

MAPPING SPATIAL INEQUALITIES IN SANITATION ACCESS: A GIS APPROACH FOR KHULNA RAILWAY SLUM, BANGLADESH

Sardar Shakir Ahmad^{*1}, Dr. Anjum Tasnuva² and Swarna Bintay Kadir³

¹*Student of Institute of Disaster Management, Khulna University of Engineering and Technology, Khulna, Bangladesh e-mail: shakir0616@gmail.com*

²*Associate Professor, Institute of Disaster Management, Khulna University of Engineering and Technology, Khulna, Bangladesh, e-mail: tasnuva@idm.kuet.ac.bd*

³*Assistant Professor, Institute of Disaster Management, Khulna University of Engineering and Technology, Khulna, Bangladesh, e-mail: swarna@idm.kuet.ac.bd*

***Corresponding Author**

ABSTRACT

Access to sustainable sanitation remains a significant challenge in the informal settlements of Bangladesh, where dense population, limited infrastructure, and environmental hazards intersect. The Khulna Railway Slum is constrained by limited sanitation facilities and experiences overcrowding, with many living in close proximity to informal waste-dumping sites. These factors exacerbate public health risks and limit equitable sanitation access. This study aims to analyze spatial accessibility to sanitation facilities in the Khulna Railway Slum using GIS-based methods, highlighting underserved areas and households near potential hazard zones. Field surveys, GPS mapping of households, toilets, and waste dumping sites, and high-resolution imagery were used to generate accurate base maps. ArcGIS was employed for service area analysis to delineate areas effectively served by existing toilets, proximity analysis to identify households near informal waste dumping sites, and hotspot analysis to detect clusters of facilities and areas with concentrated or limited access. Results indicate that about 26.5% of households are located more than 50m from the nearest functional toilet, a situation exacerbated by the lack of a proper street network that limits direct access to facilities. Service area analysis identified multiple “sanitation deserts” with no accessible facilities within 50m. Furthermore, about 25% of households in these zones are located near informal waste dumping sites, amplifying exposure to environmental health risks. Seasonal flooding and poor maintenance temporarily render some facilities unusable, forcing residents to travel longer distances. The multi-criteria overlay (PriorityScore) identified 4.2% of households as high-priority (facing triple risk) and a total of 39.1% as medium or high-priority, collectively representing the most critical intervention zones. This method provides actionable insights for optimizing toilet placement, improving accessibility, and incorporating climate-resilient designs. The study presents a GIS-based planning approach that integrates service area delineation, proximity assessment, and clustering, and overlay analysis to identify underserved households and priority locations for new facilities. This method provides actionable insights for optimizing toilet placement, improving accessibility, and incorporating climate-resilient designs. The findings underscore the importance of spatially informed planning in addressing sanitation inequalities in informal settlements. GIS-based spatial analysis offers practical insights that can guide infrastructure development, promote equitable access, and reduce health risks associated with poor sanitation and environmental exposure. The methodology demonstrated in this study is adaptable to other informal urban contexts in Bangladesh and similar developing countries, providing a replicable tool for civil engineers, urban planners, and policymakers working toward sustainable sanitation solutions.

Keywords: *GIS, spatial analysis, sanitation access, informal settlements, Khulna*

1. INTRODUCTION

Access to sustainable sanitation remains a pressing challenge in rapidly urbanizing regions of the Global South, particularly within informal settlements where infrastructure development often lags behind population growth (UN, 2017; WHO & UNICEF, 2023). In Bangladesh, rapid urbanization has led to the proliferation of slums, and informal settlements in major cities such as Dhaka, Chittagong, and Khulna. These slums and settlements, characterized by high population density, limited land availability, and inadequate public services, present significant barriers to sanitation access (Alam et al., 2020; Hossain et al., 2024). The lack of improved sanitation infrastructure in such areas exerts serious public health risks, including the spread of waterborne diseases, environmental contamination, and reduced quality of life (Ahmed et al., 2023; Foster et al., 2021).

The limited access to improved sanitation in informal settlements is often influenced by spatial inequalities. These disparities in access arise from geographic locations, unique settlement patterns, and limited scope of urban planning to intervene in such settlements, which in turn, pose a significant barrier to sustainable sanitation. Spatial inequalities in sanitation access are often more pronounced where urban and rural areas merge. Rural households further face greater barriers due to limited infrastructure, geographic isolation, and insufficient investment, resulting in higher incidences of open defecation and dependence on unimproved sanitation facilities (Abubakar, 2017; Singh, 2014). Peri-urban and informal settlements experience similar challenges, where the provision of sanitation services is minimal or absent (Abubakar, 2017; Adams et al., 2016). Within countries, regional disparities further contribute to these inequalities, ranging from uneven resource allocation to absolute historical negligence. Even within regions, marginalized communities face lower sanitation coverage than more affluent populations, demonstrating the compounded impact of social and spatial marginalization (Ghosh et al., 2022; Ghosh et al., 2023).

Topography, terrain, and settlement location significantly influence access to sanitation. In hilly, flood-prone, or remote areas, households often face steep terrain, poor road conditions, and isolation from water and sanitation infrastructure, which complicate the construction and maintenance of sanitation facilities (Wrisdale et al., 2017; Yuliawati et al., 2024). Even where facilities exist, they are often concentrated in central locations and are overburdened by high user density. This, over the long haul, drastically impacts the functionality, hygiene, and privacy of the facilities (Azage et al., 2020; Ntozini et al., 2015). Vulnerable populations, including women, the elderly, and disabled individuals, face further challenges due to unsafe, distant, and poorly maintained facilities (Bancalari & Martinez, 2018; Gopal et al., 2009; Yuliawati et al., 2024).

Spatial inequalities are particularly acute in peri-urban informal settlements, where slums expand rapidly, outpacing the development of sanitation infrastructure. In such settlements, households rely on pit latrines, septic tanks, or open defecation, which increases environmental and health risks, including contamination of water sources and increased exposure to waterborne diseases (Jia et al., 2016; Matos et al., 2021; Prabha et al., 2020). The marginalization of informal settlements in urban planning processes further contributes to spatial inequalities in sanitation. Informal settlements often lack secure land tenure and are poorly integrated into citywide infrastructure plans, limiting residents' access to safe sanitation services (Pan et al., 2018; Trimmer et al., 2020). The absence of formal recognition and underrepresentation in official data sources restricts investment in sanitation infrastructure and perpetuates a cycle of deprivation (Singh, 2014). Residents in these areas rely primarily on shared, poorly maintained community toilets, exposing themselves to elevated health risk, low safety, and compromised privacy (Gopal et al., 2009; Trimmer et al., 2020).

The Khulna Railway Slum perfectly illustrates these sanitation challenges in informal settings. Located adjacent to the Khulna Railway Station and the Rupsha river, the settlement exhibits high population density, informal housing, and limited sanitation coverage, with households mostly located along narrow and irregular pathways (Hoque et al., 2022). Most of the households lack private toilets and mostly rely on shared facilities concentrated in specific areas along the concrete roads, leaving

peripheral households underserved. Furthermore, informal waste dumping is common and occurs in close proximity to residential structures, mostly in nearby waterbodies distributed throughout the slum (Haque et al., 2018). These spatial constraints, coupled with socio-economic vulnerabilities, suggest that while physical accessibility is a primary determinant of sanitation behavior, quantitative spatial assessments of these inequalities remain overlooked in the context of Bangladesh (Shahriar et al., 2022).

Geographic Information System (GIS) offers a powerful tool for addressing this knowledge gap. Through precise mapping of household locations, existing sanitation facilities, and potential hazardous sites, GIS-based analyses can spatially quantify distances, service areas, and clustering patterns and provide actionable insights for planners and policymakers (Jia et al., 2016; Ntozini et al., 2015). Previous studies in informal settlements globally have used network analysis, service area mapping, and kernel density estimation to identify “sanitation deserts” and prioritize interventions. However, in Bangladesh, such approaches remain underutilized, particularly in quantifying the spatial inequalities in urban informal settlements with varying and unique dynamics (Haque et al., 2018; Hoque et al., 2022).

This study maps spatial inequalities in sanitation access in the Khulna Railway Slum using GIS-based techniques. By integrating field surveys, GPS mapping, network analysis, and overlay analysis, this study (i) identifies households, and areas underserved by existing sanitation facilities, (ii) assesses households’ proximity to informal waste dumping sites and polluted waterbodies, and (iii) highlights priority locations for potential sanitation interventions. This research addresses a critical gap in the literature by providing spatially explicit, evidence-based insights to inform equitable sanitation planning in urban informal settlements in Bangladesh. The findings of this study aim to guide planners and policymakers in developing targeted interventions that can improve sanitation access, enhance hygiene, and reduce exposure to environmental pollution in urban informal settlements.

2. METHODOLOGY

This study employed a GIS-based approach to map spatial inequalities in sanitation access within the Khulna Railway Slum. Precise data on household locations, toilets, and waste dumps were collected during field surveys. Service area analysis was conducted using ArcGIS network analysis tool to identify underserved areas, and households within the slum. Proximity analysis further helped determine the extent of household exposure to environmental pollution. Hotspot analysis was employed to highlight the clustering and distribution pattern of sanitation facilities throughout the slum. Finally, through overlay analysis, the integration of these spatial datasets facilitated the identification of priority household locations for future sanitation interventions.

2.1 Study Area

The study was conducted in the Khulna Railway Slum, a densely populated informal settlement located adjacent to the Khulna Railway Station and Rupsha River in Khulna. The area is characterized by overpopulation, narrow pathways, dense housing and irregular layouts, limited sanitation infrastructure, and frequent informal waste dumping sites and polluted waterbodies. These spatial and environmental constraints make access to sanitation facilities particularly challenging. The settlement’s geographic and infrastructural context provides an ideal setting to analyze spatial inequalities in sanitation access using the above-mentioned GIS-based methods.

2.2 Data Collection

Primary data were collected through field surveys. The locations of all households, existing sanitation facilities (pucca, semi-pucca, and kacha toilets), and informal waste dumping sites and waterbodies within the study area were recorded using GPS during the field survey. Household data included geographic coordinates and basic identification information to associate household locations with existing nearby sanitation facilities and dump sites. High-resolution satellite imagery and Google Earth

basemaps were used to validate the collected geographic coordinates and ensure accurate mapping of the slum's irregular housing layout and facility distribution.

2.3 GIS-Based Spatial Analysis

Spatial accessibility was analyzed using a combination of network, proximity, and overlay analyses in ArcGIS to identify underserved households and potential priority zones for further sanitation interventions.

2.3.1 Service Area Analysis

Service area analysis was conducted to delineate the catchment of each existing communal toilet facility. The slum's road and pathway network was used as the network dataset. The pedestrian network dataset was developed using a field-based, GPS-supported mapping approach. Informal pathways within the Khulna Railway Slum were recorded by physically walking routes commonly used by residents, with walking trajectories automatically captured in digital format using a GPS-enabled mobile application (MapMyWalk). These GPS tracks were subsequently imported into ArcGIS and digitized as polyline features, with Google satellite imagery used as a basemap for spatial alignment and validation. Pathway width was not incorporated into the network model, as the analysis focused on distance-based accessibility. Field observations conducted during data collection did not reveal any permanent physical obstructions along the mapped pathways. Seasonal flooding was not explicitly considered in the network analysis due to the absence of time-series or seasonal accessibility data. Service areas were generated based on a threshold network distance of 50 meters. Households and areas within the settlement located outside these polygons were identified as underserved, forming the basis for highlighting gaps in sanitation coverage.

2.3.2 Proximity Analysis to Hazard Zones

Proximity analysis was employed to assess the proximity of households to nearby informal dump sites and polluted waterbodies. Buffer zones were generated around each dump site and polluted waterbody to identify households within close vicinity. Overlaying these buffers with service area gaps helped identify households facing both limited sanitation access and increased exposure to pollution.

2.3.3 Hotspot and Clustering Analysis

To further understand spatial patterns Kernel Density Estimation (KDE) was performed. This helped identify clusters of sanitation facilities present in the slum. By combining the outputs with service area gaps, the study pinpointed areas with limited sanitation coverage and identified the sanitation deserts, and distribution pattern of toilets in the area.

2.3.4 Overlay Analysis and Priority Zones

Finally, the results from service area, proximity, and hotspot analyses were integrated through overlay analysis to generate priority household locations for potential sanitation interventions. These locations represent households with the greatest need, where households are underserved and simultaneously exposed to environmental pollution. While this study does not perform optimization for exact facility placement, the identified generate priority households, provide actionable guidance for planners and policymakers to target interventions efficiently.

3. ANALYSIS AND RESULTS

Spatial analysis was conducted in ArcGIS to assess how geographic factors influence access to sanitation within the study areas. The analyses focused on the spatial dimensions of inequality in access to sanitation by examining household distance to nearest toilet facilities, service area coverage, proximity to dumping sites, and the distribution patterns of sanitation facilities. Four analytical

approaches were applied: Network Analysis including Service Area Analysis, Proximity Analysis, Kernel Density Estimation, and Overlay Analysis.

A network dataset was created in ArcGIS to model pedestrian accessibility within the study area, using digitized roads and informal pathways. The feature layers were cleaned and snapped to ensure topological connectivity, and all data were projected in WGS 1984 UTM Zone 45N for accurate distance and walking time calculations. The network calculated two cost attributes: distance, and included all accessible paths with bidirectional movement, representing realistic pedestrian flow. This dataset served as the basis for service area analyses, providing accurate, field-relevant measures of sanitation accessibility.

3.1 Service Area Analysis

The initial spatial assessment used Service Area Analysis to determine the geographic accessibility of existing sanitation facilities. A distance threshold of 50 meters was applied as the maximum functional service distance, following the humanitarian WASH standards, which recommend that shared communal toilets be located no more than 50 m from dwellings (Sphere, 2018; UNHCR, 2025). With a larger service distance threshold (e.g. 75 meters), the proportion of households classified as unserved would likely decrease. However, this would risk overstating functional accessibility, since increased walking distances in informal settlements are associated with reduced facility usage, longer waiting times, and higher reliance on unsafe alternatives (Ghosh et al., 2022). Distance breaks (5m, 25m, 50m) were adopted to quantify the extent of service coverage provided by the toilets to the households.

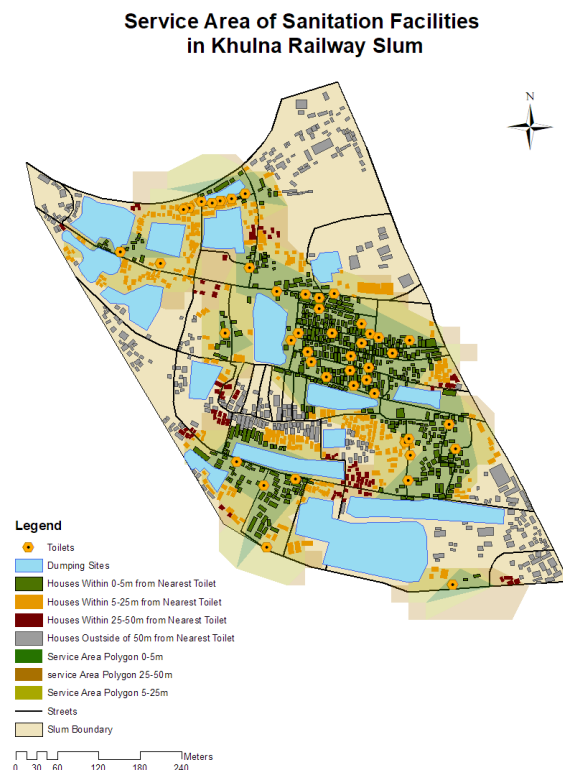


Figure 1: Service Area of Sanitation Facilities in Khulna Railway Slum

The service area analysis of 1,224 households revealed that 512 households (41.8%) were within 0–5 meters of a toilet, 306 households (25%) were within 5–25 meters, and 82 households (6.7%) were within 25–50 meters. However, 324 households (26.5%) were located beyond 50 meters, falling outside all service area polygons. These findings highlight significant spatial gaps in sanitation coverage, with over a quarter of households experiencing limited access, particularly in peripheral or irregular parts of the settlement, including one central location with no communal toilets located nearby.

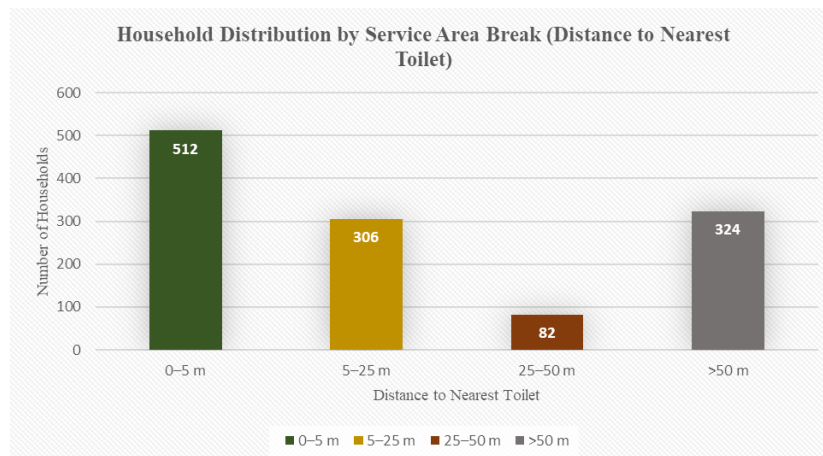


Figure 2: Household Distribution by Service Area Break (Distance to Nearest Toilet)

The service area analysis showed that out of the total slum area of 288,325.57 m², 188,437.5 m² (65.4%) fell within toilet service areas, leaving 34.6% (~99,888 m²) uncovered. Unserved areas were mainly in peripheral or irregularly shaped parts of the settlement, where residents must walk longer distances to access toilets. These gaps highlight spatial inequalities in sanitation coverage and indicate priority zones for additional facilities or improved pedestrian access to ensure more equitable service.

3.2 Proximity to Dumping Sites

Proximity analysis showed that 302 out of 1,224 households (~24.7%) were located within 10 meters of informal waste dumping sites, while the majority (~75.3%) were outside these hazard zones. A buffer distances of 10m is consistent with public health practice for capturing acute exposure zones around informal waste dumping sites, where contamination and vector presence pose heightened health risks (Othoo et al., 2020). Households near dumping sites were evenly distributed across the settlement, indicating that environmental exposure is widespread rather than concentrated. These results highlight areas at risk from informal waste and emphasize the need for targeted interventions to reduce environmental pollution.

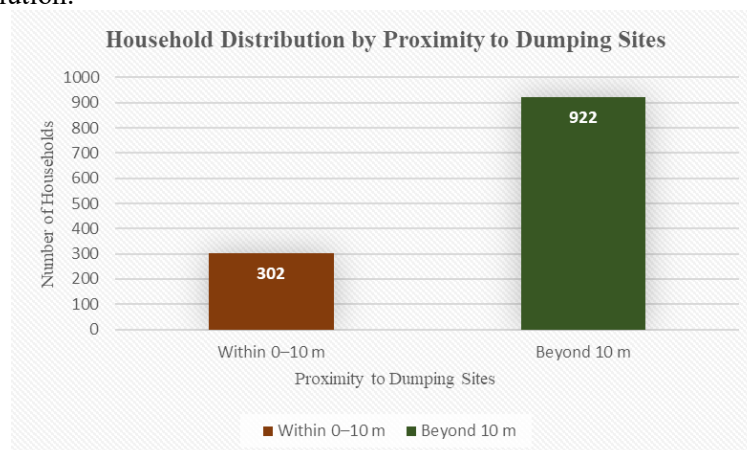


Figure 3: Household Distribution by Proximity to Dumping Sites

3.3 Kernel Density Analysis

Kernel Density Estimation (KDE) was used to analyze the spatial concentration of sanitation facilities in the Khulna Railway Slum. Using toilet facilities weighted by the number of households served, the KDE created a continuous surface highlighting both high-demand hotspots and low-coverage peripheral

areas. The analysis revealed that high-density hotspots are concentrated in central and south-eastern parts of the slum, where facilities face high usage and risk of overburdening. Medium-density zones are scattered around the center, while low-density or uncovered areas dominate the peripheries and a central region with narrow pathways, forcing residents to travel longer distances. Quantification showed that 78.2% of the slum falls in very low-density zones, whereas only 0.95% corresponds to very high-density hotspots. Spatially joining households with the KDE surface highlighted demand-driven inequalities, with some facilities serving disproportionately large numbers of residents. The KDE results reinforce service area findings, showing both under-provision in peripheral areas and overcrowding in central zones.

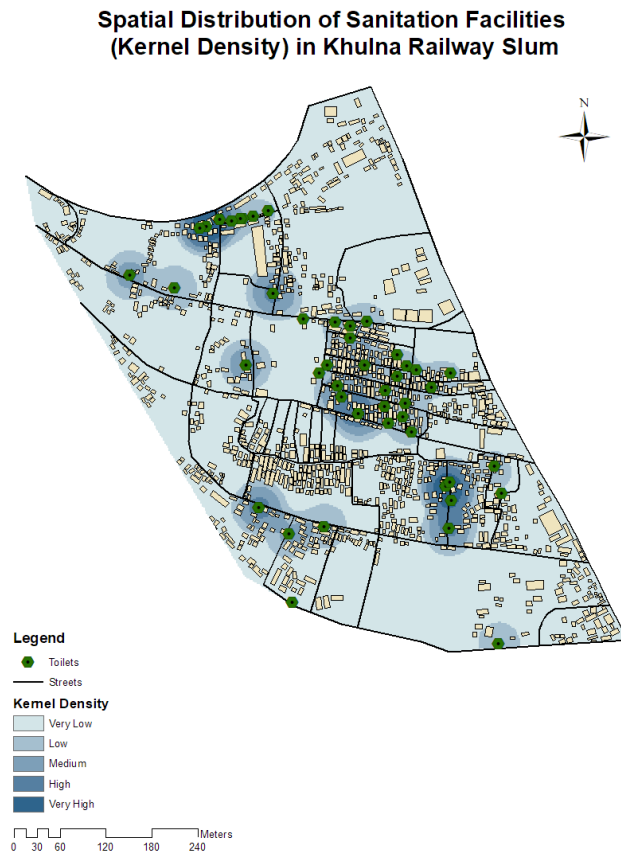


Figure 4: Spatial Distribution of Sanitation Facilities (Kernel Density) in Khulna Railway Slum

3.4 Priority Locations for Sanitation Intervention

To identify households most in need of sanitation interventions, an overlay analysis was conducted by integrating three spatial layers: service area gaps, low-density zones from kernel density estimation (KDE), and proximity to informal waste dumping sites. The household layer was augmented with the outputs from the previous analyses and populated with a score of 1 if it falls outside the 50 m toilet service area, 1 if intersecting very low-density KDE polygons, and 1 if it is located within 10 m of a dumping site; and 0 otherwise; in distinct fields. These fields were aggregated to create a composite PriorityScore ranging from 0 to 3, where higher scores indicate households simultaneously underserved, located in low-coverage areas, and exposed to environmental pollution.



Figure 5: Priority locations for potential sanitation intervention

Mapping the PriorityScore using a graduated color scheme revealed clusters of households requiring targeted sanitation interventions. High-priority households with a PriorityScore of 3 (red) represent the most urgent need, while medium (2, orange) and low (1, yellow) priority households indicate progressively lesser overlap with risk factors. Out of 1,224 households in the Khulna Railway Slum, 51 households (~4.2%) were classified as high priority, 427 households (~34.9%) as medium priority, 435 households (~35.5%) as low priority, and 311 households (~25.4%) had a PriorityScore of 0, indicating adequate sanitation coverage and minimal environmental risk. High and medium-priority households were predominantly located in peripheral and low-density areas. However, one central location with medium-priority households with high density and narrow pathways, lacks sanitation facilities entirely. This analysis highlights the priority zones where sanitation interventions should be prioritized. This analysis provides a household-level, spatially explicit framework to guide targeted interventions and improve equitable access to sanitation within the settlement.

4. DISCUSSION

The overlay analysis integrating service area gaps, low-density KDE zones, and proximity to informal waste dumping sites establishes a novel, spatially explicit framework for identifying households most in need of sanitation intervention. These multi-criteria approach significantly advances traditional methods by moving beyond simple distance measures or facility counts to capture the compounded effects of limited-service coverage, environmental hazards, and population clustering, offering a distinguished and data-driven understanding of vulnerability in informal settlements.

The analysis revealed that a small yet significant portion of households (51 out of 1,224; approximately 4.2%) were classified as high-priority (PriorityScore = 3), indicating simultaneous exposure to three spatial risk factors: location outside the 50 m toilet service area, intersection with low-density KDE zones (i.e., low facility counts relative to population density), and proximity within 10 m of informal waste dumping sites. These households are mostly concentrated in peripheral pockets of the settlement, where irregular road layouts and poor pedestrian connectivity restrict access. Furthermore, medium-priority households (PriorityScore = 2; approximately 34.9%) experience either significantly reduced

coverage or exposure to environmental pollution, while low-priority households (PriorityScore = 1; approximately 35.5%) face single-factor constraints. The remaining one-quarter of households (PriorityScore = 0; approximately 25.4%) benefit from adequate service coverage and minimal environmental risk. This gradation underscores a spatial hierarchy of vulnerability, demonstrating that sanitation interventions must be geographically differentiated to maximize both efficiency and equity.

The convergence of low facility coverage, peripheral location, and environmental hazard proximity amplifies vulnerability. Households outside service areas face longer travel times, discouraging consistent toilet use, while those in low-density KDE zones experience overuse pressure on limited infrastructure. Proximity to waste dumping sites compounds these issues through environmental contamination and heightened exposure to pollution. These quantitative spatial deficiencies are not isolated but directly correspond to health and service quality failures documented in the previous studies in Khulna. The spatial findings confirm the public health outcomes identified in the same settlement. Hoque et al. (2022) found that 63.4% of female respondents in the Khulna Railway Slum used unimproved sanitation facilities, significantly associated with both physical illnesses (e.g., urinary tract infections, diarrhea) and psychological distress. While their research clarifies the consequences of sanitation deprivation, this study identifies the underlying spatial mechanisms, specifically, the 26.5% of households beyond a 50 m walking distance from toilets and the 24.7% located within 10 m of waste dumping sites and polluted waterbodies. The 39.1% of households falling within the highest priority group therefore represent the most at-risk segment, validating the health-based urgency emphasized by Hoque et al. (2022).

The service-quality dimension explored by Shermin and Rahaman (2021) in other Khulna slums reinforces these conclusions. Their SERVQUAL-based assessment recorded critically low reliability (0.27) and responsiveness (0.23) indices due to poor facility maintenance and weak institutional oversight. These qualitative deficits align with the spatial “sanitation deserts” identified in this study, where approximately 34.6% of the area lacks adequate facility coverage. Together, these findings illustrate that physical inaccessibility and under-provisioned service are interdependent dimensions of inequality, where spatial exclusion perpetuates service deficiency, and this deficiency reinforces spatial deprivation. The mapped spatial vulnerabilities also align with broader institutional and pandemic resilience research in the area, revealing that systemic policy failures reinforce persistent inequalities. Akter et al. (2021) reported that, around 16 to 30 households frequently share a single toilet or bathing facility, often resulting in queues of up to 25 minutes. Such overcrowding and shared WASH use significantly heighten disease transmission risks, particularly during crises like COVID-19. This observation directly mirrors the overburdened sanitation hotspots identified in this study’s KDE analysis. Moreover, their finding that 35% of residents travel over 100 m for water underscores the importance of distance in everyday WASH accessibility, precisely the factor operationalized in this study’s 50 m threshold. Complementing this, Khan (2022) highlights that Khulna’s informal settlements face compounded WASH and livelihood hardships. The chronic absence of Khulna Water Supply and Sewerage Authority (WASA) services and the acute shortage of facilities demonstrate institutional neglect (Khan, 2022). These systemic deficiencies help explain the persistent sanitation gaps identified through the PriorityScore approach. Both Akter et al. (2021) and Khan (2022) emphasize that spatial considerations, long overlooked in planning informal settlements, are pivotal to reducing both health and pandemic vulnerabilities.

From a policy perspective, these findings underscore the need to integrate multi-layer spatial assessments into decision-making for informal settlements. Traditional infrastructure planning in Khulna has relied heavily on administrative boundaries and population counts, overlooking spatial accessibility and environmental risk. In contrast, this approach identifies real-world spatial patterns of access, exposure to pollution, and facility demand, enabling evidence-based and equitable resource allocation. By spatially pinpointing where exclusion is most acute, this study complements Khan (2022) policy-level critique with actionable geospatial evidence, specifically identifying where new improved sanitation facilities should be provisioned to serve the most vulnerable households. High-priority households warrant immediate intervention through facility placement that reduces travel distance and

enhances sanitation quality, directly mitigating the health risks identified by Hoque et al. (2022). Medium-priority households could benefit from extended service coverage, improved pedestrian connections, and maintenance upgrades to address the reliability deficits observed by Shermin and Rahaman (2021). Furthermore, the inclusion of environmental pollution data emphasizes the importance of co-locating sanitation improvements with solid waste management strategies to build resilience, aligning with the recommendations of Akter et al. (2021).

The household-level PriorityScore approach thus presents a replicable and contextually adaptable mechanism for maximizing equity and efficiency in sanitation planning. It offers a critical, evidence-based tool for Khulna City Corporation, WASA, and NGOs to operationalize spatial justice in the constrained environments of urban slums. The integration of spatial, health, service-quality, and policy perspectives demonstrates that sanitation inequality in Khulna's informal settlements is not merely a function of poverty, but a consequence of compounded socio-spatial and institutional negligence. By identifying the precise geographic location where these inequities intersect, this study transforms generalized observations of deprivation into actionable planning intelligence. The household-level PriorityScore approach, therefore, represents a critical, replicable tool for operationalizing spatial justice and advancing the broader objective of achieving sustainable and equitable sanitation access in constrained urban informal settings.

5. CONCLUSION

This study utilized a Geographic Information System (GIS)-based approach to quantitatively map and analyze spatial inequalities in sanitation access within the Khulna Railway Slum, a densely populated informal settlement in Khulna, Bangladesh. By integrating field survey data, network analysis, and multi-layer spatial assessments, the research provided a spatially explicit understanding of sanitation coverage gaps, facility demand, and environmental health risks.

The spatial analysis confirmed that access to sanitation in the slum is highly unequal, manifesting across multiple dimensions. The Service Area Analysis revealed that approximately 26.5% of households (324 in total) are located beyond the 50-meter walking distance threshold to an existing toilet facility, predominantly in peripheral and irregular parts of the settlement, leaving about 34.6% of the total area uncovered by sanitation services. The Kernel Density Estimation (KDE) further indicated that sanitation facilities and household demand are heavily concentrated in the central and south-eastern zones, with nearly 78.2% of the slum classified as very low-density areas, signifying both an under-provision of facilities in the peripheries and overstraining in central hotspots. The Proximity Analysis highlighted that roughly 24.7% of households (302 in total) are located within 10 meters of informal waste dumping sites, exposing residents to significant environmental and health risks that exacerbate the challenges of inadequate sanitation. Finally, the Overlay Analysis integrated these spatial dimensions through a multi-criteria PriorityScore, identifying 51 households (approximately 4.2%) as high-priority and 427 households (approximately 34.9%) as medium-priority, collectively representing the area's most in need of targeted sanitation interventions and equitable resource allocation.

6. IMPLICATIONS AND RECOMMENDATIONS

This research validates the use of GIS as a powerful, replicable tool for moving beyond simple population metrics to inform equitable and evidence-based sanitation planning in informal urban settings.

- **Targeted Infrastructure Development:** The high-priority zones, predominantly located in the peripheral areas of the slum, should be the immediate focus, including the medium-priority densely populated central location with no nearby sanitation facility, for provisioning new pucca communal toilet facilities. This targeted approach will reduce travel distances for the most underserved populations and maximize the impact of limited resources.

- **Integrated Intervention Strategy:** Policy efforts must integrate sanitation improvement with solid waste management. Addressing the proximity of households to informal waste dumping sites and polluted waterbodies, is critical to mitigating compounded health risks and enhancing the overall quality of life in the settlement.
- **Network and Access Enhancement:** For medium and low-priority zones, interventions should focus on improving pedestrian pathways and network connectivity to existing facilities, alongside a program for upgrading and regular maintenance to address facility overcrowding and functionality.

In conclusion, this study provides actionable, spatially explicit data that can guide planners in Khulna to develop more equitable and sustainable urban sanitation systems. By addressing the spatial dimensions of inequality, future interventions can be more effective in improving public health outcomes and reducing the inequalities faced by residents of the Khulna Railway Slum.

DECLARATION OF USE OF AI

Generative AI was used in a limited capacity, and under thorough supervision, only during the writing process for improved readability, language refinement, academic tone adjustment, and improving the clarity and flow of the manuscript.

REFERENCES

- Abubakar, I. R. (2017). Access to sanitation facilities among Nigerian households: determinants and sustainability implications. *Sustainability*, 9(4), 547.
- Adams, E. A., Boateng, G. O., & Amoyaw, J. A. (2016). Socioeconomic and demographic predictors of potable water and sanitation access in Ghana. *Social Indicators Research*, 126, 673-687.
- Ahmed, A., Sayeed, A., Tanwi, T. S., Saha, N., Hanson, M., Protyai, D. A., . . . Akter, E. (2023). Trends and inequity in improved sanitation facility utilisation in Bangladesh: Evidence from Bangladesh Demographic and Health Surveys. *BMC Research Notes*, 16(1), 303.
- Akter, S., Hakim, S. S., & Rahman, M. S. (2021). Planning for pandemic resilience: COVID-19 experience from urban slums in Khulna, Bangladesh. *Journal of Urban Management*, 10(4), 325-344.
- Alam, M.-U., Sharior, F., Ferdous, S., Ahsan, A., Ahmed, T., Afrin, A., . . . Hasan, K. (2020). Strategies to connect low-income communities with the proposed sewerage network of the Dhaka sanitation improvement project, Bangladesh: a qualitative assessment of the perspectives of stakeholders. *International Journal of Environmental Research and Public Health*, 17(19), 7201.
- Azage, M., Motbainor, A., & Nigatu, D. (2020). Exploring geographical variations and inequalities in access to improved water and sanitation in Ethiopia: mapping and spatial analysis. *Heliyon*, 6(4).
- Bancalari, A., & Martinez, S. (2018). Exposure to sewage from on-site sanitation and child health: a spatial analysis of linkages and externalities in peri-urban Bolivia. *Journal of Water, Sanitation and Hygiene for Development*, 8(1), 90-99.
- Foster, T., Falletta, J., Amin, N., Rahman, M., Liu, P., Raj, S., . . . Moe, C. (2021). Modelling faecal pathogen flows and health risks in urban Bangladesh: implications for sanitation decision making. *International Journal of Hygiene and Environmental Health*, 233, 113669.
- Ghosh, P., Hossain, M., & Alam, A. (2022). Water, sanitation, and hygiene (WASH) poverty in India: a district-level geospatial assessment. *Regional Science Policy & Practice*, 14(2), 396-417.
- Ghosh, P., Hossain, M., & Sarkar, S. (2023). Inequality among social groups in accessing improved drinking water and sanitation in India: a district-level spatial analysis. *The Professional Geographer*, 75(3), 361-382.
- Gopal, S., Sarkar, R., Banda, K., Govindarajan, J., Harijan, B., Jeyakumar, M., . . . Suresh, C. (2009). Study of water supply & sanitation practices in India using geographic information systems: some design & other considerations in a village setting. *Indian Journal of Medical Research*, 129(3), 233-241.

- Haque, M. N., Islam, M. R., & Ansar, S. B. (2018). Assessing the water supply, sanitation and waste dumping condition of urban slum: a GIS based approach. *The Jahangirnagar Review, Part II: Social Sciences*, 42, 45.
- Hoque, F., Khan, M. A., & Preya, I. J. (2022). Implications of sanitation environment on women's health: a case on railway slum of Khulna city in Bangladesh. *Journal of Science Technology and Environment Informatics*, 12(1), 775-785.
- Hossain, I., Ullah, S. A., & Haque, A. M. (2024). Water and sanitation services at the local government level in Bangladesh: an analysis of SDG 6 implementation status and way forward. *Asia Social Issues*, 17(3), e265358-e265358.
- Jia, P., Anderson, J. D., Leitner, M., & Rheingans, R. (2016). High-resolution spatial distribution and estimation of access to improved sanitation in Kenya. *PLoS One*, 11(7), e0158490.
- Khan, M. (2022). Livelihood, WASH related hardships and needs assessment of climate migrants: evidence from urban slums in Bangladesh. *Heliyon*. 8 (5), e09355. In.
- Matos, R. V., Ferreira, F., Alves, L., Ramos, E., Costa, L., & Matos, J. S. (2021). Multi-Criteria Framework for Selection of City-Wide Sanitation Solutions in Coastal Towns in Northern Angola. *Sustainability*, 13(10), 5627.
- Ntozini, R., Marks, S. J., Mangwadu, G., Mbuya, M. N., Gerema, G., Mutasa, B., . . . Zungu, L. I. (2015). Using geographic information systems and spatial analysis methods to assess household water access and sanitation coverage in the SHINE trial. *Clinical infectious diseases*, 61(suppl_7), S716-S725.
- Othoo, C. O., Dulo, S. O., Olago, D. O., & Ayah, R. (2020). Proximity density assessment and characterization of water and sanitation facilities in the informal settlements of Kisumu city: Implications for public health planning. *Journal of UOEH*, 42(3), 237-249.
- Pan, S., Armitage, N., & van Ryneveld, M. (2018). Assessing equity: a way to improve sanitation service delivery in South African informal settlements. *Journal of Water, Sanitation and Hygiene for Development*, 8(3), 429-438.
- Prabha, A. S., Ram, A., & Irfan, Z. B. (2020). Exploring the relative water scarcity across the Indian million-plus urban agglomerations: an application of the Water Poverty Index. *HydroResearch*, 3, 134-145.
- Shahriar, A. T. M., Mahfuz-ud-Darain, K., & Islam, M. T. (2022). Towards environmentally safe faecal sludge management in informal settlements of bangladesh: A context-sensitive model. *Khulna University Studies*, 104-119.
- Shermin, N., & Rahaman, S. N. (2021). Assessment of sanitation service gap in urban slums for tackling COVID-19. *Journal of Urban Management*, 10(3), 230-241.
- Singh, K. (2014). Mapping poverty to reach the urban poor. *Social Change*, 44(4), 579-591.
- Sphere. (2018). *The Sphere handbook: Humanitarian charter and minimum standards in humanitarian response*. Geneva, Switzerland: Sphere Association.: Sphere Association.
- Trimmer, J. T., Lohman, H. A., Byrne, D. M., Houser, S. A., Jjuuko, F., Katende, D., . . . Guest, J. S. (2020). Navigating multidimensional social–ecological system trade-offs across sanitation alternatives in an urban informal settlement. *Environmental Science & Technology*, 54(19), 12641-12653.
- UN. (2017). Sustainable Development Goal 6: Ensure availability and sustainable management of water and sanitation for all. Retrieved from <https://sdgs.un.org/goals/goal6>
- UNHCR. (2025). Emergency Handbook: Principles and standards for settlement planning. Retrieved from <https://emergency.unhcr.org/emergency-assistance/settlement-and-shelter/guidance-settlements/principles-standards-settlement-planning>
- WHO, & UNICEF. (2023). *Water, sanitation, hygiene, waste and electricity services in health care facilities: progress on the fundamentals. 2023 global report*: World Health Organization.
- Wrisdale, L., Mokoena, M. M., Mudau, L. S., & Geere, J.-A. (2017). Factors that impact on access to water and sanitation for older adults and people with disability in rural South Africa: An occupational justice perspective. *Journal of Occupational Science*, 24(3), 259-279.
- Yuliawati, R., Denny, H., Patriajati, S., & Hanani, Y. (2024). Explore Indonesian Spatial Patterns: Poor House Sanitation and Critical Environmental Disease in East Kalimantan. *The Open Public Health Journal*, 17(1).