bodies (**a**), Slope (**b**) on Sewer-line Route

Forests were reclassified into two categories: forested areas and non-forested areas. Forested areas were assigned a value of five, representing unsuitable areas, and non-forested areas a value of two. This was done to avoid forested areas to help protect forest cover in accordance with NEMA regulations. The optimal route avoided forest cover, hence no deforestation is required to accommodate the route. Figure 6a show the effect of forests on the optimal sewer-line route.

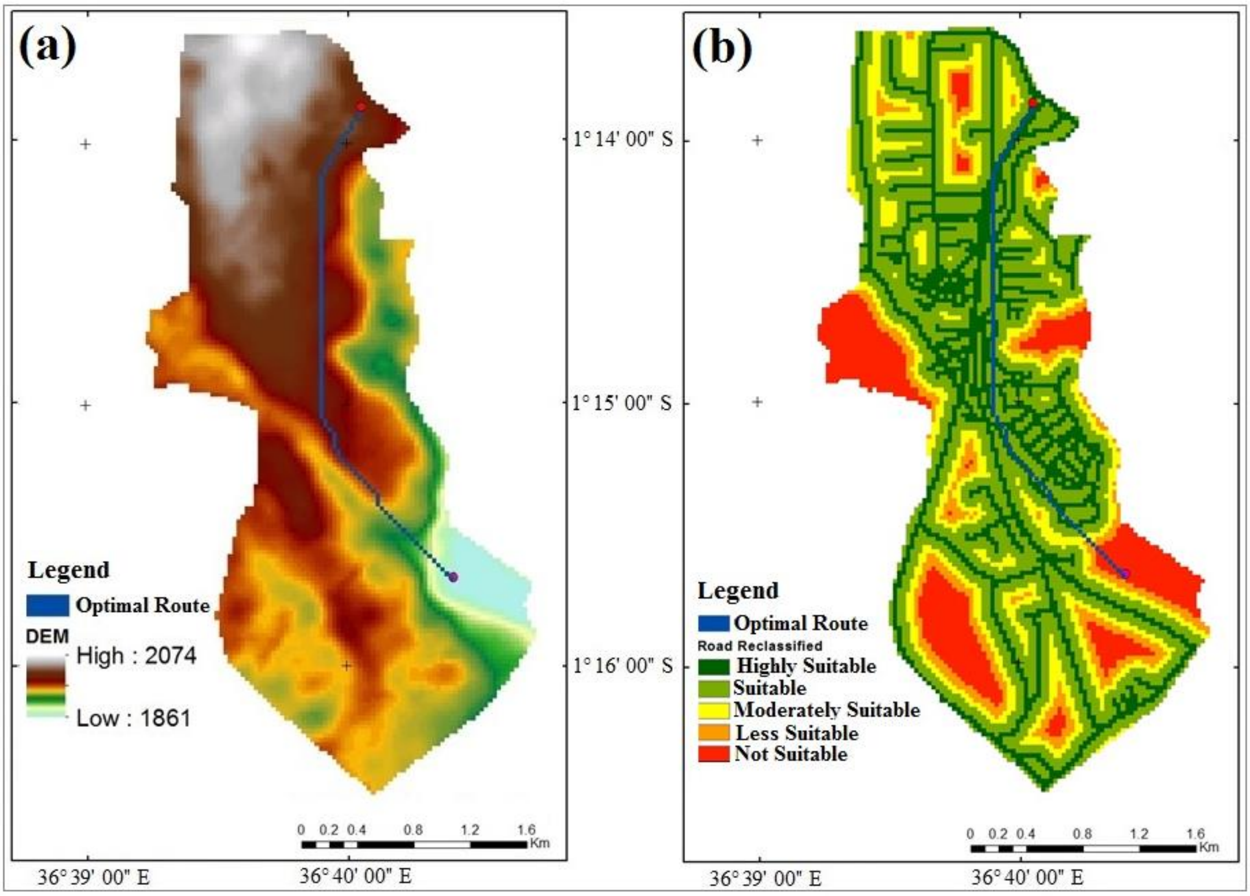

Figure 5: Effects of DEM (**a**) and Roads (**b**) on Sewer-line Route

To avoid the acquisition of private land, the optimal route was proposed to avoid passing through private land. Hence, private land was allocated a value of five, representing unsuitable region, while Euclidean distance from the roads was given value in ascending order. The optimal route did pass through private land; however, this being the main trunk, this could not be avoided, as the route should also pass close to settlements. Figure 6b shows the effect of settlement (land parcel) on the optimal sewer-line route.

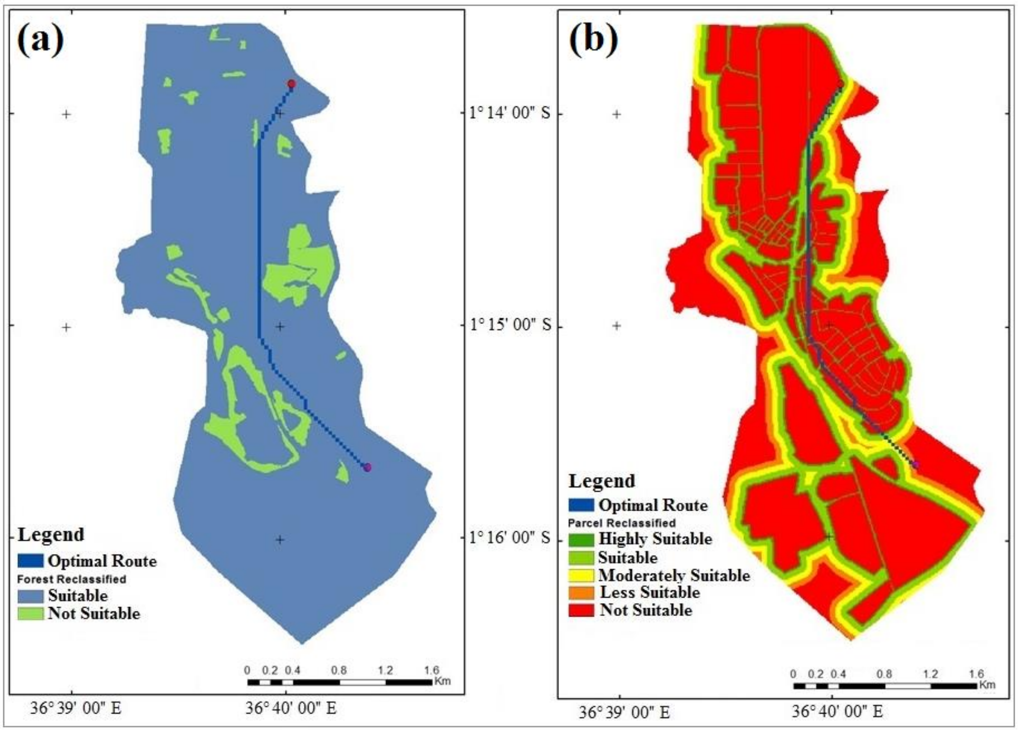

Figure 6: Effects of Forests (**a**) and Settlement (**b**) on Sewer-line Route

Conclusions

The current methods of sewage collection in Kikuyu Town are insanitary and unfriendly to the environment, hence the need to provide an effective and environmentally friendlier method of sewage collection, treatment and disposal. An optimal route for the main trunk sewer-line for Kikuyu town has been proposed using geospatial technologies. Several factors have been integrated in the analysis; slope was given the highest weight, road reserves were effectively used, water bodies and forests were avoided. Registry index maps provided data on the parcel boundary while a geo-referenced Google earth image served as the base map that enabled digitisation of features including roads, forests, water bodies and railway-line. The analysis was performed using Euclidean distance, cost path and weighted overlay tools in ArcGIS. Kikuyu Town will benefit highly from this research, as it proposes a sewerage system to replace the traditional methods of sewage collection. With a feasible site for a treatment plant and a proposed main trunk sewer-line, branch sewer-lines and building sewer-lines can be designed.

Acknowledgements

We are grateful to the Jomo Kenyatta University of Agriculture and Technology for the support granted to us to carry out this research. We appreciate the support granted to us by Mr. Paul

Macharia Kibuthi, Dr. Eng. Mwangi and Mr. Peter Macharia during the execution of the study. We are grateful to the anonymous reviewers for the constructive comments and suggestions that have helped improve the paper.

References

Abuga, H. & Mundia, C.N. (2015). Developing a Sewage Management System for Kisii Town Using GIS and Remote Sensing. Proceedings of 2015 International Conference on Sustainable Research and Innovation, 6-8 May 2015, Kenya School of Monetary Studies, Kenya, 6, 167–176.

Balogun, A-L., Matori, A-N., Lawal, D.W. & Chandio, I. (2012). Optimal Oil Pipeline Route Selection using GIS: Community Participation in Weight derivation and Disaster Mitigation. International Conference on Future Environment and Energy IPCBEE, IACSIT Press, Singapore, 28, 100–104.

Cheng, M-Y. & Chang, G-L. (2001). Automating Utility Route Design and Planning through GIS. Automation in Construction, 10, 507–516.

Gipps, P.G., Gu, K., Held, A. & Barnett, G.B. (2001). New technologies for transport route selection. Transportation Research Part C: Emerging Technologies, 9(2), 135–154.

Kamau J.M. (2012). EIA Report -Construction of sewerage system for Ruiru municipality, Report 2.

Kathuo, P.W. & Mubea, K. (2016). Application of GIS Technologies in Optimal Routes Modelling of Water Utilities to Spur Development. International Journal of Science and Research (IJSR), 5(2), 434–441.

Macharia, P.M. & Mundia, C.N. (2014). GIS Analysis and Spatial Modelling for Optimal Oil Pipeline Route Location. A Case Study of Proposed Isiolo-Nakuru Pipeline Route. Proceedings of 2014 International Conference on Sustainable Research and Innovation, African Institute of Capacity Building, Kenya, 5, 91–94.

Nagoshe S.R., Rai R.K., Kadam K.N. (2014). Optimization of sewerage network by dynamic programming. Proceedings of third IRF International Conference (pp. 120-125), 10 May 2014, Goa, India.

Saaty, T.L. (2008). Decision Making with Analytic Hierarchy Process. International Journal of Services Sciences, 1(1), 83–98.