Journal of Science and Technology in Civil Engineering, HUCE, 2025, 19 (4): 46–57

UTILIZING UNMANNED AERIAL VEHICLES AS A LOW-COST SURVEYING METHOD FOR LANDFILL MANAGEMENT: A CASE STUDY AT QUANG LOI

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Article history:
Received 29/9/2025, Revised 14/12/2025, Accepted 23/12/2025

Abstract

Landfilling remains the primary method of municipal solid waste (MSW) management in Vietnam, particularly in rural areas, where small, unsanitary landfills lack monitoring systems. Traditional ground-based survey methods are costly, time-consuming, and pose safety risks, leading to a lack of crucial data for landfill management and environmental control. This study presents a low-cost unmanned aerial vehicle (UAV) photogrammetry method to assess the current status and propose appropriate management solutions for the Quang Loi landfill in Thua Thien Hue province. High-resolution orthophotos and a digital surface model were generated, allowing for accurate estimation of waste volume (82,200 m^3) and remaining capacity (60,000 m^3). At the current waste inflow rates, the landfill is projected to be full within 5-7 years. UAV imagery also revealed operational deficiencies, including a lack of daily cover, limited compaction, inadequate stormwater management, and widespread exposed plastic waste. A phased remediation and closure strategy is proposed to mitigate environmental risks. Overall, the results confirm that UAV photogrammetry provides a reliable, cost-effective, and integrated framework for holistic volumetric, operational, and environmental risk assessment for supporting informed landfill management decisions.

Keywords: UAV photogrammetry; landfill management; waste volume estimation; environmental risk assessment.

https://doi.org/10.31814/stce.huce2025-19(4)-04

1. Introduction

Landfilling continues to be the predominant method of municipal solid waste (MSW) disposal worldwide, particularly in low- and middle-income countries (LMICs) where advanced waste treatment technologies such as incineration, composting, or anaerobic digestion remain economically or technically inaccessible [1]. Globally, more than 70 % of solid waste is still deposited in landfills, making them the most widespread waste management solution, ranging from engineered facilities to non-engineered dumpsites. However, the environmental sustainability of landfilling is increasingly questioned. Poorly managed or non-engineered landfills represent major environmental threats, contributing to greenhouse gas (GHG) emissions, uncontrolled leachate infiltration, odor nuisance, and long-term soil and groundwater contamination [2, 3]. As cities and rural areas struggle with rising waste generation, the lack of reliable data on landfill conditions exacerbates risks and hinders the planning of rehabilitation or closure strategies.

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Vietnam exemplifies these challenges. According to the Ministry of Natural Resources and Environment [4], over 70 % of the country's MSW is disposed of in landfills, the majority of which are small, rural, and non-engineered [5]. As a result, they impose severe risks on surrounding agricultural lands, surface water, and shallow groundwater resources. The situation is particularly concerning in central Vietnam, where high rainfall and sandy soil conditions facilitate rapid leachate infiltration. Therefore, surveys are necessary to properly assess the severity of environmental pollution problems for effective management and operation. Traditional ground-based methods for landfill surveying and monitoring are poorly suited to this context. They are costly, labor-intensive, time-consuming, and unsafe for workers who must operate on unstable and contaminated waste surfaces. Consequently, reliable data on landfill volumes, remaining capacity, and operational risks are rarely available for local authorities. This data gap makes it difficult to develop evidence-based waste management strategies, to prioritize landfill closures, or to design safe remediation measures.

Unmanned aerial vehicles (UAVs) have emerged as a cost-effective and versatile tool for landfill monitoring, offering an alternative to conventional ground-based surveys. Recent reviews highlight the rapid development of UAV applications in waste management. Fosco [6] provided a comprehensive overview of UAV-based methane monitoring technologies, emphasizing their growing role in greenhouse gas mitigation at landfills. Similarly, Fraternali [7] examined drone and satellite applications in complex environments and concluded that UAV photogrammetry is among the most accessible and scalable monitoring solutions for developing countries.

UAV-based photogrammetry enables the generation of high-resolution orthomosaics and digital surface models (DSMs), achieving centimeter-level accuracy at significantly lower cost than traditional surveying methods [8]. Empirical evidence confirms these advantages: Baiocchi [9] monitored landfill settlement in Italy with UAV-derived DSM at 2–3 cm vertical accuracy; de Sousa Mello [10] demonstrated that UAV-based volume estimates in Brazil matched the accuracy of terrestrial surveys; and Daugela [11] successfully applied UAV photogrammetry for capacity monitoring in Lithuanian landfills. Beyond volumetric assessment, UAVs are increasingly applied to environmental monitoring. Tanda [12] used UAV-mounted thermal infrared (TIR) imaging to detect methane hotspots in Italian landfills, with ground measurements validating the anomalies. Fjelsted [13] reported similar success in Denmark, although sensitivity to meteorological conditions remained a limitation. Mønster [14] further emphasized the role of UAVs as a complementary tool for landfill gas monitoring, bridging gaps in conventional measurement approaches.

Despite these advances, UAV applications in landfill monitoring remain rare in Vietnam. Most UAV deployments have focused on agriculture, forestry, or land-use management [15], with little application to small rural landfills. This technological gap limits data availability on landfill volumes, remaining capacity, and environmental risks—information critical for closure and rehabilitation planning. In particular, no existing studies in Vietnam have comprehensively assessed landfill volume, operational risks, and proposed renovation strategies based on UAV-derived data.

Thus, this study aims to develop an integrated approach that combines UAV-based photogrammetry and risk assessment to support the informed decision-making for rehabilitation and closure strategy of the Quang Loi landfill. Specifically, the study (i) acquires high-resolution UAV images to generate orthomosaics and digital surface models; (ii) estimates the current waste volume and remaining capacity to provide essential inputs for rehabilitation design; (iii) evaluates the environmental and operational risks to determine the urgency and priority areas for intervention; and (iv) proposes a technically feasible rehabilitation and closure plan based on the combined results of the risk assessment and UAV-derived datasets.

2. Materials and Methods

2.1. Study site: Quang Loi landfill

The study focuses on the Quang Loi landfill, which serves as the primary waste disposal site for the Quang Dien District, Thua Thien Hue Province, Vietnam. The site has a total area of approximately 2.5 hectares (Fig. 1). It is located in a rural setting, surrounded by agricultural land and production forests, about 1,800 meters from the nearest residential area and 280 meters south of a large pond. The landfill was constructed as a floating model with a sloped bottom (1 %) and features a 6-meter-high embankment. The liner system consists of multiple layers, including compacted natural sand, an HDPE geomembrane, compacted clay, geotextile, and crushed stone. A leachate collection system with two parallel HDPE pipes (D 250 mm) is installed at the bottom to channel leachate to a series of six treatment ponds.

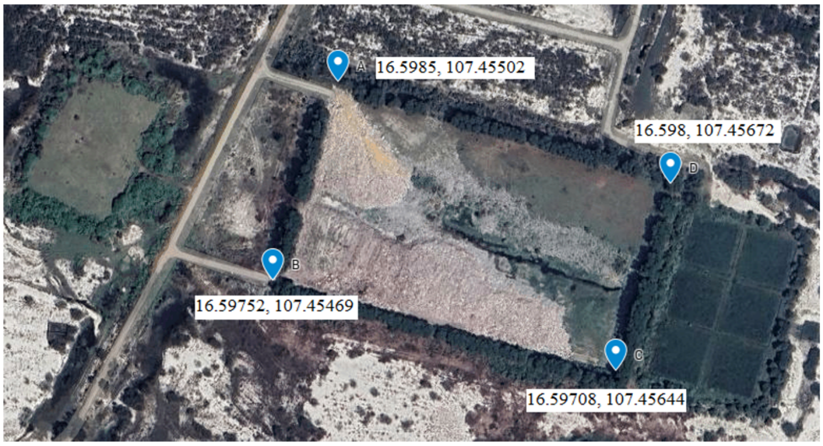


Figure 1. Coordinates of the Landfill Site

2.2. Landfill risk assessment

A semi-quantitative risk screening approach based on the framework of Kurian [16] was applied to evaluate the environmental and operational hazards of the Quang Loi landfill. The tool evaluates 27 key parameters categorized under site-specific criteria, waste characteristics, and leachate quality. These parameters and their respective predefined weights (Wi) were directly adopted from the study of Kurian [16]. Each parameter is assigned a predefined weight (Wi) based on its relative importance, with the total weights summing to 1,000. A sensitivity index (Si) from 1 (very low risk) to 4 (very high risk) is assigned to each parameter based on the specific conditions at the Quang Loi site. The total Risk Index (RI) is calculated by summing the weighted sensitivity values, providing a quantitative score of the overall risk level, as shown below. The input data were taken from the report on environmental protection work of Quang Loi landfill in 2024 of Quang Dien District people's committee, details see the supporting data.

$$RI = \sum_{i=1}^{n} \frac{W_i \times S_i}{4} \tag{1}$$

2.3. UAV survey and data acquisition

A DJI Phantom 4 Pro v2 UAV was used for the aerial survey. This UAV is equipped with a 20MP camera with a 1-inch CMOS sensor, capable of capturing high-resolution images. The flight mission was planned and executed automatically using a mobile application (DJI GO 4 and DroneDeploy), a standard procedure in UAV-based photogrammetry to ensure consistent image overlap and data quality [8]. The conditions included image resolution (GSD): 1.7 cm/pixel, overlap: 80 % along the path and 70 % across the path to ensure sufficient data for 3D model reconstruction and the survey were conducted at different altitudes of 30 m (speed 6 m/s), 40 m (speed 8 m/s) and 60 m (10 m/s) to validate data consistency (Fig. 2). The collected data were georeferenced to the WGS 84 coordinate system.

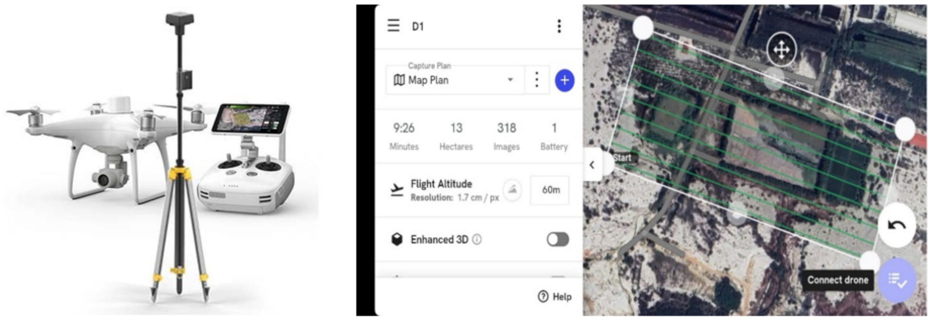


Figure 2. DJI Phantom 4 Pro v2 and survey area

2.4. Data processing and analysis

a. 3D model generation

The collected aerial images were processed using photogrammetry software, following the Structure from Motion (SfM) workflow. As shown in Fig. 3, this process reconstructs the 3D topography by aligning overlapping images to generate a dense point cloud, from which DSM and an orthomosaic were derived [8, 10]. This study utilized Golden Software Surfer for creating 2D contour maps and 3D surface models from the processed data. The software's gridding and interpolation algorithms were used to create a detailed representation of the landfill's topography.

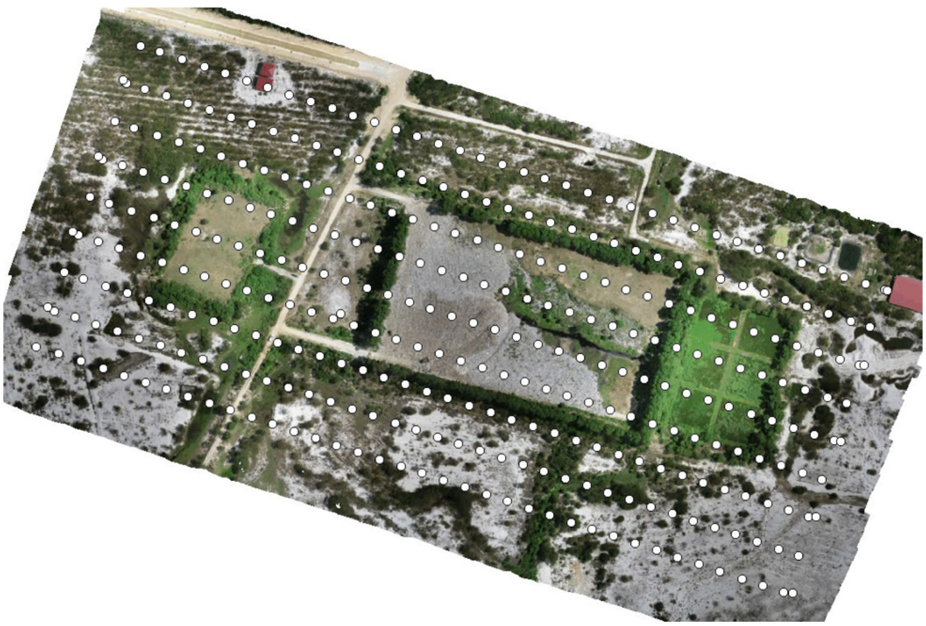


Figure 3. The image of the landfill after merging processing (from 408 images)

b. Validation

Although UAV technology has been widely proven for its accuracy in topographic measurements [9, 17, 18], the authors still conducted independent validation to ensure the highest reliability of landfill data. The validation focused on geometric accuracy by comparing the UAV-derived map against the official as-built drawings of the landfill.

- Reference Data: Key geometric parameters (boundary lengths and footprint area) were extracted from the as-built drawings.

- Comparison: These parameters were directly compared to the measurements taken from the UAV-generated DSM.

c. Waste volume calculation

To calculate the total volume of waste, the surveyed area was subdivided into a grid of 10 × 10 meter cells (Fig. 4). The volume of waste in each cell was calculated by determining the difference between the top elevation of the waste (from the UAV-derived DSM) and the bottom elevation of the landfill (from design drawings). The total volume was determined by summing the volumes of all individual cells using the formula:

$$V = \sum_{i=1}^{n} V_i = \sum_{i=1}^{n} 10 \times 10 \times \left(H_i^T - H_i^B\right) \tag{2}$$

where V is the total volume, H_i^T is the top elevation of a cell, and H_i^B is the bottom elevation of that cell. The H_i^B values are taken from the as-built drawings of the Quang Loi landfill project. The study employed both Trapezoidal and Convex Hull algorithms to ensure the accuracy of the volume calculation, finding the error between the two methods to be less than 1 %.

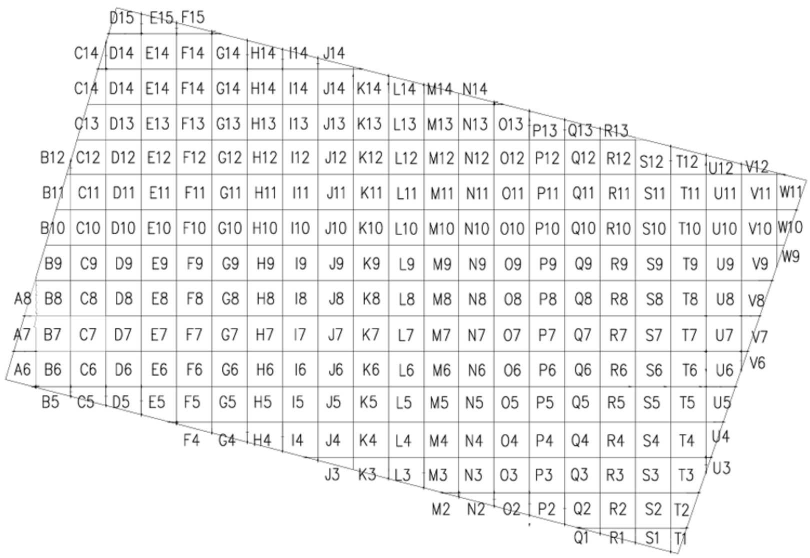


Figure 4. Grid division for volume calculation (Details see Annex 1)

3. Results and Discussions

3.1. Topographic analysis

The data collected from the drone follows the WGS 84 coordinate system (latitude/longitude), and the elevation follows the WGS 84 ellipsoid standard (GPS). The UAV photogrammetry survey produced a high-resolution DSM and orthomosaic for the Quang Loi landfill (Fig. 5(a)). The terrain results are recorded in the form of contour lines shown in Fig. 5(b). The error between the digital map and the completed drawing is about 2 %. This indicator confirms that the UAV methodology meets the necessary precision standards for waste volume estimation.

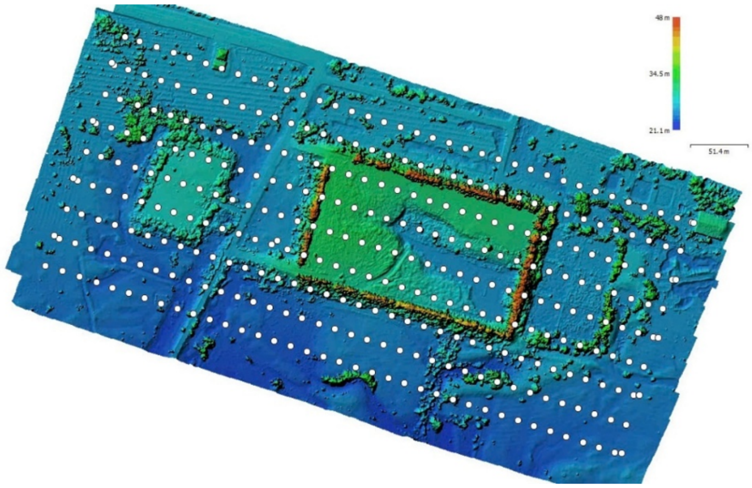
The results showed that the ground elevation was approximately 25.8–26.0 m, with the embankment surface 6.0 m above ground level. Waste at 31–32 m elevation accounts for 50 % of the area, while about 10 % of the area remains unburied. The volume of the waste body was calculated by comparing the UAV-derived DSM of the current landfill surface against the baseline digital model representing the landfill's bottom topography. This cut-and-fill analysis is a standard and validated method for volumetric estimation in landfill management [17, 18]. The active disposal area was approximately 20,800 m^2, with an estimated waste volume of 82,200 m^3, the detailed cell-by-cell volumetric calculations are provided in Annex 1.

The error between different UAV flight levels is less than 1 %, demonstrating the suitability of the method. To evaluate the reliability of the results at Quang Loi landfill, this study compared the error and estimated volume with some international works using UAVs in landfill management. The summary results are shown in Table 1. The results in the current study are in agreement with international findings. Baiocchi [9] reported that UAV photogrammetry achieved ±10 cm vertical accuracy when monitoring landfill settlement in Italy. de Sousa Mello [10] monitored landfill volumes in Brazil over one year, confirming UAV photogrammetry as a reliable and replicable technique for continuous operational control. Similarly, Filkin [17] demonstrated that UAV-based waste volume estimation achieved < 5 % error compared with ground-truth surveys in the United Kingdom. Kaamin [18] also emphasized that monthly UAV photogrammetry in Malaysia effectively tracked short-term changes in landfill capacity.

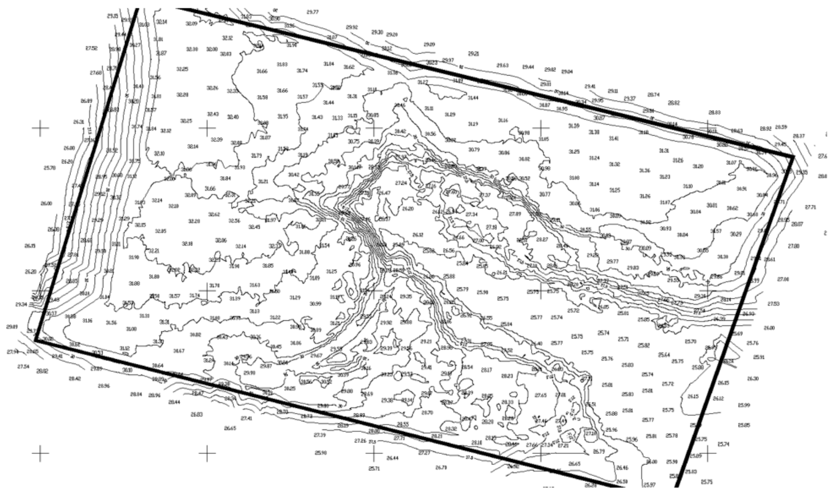
Table 1. UAV-based landfill volumetric studies compared with Quang Loi

Location	UAV	Calculation tool	Heigh/ GSD	Accuracy	Volume/ Area	Notes	Study (Year)
Italy	FlyNovex hexacopter (ILCE camera)	Agisoft Photoscan v.1.3.5	H 120 m/ 2.2 cm	±10 cm vertical	350,000 m^3/ 75 ha	Settlement monitoring	[9] (2019)
UK	DJI Phantom 3 Pro	Agisoft Metashape Pro	H 69 m/ 2.6 cm	< 5 %	100,000 m^3/ 20 ha	Compared with ground surveys	[17] (2022)
Brazil	DJI Phantom 4 Pro	Agisoft Metashape 1.5.1	H 75 m/ 2.0 cm	4 %	NA 12 ha	Year-long monitoring	[10] (2022)
Malaysia	DJI Phantom 4 Pro	Pix4dmapper	H 100 m; GSD	< 5 %	34,600 m^3; 12 ha	Monthly survey	[18] (2019)
USA	DJI Air 2S	Pix4dmapper	H 25 m/ 1 cm	< 5 %	1,650 m^3/ NA	Fly ash stockpile	[19] (2023)
Vietnam	DJI Phantom 4 Pro	Agisoft Metashape Pro	H 40m/ 2 cm	< 2 %	82,200 m^3; 2 ha	Near embankment limit	This study (2025)

Conventional ground-based surveys are inherently inefficient, requiring teams of surveyors with expensive equipment to spend days on-site in a process that is both labor-intensive and time-consuming [17]. Moreover, these methods pose significant safety hazards on unstable landfill surfaces, making UAVs that operate without direct physical access a preferable alternative for safety reasons [9]. In stark contrast, the UAV survey at Quang Loi was completed by a single operator in under 10 minutes,



(a) Digital elevation model of the landfill



(b) Contour surface model of the landfill

Figure 5. Topographic map of the Quang Loi landfill area

drastically reducing field time and eliminating exposure to on-site risks [20]. This operational efficiency confirms the standing of UAVs as a safer, faster, and more cost-effective surveying solution, a conclusion widely supported in remote sensing literature [8].

3.2. Landfill Capacity and Remaining Space

Based on DSM-derived elevation data and design limits, the Quang Loi landfill has approximately 60,000 m^3 of remaining capacity. With current daily inflows of 25–30 tons (9,000–10,500 tons/year) and the landfill waste density of 0.5–0.7 t/m^3 [21], the landfill is projected to reach full capacity in the next 5–7 years. This projection aligns with Vietnam's national solid waste management strategy, which targets the closure of small rural landfills by 2030 [4].

Several recent studies have also recommended the use of UAV data to predict landfill waste capacity. De Sousa Mello [10] used UAV data to accurately predict short- and long-term capacity utilization in Brazilian landfills. Kuinkel [19] highlighted UAVs as essential tools for projecting landfill lifespan in resource-limited regions such as USA. Similarly, Kaamin [18] demonstrated the integration of

UAV photogrammetry with waste generation rates as an effective approach for lifespan forecasting in Malaysia.

For Quang Loi, UAV-based projections underscore the urgency of implementing waste diversion strategies such as composting and recycling, which could extend the landfill's operational life by 5–7 years and reduce the immediate need for costly closure operations. UAV data also allows for landfill life prediction when compared with published international studies. Table 2 presents the comparison results of remaining capacity, waste intake rate and expected exploitation time.

Table 2. Landfill lifespan projections using UAV-derived data

Country	Remaining capacity	Filling rate	Projected lifespan	Study (year)
Brazil	100,000 m^3	40–50 t/day	5–8 years	[10] (2022)
Malaysia	60,000 m^3	20–25 t/day	6–7 years	[18] (2019)
Vietnam	60,000 m^3	25–30 t/day	5–7 years	This study 2025

3.3. Landfill Risk Assessment and Landfill Renovation

The calculated Risk Index (RI = 598) categorizes Quang Loi as a moderate-risk landfill according to the criteria proposed by Kurian [16]. Importantly, the sub-scores of the RI highlight which environmental factors are most critical and should therefore guide the renovation strategy.

Hydrogeological conditions received one of the highest risk sub-scores due to sandy soils, shallow groundwater (1.5–1.7 m), and heavy rainfall (> 2,500 mm/year). These conditions significantly increase leachate infiltration risk. Accordingly, renovation must prioritize stormwater management through diversion channels, leachate pond reinforcement, and protective clay or geomembrane barriers.

Waste management practices scored high because of the absence of daily cover and limited compaction. These deficiencies suggest an urgent need for operational improvements, including regular soil cover application, installation of litter fences, and deployment of low-cost compactors. Such measures would reduce vector nuisance, odor, and fire hazards.

Gas management presented a medium risk score, as the waste body has nearly reached embankment height without a gas collection system. To address this, passive gas wells should be installed during the interim phase, followed by an active collection system integrated into the final capping.

Slope stability scored lower but remains a concern given the embankment height and limited freeboard. To mitigate potential settlement or sliding, periodic UAV monitoring is recommended to detect surface deformations, combined with phased filling restrictions.

The calculated RI and its components are illustrated in Fig. 6, illustrating the level of environmental impacts that need to be prioritized for treatment in Quang Loi.

By explicitly linking RI sub-scores to targeted actions, the renovation plan becomes evidence-based rather than generic. UAV-derived DSMs can further support this process by providing precise inputs for drainage design, capping volume calculation, and gas well placement. This integrated approach ensures that renovation directly addresses the most critical risks identified at Quang Loi, while also serving as a replicable model for other small rural landfills in Vietnam.

To illustrate international experience in applying UAVs for landfill reclamation, Table 3 summarizes some case studies and lessons learned for the Quang Loi case. International experiences highlight similar benefits. Filkin [17] showed that UAV-supported closure planning reduced errors in soil and liner material estimation, lowering costs. Incekara [20] emphasized the utility of low-cost UAVs in supporting renovation planning for small rural landfills in Turkey.

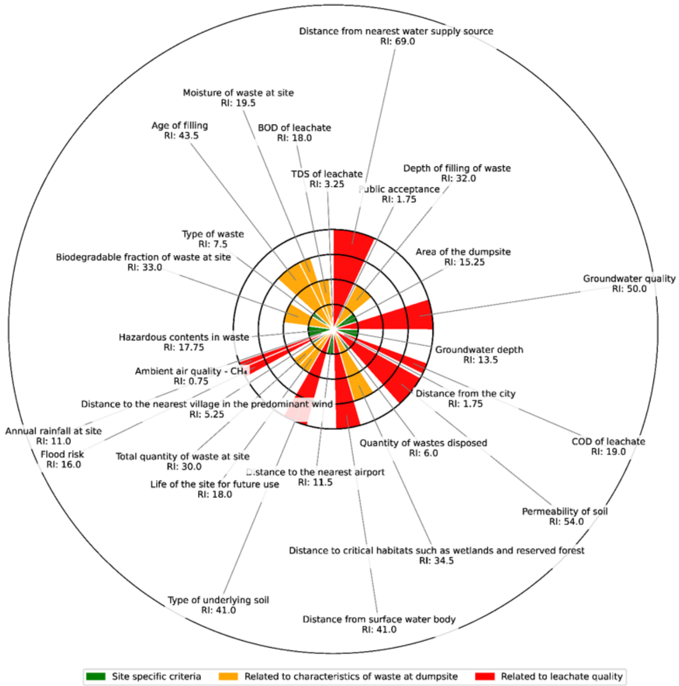


Figure 6. Risk assessment for Quang Loi landfill (Annex 2)

Table 3. UAV-supported landfill renovation approaches

Country	UAV application	Renovation focus	Lessons for Quang Loi	Study (year)
UK	UAV DEM for closure design	Soil & liner estimation	Reduce material costs	[17] (2022)
Turkey	Low-cost UAV survey	Small rural landfills	Affordable & scalable	[20] (2019)
Vietnam	UAV photogram & risk eval	Immediate–long-term strategy	Integrate UAV across phases	This study (2025)

3.4. Solutions

To improve operational efficiency and minimize environmental risks, the Quang Loi landfill should implement a five-phase rehabilitation and operation plan.

- Phase 1: Waste relocation and elevation adjustment.

Relocate and compact the accumulated waste from the current central zone to a temporary closure area. The waste should be compacted to a height of 7.0–9.0 meters to create a stable surface for future covers.

- Phase 2: Temporary capping

Apply a temporary soil cover over the former central area using locally sourced materials. This cover will control odor, prevent waste scattering, reduce rainwater infiltration, and limit vector breeding.

- Phase 3: Infrastructure enhancement

Upgrade or install essential infrastructure systems, including: Access roads for waste transport;

Leachate drainage ditches and collection pipes; Stormwater diversion channels; Perimeter fencing and site signage. These improvements will support safer, more efficient operations.

- Phase 4: Controlled operation

Operate the remaining open area as a new waste disposal cell. This phase must follow a technical plan that includes daily waste compaction, routine soil covering, controlled tipping, and monitoring of leachate and gas emissions.

- Phase 5: Final closure preparation

Prepare for final closure by: Designing and installing a landfill gas collection system; Finalizing the closure plan, including cover layers, drainage, and vegetation; and Developing a post-closure environmental monitoring program.

Throughout all phases, engineered earthen embankments with a 3:1 (horizontal:vertical) side slope ratio should be used along the perimeter to ensure stability and manage surface runoff.

Use available waste in the landfill to raise half of the landfill surface as shown in Fig. 7 and Fig. 8. The waste is compacted with a coefficient K = 0.9, creating a slope of 2-5 %, covered with 20cm thick soil (or mud), and covered with a layer of waterproof plastic tarpaulin. Before covering the soil and tarpaulin, install passive gas wells.

The volume of waste (compacted) that needs to be moved is 20,000 m^3. The volume of soil (sludge) needed is 2000 m^3. The area of the tarpaulin is 11.000 m^2 (High-density polyethylene or similar waterproof tarpaulins with density 200 g/m^2 should be used).

Remaining effective volume 60,000 m^3; 40 % of rainwater is allowed to flow out of the landfill; Coverage area to prevent free-surface of plastic waste 40-50 %. UV-resistance lifespan of tarpaulin 5-7 years.

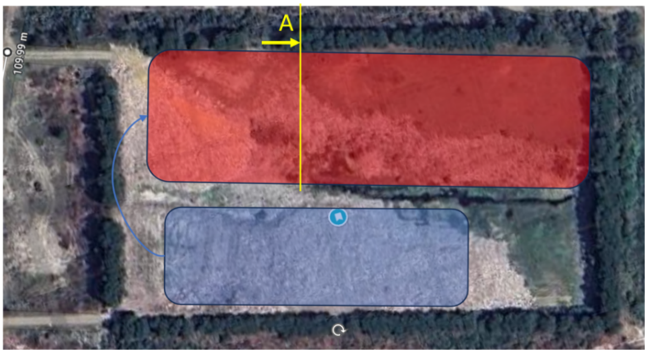


Figure 7. Waste transportation direction

Note: Red indicates the area where the waste will be raised and temporarily covered. Blue indicates the area where the waste will be excavated and moved to the red area

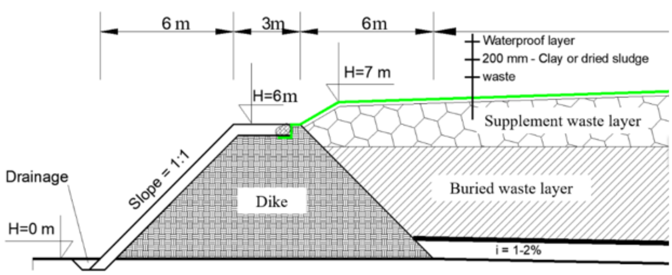


Figure 8. Landfill closure structure

3.5. Limitations

Firstly, the assessment relies on the as-built drawings to determine the base elevation for waste volume calculations. In long-operating landfills, uneven settlement or deviations from actual conditions may occur, potentially affecting volume estimates. Direct verification of subsurface elevations (e.g., elevation benchmarks from boreholes or ground-penetrating radar) would increase the reliability of the base model.

Secondly, the landfill risk assessment uses a semi-quantitative screening framework based on expert-assigned weights and sensitivity scores. While this method effectively highlights key risk factors, it is susceptible to subjective judgment and cannot replace detailed environmental monitoring, such as leachate sampling, groundwater quality testing, or methane emission measurements. A more comprehensive multi-parameter dataset would provide a stronger basis for prioritizing risk mitigation measures.

Finally, the study is limited to optical photogrammetry methods. While drone imagery successfully identified operational deficiencies such as missing daily cover and exposed plastic waste, additional sensors (e.g., thermal infrared or multispectral cameras) could more effectively detect methane hotspots, leachate seepage areas, and vegetation stress patterns. Future studies should integrate multi-sensor drone platforms and conduct periodic surveys to quantify settlement trends, emissions, and the effectiveness of closure measures over time.

4. Conclusions

Firstly, the quantitative risk assessment successfully confirming Quang Loi landfill as a moderate-risk landfill. This assessment utilized environmental and operational inputs to highlight specific areas of high concern, particularly the Hydrogeology risk. Furthermore, the high-resolution UAV imagery also provided visually documenting critical operational deficiencies (such as lack of daily cover and inadequate stormwater management), which directly contribute to the observed risk score.

Secondly, the UAV-derived DSM, rigorously validated against as-built drawings with a volumetric error of less than 2 %, enabled the accurate estimation of the current waste volume (82,200 m^3) and remaining capacity (60,000 m^3). This critical volumetric data directly determine the landfill is projected to reach capacity within 5–7 years.

Finally, the strong evidence base-derived from both the quantified risk score and the volumetric data-informed the design of the phased renovation and closure strategy. The validity of this proposed strategy is demonstrated by its direct link to the quantified high-risk sub-scores, ensuring prioritized actions (such as stormwater management and capping) address the most critical environmental pathways first. Overall, this study's primary contribution is the development of a robust, integrated framework that transforms high-accuracy UAV data into actionable management decisions-a replicable model for similar small and unmonitored landfills across developing regions.

Future research: we will focus on integrating time-series UAV data to monitor the effectiveness of the proposed renovation phases.

Acknowledgments

This study is funded by the World Wilde Fund for Nature - Vietnam under grant number FY25-0664-CA.

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