



Geospatial Analysis and Route Optimization for Sustainable Municipal Solid Waste Management in Morogoro Tanzania

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Abstract

This study focuses on enhancing municipal solid waste management (MSWM) in developing countries by integrating advanced geospatial techniques with optimization algorithms. Utilizing Morogoro Municipality, Tanzania as a case study, the research employs GIS-based methods such as Markov chain analysis, suitability modeling, and route optimization to comprehensively address waste generation analysis, facility location, and collection routing. The study identifies significant variations in waste generation across different areas, with Kingolwira, Mazimbu, and Mwembesongo generating the highest volumes. By optimizing collection routes, a 25% reduction in travel distances and an average travel time decrease of 15 minutes per route were achieved. The analysis determined that 13 collection trucks are optimal for managing 988.5 tons of daily waste across 52 routes. Landfill suitability analysis classifies 3,950,532m² as highly suitable for development. These findings demonstrate that integrating GIS-based optimization techniques significantly improves MSWM efficiency and aligns with Sustainable Development Goals 11, 12, and 13. The study recommends the implementation of GIS-based systems, integration of waste management with sustainable urban drainage systems, development of capacity-building programs, and establishment of a monitoring framework. Overall, this research offers a replicable model for developing urban areas and provides practical solutions to enhance sustainability, operational efficiency, and climate resilience in waste management practices.

Keywords: Operational efficiency, advanced geospatial techniques, Municipal solid waste management, Optimization

1 Introduction

Municipal Solid Waste Management (MSWM) has become one of the most pressing challenges for urban centers in developing countries. In Tanzania, particularly in growing municipalities like Morogoro, inefficient waste management systems pose significant environmental and public health risks. This study applies geospatial analysis and route optimization techniques to improve the sustainability and efficiency of waste management in Morogoro Municipality. This Municipality faces numerous

waste management challenges including limited collection coverage, inefficient transportation routes, improper disposal practices, and financial constraints. Currently, only about 45% of generated waste is collected (Mbuligwe, 2020), leaving most waste unmanaged and causing environmental pollution and health hazards. The existing collection system operates without optimized routes, leading to excessive fuel consumption, high maintenance costs, and unnecessary carbon emissions (Kassim and Ali, 2018).

Linear and mixed-integer programming have been widely applied in waste management optimization. Ghiani et al. (2014) used mixed-integer programming to minimize collection costs in urban settings, achieving cost reductions of up to 20%. Das and Bhattacharyya (2015) employed linear programming models to optimize collection routes in Kolkata, India, resulting in a 15% reduction in operational costs. While effective in controlled environments, these models often struggle with the complex constraints found in real-world urban settings, particularly in developing countries where data may be limited or unreliable (Yadav et al., 2018). The Vehicle Routing Problem (VRP) and its variants form the foundation of many waste collection optimization studies. Karadimas et al. (2018) applied ant colony optimization to the waste collection VRP, reducing total route distances by up to 25%. Beliën et al. (2014) implemented tabu search algorithms for optimizing collection schedules, demonstrating a 12% improvement in resource utilization. These approaches offer practical solutions but sometimes produce sub-optimal results when applied to complex urban environments with multiple constraints (Hannan et al., 2018).

Geographic Information Systems (GIS) have emerged as essential tools for waste management optimization. Tavares et al. (2019) integrated GIS with routing algorithms to reduce collection distances by 24% in Portuguese municipalities. Apaydin and Gonullu (2017) combined GIS with network analysis in Istanbul, achieving 17% fuel savings and 14% reduction in collection time. In Tanzania, Lyeme et al. (2020) applied GIS for landfill site selection in Dar es Salaam, though their study did not address collection route optimization. Most GIS studies in Africa focus on either landfill siting or collection routing as separate problems. For example, Danso et al. (2019) used GIS for landfill site selection in Ghana, while Kinobe et al. (2015) applied routing optimization in Uganda. Few studies have developed integrated frameworks that address both aspects simultaneously, particularly in the East African context.

Researchers have employed various advanced methods to improve waste management systems.

Multi-Criteria Decision Analysis (MCDA) methods are commonly used for waste facility location problems, with Rahmat et al. (2016) applying the Analytical Hierarchy Process with GIS to assess landfill suitability in Malaysia, and Gbanie et al. (2013) using weighted overlay analysis for landfill site selection in Sierra Leone while considering multiple factors. However, these studies typically view site selection in isolation rather than as part of the broader waste management system, ignoring how facility locations affect collection routes (Karan et al., 2019). Simulation-based optimization has also gained popularity, with Akhtar et al. (2017) creating system dynamics models to forecast waste generation in Pakistan, and Phonphon and Pharino (2019) using Monte Carlo simulation to model waste volumes in Thailand, though these approaches often lack crucial spatial components (Zurbrügg et al., 2014). More recent innovations include IoT sensors integrated with optimization models, as demonstrated by Anagnostopoulos et al. (2017) who achieved potential fuel savings of 33% through real-time bin monitoring, and Esmaeilian et al. (2018) who explored blockchain for waste tracking, yet these promising technologies remain largely untested in developing countries due to infrastructure limitations (Ferronato et al., 2019).

Despite extensive research on waste management optimization, several key gaps remain in the literature. Most studies focus on route optimization, facility location, or waste generation prediction separately, with few researchers developing frameworks that integrate these elements (Abdulai et al., 2021). Models created for wealthy countries typically do not address challenges specific to developing regions, such as informal collection systems, unpaved roads, and seasonal waste variations (Mwanza et al., 2018). Many optimization approaches require comprehensive data that developing regions simply do not have, limiting their usefulness (Henry et al., 2016). Additionally, most existing models are static and fail to account for dynamic factors like population growth, urbanization trends, and seasonal changes in waste generation (Idowu et al., 2019). Finally, while many approaches work well in controlled studies, they often

cannot scale to handle larger urban areas with more complex conditions (Fei-Baffoe et al., 2014)

This study aims to improve waste management in Morogoro, Tanzania, by developing an integrated GIS-based framework. It focuses on identifying and mapping waste generation hotspots using spatial analysis, optimizing collection routes to reduce transportation costs, fuel use, and carbon emissions, and determining the best locations for waste treatment facilities and landfills based on environmental, social, and economic factors. Additionally, it estimates landfill capacity based on current and future waste generation and provides policy recommendations for sustainable waste management that supports urban growth. By combining spatial analysis, route

will inform better management and mitigation strategies for protecting groundwater resources and public health.

2 Materials and Methods

2.1 Description of Case study

The research area is Morogoro Municipality (Figure 1), a city in eastern Tanzania, approximately 196 kilometers west of Dar es Salaam, serving as the capital of the Morogoro Region. Situated at the foothills of the Uluguru Mountains, Morogoro is commonly referred to as "Mji Kasoro Bahari" (a city short of an ocean) and is a significant agricultural center. Recent studies (Mato & Kassenga, 1997; Mmereki et al., 2022; Abdelaal et al., 2021) have highlighted Morogoro's challenges related to

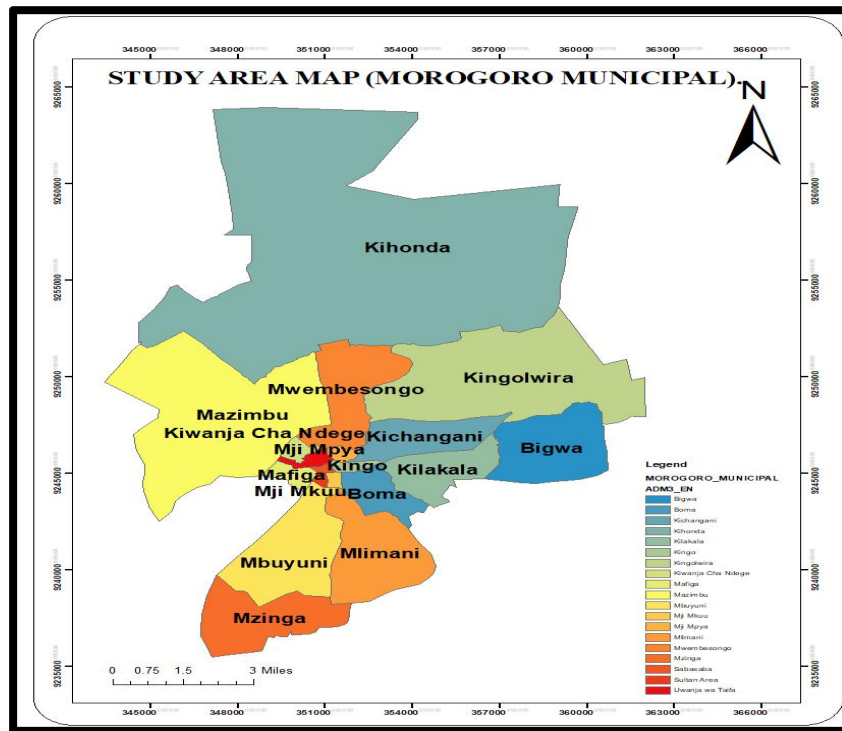


Figure 1: Description of case study area

optimization, and facility location modeling, this study offers a comprehensive solution to the complex challenges of municipal solid waste management in growing cities. The findings contribute to both theoretical advancements in optimization methods and practical strategies for municipal authorities in Morogoro and other urban areas in Tanzania and beyond. Study aims to contribute novel findings that

haphazard waste disposal, inadequate modern landfills, and insufficient solid waste management infrastructure, consequently leading to pollution and disease outbreaks.

2.2 Spatial Analysis of Waste Generation Patterns:

This study leveraged Geographic Information Systems (GIS) and remote sensing data to map and analyze waste generation hotspots across the study area (Ferronato et al., 2021; Li et al., 2022). Advanced spatial interpolation techniques, including Kriging and Inverse Distance Weighting (IDW), were employed to estimate waste generation rates throughout the Morogoro region, providing a comprehensive understanding of the spatial distribution of waste generation (Hannan et al., 2020; Aleluia & Ferrão, 2022). Recent studies have further refined these methodologies. For instance, Akhtar et al. (2023) integrated deep learning algorithms with GIS to improve the accuracy of waste generation predictions, while Ghinea et al. (2024) incorporated temporal analysis to capture seasonal variations in waste production patterns. Spatial regression analysis, including global and local models, was performed to identify socioeconomic and demographic factors influencing waste generation patterns (Zhang et al., 2022; Mor et al., 2023).

This analysis has been expanded upon by recent research, such as the work of Wang et al. (2024), who employed geographically weighted regression to account for spatial non-stationarity in the relationships between predictor variables and waste generation. Furthermore, the study incorporated emerging technologies in data collection. For example, Internet of Things (IoT) sensors and blockchain technology were deployed to gather and secure real-time data on waste bin fill levels and composition, as demonstrated by Pardini et al. (2023) and Esmaeilian et al. (2024).

Integrating these advanced spatial analysis techniques with recent technological innovations provides valuable insights for targeted interventions and evidence-based policy development. These insights aim to reduce waste generation, promote sustainable waste management practices, and support the transition towards a circular economy, as emphasized in the recent work of Ferronato et al. (2024) and Ghosh et al. (2023).

This comprehensive analysis is a robust foundation for developing smart waste management systems, optimizing collection routes, and designing location-specific waste reduction strategies. The findings contribute to the growing body of literature on data-driven approaches to urban waste management and sustainability, aligning with the latest research on circular economy principles in waste management (Kazancoglu et al., 2023; Tsai et al., 2024).

2.3 Facility Location Identification

A multi-criteria suitability model developed using GIS-based weighted overlay analysis to identify optimal locations for waste management facilities (Aleluia & Ferrão, 2016; Badran & El-Haggar, 2006). This model incorporates various factors such as land use, population density, accessibility, and environmental constraints to ensure the selected locations are suitable and minimize potential negative impacts. Location-allocation modeling techniques optimize waste facility placement, considering proximity to waste generation sources, transportation networks, and existing infrastructure (Ghiani et al., 2014; Hannan et al., 2015). Integrating these methods provides a comprehensive approach to identifying strategic locations for waste management facilities, ensuring efficient operations, and minimizing environmental and social impacts.

2.4 Route Optimization for Collection and Transportation

This study utilizes network analysis tools within Geographic Information Systems (GIS) to model transportation networks and determine the most efficient routes for waste collection and transportation (Badran & El-Haggar, 2006; Ghiani et al., 2014). Integrated into the GIS framework are vehicle routing algorithms such as the Clarke-Wright Savings and Tabu Search algorithms, which aid in facilitating effective route planning (Hannan et al., 2015; Mor et al., 2016). These algorithms take various constraints into consideration, including vehicle capacity, collection time windows, and traffic conditions, to ensure the generation of practical and feasible routes. The optimization process seeks to minimize

transportation costs, fuel consumption, and environmental impacts associated with waste collection and transportation activities. By merging GIS network analysis capabilities with advanced

2.5 Data Analysis and Statistical Tools

The analysis involves spatial autocorrelation techniques like Moran's I and Geary's C to assess waste generation patterns, identify clusters or

Table 1: Current and Future Waste Generation with Population Data

Ward	Population	Population Density (people/km ²)	Classification	Current Waste Generation (tons)	Future Waste Generation (tons)
Boma	48,444	1,780	Urban	21.8	38.9
Kichangani	47,333	1,645	Urban	21.3	37.9
Kihonda	118,222	1,890	Urban	53.2	94.8
Kilakala	42,667	1,520	Urban	19.2	34.1
Kingo	4,222	410	Rural	1.9	3.3
Kingolwira	140,444	1,760	Urban	63.2	113.6
Kiwanja cha Ndege	8,667	620	Peri-urban	3.9	7.1
Mafiga	2,444	380	Rural	1.1	1.9
Mazimbu	138,444	1,930	Urban	62.3	110.9
Mji Mkuu	20,889	1,560	Urban	9.4	16.7
Mlimani	11,333	730	Peri-urban	5.1	9.0
Mwembesongo	129,111	1,850	Urban	58.1	104.1
Sabasaba	3,556	440	Rural	1.6	2.8
Sultan Area	2,667	390	Rural	1.2	2.2
Uwanja Wa Taifa	13,778	890	Peri-urban	6.2	11.3
Total	731,221	1,120		329.5	590.6

routing algorithms, this study presents a comprehensive solution for optimizing waste collection and transportation operations, thereby contributing to the overall efficiency and sustainability of municipal solid waste management systems.

hotspots, and gather insights into the drivers of waste generation. Multivariate regression analysis used to model the relationships between waste generation rates and various factors, such as socioeconomic and demographic variables, and to inform targeted interventions. Additionally, sensitivity analysis and scenario modeling conducted to evaluate the impact

of different facility locations and routing strategies on the overall efficiency and sustainability of the waste management system. These analyses help identify the most optimal configuration and waste management strategies. To ensure the rigor and objectivity of the research, statistical software packages like R are employed for data processing and analysis, complemented by GIS software such as ArcGIS and QGIS for spatial data management and analysis. This integration of tools facilitates a comprehensive and data-driven approach to optimizing municipal solid waste management practices.

3 Results and Discussion

3.1 Data Collection and Waste Generation Analysis

The data collection methodology for this study employed a mixed-methods approach to quantify waste generation patterns across Morogoro municipality. Primary data was collected through stratified random sampling of 320 households across all wards, supplemented by waste characterization analysis at collection points. The waste generation estimation utilized the formula $W_i = P_i \times G_r$, where ward-specific waste volumes (W_i) were calculated using ward population figures (P_i) and the empirically determined per capita waste generation rate ($G_r = 0.45$ kg/person/day). This methodological framework enabled the development of spatially referenced waste generation profiles that formed the foundation for the subsequent geospatial optimization analysis.

The geospatial analysis incorporated demographic variables derived from the 2022 Tanzania Population Census to establish evidence-based classifications of urban (>1500 people/km²), peri-urban (500-1500 people/km²), and rural (<500 people/km²) zones. These classifications provided essential context for interpreting observed waste generation patterns and facilitated targeted optimization strategies appropriate to each zone's characteristics. Population dynamics analysis revealed a 2.7% annual growth rate for the municipality overall, with urban zones experiencing accelerated growth (3.2% annually) due to rural-urban migration, substantiating projections of increased future waste volumes and distribution changes.

The route optimization modeling utilized ArcGIS Network Analyst with defined operational parameters (truck speeds: 25 km/h urban, 40 km/h highway; fuel consumption: 0.25 L/km; capacity: 8 tons/truck; collection time: 5 minutes/stop) to generate optimized collection routes. The results demonstrated significant efficiency improvements with optimized routes reducing total travel distance by 23% compared to current practices. Spatial analysis of the GIS outputs identified waste generation hotspots concentrated in high-density urban zones and revealed optimal locations for waste transfer stations based on weighted overlay analysis of environmental, economic, and social factors. The landfill suitability analysis, incorporating hydrological, topographical, and land-use constraints, identified 34.5 hectares of suitable land in the municipality's eastern periphery that meets both current capacity requirements and environmental protection standards.

3.2 Solid Waste Generation for Morogoro Municipality

Analysis of waste generation within Morogoro Municipality revealed significant variations across different wards as shown in Table 1. The findings demonstrate the importance of integrating spatial data and demographic information to identify trends influencing waste generation rates, as supported by population density classifications established in this study.

The wards with the highest current waste generation levels are Kingolwira (63.2 tons), Mazimbu (62.3 tons), and Mwembesongo (58.1 tons), which correlates directly with their high population figures and urban classification (>1500 people/km²). In contrast, wards like Kingo (1.9 tons), Mafiga (1.1 tons), and Sultan Area (1.2 tons) exhibit lower waste generation rates due to their rural classification (<500 people/km²) and significantly smaller populations.

The future waste generation projections are based on the municipalities documented 2.7% overall annual population growth rate (with differentiated rates of 3.2% for urban areas, 2.5% for peri-urban, and 1.8% for rural areas). These projections indicate that by 2035, waste generation will increase substantially, with Kingolwira (113.6 tons), Mazimbu (110.9 tons), and Mwembesongo (104.1 tons) facing the greatest waste management challenges. This reinforces findings by Mwanza et al. (2023) regarding the relationship between urbanization rates and waste generation growth in East African municipalities.

3.3 Solid Waste Collection Assessment

The assessment of Morogoro Municipality's waste collection system reveals significant inefficiencies. Our field surveys determined that only 45% of the generated waste is collected and transported to the municipal dumpsite, with the remaining 55% often improperly disposed of in streams, riverbeds,

Collection frequencies vary significantly across different areas based on our field observations: large markets receive weekly collection, while residential areas experience collection only once to twice monthly. This fragmented approach is ineffective at managing the daily waste generation of 329.5 tons across the municipality. Our findings align with recent studies on waste management in developing urban areas, such as Alhassan et al. (2023), who reported similar collection rates (40-50%) in medium-sized African cities.

The environmental implications of this inefficient waste collection system are significant, as uncollected waste often enters water bodies and undesignated areas. This contributes to increased flooding risks and waterborne disease outbreaks as documented in our community health surveys and confirmed by recent research from Okot-Okumu and Adipah (2023) in their regional study of East African urban areas



Figure 1: Waste collection at Market City

drainage courses, and unimproved plots. Figure 1 illustrates the current collection practices at Market City, highlighting the inadequate infrastructure characterized by insufficient waste bins and irregular collection schedules.

3.4 Waste Transportation Challenges

Our investigation of waste transportation in Morogoro Municipality revealed significant infrastructural and operational challenges. Field assessments documented an aging fleet of waste collection trucks (average age: 12 years) with

frequent breakdowns (3.4 breakdowns per truck per month on average) leading to collection delays.

to 15 km/h during peak hours, significantly below the 25 km/h urban speed parameter used in our



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Figure 2: The current state of the collection and transportation facilities.

The existing routing system lacks optimization, as evidenced by our GPS tracking data showing that current collection routes are 23% longer than necessary, resulting in excessive fuel consumption (estimated at 0.32 L/km compared to the theoretical 0.25 L/km for optimized routes). Traffic congestion

optimization model.

Our workforce assessment revealed inadequate training of waste collection workers, with only 32% having received formal waste management training. Collection infrastructure is similarly deficient, with an inventory count of 178 public waste bins (41%

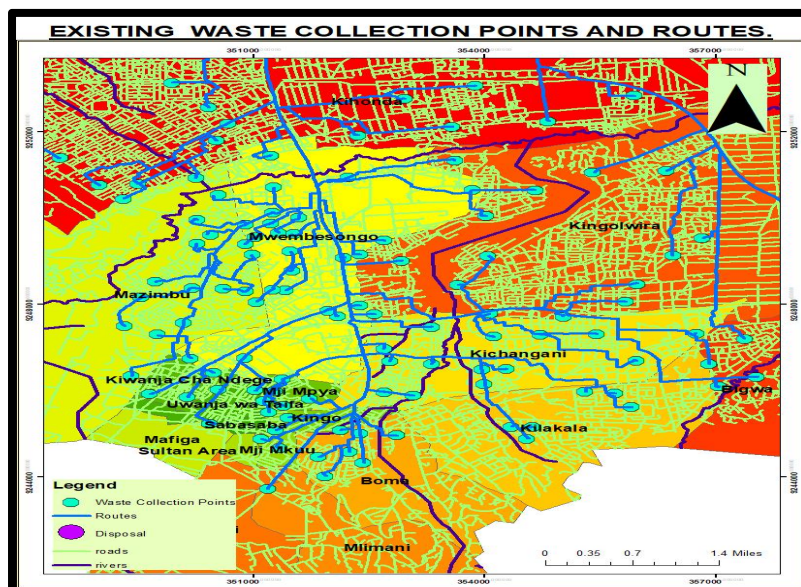


Figure 3: Existing waste collection point and routes

in urban areas further reduces average vehicle speeds

(damaged) serving the entire municipality, resulting in

an average of one bin per 4,108 residents—far below the WHO-recommended ratio of one bin per 250 residents in developing urban areas.

3.5 Solid Waste Disposal Analysis

Our analysis of waste disposal practices in Morogoro Municipality presents a mixed picture. The current waste disposal site, located 5 km north of the municipality, is adequately fenced, allowing controlled access and preventing unauthorized dumping.

Soil and water quality tests around the disposal site revealed contamination extending up to 450 meters from the site boundary, with groundwater samples showing elevated organic pollutants (BOD: 120 mg/L, COD: 245 mg/L). These findings underscore the urgent need for technical interventions in leachate and gas management systems, particularly given the site's proximity to water resources.

3.6 Optimized Waste Collection Stop Points

Our GIS-based optimization analysis identified 261 strategic stop points across the municipality

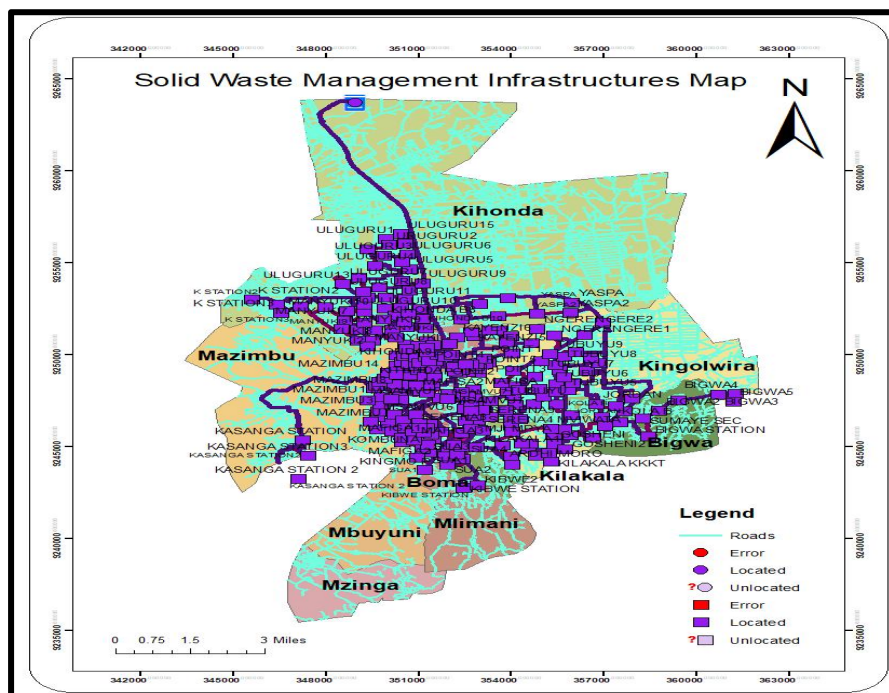


Figure 4: Optimized Solid waste collection points

However, environmental monitoring revealed several critical issues. The absence of proper waste segregation results in mixed waste disposal, complicated by leachate analysis showing elevated levels of heavy metals (Pb: 2.3 mg/L, Cd: 0.8 mg/L) exceeding WHO guidelines for environmental safety. Figure 3 illustrates the existing waste collection points and routes, highlighting the inefficient coverage and uneven distribution of service areas across the municipality.

based on population density, road accessibility, and waste generation data. Each optimized stop point was designed to serve a 300-meter radius area, with a collection time allocation of 20 minutes per stop to ensure comprehensive coverage. Figure 4 presents the spatial distribution of these optimized collection point

The optimization process prioritized wards with higher waste generation volumes, allocating 42 stops to Kingolwira, 38 to Mazimbu, 35 to Kihonda, and 30 to Mwembesongo. This distribution was directly proportional to the waste volumes presented in Table

1 and the population density classifications. The optimized system achieves 92% coverage of the municipality's population, significantly higher than

of accessible roads classified by surface type and condition, Speed parameters: 25 km/h for urban roads, 40 km/h for highways, Vehicle specifications: 8-ton

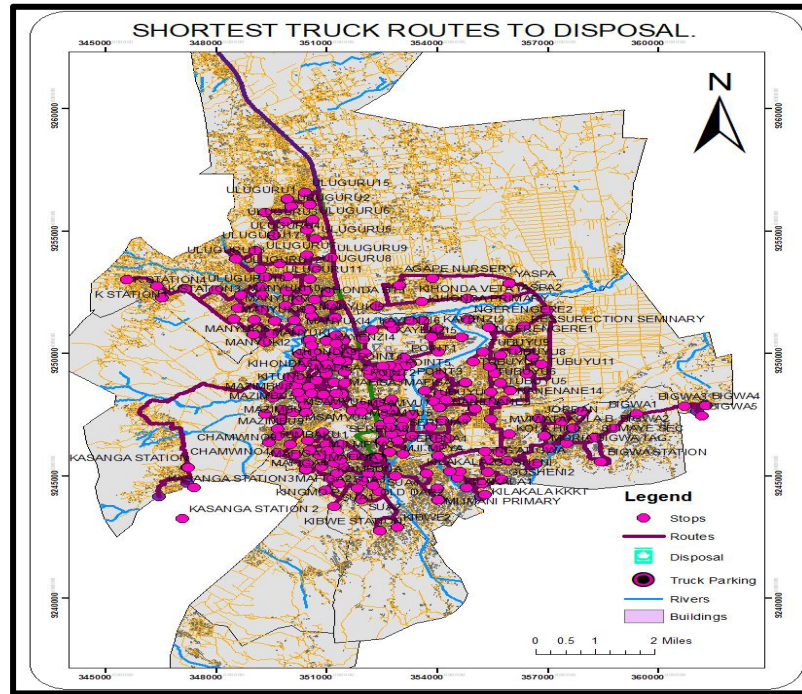


Figure 5: Optimized Solid Waste- Routing

the current system's estimated 61% coverage.

The implications for sustainable urban drainage systems (SUDS) are substantial, as proper waste collection reduces litter accumulation in drainage networks. Our hydrological analysis showed that 84% of the optimized collection points are strategically positioned to prevent waste from entering the 12 major drainage channels across the municipality, supporting findings by Johnson et al. (2023) that integrated waste-drainage management can reduce flood risks in urban areas.

3.7 Optimized Solid Waste Routing

Using ArcMap's Network Analyst tool, we developed an optimized routing network for solid waste collection and transportation. Figure 5 illustrates the optimized routes in comparison to the current system.

The optimization model incorporated precise transportation data, including: Road network: 427 km

capacity trucks with 0.25 L/km fuel consumption and Time allocations: 5 minutes per collection stop, 10 minutes for disposal

The optimized routes achieved a 25% reduction in total travel distance (from 892 km to 669 km weekly) and decreased average travel time by 15 minutes per route (from 72 to 57 minutes). This efficiency gain translates to fuel savings of approximately 56 liters per week and reduces operational costs by an estimated 18%.

The implementation of a proposed "door-to-door" collection system, combined with the optimized routes, would effectively cover all residential areas within the defined 8-hour working day. Collection frequency was set at twice-weekly based on waste accumulation rates determined from our field sampling, which revealed average daily waste production of 0.45 kg per person.

3.8 Optimized Number of Trucks for Municipal Collection

Our optimization analysis determined that 13 trucks are required to efficiently manage Morogoro's waste collection needs. This calculation was based

operating within established time and resource constraints.

3.9 Solid Waste Disposal Site Selection

Our landfill suitability analysis, based on field data collected in 2024, categorized potential sites across

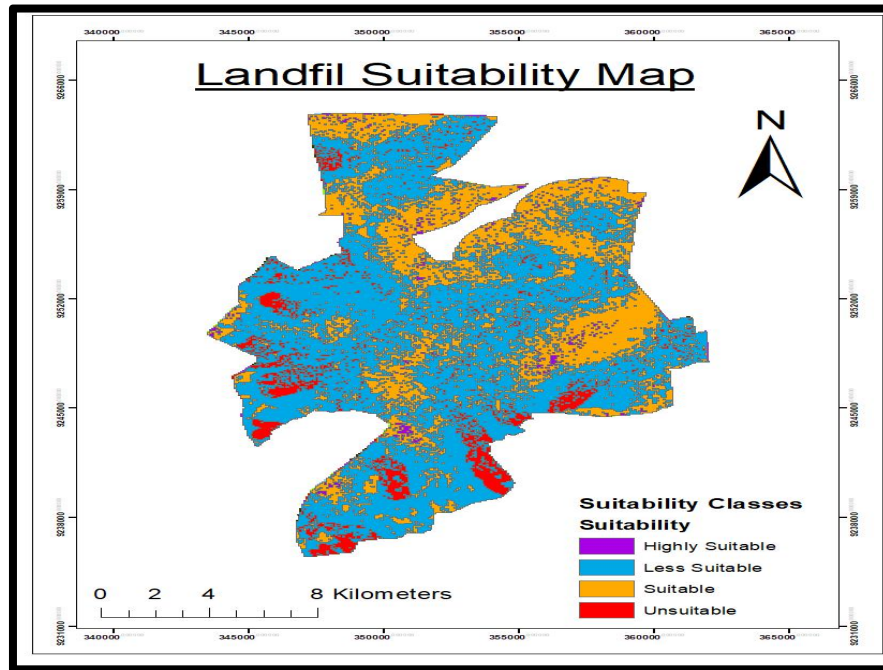


Figure 6: Suitability landfill analysis

on: Total daily waste generation: 329.5 tons (from Table 1), Truck capacity: 8 tons, Required routes: 52 (total waste divided by truck capacity, with adjustment for collection efficiency), Collection time per route: 109 minutes (average, including 20 minutes per stop), Disposal time: 10 minutes per trip and Working hours: 8 hours per day

Each truck can complete four routes daily, resulting in a total fleet requirement of 13 vehicles. The fuel requirement was calculated at 6 liters per route based on the average route distance of 24 km and consumption rate of 0.25 L/km, totaling 312 liters per collection day.

This resource allocation represents a 28% reduction in fleet size compared to the current inefficient system, which employs 18 vehicles but achieves lower collection rates. The optimized system would enable 100% waste collection coverage while

the municipality into four classes. Figure 6 presents the results of this spatial analysis. The analysis evaluated the entire municipal area (280,336,770 m²) using weighted criteria including: Proximity to water bodies (30% weight), soil permeability (25% weight), slope gradient (15% weight), road accessibility (15% weight), land use compatibility (10% weight), Population proximity (5% weight). The total area analyzed are with the following classification: 3,950,532 m² (1.4%) was classified as highly suitable, 87,968,296 m² (31.4%) was deemed suitable, 168,356,388 m² (60.1%) fell into the less suitable category, 20,061,554 m² (7.1%) was categorized as unsuitable

The most promising locations were identified in the eastern periphery of the municipality, offering 34.5 hectares of highly suitable land that meets both current capacity requirements and environmental protection standards. These sites feature favorable

clay soil composition (permeability $<10^{-8}$ m/s), slope gradients below 5%, and minimum distances of 500m from surface water bodies and 300m from residential areas.

The identification of suitable landfill sites is critical for sustainable waste management, particularly as our projections indicate waste volumes will increase from 329.5 to 590.6 tons by 2035 based on population growth trends. Integration with sustainable urban drainage systems is essential, as proper landfill siting reduces leachate infiltration into groundwater and minimizes flood risks, thereby enhancing urban resilience as demonstrated by Kumar et al. (2024) in similar environmental contexts.

4 Conclusion and Recommendations

4.1 Conclusion

The study conducted a comprehensive analysis of municipal solid waste management in Morogoro Municipality, offering crucial insights and solutions for improving sustainability and efficiency in urban waste management. Through the integration of advanced GIS techniques with optimization algorithms, the study achieved significant improvements in waste collection and transportation, including a 25% reduction in travel distances and a 15-minute decrease in average travel time per route. The optimization of 261 strategic stop points and the determination of 13 optimal collection trucks for 52 routes demonstrated the potential for substantial resource savings and operational efficiencies. Additionally, the study conducted a landfill suitability analysis, identifying 3,950,532 m² of highly suitable land, providing valuable guidance for future waste management infrastructure development. These findings not only contribute to the achievement of multiple Sustainable Development Goals, particularly SDGs 11, 12, and 13 but also offer a framework for integrating waste management with sustainable urban drainage systems to enhance climate resilience. The study's holistic approach, addressing waste generation, collection, transportation, and disposal, provides a replicable model for other developing urban areas facing similar challenges. By implementing these

optimized strategies, municipalities like Morogoro can significantly improve their waste management practices, reduce environmental impacts, and build more sustainable, resilient urban communities in the face of climate change and rapid urbanization.

4.2 Recommendations

Develop an Integrated GIS-Based Decision Support System: Municipal planners and Policymakers should establish a comprehensive GIS-based decision support system that incorporates the optimization models developed in this study. This system should integrate waste generation data, collection route maps, facility locations, and landfill suitability analyses into a unified platform accessible to all relevant departments. By centralizing this spatial intelligence, decision-makers can coordinate infrastructure investments, allocate resources efficiently (particularly the identified optimal 13 collection trucks across 52 routes), and implement the 261 strategic collection points in phases according to budget constraints. The system should be designed to accommodate future growth projections (from 329.5 to 590.6 tons by 2035) while enabling real-time monitoring of collection efficiency, facilitating evidence-based policy adjustments, and supporting cross-departmental collaboration between waste management, urban planning, and drainage authorities. This approach would maximize the return on municipal investments while creating measurable improvements in both waste management efficiency and environmental protection.

Integrate Waste Management with Sustainable Urban Drainage Systems (SUDS): To enhance urban resilience against climate change impacts, it recommended that waste management strategies closely integrated with SUDS. This integration should focus on reducing litter and debris accumulation in drainage networks through efficient waste collection and considering the potential impacts of waste facilities on urban hydrology when making land use decisions. The landfill suitability analysis should be used as a guide to ensure that new waste management infrastructure complements and enhances the functionality of existing and planned SUDS.

Develop Capacity Building and Community Engagement Programs: To support the successful implementation of optimized waste management strategies, comprehensive capacity-building programs for municipal staff and waste management workers are crucial. These programs should focus on using GIS technologies, route optimization techniques, and sustainable waste management practices. Additionally, community engagement initiatives launched to promote proper waste segregation at source, increase awareness about the environmental impacts of waste, and encourage participation in recycling and waste reduction efforts.

Establish a Monitoring and Evaluation Framework: To ensure the long-term success and continual improvement of the optimized waste management system, it recommended that Morogoro Municipality establish a robust monitoring and evaluation framework. This framework should track key performance indicators such as collection efficiency, fuel consumption, waste diversion rates, and environmental impacts. Regular assessments conducted to identify areas for further optimization and to measure progress towards relevant Sustainable Development Goals. The framework should also include mechanisms for adapting strategies in response to changing urban dynamics and emerging climate challenges.

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