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An Evaluation of Spatial Network Modeling To Aid Sanitation Planning In Informal Settlements Using Crowd-Sourced Data

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Abstract: Limited water and sanitation infrastructure in rapidly urbanising informal settlements can present significant health and environmental risks to the populations of developing nations. Where formal piped networks are not available, road-based sewage treatment-transportation options have been cited as a viable alternative. However, little research has been undertaken to evaluate the long-term operational costs of such systems. In this paper we present an evaluation of network modelling, as a novel method to evaluate the costs of road-based sewage treatment-transport options. Such analysis is made possible using crowd-sourced, open geospatial data sets that allow us to examine costs based on different spatio-topological network configurations. It is envisaged that engineers could use such a tool as part of the sanitation planning process, to evaluate sanitation network implementation options. This study provides an evaluation of the methods using a case study from the Kibera settlement in Kenya.

Key words: Sanitation; Infrastructure; Spatial Analysis; Networks.

I. Introduction

In many developing nations a lack of sanitation infrastructure results in significant risks to public health through unsafe collection and treatment of sewage before discharge[1,2]. This is often exacerbated in rapidly urbanising and informal settlements, which have limited access to formal water and sanitation services[3]. For example, Banerjee and Morella state that only half of Africa's large cities have sewerage networks[4]. Where formal piped networks are not available, the only option for collection and transportation of waste is via the road network, a process that is often undertaken manually[5], as infrastructure constraints of informal

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settlements mean that motorised collection and emptying vehicles are often unable to access toilet facilities[5].

In response to this, the United Nations HABITAT programme has developed the 'Vacutug', a small motorised vacuum pump truck specifically designed to meet the infrastructure challenges of developing nations [6]. However, a major barrier to the successful implementation of road-based sanitation schemes is the operational and maintenance costs associated with sewage transportation vehicles[6,7]. This is especially the case with Vacutugs due to their limited capacity (0.5 m3) and speed (5 Km/h)[6]. A potential solution to decrease costs is to employ an intermediate transfer station for waste, located at the boundary of a settlement, where Vacutugs deposit waste and from which large tanker trucks can collect and transport sewage the remaining distance to a treatment plant over the main road network[5,6].

With respect to these issues we propose that when planning a road-based sewage sanitation scheme, spatial network analysis be used to optimise the location of transfer stations, in order to minimise associated costs of sewage transportation. However, whilst in developed nations network analysis can be performed within a Geographical Information System (GIS) using formal spatial data (e.g. topographic survey), in developing nations the utility of such techniques is restricted by the limited availability of spatial data. One solution is to use crowd-sourced maps which provide an alternative to nonexistent or incomplete formal spatial data sources[8–10]. Created by volunteers using GPS data, aerial photos and existing paper maps, crowd-sourced maps have been successfully developed in a number of developing nations and used for community engagement[9], urban planning[11], and disaster response[12]. Crucially, the information provided by these maps is playing an increasingly important role in the lives and livelihoods of many inhabitants of developing urban regions worldwide[13]. In these regions, crowd-sourced spatial data-sources have been cited as being more current, complete, and reliable the traditional formal sources of data[9,12]. The Map Kibera project is an example of one such scheme where members of a developing urban community, working with OpenStreetMap (OSM), for the first time created a free and open, highly-detailed map of the informal settlement of Kibera (Nairobi, Kenya). The data collected includes land cover, the road/footpath network, and the location of amenities such as water taps, toilets, and health clinics[13,9,11].

As such, crowd-sourced spatial data present a viable alternative to traditional formal data-sources, with which to perform road network analysis in developing urban regions. This study presents an evaluation of the utility of spatial network modelling for improved sanitation using crowd-sourced spatial data. A simple model representing a road-based sewage treatment-transportation system which could be implemented to manage waste from Kibera's public toilets was created[5,6] and used to identify the optimum location and number of transfer stations around Kibera to minimise sewage transportation time across the network.

II. **Methods**

Kibera is an informal settlement located 5 Km south west of the centre of Nairobi, Kenya, and spans an area of more than 550 acres[9]. Sanitation provision for Kibera's 200,000 residents is poor, with little or no formal sewage infrastructure[14]. Where they exist, toilet facilities are shared and data from the Map Kibera project show 158 public toilets within the Kibera boundary. For the purpose of this study we use a hypothetical road-based improved sanitation scheme using a Vacutug and transfer station system to manage waste from Kibera's public toilets[5,6]. The Dandora treatment plant was selected as a potential end-point for treatment of Kibera's sewage. Dandora is Nairobi's largest treatment plant and is situated

approximately 20 Km east of the city centre[15]. Dandora is a lagoon-based plant with a daily treatment capacity of 80,000 m3, which is discharged as partially treated effluent to the Nairobi river system[15].

Road, footpath, and land cover data were extracted from OSM data for Nairobi and Kibera. The Kibera boundary and locations of public toilets were obtained from the Map Kibera project[9], and spatial database tables representing each of the extracted data sets were created. A number of pre-processing steps were undertaken before creation of the road network model for analysis. First a Boolean multicriteria evaluation was used to identify areas suitable for transfer stations at the Kibera-Nairobi boundary. Based on descriptions of existing transfer stations from the literature[5,6,14], suitable land areas were selected if; they were free of existing development, had an area greater than 64 m^2, were within 50 metres of the Kibera boundary and were within 5 metres of a road connected to both Kibera and Nairobi. This ensured that the Vacutug journey distances were minimised and that there was suitable access for both Vacutugs into Kibera and large tanker trucks to Nairobi. The centroids of areas identified as suitable for transfer stations were used to represent transfer station nodes in the network model.

The second pre-processing step was to calculate travel time for each road in the network so that shortest path calculations of routes could account for both distance and vehicle speed[16]. The lengths of each road were based on their geometric length as derived from the OSM data. For all roads inside Kibera road speeds were set to 5 Km/h based on maximum Vacutug velocity[5]. Road speeds in Nairobi were set to 25 Km/h based on averages recorded during an empirical study for the International Vehicle Emissions Model[17]. The time to travel each road segment was then calculated using road length and seed.

After pre-processing a spatio-topological model of the sanitation road network was constructed using the spatial database schema and coupled Python interface to the NetworkX graph analysis package, developed by Newcastle University[18]. The complete road network model for Kibera and Nairobi consisted of 19,558 edges covering 4,686,483 Km of road, and 16,347 nodes representing road junctions, toilets, the transfer stations, and the treatment plant.

To minimise transport time and so minimise sewage transportation costs, the network model was used to identify the transfer station which represented the total minimum time required for sewage transportation. Total sewage transportation time was defined as the time taken to transport one Vacutug load of sewage from each toilet in Kibera to a transfer station and then the transportation by large tanker of the accumulated waste from transfer station to the Dandora treatment plant. To achieve this, the sum of the journey time over the shortest paths from each of the toilets in Kibera to a transfer station, plus the travel time from transfer station to treatment plant was computed. The shortest path between network locations was calculated using Dijkstra's algorithm and the transfer station with minimum total time was identified as the most efficient (Equation 1).

$$t_j = \min \left(\left(\sum_{i=1}^{n} d_{ij} \right) + d_{jk} i_n \frac{c_{lt}}{c_{vt}} \forall_j \right)$$

Equation 1. Calculating the station with the minimum total sewage transportation time.

In the transportation time calculation the number of large tanker journeys from transfer station to treatment plant was proportional to the capacity ratio between Vacutugs and large

tankers. Given a Vacutug capacity (cvt) of 500 litres and a large tanker capacity (clt) of 10,000 litres[5] it can be seen that for every 20 Vacutug deposits at the transfer station the large tanker must make one journey to the treatment plant. Therefore, the total number of large tanker journeys is this ratio multiplied the number of toilets (Equation 1). Thus, total sewage transport time via each transfer station is the time taken for a Vacutug journey from each of the 158 toilets in Kibera (i) and the 7.9 large tanker trips required from the transfer station (j) to the treatment plant (k).

III. Results

Figure 1 shows the locations of 14 areas of land identified as suitable for transfer stations by the MCE. The spatial distribution of stations around Kibera is uneven, with 11 of the 14 stations lying to the northwest. Two stations lie to the far east of the settlement (one and two) and are closest by straight-line distance to the Dandora treatment plant (~25 Km). One additional station (station three) is situated to the southwest of Kibera. Stations four, five, and six present interesting locations selected by the MCE as they are situated on a road which bisects two segments of Kibera and unlike the other stations are situated in amongst a number of toilets in north-western Kibera, reducing the distances to nearby toilets at these sites.

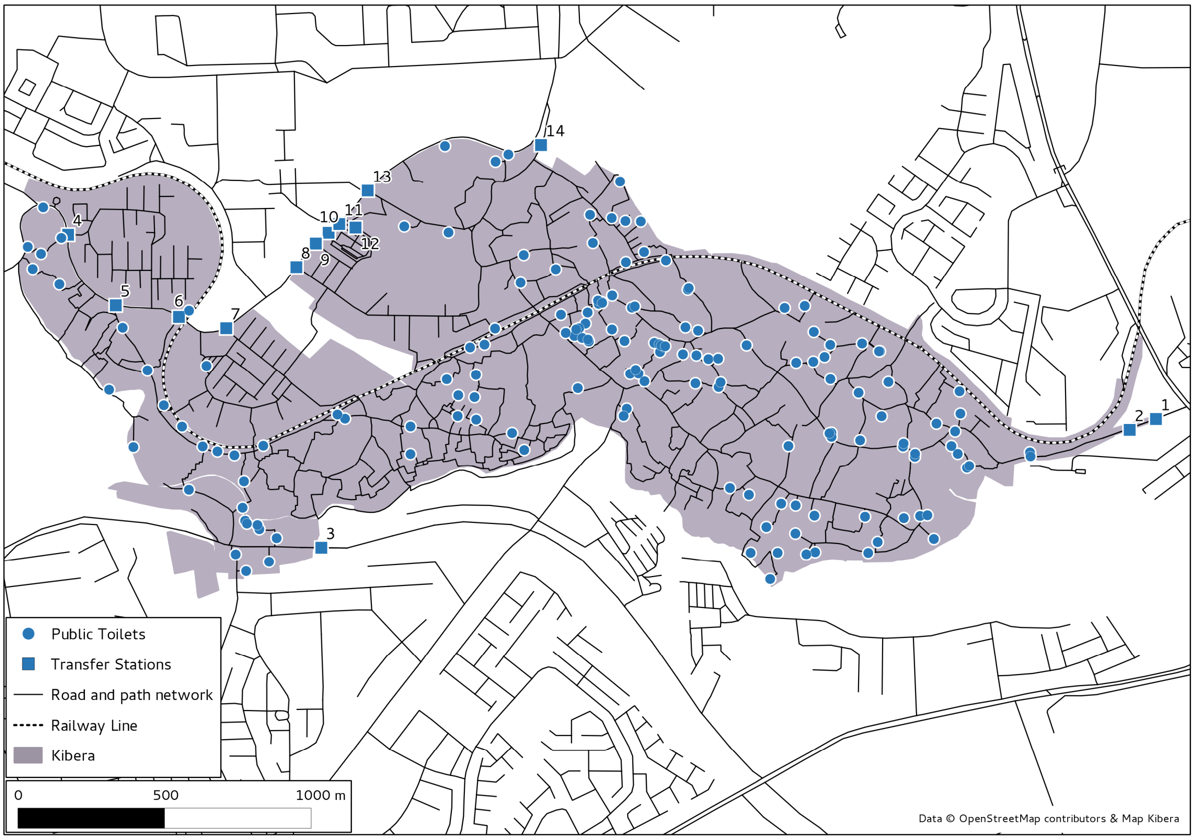

Figure 1. Map showing Kibera settlement, public toilets and locations identified as suitable for transfer stations by the multicriteria evaluation.

Table 1 shows the total sewage transport time for each station from which it can be seen that the total sewage transportation time from station three is 42.39 hours, the minimum value for all stations (Equation 1). Station three represents the location that provides the best balance between overall distance to the treatment plant and total distance for all 158 Vacutug journeys. The total sewage transportation time from station three is 5.51 hours less than that of station 14, the next fastest route, and 13.34 hours less than station four, the least efficient station which is situated at the western end of the settlement. These results are to be expected somewhat as the geography of Kibera shows that the settlement runs broadly east west (Figure 1). This means that station four is not only furthest from the Dandora treatment plant but also from the majority of Kibera's toilets, increasing both its Vacutug and large tanker journey times. In contrast, stations three and 14 (the first and second most efficient station locations) are located more towards the centre of Kibera thus reducing the time for Vacutug journeys to toilets across the settlement from these stations.

However, whilst station three exhibits the lowest overall sewage transport time, the journey time from transfer station to treatment plant (large tanker journey time) is between 1.61 and 0.04 hours slower than the large tanker trip times from the next six fastest transfer stations (Table 1). Additionally, the standard deviation of Vacutug journeys across all stations in Table 1 ($\sigma = 3.03$, $\bar{x} = 40.97$ hours) is almost eight times that of the large tanker journeys ($\sigma = 0.39$, $\bar{x} = 9.92$ hours). As a result the Vacutug journey times have a greater influence on overall station transport time than large tanker journeys. The latter have a low variation due to the lack of ring roads in Nairobi which forces many vehicles traversing the city to pass through the central business district[19], leading to convergence of shortest path route from each transfer station to the treatment works, minimising differences in large tanker journey times.

Table 1. Sewage transport times for each transfer station, based on the first model configuration.

Transfer station	∑ Vacutug time (hours)	Large tanker time (hours)	Total sewage transport time (hours)	Number of large tanker journeys
3	**32.32**	**10.07**	**42.39**	**7.9**
14	37.99	9.91	47.90	7.9
13	39.73	9.92	49.64	7.9
11	40.21	9.97	50.18	7.9
10	40.43	9.99	50.41	7.9
9	40.56	10.00	50.56	7.9
8	40.79	10.03	50.82	7.9
7	41.55	10.13	51.69	7.9
12	41.69	10.04	51.73	7.9
1	43.09	8.96	52.05	7.9
6	42.34	10.19	52.52	7.9
2	43.97	9.08	53.05	7.9
5	43.53	10.26	53.79	7.9
4	45.37	10.36	55.73	7.9

IV. Conclusions

This study has demonstrated the use of network modelling to calculate sewage transportation time over a road-based sanitation network, cited as a solution to poor sewage infrastructure in developing nations[6]. This research was enabled by using crowd-sourced geospatial data, which provided information on the road network and existing sanitation infrastructure within Kibera not previously available[9]. Using the network model it was possible to identify the transfer station location with the minimum sewage transportation time that could be used to reduce costs in a road-based improved sanitation scheme[6].

As populations in informal settlements around the world continue to rise[3] it will become increasingly necessary to evaluate the long term operating costs of improved sanitation options, to provide an economically sustainable method of reducing health and environmental risks. As such, future feasibility studies will need to consider transportation network options for sewage alongside conventional piped networks and in particular, the associated current and future costs of different systems. There is currently limited research about road-based faecal sludge emptying and transportation, and methods to assess its effectiveness[7]. It is envisaged that the network modelling tools and methods presented in this paper will help to improve the knowledge gap related to transport based sanitation services and could be used by engineers as part of the sanitation planning process to optimise the configuration of improved sanitation networks in developing nations.

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List of notation

- t_j is the minimum sewage travel time for station j where station j has the lowest time of any station, using the single station model configuration
- t_m is the total minimum sewage travel time using the multiple station model configuration
- j is the transfer station node
- i is the public toilet node
- k is the treatment plant node
- d_{ij} is the shortest path between toilet node i and transfer station j weighted by time
- d_{jk} is the shortest path between transfer station j and treatment plant k weighted by time
- i_n is the number of toilets serviced by transfer station j
- c_{vt} is the Vacutug capacity
- c_{lt} is the large tanker capacity