GIS-BASED ROUTE OPTIMIZATION FOR FAECAL SLUDGE COLLECTION IN KHULNA CITY CORPORATION

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ABSTRACT

Rapid urbanization in Bangladesh has heightened the challenges of Faecal Sludge Management (FSM), especially in Khulna City Corporation (KCC), where the majority of households rely on on-site sanitation systems. While existing research largely focuses on treatment methods, the present study aimed to optimize faecal sludge collection routes using a GIS-based approach in KCC, thereby reducing the operational fuel costs. This study employed field observations, a questionnaire survey, and the development of route plans from different collection points to the faecal sludge treatment plant (FSTP). The field survey indicates that KCC currently lacks a systematic time schedule or route plan for FS collection. It is also highlighted that faecal sludge collection constitutes a complex logistical challenge, especially in densely populated areas of KCC, where the full cycle from extraction at individual building septic tanks to subsequent routing and transportation requires careful planning. In coordination with the FSTP authority, the study delineated the investigation by selecting nineteen representative collection points via a random sampling technique in the study area. Based on these selected spatial nodes, nineteen distinct collection routes were subsequently subjected to optimization modelling. The final empirical analysis confirmed the efficacy of this optimization strategy, demonstrating a quantifiable operational benefit evidenced by a 9.22% reduction in fuel consumption upon the simulated implementation of the optimized routes. Future research is necessary to expand this framework by collaborating with KCC authorities to develop a sustainable operational plan within the existing infrastructure.

Keywords: *Faecal Sludge Management, GIS, Route Optimization, Urban Sanitation, Sustainable Development*

1. INTRODUCTION

The accelerated pace of urbanization in developing countries has created immense challenges for municipal sanitation systems, especially in the management of faecal sludge generated from the on-site sanitation facilities (Harada et al., 2016). Historically, wastewater management primarily targeted on off-site sewerage systems. However, in recent years, the faecal sludge management has been developed in many cities all over the world especially in developing countries. The access of onsite sanitation has changed and is considered a sustainable long-term sanitation technology that can be applied in urban areas in developing countries that do not have sewerage infrastructure (Dodane et al., 2012). The Faecal Sludge Management (FSM) service chain encompasses three core functional process, containment with on-site facilities followed by emptying and transport into Faecal sludge treatment facilities (FSTF) (Peal et al., 2014). FSM has been applied in many countries throughout Southeast Asia (Anh et al., 2018; Bassan et al., 2013). On-site systems including FSM offer vital privilege in terms of both investment and operational cost, reckoned at only $11.63 per capita annually. This expenditure is five times lower than that of traditional sewerage systems (Dodane et al., 2012). Faecal sludge also shows as a possible material of solid fuel. (Gold et al., 2017; Andriessen et al., 2019).
Khulna is the third largest city in Bangladesh is a substantial industrial and commercial hub situated in the south-western part of the country (Murtaza, 2001; Rana & Ahmed, 2022). This city is located in the Ganges Delta on the low-lying floodplain near the Rupsha and Bhairab rivers (Islam & Kabir, 2025). The Khulna City Corporation (KCC) has veteran swift often spontaneous urban growth due to population pressure and industrialisation (Roy et al., 2018; Alam, 2025). Throughout the history of the KCC there has been a lack of a systematic unified sewer network, which is a crucial environmental challenge (Islam et al., 2014). Most domiciles depend on site infrastructure, mainly septic tanks and ring latrines, with concerns lack of maintenance and effluent overflow, especially in low-income and slum areas (Roy et al., 2020). FSM is actually a complex and sensitive concern in this city because its effective implementation is appraisingly hampered by interconnected economic, environmental and operational constraints that directly impact public health and quality of life (Strande & Brdjanovic, 2014). One of the basic components of FSM is the gathering of sludge at a designated pickup point, followed by transportation to a specific treatment and disposal facility, where the vehicles are unloaded for processing (Strande & Brdjanovic, 2014). Labour costs and fuel prices are the key expense factors in the operation of municipal Faecal Sludge (FS) collection and haulage systems (Doğan & Süleyman, 2003).

The methodology for finding the minimum and most efficient collection routes for FSM is known as route optimization (Ferrão et al., 2024). Geographic Information Systems (GIS) is one of the leading and most thoroughly applied methodical tools for the processing, management and spatial visualization of data (Madhu et al., 2023). Its primary implementation in FSM requires the optimization of collection routes to find out the most efficient service itineraries (Hossain et al., 2016; Tavares et al., 2008). The concern of FSM is not only due to the expanding generation volume, but is analytically amplified by the state of an ineffective and insufficient management infrastructure (Tınmaz & Demir, 2006). The main goal of this research is to identify and propose the optimum route for minimizing the carrying distance of FSM to the disposal facility, and consequently to assess the related fuel consumption for the proposed route.

2. MATERIALS AND METHODS

The empirical data underpinning this investigation were methodically compiled through primary research conducted within the study area. Specifically, primary research data were methodically compiled through a randomized questionnaire survey administered within the study area. The major portion of faecal sludge is collected by FSTP Vacutug and transported to the FSTP of KCC. The following research activities were executed utilizing the ArcGIS Network Analyst tool: a comprehensive situational assessment of the existing FSTP and the overall FSM framework within the study area. The collection of practical data through direct observation and surveys has been explore between the local people, community leaders and relevant organizations. An analysis of the present vehicles transport route and the determination of the optimal collection.

2.1 Study Area

The research area is the city of Khulna, a pivotal administrative and commercial center that situated in the southwest region of Bangladesh along with the Bhairab-Rupsha River, as shown in Figure 1. The city encompasses an area of 45.46 km^2 and supports an estimated population of 1.5 million inhabitants.

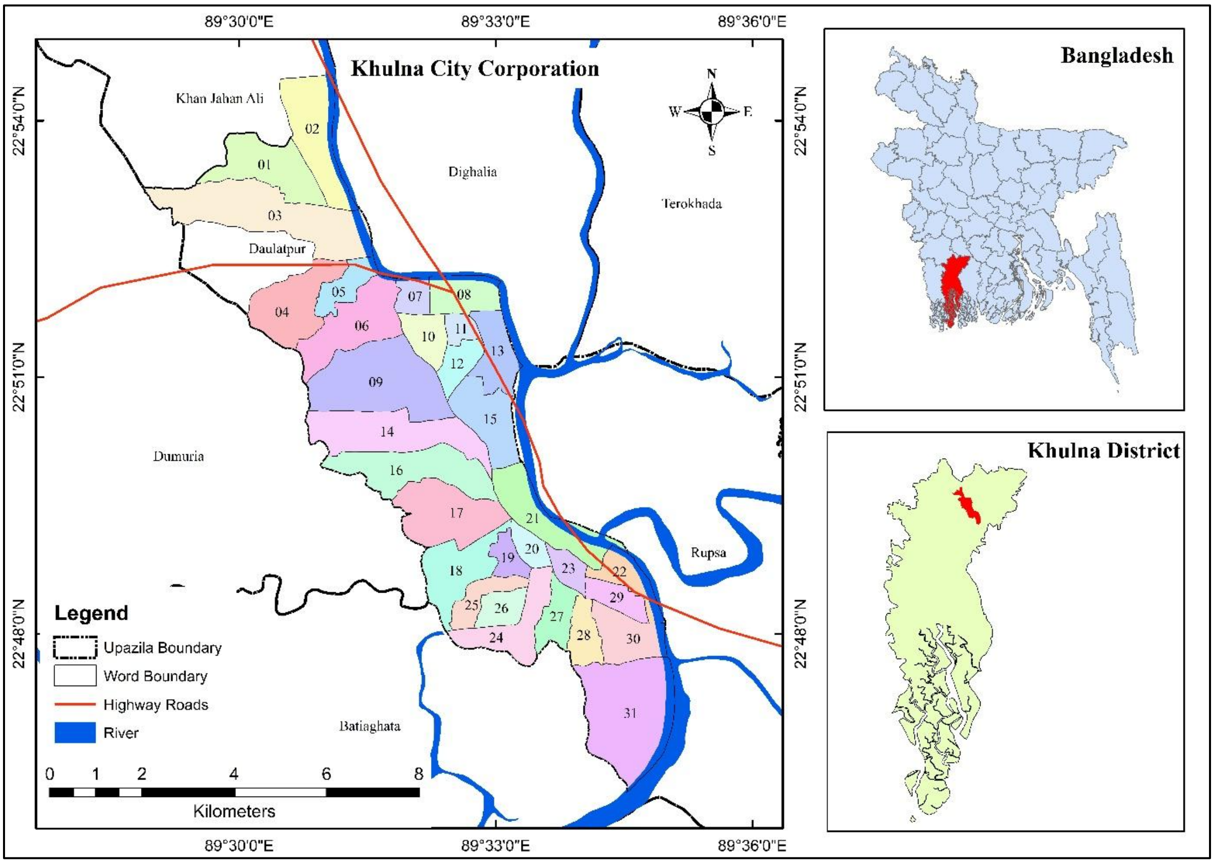

Figure 1: Study area map

The KCC is segmented into 31 wards and is facing the adverse effects of rapid urban expansion. Key challenges include traffic constraints, ineffective waste management, and deficient sewage infrastructure. The extensive road network and high population density make it an exemplary case study for spatial GIS-based planning and network modelling to improve the FSM.

2.2 Field Observation and Questionnaire Survey

The research employed a studious methodological approach to gather the requisite empirical data, beginning with a randomized questionnaire survey (11th August, 2025 to 12th September, 2025) administered to a sample population of 200 citizens to assess local people perceptions and feedback regarding the FSM systems. Concurrently, a field investigation was executed to collect spatial data on the existing FSM infrastructure and operations. Due to constraints (time and funding limitations), a survey of the entire city was not feasible. Therefore, a stratified random sampling technique was applied, ensuring a statistically representative sample by covering the FSTP authority of the KCC. This combination data set forms the foundation for subsequent route optimization modelling and the strategic route development of viable FSM enhancement options.

2.3 Problem Definition and GIS Approach

Let $G = (V, E)$ be a directed graph with vertices $V = \{0, 1, \dots i\}$ and edges $E = \{1, \dots m\}$. The depot is represented by vertex 0, and each remaining vertex i represents a septic tank with a positive demand di. Each edge $e \in E$ has a nonnegative length cij. The vehicle routing problem (VRP) considers of finding routes for K vehicles satisfying the following Vacutug: (i) each septic tank is visited by an only one Vacutug, (ii) each route starts at the depot and returns to the depot, and (iii) the total demand of all septic tank must be answered without exceeding the capacity of Vacutug. The goal is to minimize the sum of the lengths of all routes. An illustration of VRP is presented in Figure 1. There are 21 septic tank and one depot on the left side of Figure 2. The numbers near nodes represent the demands. Optimal five routes are depicted on the rights side of the Figure 2.

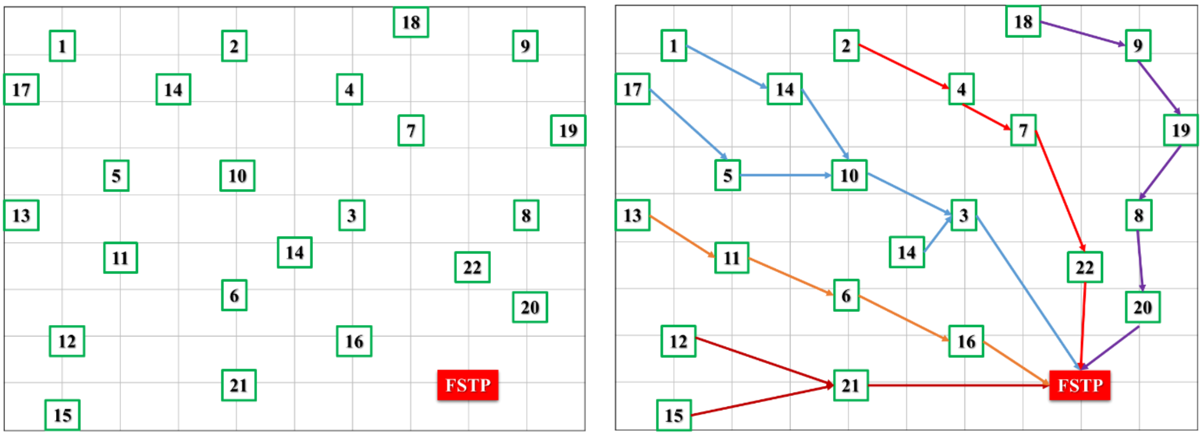

Figure 2: An example of capacitated route with one depot, 21 septic tanks, and 5 Vacutugs

GIS is instrumental in conducting both comprehensive and situational assessments and the forecasting of future spatial trends, capabilities pivotal for strategic long-term solution development. The Network Analyst Tool is one of the tools in ArcGIS software. Under the Network Analyst Tool, a vehicle routing problem VRP analysis finds the best routes for a fleet of vehicles. The VRP was first proposed in 1959 by (Dantzig & Ramser, 1959) and has received close attention from the optimization community since then. The mathematical formulation that is used in this study is described below (Toth & Vigo, 2002).

- Indices

  i, j *nodes*

- Decision variables

  x_{ij} *takes value 1 if edge belongs to optimal solution, & value 0 otherwise,* $\forall i, j \in V$: $i \neq j$

  u_i *additional continuous variable representing the load of the vehicle after visiting customer* i

- Parameters

  c_{ij} *distance/cost between nodes* i *and* j

  Q *vehicle capacity*

  K *number of vehicles*

  V *nodes*

  N_c *customer nodes*

  d_i *demand of customer*

- Objective function

$$Min\ Z = \sum_{(i,j)\in N} x_{ij} c_{ij} \qquad (1)$$

- Constraints

$\sum_{i \in V} x_{ij} = 1 \qquad \forall j \in V_c \qquad (2)$

$\sum_{j \in V} x_{ij} = 1 \qquad \forall i \in V_c \qquad (3)$

$\sum_{i \in V} x_{i0} = K \qquad (4)$

$\sum_{i \in V} x_{0j} = K \qquad (5)$

$u_i - u_j + Qx_{ij} \leq Q - d_i \qquad \forall i, j \in V_c \quad i \neq j \qquad (6)$

$d_i \leq u_i \leq Q \qquad \forall i \in V_c \qquad (7)$

$x_{ij} \in \{0,1\} \qquad \forall i, j \in V_c \qquad (8)$

The VRP consists of finding a collection of simple circuits (corresponding to vehicle routes) with minimum cost, defined as the sum of the costs of the arcs belonging to the circuits (Objective function). The problem in this paper is directed, x_{ij} and x_{ji} may represent the same or different variable. Constraints (2) and (3) (indegree and outdegree of nodes) impose that exactly one edge enters and leaves each vertex associated with a customer, respectively. Analogously, constraints (4) and (5) ensure the degree requirements for the vertex of the depot. Constraints (6) and (7) impose the capacity requirements of VRP while eliminating the sub-tours (Ref). Finally, constraint (8) is the integrality condition.

3. RESULTS AND DISCUSSIONS

3.1 Current FSM in Khulna City

The field survey and secondary data revealed that FS generates approximately 1720 m^3 per day in the KCC, where only 10 m^3 to 15 m^3 are collected per day and treated into the FSTP (Hosna, 2023). This data indicates that a significant number, between 70% and 80% of FS produced is either inadequately managed or uncollected. This untreated sludge is improperly dumped into drains, agricultural land, water bodies, or poorly maintained on-site systems (septic tanks/pit latrines), causing severe public health hazards and Environmental contamination. Due to insufficient collection capacity and monitoring, informal Vacutug are forced to dispose of untreated waste in unauthorized locations. The main sources of FS in Khulna city include residential households (relying mainly on poorly maintained septic tanks and pit latrines), commercial establishments, hospitals and clinics, hotels and restaurants, educational institutions and market. Current transportation facility for solid waste management. The present scenario of transportation of solid waste management is shown in Table 1.

Table 1: Information of Vacutug facility in KCC (Source: KCC records, 2024)

Capacity of Vacutug (Litre)	No. of Vacutug
2000	04
5000	01
7000	01

3.2 Visualization of Septic Tank, FSTP, and Existing Routes

Figure 3 represent the visual representation of the map of the faecal sludge collection routes within the KCC area. The map highlights the geographic distribution of faecal sludge collection points (septic tank locations), which are scattered widely across the northern and eastern portions of the city. The operational endpoint for all collected sludge, the FSTP is on the western side, establishing the primary travel objective for the collection vehicles. The existing route, shown by a thick black line, serves as the baseline for analysis, illustrating the current, often lengthy, path that vehicles must follow to service multiple collection points across various wards before making the long haul back to the FSTP.

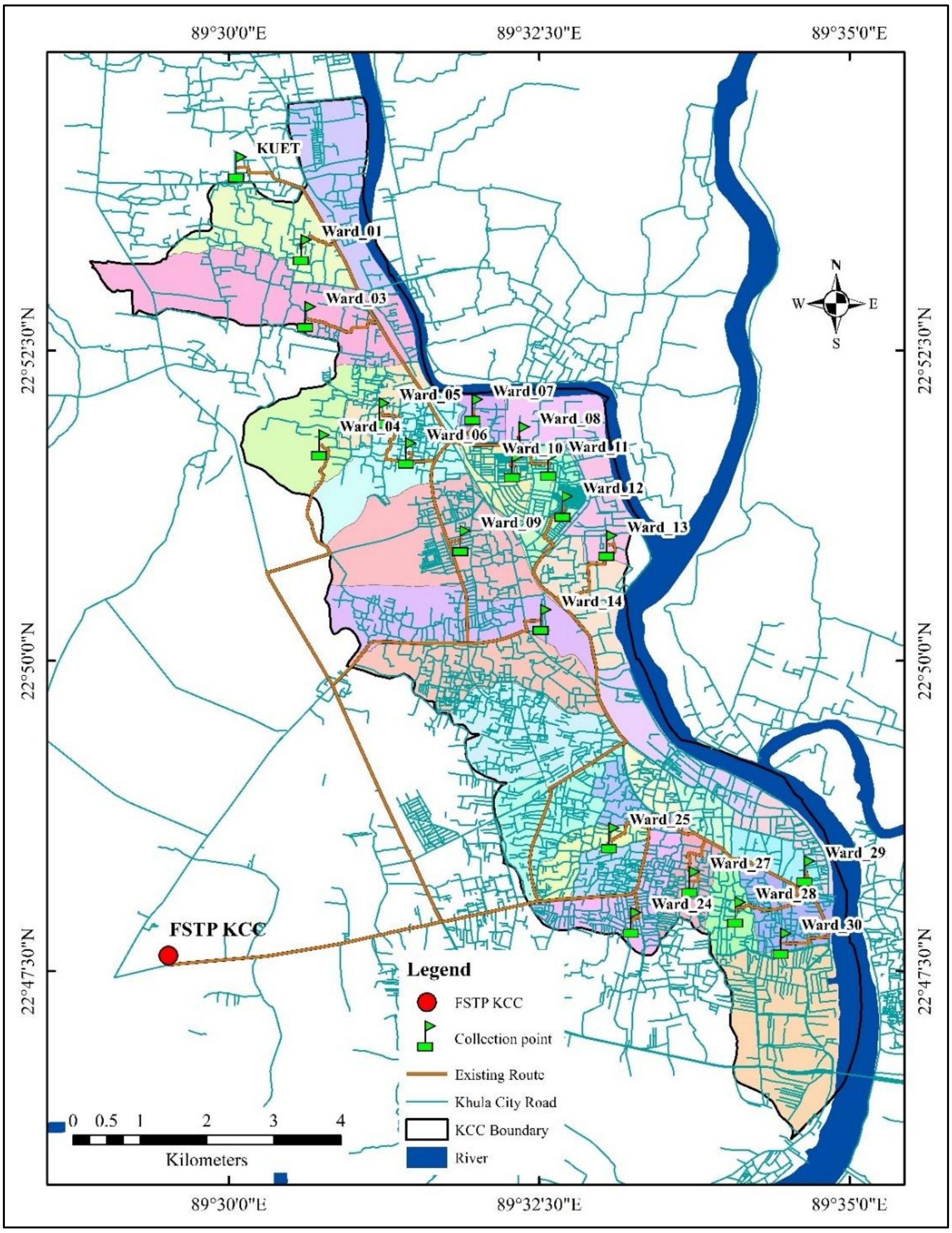

Figure 3: Location of collection point, FSTP, and the existing routes

3.3 Optimized Routes Using GIS

The spatial analysis, executed using the Network Analyst tool in ArcGIS 10.8, successfully generated a series of optimal routes designed to minimize logistical impedance, primarily focusing on travel distance, road condition and static road network constrains. This optimization, which was constrained to ensure the vehicular cycle began at the FSTP garage, collected faecal sludge from all designated septic tank, and concluded at the FSTP, yielded a significantly more efficient operational plan. By prioritizing the optimum travel distance, selecting the least congested road routes, and strategically avoiding densely populated market areas during peak traffic, the model effectively mitigated operational delays and unnecessary fuel burn. Furthermore, the routes-maintained feasibility by strictly adhering to constraints related to vehicle accessibility and road width. The quantitative outcome of this meticulously modelled plan was highly encouraging: the final empirical analysis confirmed that the implementation of these optimized collection routes resulted in a significant reduction in fuel consumption compared to the existing, non-optimized practices, thereby validating the economic and environmental benefits of this GIS-based approach and supporting the proposition of a sustainable and cost-effective operational strategy for the FSM of KCC.

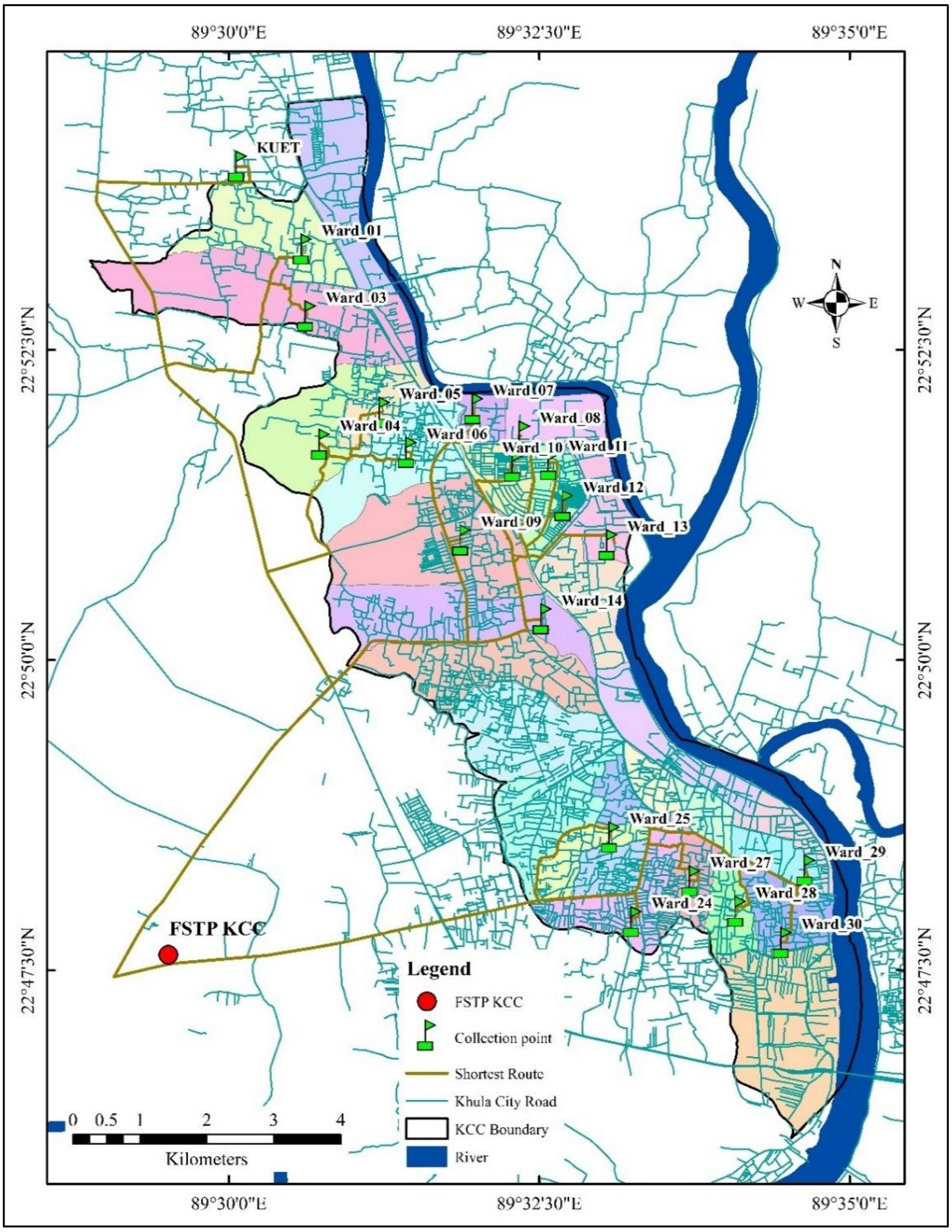

Figure 4: Optimized routes of faecal sludge collection and transportation

3.4 Fuel Calculation for Faecal Sludge Transportation

The financial analysis of the faecal sludge transportation logistics confirmed substantial gains in fuel efficiency and cost-effectiveness through the implementation of the GIS-optimized "Shortest Route". The structural optimization minimized the distance vehicles must travel, reducing the total travel distance from the existing 488.86 km to the optimized 443.80 km (Table 2) for each round trip of these nineteen trips. This distance reduction directly impacted the resource requirements for the KCC, decreasing the required fuel for a round collection trip from 200.42 Liters to 181.96 Liters (Here, 0.44 liter fuel consumption per kilometer). Financially, this change translated to a significant reduction in operational expenditure: the fuel cost per trip dropped from approximately $167.40 USD on the existing route to approximately $151.96 USD on the shortest route (Table 3).

Table 2: Summary of the existing and the shortest route distances

Serial No.	Collection Point Name	Collection Point Location		Existing Route Distance (km)	Shortest Route Distance (km)
		Latitude	Longitude		
01	KUET	22.899707	89.501208	18.46	17.10
02	Ward_01	22.888581	89.509927	17.14	15.10
03	Ward_03	22.879606	89.510478	16.33	15.14
04	Ward_04	22.862385	89.512346	12.53	10.97
05	Ward_05	22.866657	89.520404	14.46	12.12
06	Ward_06	22.861282	89.524004	13.28	12.19
07	Ward_07	22.867148	89.532931	14.02	12.92
08	Ward_08	22.863453	89.539205	14.18	13.07
09	Ward_09	22.849499	89.531277	11.68	10.58
10	Ward_10	22.859439	89.538273	14.35	12.86
11	Ward_11	22.859656	89.543113	14.78	12.65
12	Ward_12	22.85413	89.545004	12.56	12.07
13	Ward_14	22.83893	89.542122	11.20	10.10
14	Ward_24	22.798254	89.554196	7.22	7.23
15	Ward_25	22.809613	89.551263	8.40	7.43
16	Ward_27	22.803722	89.562071	9.79	8.84
17	Ward_28	22.79963	89.568189	11.38	10.05
18	Ward_29	22.805163	89.577498	10.81	10.55
19	Ward_30	22.795445	89.574325	11.85	10.92
		Total single trip distance (km)		244.42	221.89
		Total round trip distance (km)		488.86	443.80

Table 3: Comparison of fuel cost between the existing and the optimized shortest routes

Route	Round Trip Distance (km)	Fuel Required (Liter)	Costing for Required Fuel (USD)	Cost Reduction (%)
Existing Route	488.86	200.42	$167.40	9.22%
Shortest Route	443.80	181.96	$151.96	

The total savings achieved through this optimized plan amounted to an overall 9.22% cost reduction in fuel consumption per round trip for these nineteen routes, directly enhancing operational effectiveness, reducing vehicle depreciation, and minimizing greenhouse gas emissions.

Despite the fact that this study successfully optimized the routes based on spatial distance to minimize fuel consumption, it is important to acknowledge certain limitations. The present study, primarily addresses linear distance reduction and static road network data. Nonetheless, real-world scenarios involve dynamic factors including real-time traffic congestion, varying road surface conditions (e.g., roughness), and waiting times at collection points. These dynamic variables were not included in this simulation due to data constraints but are critical for a comprehensive real-time optimization.

4. CONCLUSION

In conclusion, this study unequivocally demonstrates that the GIS-based route optimization method, primarily implemented through the ArcGIS Network Analyst tool, provides a crucial mechanism for transforming faecal sludge transportation into a sustainable and fiscally responsible operation within the Khulna City Corporation (KCC). The meticulous modelling which successfully minimized the logistics factor of impedance by accounting for distance, traffic, and road constraints resulted in a highly superior operational plan compared to existing practices. Specifically focusing on the core challenge of fuel calculation for faecal sludge transportation, the optimized "Shortest Route" achieved a significant reduction in total travel distance and the corresponding fuel volume required per collection cycle. This efficiency directly generated substantial cost savings on transportation expenditure, simultaneously enhancing overall operational effectiveness and extending the useful life of the vehicle fleet by reducing wear and tear. Crucially, this optimization delivers profound sustainable environment benefits by minimizing the consumption of fossil fuels, thereby mitigating the output of greenhouse gas emissions associated with the service chain, aligning KCC's sanitation strategy with modern environmental goals. Furthermore, this study primarily considered optimizing the routes based on spatial distance to minimize fuel consumption, showing an improvement over the present scenarios. Nevertheless, a complete scenario of optimization involving dynamic factors can be further explored in future studies to gain deeper insights. Future research should focus on incorporating real-time variables, such as GPS data from collection vehicles, to account for live traffic and sudden changes in road accessibility.

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