The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-5/W4-2025
Philippine Geomatics Symposium (PhilGEOS) 2025 "Enhancing Human Quality of Life through Geospatial Technologies",
24–25 November 2025, Quezon City, Philippines

Dumpsite Inspection Priority Index (DIPI) for Illegal Dumping Monitoring in CALABARZON Using Decision-Making Trial and Evaluation Laboratory, GIS, and Remote Sensing

Mark James J. Broqueza [1], Nathaniel V. Navoa [1], Bienvenido G. Carcellar III [1, 2]

[1] Department of Geodetic Engineering, University of the Philippines Diliman, Quezon City, Philippines - (mjbroqueza, nvnavoa, bgcarcellar)@up.edu.ph
[2] New Space Intelligence Inc. - 329-22 Nishikiwa, Ube, Yamaguchi 755-0151 Japan - bien-carcellar2022@newspaceint.com

Keywords: Dumpsite Prioritization, Decision Support System, Waste Management, Risk Assessment, Illegal Dumping.

Abstract

Illegal dumping of waste persistently threatens environmental sustainability and public health in the CALABARZON region (Cavite, Laguna, Batangas, Rizal, and Quezon), despite the Ecological Solid Waste Management Act and regional waste management initiatives. Rapid urbanization, uneven enforcement, and limited sanitary landfill capacity leave monitoring efforts reactive, sporadic, and resource-constrained. Building on a previously developed graph-based anomaly detection model, which identifies spatial and temporal irregularities in waste disposal patterns from satellite and infrastructure data, this study applies its outputs to develop a decision-support tool for prioritizing illegal dumpsite inspections in CALABARZON. This study introduced the Dumpsite Inspection Priority Index (DIPI), a geospatially grounded, expert-informed decision-support framework to prioritize inspection of illegal dumpsites across the region. Using Decision-Making Trial and Evaluation Laboratory (DEMATEL) method, six spatial and contextual factors were identified and weighted, including proximity to residential areas and frequency of illegal dumping of waste, through expert consultations and spatial datasets: Sentinel satellite imagery, OSM infrastructure data, and monitoring records. Results from computed DIPI scores across 28 sites revealed that 46% fall under High to Critical Priority, indicating widespread but uneven risks. Notably, sites in Batangas, Quezon, and Laguna exhibited both high and low priority levels in proximity, implying localized disparities in land use practices and enforcement. The DIPI enables a transparent, data-driven prioritization tool, addressing inefficiencies in the current framework. To maximize its impact, the study recommends integrating DIPI into centralized digital platforms, addressing data and technological gaps, and strengthening inter-agency coordination to enhance the responsiveness and sustainability of waste governance.

1. Introduction

1.1 Background of the Study

Illegal dumping of wastes remains a persistent problem in the provinces of Cavite, Laguna, Batangas, and Quezon, collectively known as the CALABARZON region, despite legislative frameworks such as the Ecological Solid Waste Management Act (R.A. No. 9003), which mandates comprehensive solid waste management, and regional initiatives like the Solid Waste Enforcement & Education Program (SWEEP). These policies aim to regulate waste disposal and promote environmental stewardship. However, rapid urban growth, insufficient waste management infrastructure, and weak enforcement capacities have allowed illegal dumpsites to continue proliferating. Although 70 illegal open dumpsites were closed since 2017, some sites have resumed dumping activities, and waste generation increased by 14.33% in 2023 alone (Environmental Management Bureau CALABARZON, 2024).

While advances in remote sensing and Geographic Information Systems (GIS) have enhanced the identification and mapping of illegal dumpsites, local governments lack systematic frameworks to prioritize inspection and enforcement efforts. Inspections are typically reactive, sporadic, and inefficient, constrained by limited manpower and financial resources, which undermines the effectiveness of monitoring programs, and without structured prioritization, critical sites that pose the highest environmental and public health risks may receive insufficient attention. To address this gap, this study develops the Dumpsite Inspection Priority Index (DIPI), an integrated decision-support tool that combines environmental, social, and economic factors influencing dumpsite risk. Building upon a previously developed semi-supervised Graph Transformer Neural Network designed to detect illegal dumping activity in CALABARZON using remote sensing and spatiotemporal data, DIPI provides a transparent, multi-criteria prioritization framework to optimize resource allocation and enhance enforcement efficacy, ultimately contributing to more sustainable waste management practices in the region.

1.2 Research Objectives

This study aims to develop a Dumpsite Inspection Priority Index (DIPI) to support the prioritization of illegal dumpsite inspections in CALABARZON. Specifically, it aims to (1) identify and weight key factors affecting dumpsite inspection using expert input and spatial data; (2) compute the DIPI using the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method; and (3) map and analyze patterns in DIPI across the region.

1.3 Research Significance

This study supports the achievement of several Sustainable Development Goals (SDGs), notably SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production). It aligns with Target 11.6, which emphasizes reducing the environmental impact of urban areas through effective solid waste management, and Target 12.5, which promotes the substantial reduction of waste generation through prevention, reduction, and proper disposal. By developing this multi-criterion, geospatially informed index, the study provides a structured tool for improving environmental monitoring and decision-making, aligning policy enforcement with global sustainability objectives.

1.4 Related Literature

Multi-Criteria Decision-Making (MCDM) is a widely used approach for tackling complex waste management problems, such as illegal dumping, by evaluating multiple competing criteria (Eghtesadifard et al., 2020; Gutierrez-Lopez et al., 2023). When combined with Geographic Information Systems (GIS), it enables spatially informed decision-making by integrating environmental, economic, and social data, resulting in more transparent and community-aligned prioritization of dumpsites (Eghtesadifard et al., 2020; Massoud et al., 2023; Sisman & Aydinoglu, 2020).

The process begins with structuring the decision problem, defining objectives, identifying alternatives, and formulating criteria, often in consultation with stakeholders to ensure relevance and inclusivity (Adem Esmail & Geneletti, 2018; Gutierrez-Lopez et al., 2023). Evaluation involves assigning weights to criteria and scoring alternatives using tools such as the Analytic Hierarchy Process (AHP), which handles both qualitative and quantitative inputs (Adem Esmail & Geneletti, 2018; Bafail & Abdulaal, 2022). However, AHP's inability to account for interdependent or uncertain criteria has led researchers to adopt methods like DEMATEL and the Analytic Network Process (ANP), which offer more nuanced modeling of causal relationships and feedback loops (Eghtesadifard et al., 2020; Gutierrez-Lopez et al., 2023). MCDM has been applied in various contexts to identify and prioritize waste sites. De Feo et al. (2014) ranked illegal dumpsites in Italy based on environmental hazards, while Bhowmick et al. (2024) used AHP and GIS in India to select disposal sites considering proximity to water bodies and communities. Massoud et al. (2023) developed a risk-based prioritization model focusing on public health impacts, and Eghtesadifard et al. (2020) combined GIS and MCDM to optimize landfill placement in Iran.

Commonly used criteria reflect sustainability's three pillars. Environmental indicators include proximity to flood-prone areas, drainage networks, slope, and land cover (Bhowmick et al., 2024; Eghtesadifard et al., 2020). Economic factors, such as transport cost and land value, ensure financial feasibility (Eghtesadifard et al., 2020). Social criteria, including proximity to residential areas, schools, and perceived visibility, address health risks and social acceptability (Gutierrez-Lopez et al., 2023; Jakeni et al., 2024). Other MCDM techniques like TOPSIS, COPRAS, and Fuzzy Logic are also used, each suited to different decision complexities (Bafail & Abdulaal, 2022; Sisman & Aydinoglu, 2020). Combining methods, such as using AHP for weighting and TOPSIS for ranking, can enhance decision robustness (Bafail & Abdulaal, 2022; Eghtesadifard et al., 2020).

Despite their strengths, MCDM applications face challenges such as limited data, difficulty quantifying social impacts, and ensuring meaningful stakeholder engagement. Addressing these issues is vital for developing waste management strategies that are not only technically sound but also socially responsive (Adem Esmail & Geneletti, 2018; Gutierrez-Lopez et al., 2023).

2. Methodology

2.1 Study Area

The CALABARZON region remains a focal point for environmental governance due to its continued struggle with illegal waste disposal despite extensive cleanup and policy initiatives (Figure 1). Although 70 open dumpsites have been closed since 2017, the reopening of seven sites and persistent reports of informal dumping indicate the limitations of current enforcement mechanisms (EMB CALABARZON, 2024). With only 48 operational sanitary landfills serving a rapidly urbanizing population, LGUs face significant challenges in monitoring and prioritizing illegal dumpsite inspections across geographically and socioeconomically diverse municipalities. The region's administrative complexity and varying accessibility of sites necessitate a spatial decision-support system for inspection prioritization. As such, CALABARZON provides an ideal setting enabling the integration of spatial, environmental, and economic factors to support evidence-based resource allocation and targeted enforcement.

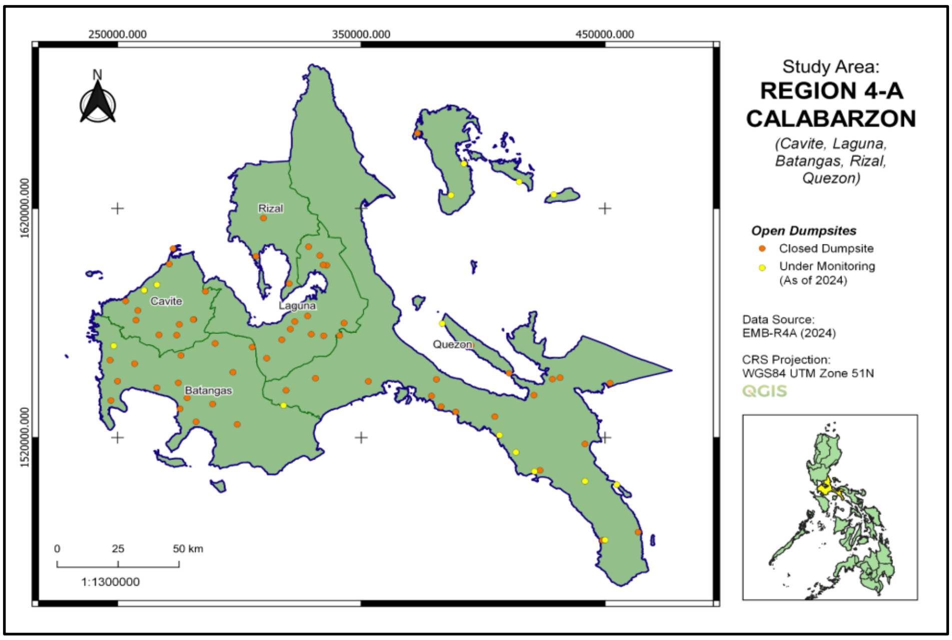

Figure 1. Study Area and Distribution of Open Dumpsites in the CALABARZON region.

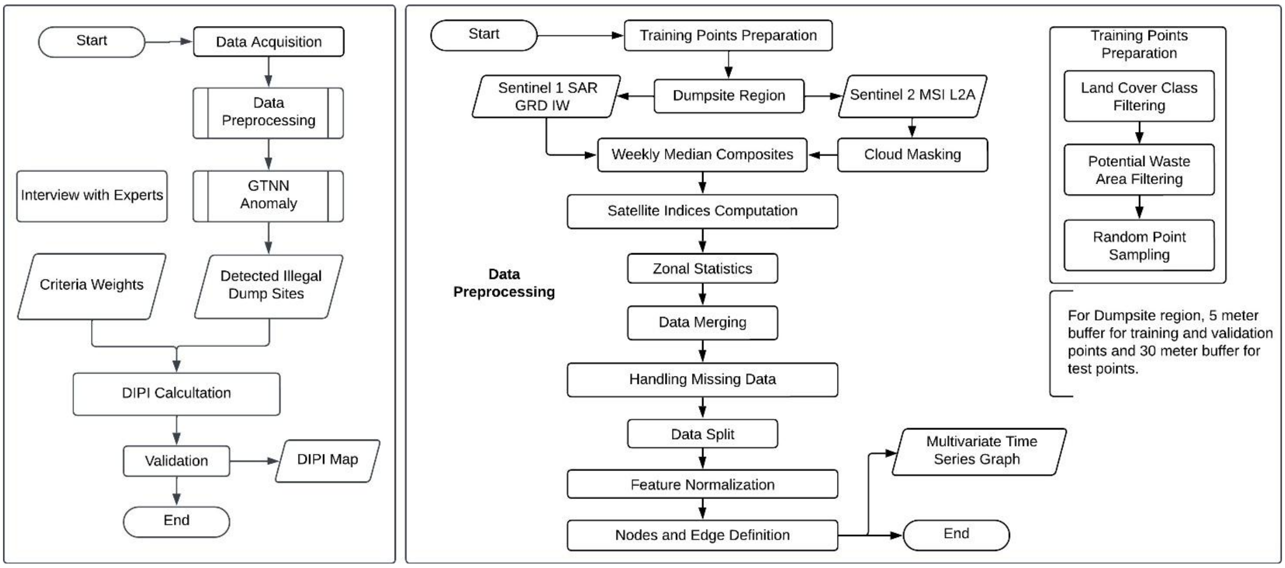

Figure 2. General Methodology Flowchart and Detailed Data Preprocessing Workflow.

2.2 Data Acquisition

Figure 2 illustrates the general methodology flowchart along with the detailed data preprocessing workflow used in this study. The prioritization framework employed an integrated geospatial dataset combining remote sensing, vector data, and official records. Sentinel-1 SAR and Sentinel-2 MSI imagery, acquired via GEE from July 2019 to June 2021, were used to spatially characterize the environmental context of illegal dumping sites of waste across CALABARZON. The radar and optical imagery provided consistent and high-resolution information on land surface dynamics, vegetation cover, and potential dumping activity, supporting the environmental risk component of the prioritization index.

Land cover classification was based on the 2020 NAMRIA Land Cover Map, which was used to identify sensitive or exposed areas such as forests, water bodies, and built-up zones. This served as a reference for environmental sensitivity scoring within the index. OpenStreetMap (OSM) contributed proximity-based indicators crucial to logistical feasibility assessment, specifically, euclidean distances of each site to roads, residential areas, water networks, and public facilities. These metrics were integrated as spatial risk factors that influence the likelihood of waste site recurrence, human exposure, and inspection accessibility.

A comprehensive inventory of historical and active dumping sites was obtained from the DENR-EMB CALABARZON, including metadata such as geographic coordinates, classification (e.g., open or controlled), monitoring status, and closure dates under the Safe Closure and Rehabilitation Program (SCRP). These records were essential in identifying inspection targets and verifying model outputs and served as the foundation for constructing the prioritization dataset.

Expert input was systematically gathered from a diverse group regional and provincial solid waste management officers in CALABARZON. Participants included personnel involved in various roles such as planning, enforcement, data management, and field inspections, ensuring representation from different functional perspectives and geographic areas within the region. Structured interviews and detailed questionnaires were employed to capture comprehensive insights into operational challenges, priority factors, and resource constraints. This approach ensured that the prioritization factors and their relative weights reflected a broad and inclusive institutional understanding rather than a limited or homogeneous viewpoint. The collected qualitative and quantitative data were then analyzed using the DEMATEL method, integrating both geospatial and institutional dimensions to develop the DIPI, tailored specifically to local enforcement contexts.

Anomaly detection scores from a Graph Transformer Neural Network (GTNN) were included in the prioritization framework due to its strength in capturing complex spatial-temporal patterns. This graph-based model effectively identifies irregularities in waste disposal using satellite and infrastructure data.

2.3 Data Preprocessing

2.3.1 Illegal Dumpsite Definition: Spatial data on illegal dumpsites in CALABARZON were sourced from DENR-EMB monitoring records, which provided site locations, status, and classifications critical for modeling the DIPI. Illegal dumpsites, as defined by RA 9003, are open disposal sites lacking proper environmental controls, posing significant health and ecological risks, and are legally mandated for closure and rehabilitation. Due to the absence of consistent boundary delineations and the irregular, dispersed nature of dumping areas, single point locations inadequately represent their spatial extent. To address this, a 5-meter buffer was applied around each site to approximate the affected area and capture relevant environmental context, balancing spatial generalization and accuracy under data constraints. This buffering approach, preferred over complex boundary delineation in the absence of high-resolution imagery, enables effective spatial overlay and prioritization analyses of proximity and landscape risk factors. All spatial processing was performed using UTM projection (EPSG:32651) for precise distance measurement, then reprojected to EPSG:4326 to ensure compatibility with other geospatial datasets, thereby supporting robust monitoring and risk assessment of illegal dumping of waste activities.

2.3.2 Satellite Data Preprocessing: Sentinel-1 SAR data were obtained from the COPERNICUS/S1_GRD collection via Google Earth Engine, providing analysis-ready imagery that had been radiometrically calibrated and terrain-corrected. To account for topographic effects and ensure consistent backscatter interpretation, normalization was applied to the VV and VH polarizations using the local incidence angle. This correction aligned backscatter responses to a standard reference angle of 35°, improving comparability across varied terrain. Additionally, the Radar Vegetation Index (RVI) was derived from dual-polarized bands (VV and VH) to characterize vegetation structure, useful for detecting disturbances such as clearing, exposure, or dumping activity.

Sentinel-2 Level-2A surface reflectance imagery, preprocessed through ESA's Sen2Cor processor, was also accessed via Google Earth Engine. To improve the accuracy of surface analysis, cloud and shadow masking were performed using the Scene Classification Layer (SCL). From these corrected images, multiple spectral indices were computed to assess land cover and environmental conditions. These included the Normalized Difference Vegetation Index (NDVI) and Modified Soil-Adjusted Vegetation Index (MSAVI) for assessing vegetation health, the Normalized Difference Built-up Index (NDBI) for detecting built-up areas, and the Normalized Difference Water Index (NDWI) and Modified NDWI (MNDWI) for identifying water bodies and soil moisture. The Normalized Difference Bareness Index (NDBaI) highlighted bare soil, the Normalized Difference Tillage Index (NDTI) detected soil disturbance, and the Normalized Difference Index using red-edge and red bands (NDI45) captured subtle vegetation stress and surface changes.

Spatial statistics (mean, minimum, maximum, and standard deviation) of the indices were calculated within 5-meter buffers around known and potential dumpsites. These summaries detailed surface conditions, aiding anomaly detection related to waste. The processed satellite data were then integrated into the analytical framework to support spatial prioritization for the DIPI.

2.3.3 Graph-based Input Preparation: Spatiotemporal data points were structured into a graph format as part of the Graph Transformer Neural Network (GTNN) anomaly model. The satellite data were fused through their matched 10-meter pixel spacing and resolution for precise spatial alignment, with weekly compositing approach based on the ISO 8601 standard, anchoring each composite to Monday as the start of the week. This approach maximized temporal coverage and reduced noise from irregular revisit schedules. In this structure, each site and time step became a node with features from the data fused SAR and Sentinel-2 datasets, in which complex temporal and spatial patterns of waste dumping were learned and analyzed. Furthermore, anomaly scores were generated by the GTNN model based on deviations from normal spatiotemporal patterns observed in the input data. These scores quantified the likelihood of a site exhibiting unusual environmental behavior, serving as a key factor in ranking inspection priority under the DIPI framework.

2.4 DEMATEL-DIPI

The DIPI framework combines stakeholder-informed criteria and environmental data to prioritize illegal dumpsites for inspection. At its core are six interrelated factors selected from regulatory guidance (EMB IV-A, NSWMC, JICA), stakeholder consultations, and relevant literature. These factors span environmental, social, and economic dimensions (Table 1).

While the DIPI framework prioritizes observable spatial risks for scalability and data reliability, Factors 1 to 4, it may also capture systemic patterns through the anomaly detection scores, Factor 5 and 6, which reflects unusual dumping behaviors over time. Although social behavioral and governance-related drivers are not explicitly modeled, they may be indirectly represented.

Factor	Description
1	***Proximity to Residential Areas***. Indicates health and safety risks to nearby populations.
2	***Proximity to Water Bodies.*** Reflects the potential for contamination of aquatic systems.
3	***Distance from Waste Facility.*** Captures infrastructural inaccessibility that may drive illegal dumping of waste.
4	***Proximity to Main Roads.*** Highlights easily accessed yet poorly monitored areas prone to dumping.
5	***Anomaly Detection Score.*** Indicates the probability that illegal waste dumping was present in the area.
6	***Frequency of Illegal Dumping***. Calculated as the average weekly anomaly score to indicate recurrence probability.

Table 1. Description of Factors Used in Dumpsite Inspection Priority Index (DIPI) Computation.

Given the interdependencies among criteria, DEMATEL was used to assign weights, as it reveals causal relationships and avoids assuming independence among factors, unlike AHP, which becomes less effective in such contexts. It begins with the construction of a Direct Influence Matrix, where experts assess the degree to which one criterion directly affects another using a predefined scale. This matrix is then normalized to ensure comparability, followed by the computation of a Total Influence Matrix (T), which captures both direct and indirect influences among criteria (Equation 1). Each element t_{ij} in T represents the total influence of criterion i on criterion j.

$$T = \sum_{i=1}^{\infty} N^k = N(I - N)^{-1} \quad (1)$$

where $T = \text{Total Influence Matrix}$
$N = \text{Normalized Direct} - \text{Relation Matrix}$
$I = \text{Identity Matrix}$
$(I - N)^{-1} = \text{Cumulative Indirect Influences}$

From the Total Influence Matrix, two key metrics are derived: Prominence and Relation. Prominence (P_i) represents the total involvement of a criterion in the system (Equation 2). It is the sum of its influence on others and the influence it receives. This reflects the overall importance of the criterion in the decision-making context. Relation, in contrast, highlights the directional influence of a criterion (Equation 3). A positive Relation (R_i) value indicates that a criterion primarily influences others, while

This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLVIII-5-W4-2025-47-2026

a negative value suggests it is more influenced by them. These values offer insight into both the strength and role of each criterion within the broader network.

$$P_i = \sum_{j=1}^{n} t_{ij} + \sum_{j=1}^{n} t_{ji} \quad (2)$$

$$R_i = \sum_{j=1}^{n} t_{ij} - \sum_{j=1}^{n} t_{ji} \quad (3)$$

where P_i = Prominence of criterion i
R_i = Relation of criterion i
n = Total number of criteria
t_{ij} = Influence of criterion i to j
t_{ji} = Influence of criterion j to i

Using the Prominence and Relation values, the influence-based weights for each criterion are calculated. These weights are then applied in the final stage of the model to compute the DIPI, where W_i represents the weight of the *i*-th criterion, X_i is the normalized score of the *i*-th criterion for a specific dumping site, and *n* is the total number of criteria. This allows for a prioritized ranking of illegal dumpsites based on the cumulative influence and significance of each criterion (Equation 4).

$$DIPI = \sum_{j=1}^{n} (W_i \times X_i) \quad (4)$$

where $DIPI$ = Dumpsite Inspection Priority Index
W_i = Weigth of the $i-$ th criterion
X_i = Weigth of the $i-$ th criterion
t_{ij} = Influence of criterion i to j

DIPI	Interpretation
0.00 – 0.20	***Very Low Priority***. Site poses minimal concern; routine monitoring may suffice.
0.21 – 0.40	***Low Priority.*** Minor issues detected; inspection not urgent.
0.41 – 0.60	***Moderate Priority.*** Moderate concern; schedule for regular inspection.
0.61 – 0.80	***High Priority*** Significant indicators of risk; inspection should be prioritized soon.
0.81 – 1.00	***Critical Priority.*** Immediate concern where site requires urgent inspection and possible intervention.

Table 2. Description of Factors Used in Dumpsite Inspection Priority Index (DIPI) Computation.

For simpler interpretation, the classification thresholds were initially set using an equal-width binning approach over the normalized DIPI range [0, 1], ensuring interpretability and consistent scaling (Table 2). While equal binning may not reflect the actual distribution of risk severity, it provides a baseline categorization structure that can be refined over time. Future versions may adopt stakeholder-driven thresholding to better align class boundaries with observed risk patterns.

2.5 Stakeholder Post-Consultation

To assess the reliability and practical applicability of the DIPI, a follow-up post-consultation was conducted with a senior domain expert in solid waste management. This session involved an in-depth review of the computed priority rankings and criteria relevance, as well as a discussion on operational challenges and contextual factors affecting waste monitoring in CALABARZON. The expert provided constructive feedback on how the index aligns with on-ground realities and offered recommendations for its integration into existing workflows and decision-making processes. This consultative step was crucial for validating the model outputs and enhancing the inclusivity and responsiveness of the framework.

3. Results and Discussion

3.1 Weights derived from DEMATEL

The prioritization framework was developed using empirical data from documented illegal dumping sites of waste and expert input. Eleven environmental officers and waste management personnel from the Provincial Environment and Natural Resources Office (PENRO) and the Environmental Management Bureau Region IV-A (DENR EMB-R4A) participated in the evaluation through assessment of direct influence of each criterion on the others using a standardized 0–3 scale (0 = no influence, 3 = very high influence), providing the basis for the DEMATEL-based analysis.

The causal relationship analysis reveals that "Frequency of Illegal Dumping" is the most prominent and influential factor, determined by its Prominence value, underscoring its critical role in prioritizing inspections and its capacity to affect other criteria (Table 3). Meanwhile, Relation determines if the factor is causative or reactive. Factors such as "Distance from Waste Facility" and "Proximity to Main Roads" exhibited positive Relation values, marking them as causal drivers. These infrastructural elements may actively shape waste dumping behaviors by enabling or discouraging waste disposal. Conversely, "Anomaly Detection Score", with the most negative Relation, is a reactive indicator, influenced by other factors and thus best used as a signal rather than a root cause. The prominence of "Proximity to Residential Areas" and "Water Bodies" suggests they are essential for assessing impacts, although they are more responsive than directive.

These findings imply that effective monitoring should not only consider reactive signs of dumping but also address root infrastructural and behavioral causes to pre-emptively mitigate risks.

From Table 4, "Frequency of Illegal Dumping" receives the highest weight (0.18153), affirming its role as the most central and influential driver of inspection priority. This suggests that past and recurring dumping behavior is a strong signal for future risk, and thus, a key basis for allocating enforcement efforts. Following closely is "Proximity to Residential Areas" (0.16954), highlighting the emphasis placed on protecting human health. However, its slight edge over "Proximity to Water Bodies" (0.16827) and "Distance from Waste Facility" (0.16694) suggests that infrastructural drivers of dumping may be under-emphasized.

Factor	D	R	D + R (Prominence)	D – R (Relation)	Interpretation
Proximity to Residential Areas	8.78212	8.84085	17.62297	-0.05873	Highly involved, but more influenced than influencing.
Proximity to Water Bodies	8.73324	8.75773	17.49097	-0.02449	Responsive but central to the overall structure.
Distance From Waste Facility	8.77655	8.57650	17.35305	0.20005	A net influencer, operational driver.
Proximity to Main Roads	8.22283	7.62262	15.84546	0.60021	Strong net influencer, logistical concern.
Anomaly Detection Score	7.96149	8.80265	16.76414	-0.84116	Primarily reactive, significantly influenced.
Frequency of Illegal Dumping	9.49668	9.37257	18.86925	0.12411	The most prominent and influential criterion.

Table 3. Causal Relationship Metrics of DIPI Criteria based on DEMATEL.

Factor	Weight
Proximity to Residential Areas	0.16954
Proximity to Water Bodies	0.16827
Distance From Waste Facility	0.16694
Proximity to Main Roads	0.15244
Anomaly Detection Score	0.16128
Frequency of Illegal Dumping	0.18153

Table 4. Final Weights of DEMATEL-DIPI Criteria.

Interestingly, “Anomaly Detection Score” (0.16128), despite its potential to provide near-real-time evidence of illegal activity, ranks lower, possibly reflecting skepticism over data reliability or its reactive nature, as supported by the DEMATEL relation values. The relatively lowest weight given to “Proximity to Main Roads” (0.15244), despite its strong causal role, may signal a gap in aligning logistical concerns with enforcement strategies. Overall, while the framework balances social, environmental, and operational dimensions, the weights hint at a conservative approach that favors observable, proximity-based risks over predictive or systemic factors, which may limit responsiveness to emerging or hidden threats.

3.2 Dumpsite Inspection Priority Index

Among the 28 evaluated sites, 13 locations (46%) fall under High to Critical Priority, indicating a significant proportion of areas that demand urgent or near-term inspection due to signs of illegal waste dumping or environmental threats (Figure 3). Notably, 6 sites fall in the Critical Priority (DIPI ≥ 0.81) rang3e, reflecting conditions that may require immediate field verification and responsive action. In contrast, only 5 sites (18%) fall under Very Low Priority (DIPI ≤ 0.20), suggesting that few areas are entirely free of concern. The rest are divided between Moderate and Low Priority, implying that timely inspections and preventive monitoring can still mitigate worsening conditions in these zones. This spread reflects a region-wide but uneven distribution of risk across CALABARZON, emphasizing the need for a targeted inspection strategy that prioritizes the most vulnerable areas without neglecting early warning signals in moderate-priority locations.

A closer look at the spatial distribution reveals that Quezon, Batangas, and Laguna dominate both the highest and lowest DIPI scores, pointing to intra-provincial disparities in environmental risk. For example, Critical Priority sites like Burdeos (Quezon) and Calaca (Batangas) exist near Low or Very Low Priority neighbors like Padre Burgos (Quezon) and Calatagan (Batangas), suggesting that proximity alone does not predict risk, and that localized land use, enforcement, or dumping practices heavily influence DIPI levels. Consequently, clusters of moderate to high-priority sites appear in southeastern Quezon and southern Laguna, hinting at potential regional hotbeds of concern. The presence of adjacent barangays or towns with differing DIPI scores further underscores the importance of fine-scale, LGU-specific interventions over broad regional policies. Moreover, repeated locations such as Dahican in Catanauan highlight potential hotspots requiring continued observation or deeper contextual investigation.

In Table 5, the top 10 anomaly-prone sites show that Magahis (Tuy, Batangas) and Ibabang Palina (Liliw, Laguna) recorded the highest anomaly frequency, each with a 17.39% anomaly rate, suggesting persistent or recurring illegal dumping of waste activities. These hotspots warrant immediate attention and possibly targeted interventions, such as community enforcement, surveillance, or waste management reforms. Meanwhile, Quezon and Laguna dominate the list, with multiple entries each, indicating a broader geographic pattern of concern.

Dumpsite	No. of Anomaly	Anomaly Rate %
Magahis, Tuy	4	17.39
Ibabang Palina, Liliw	4	17.39
1st District, Jalajala	3	13.04
Sildora, Agdangan	2	8.7
Poblacion, Jomalig	2	8.7
Wasay Ibaba, Buenavista	2	8.7
Daniw, Victoria	2	8.7
Salubungan, Siniloan	2	8.7
Dalipit East, Cuenca	1	4.35
Cemetery, Novelata	1	4.35

Table 5. Top 10 Sites with Highest Detected Anomalies.

Although most anomaly rates are below 10%, even lower-frequency sites like Cemetery (Novelata, Cavite) may represent emerging risks and should be closely monitored. This distribution reinforces the value of anomaly-based prioritization for efficient inspection scheduling and localized environmental governance. Building on these spatial insights, the DIPI framework offers a structured decision-support tool that integrates DEMATEL-based causal analysis with GIS-MCDM. By accounting for interdependencies among criteria, it more accurately reflects real-world complexity than traditional, independent-factor models. This enables decision-makers to pinpoint not only the most critical factors but also how they interact, supporting more informed and adaptive planning. The DIPI’s flexibility, through context-specific weighting and stakeholder engagement, further enhances its utility in multi-scenario infrastructure planning, especially in dynamic and evolving environments.

https://doi.org/10.5194/isprs-archives-XLVIII-5-W4-2025-47-2026

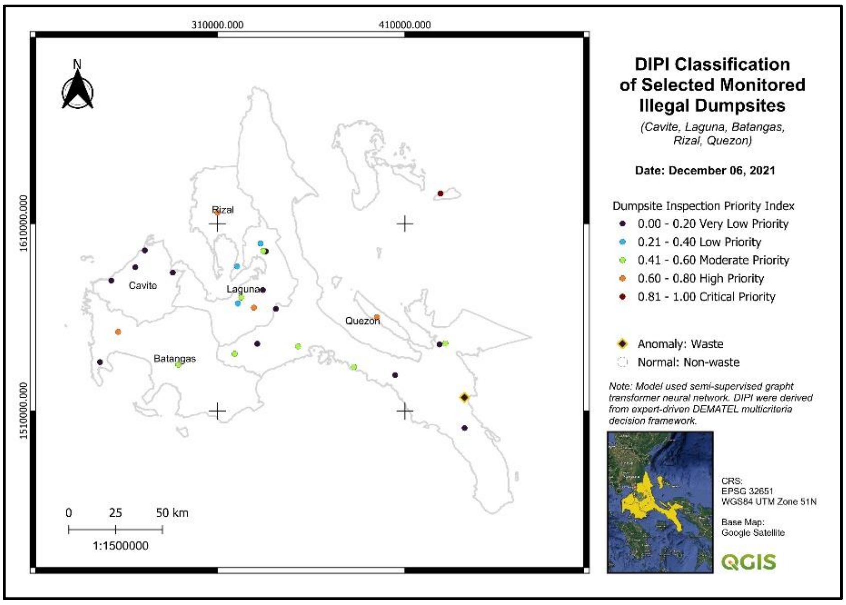

Figure 3. DIPI Classification of Selected Monitored Illegal Dumpsites (Date: December 06, 2021).

3.3 Challenges, Current Status, and Pathways Forward

Post-analysis consultations with monitoring personnel and experts revealed three key, interconnected challenges in CALABARZON's solid waste management: data limitations, technological constraints, and institutional capacity. A key obstacle is the lack of reliable and accessible waste management data. Many critical records, such as dumpsite status, closures, and inspection histories, remain fragmented or paper-based, hindering both real-time monitoring and long-term analysis. While digitalization efforts have begun, they are fragmented, with persistent data silos, limited centralized access, and infrequent updates that prevent timely, data-driven responses.

Technological adoption remains limited due to minimal training, low technical capacity, and the lack of user-friendly, locally adapted systems. This leads many field personnel to rely on manual reporting, causing delays, inconsistent responses, and missed opportunities for early intervention. Addressing these challenges requires improved infrastructure, ongoing training, and user-centered system design tailored to local needs. Smart city or smart region initiatives offer a scalable solution by enabling real-time reporting from both monitoring staff and citizens. However, their success depends on institutional readiness, inter-agency coordination, and enhanced digital access and literacy, especially in rural areas, to support inclusive and responsive waste monitoring.

Furthermore, spatial disparities in inspection coverage further reflect operational constraints. The region's varied geography, from coastal Quezon to upland Batangas and Rizal, creates logistical barriers for routine site visits, especially in remote or hard-to-reach areas. Weak digital connectivity in rural zones exacerbates the problem, limiting real-time data transmission. These disparities are not the result of urban-centric bias, but of resource-driven decisions. Urbanized areas like Cavite often receive more attention due to higher complaint volumes and easier access, while smaller LGUs lack full-time inspection staff, leading to inconsistent coverage. Consequently, some high-risk zones remain under-monitored, not due to lower urgency, but due to limited operational capacity.

Despite challenges, the study found strong alignment between DIPI outputs and the monitoring office's identification of hotspot areas, indicating the tool's relevance and potential for operational integration. Embedding DIPI into a centralized, continuously updated system could enhance inspection prioritization, resource allocation, and decision-making transparency. Stakeholder feedback also showed strong interest in such digital innovations. To move forward, it is recommended to digitize and consolidate legacy records into an accessible database, customize digital tools for local use, implement capacity-building programs for sustained engagement, and foster collaboration among local agencies, technical teams, and communities. These steps can transform the current reactive, fragmented system into a proactive, integrated, and data-driven waste management approach.

3.4 Limitations

This study faces several limitations that impact its scope and robustness. Data availability was a significant constraint, with gaps and inconsistencies in official records limiting comprehensive analysis. Time and financial resources also restricted the ability to conduct extensive field validation, such as site inspections and waste characterization surveys, which would have strengthened empirical verification of the model's predictions. Additionally, limited participation and response from some municipalities, often due to the lack of updated contact information or institutional capacity, hindered broader stakeholder engagement and feedback. These challenges, combined with reliance on secondary data sources and partial digital records, highlight the need for more integrated data management and increased collaboration in future research to enhance the accuracy and applicability of the findings. Consequently, these limitations may affect the validity and precision of the results, and thus, the findings should be interpreted with appropriate caution.

4. Conclusion

The Dumpsite Inspection Priority Index (DIPI) offers a data-driven framework to enhance strategic and transparent monitoring of illegal dumpsites in CALABARZON. Building on anomaly detection outputs, it translates machine learning insights into practical decision support. By integrating expert input, spatial data, and multi-criteria analysis, DIPI addresses inefficiencies in reactive monitoring systems, enabling prioritized inspections based on a comprehensive view of environmental, social, and infrastructural risks. Application of the index to 28 monitoring sites revealed that 46% fall under the High to Critical Priority categories for December 6, 2021, reflecting significant spatial heterogeneity in risk levels across the region. Sites such as Magahis in Tuy, Batangas and Ibabang Palina in Liliw, Laguna were flagged for urgent attention due to recurring anomalies and elevated risk indicators. This spatial variability suggests that illegal dumping is shaped by localized dynamics, including population proximity, land use, accessibility, and enforcement presence, indicating that uniform policy interventions may be insufficient without localized diagnostics and tailored response mechanisms.

The analysis of factor influence, derived from the DEMATEL method, further elucidated structural interdependencies within the decision framework. “Frequency of Illegal Dumping” emerged as the most influential and weighted factor, followed by proximity to residential areas and water bodies, emphasizing both environmental and public health dimensions. While these factors function as primary drivers, others such as anomaly detection and access to roads serve more symptomatic or reactive roles, reinforcing the importance of addressing upstream causes. The study also identified barriers to effective waste monitoring, including limited historical data, outdated databases, and capacity gaps in geospatial tool use at the local level. Nonetheless, the DIPI’s alignment with local field knowledge highlights its practical value and adaptability, and with institutional support, it could serve as a scalable model for similar environmental enforcement contexts.

A key limitation of this study is the current lack of empirical validation to confirm the model’s predictions. To address this, validation can be pursued through field-based ground truthing, such as site inspections and waste characterization surveys, to verify high-priority illegal dumpsites, while complementary datasets, including municipal waste management records and community reports, could support comparative analysis. To enhance the framework’s ability to address upstream drivers of illegal dumping, future iterations of DIPI may incorporate behavioral, governance, or socio-economic indicators alongside geospatial factors. Integrating such data can improve risk interpretation and intervention design, especially in areas where institutional capacity or public waste practices influence dumping behavior. Furthermore, future work should refine the thresholding methodology by combining statistical distribution analysis with proactive stakeholder input. Adaptive binning techniques guided by machine learning or expert elicitation can better capture true risk gradients, hence, improving the sensitivity and contextual accuracy of the prioritization framework and aligning thresholds more closely with local conditions and operational needs.

To strengthen the representativeness and robustness of the prioritization model, future iterations should expand expert participation to include a broader range of stakeholders across all administrative levels, from regional to barangay units. Involving practitioners with firsthand knowledge of local conditions and site-level waste issues would enrich the analysis and enhance the contextual validity of the criteria and influence assessments. Finally, to ensure the long-term effectiveness of the DIPI framework, it should be integrated into a centralized digital monitoring system with regular data updates, improved inter-agency sharing, and enhanced technical capacity, especially at the LGU level. Strengthened collaboration between DENR, EMB, and local stakeholders is vital for real-time response, data continuity, and embedding environmental intelligence into governance. Ultimately, these measures will increase inspection efficiency and support a proactive, risk-based approach to illegal waste management, fostering sustainable and resilient communities.

References

Adem Esmail, B., Geneletti, D., 2018. Multi-criteria decision analysis for nature conservation: A review of 20 years of applications. *Methods in Ecology and Evolution*, *9*(1), 42–53. doi.org/10.1111/2041-210X.12899.

Bafail, O.A., Abdulaal, R.M.S., 2022. A Combined BWM-TOPSIS Approach Versus AHP-TOPSIS Approach: An Application to Solid Waste Management. *2022 The 3rd International Conference on Industrial Engineering and Industrial Management*, 27–33. doi.org/10.1145/3524338.3524343.

Bhowmick, P., Das, S., Das, N., 2024. Identification of suitable sites for municipal waste dumping and disposal using multi-criteria decision-making technique and spatial technology: A case of Bolpur municipality, Birbhum district, West Bengal. *Waste Management Bulletin*, *2*(1), 250–265. doi.org/10.1016/j.wmb.2024.02.001.

De Feo, G., Cerrato, F., Siano, P., Torretta, V., 2014. Definition of a multi-criteria, web-based approach to managing the illegal dumping of solid waste in Italian villages. *Environmental Technology*, *35*(1), 104–114. doi.org/10.1080/09593330.2013.816328.

Eghtesadifard, M., Afkhami, P., Bazyar, A., 2020. An integrated approach to the selection of municipal solid waste landfills through GIS, K-Means and multi-criteria decision analysis. *Environmental Research*, *185*, 109348. doi.org/10.1016/j.envres.2020.109348.

Environmental Management Bureau CALABARZON, 2024. *Annual Report 2023*.

Gutierrez-Lopez, J., McGarvey, R.G., Costello, C., Hall, D.M., 2023. Decision Support Frameworks in Solid Waste Management: A Systematic Review of Multi-Criteria Decision-Making with Sustainability and Social Indicators. *Sustainability*, *15*(18), 13316. doi.org/10.3390/su151813316.

Jakeni, Y., Maphanga, T., Madonsela, B.S., Malakane, K.C., 2024. Identification of Illegal Dumping and Community Views in Informal Settlements, Cape Town: South Africa. *Sustainability*, *16*(4), 1429. doi.org/10.3390/su16041429.

Massoud, M.A., Abdallah, C., Merhbi, F., Khoury, R., Ghanem, R., 2023. Development and application of a prioritization and rehabilitation decision support tool for uncontrolled waste disposal sites in developing countries. *Integrated Environmental Assessment and Management*, *19*(2), 436–445. doi.org/10.1002/ieam.4665.

Sisman, S., Aydinoglu, A.C., 2020. Using GIS-Based Multi-Criteria Decision Analysis Techniques in the Smart Cities. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLIV-4/W3-2020, 383–389. doi.org/10.5194/isprs-archives-XLIV-4-W3-2020-383-2020.