ISSN: 2447-3359

REVISTA DE GEOCIÊNCIAS DO NORDESTE

Northeast Geosciences Journal

v. 11, nº 1 (2025)

https://doi.org/10.21680/2447-3359.2025v11n1ID39327

Remotely Piloted Aircraft Systems (RPAS): a fast and accurate way for monitoring landfills

Aeronaves Remotamente Pilotadas (ARP): um meio rápido e acurado para monitoramento de aterros sanitários

Barbara Fernanda da Cunha Tasca[1]; Fernanda Miguel Franco[2]; Auberto José Barros Siqueira[3]

[1] Mato Grosso State Public Prosecutor's Office, Technical Support Center for Environmental Enforcement, Cuiabá/MT, Brazil. Email: barbarafernandatasca@gmail.com
ORCID: https://orcid.org/0000-0003-0034-0892

[2] Ministry of Agrarian Development and Family Farming, Mato Grosso State Superintendency, Várzea Grande/MT, Brazil. Email: fermigfran@gmail.com
ORCID: https://orcid.org/0000-0002-3903-2435

[3] Federal University of Mato Grosso, Department of Sanitary and Environmental Engineering, Cuiabá/MT, Brazil. Email: ajbsiqueira@gmail.com
ORCID: https://orcid.org/0000-0002-9364-4520 /

Abstract: Sanitary landfills are one of the main alternatives for solid waste disposal in Brazil. However, many of them have turned into open dumps due to operational inefficiencies, highlighting the need for effective monitoring. This study evaluated the applicability of orthomosaic and digital surface model obtained via remotely piloted aircraft system for the environmental monitoring of landfills. The study area was the landfill of Cuiabá, Brazil. The aerial survey followed photogrammetric procedures, utilizing control points collected with geodetic GPS to ensure altitude correction. The images captured by the remotely piloted aircraft system were processed using photogrammetry software to produce a high-resolution orthomosaic and digital surface model, which served as a basis for analyzing the structural and operational conditions of the landfill. The analysis revealed critical issues such as leachate leaks, abandonment of leachate treatment ponds, improper exposure of waste, and evidence of solid waste burning. These conditions pose significant environmental risks, such as soil and groundwater contamination, as well as public health impacts. The study concludes that remotely piloted aircraft systems are an efficient tool for continuous landfill monitoring, providing accurate data to identify operational failures and improve environmental management.

Keywords: Solid waste; Monitoring; Aerial survey.

Resumo: Os aterros sanitários são uma das principais alternativas para a disposição de resíduos sólidos no Brasil. No entanto, muitos deles se transformaram em lixões a céu aberto devido às ineficiências operacionais, destacando a necessidade de monitoramento ambiental. Este estudo avaliou a aplicabilidade de ortomosaico e de modelo digital de superfície obtidos via aeronave remotamente pilotada para o monitoramento de aterros sanitários. A área de estudo foi o aterro sanitário de Cuiabá, Brasil. O aerolevantamento seguiu procedimentos fotogramétricos, utilizando pontos de controle coletados com GPS geodésico para garantir a correção da altitude. As imagens capturadas foram processadas por meio de software de fotogrametria para produção do ortomosaico e do modelo digital de superfície de alta resolução. A análise revelou problemas críticos na estrutura e operação do aterro, como vazamentos de chorume, abandono de lagoas de tratamento de chorume, exposição inadequada de resíduos e evidências de queimada de resíduos sólidos. Essas condições representam riscos ambientais significativos, como contaminação do solo e de águas subterrâneas, bem como impactos à saúde pública. O estudo conclui que a aeronave remotamente pilotada é uma ferramenta eficiente para monitoramento contínuo de aterros sanitários, fornecendo dados precisos para identificar falhas operacionais e melhorar a gestão ambiental.

Palavras-chave: Resíduos sólidos; Monitoramento; Aerolevantamento.

Received: 03/03/2025; Accepted: 16/05/2025; Published: 09/06/2025.

1. Introduction

The continuous growth of solid waste in Brazil has brought significant challenges to public-health management. According to data of Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais (ABRELPE, 2020), the total generation of municipal solid waste in Brazil recorded a considerable increase between 2010 and 2019, from 67 million to 79 million tons per year, and the per capita generation increased from 348 to 379 kilograms per year.

Most of this waste is destined for landfills, with a rise from 33 million tons per year in 2010 to 43 million tons per year in 2019. An increase of about 10 million tons. However, the quantity of solid waste being disposed into inadequate sites (open dumps and "controlled" dumps) also grew, rising from 25 million tons per year to more than 29 million tons per year (ABRELPE, 2020).

To face the increasing generation of solid waste and mitigate the environmental impacts of its inadequate disposal, it was instituted the National Solid Waste Policy (NSWP) through Law Number 12.305 on 2nd August 2010 (BRASIL, 2010). This legislation establishes guidelines for the management of solid waste, with emphasis on environmentally adequate disposal. The implantation of landfills is commonly practiced for public managers due to its simple operation and low costs compared to other treatment techniques. In addition, when well managed, it is effective in controlling environmental problems (LIMA, 2005).

Despite that, many landfills that initially meet environmental compliance standards quickly degrade into open dumps or "controlled" dumps because of insufficient monitoring and maintenance. This deterioration exacerbates environmental damage and poses significant public health risks, as observed in the city of Cuiabá, State of Mato grosso (MT), Brazil (LAUREANO; SHIRAIWA, 2008). Thus, it is essential to explore new technologies and tools to support the diagnostic and monitoring of degraded areas by inadequate solid waste disposal (PARENTE, 2016).

The use of geotechnologies, such as Geographic Information System (GIS) and aerial imagery, has excelled as a tool to assist with the diagnosis and monitoring of landfills, being used from selecting optimal locations for their implementation to conducting environmental monitoring after their closure (BEZERRA, 2014). Remotely Piloted Aircraft System (RPAS) offer a practicable alternative to obtain high-resolution aerial images and digital surface models as it models precisely the terrain topography when combined with geodetic Global Positioning System (GPS) (GALIN *et al*., 2019; LINDSAY, 2016). Furthermore, this technology provides superior quality and cost-effectiveness compared to traditional topographic surveying methods (SILVA *et al*., 2015).

Studies have explored the effectiveness of RPAS in monitoring landfills. Mello and Simões (2019) compared volumetric data obtained by RPAS with measurements carried out by a total station on a landfill located in Betim, Minas Gerais. The results show that the RPAS is a precise tool for volumetric monitoring of landfills, being highly effective to guarantee its operational compliance. Wyard *et al*. (2022) focused on the mapping of landfill land cover using RPAS. The research emphasizes the optimization of the data acquisition protocols and the processing through open-source tools, making the technology more accessible and efficient. Additionally, Hassan *et al*. (2023) examined an approach based on RPAS for landfill monitoring, highlighting the sensor fusion to detect problems like accumulation of water in the area.

The versatility and low cost of RPAS are particularly advantageous for the monitoring and operation of landfills, offering flexible temporal resolution, with the possibility of multiple surveys throughout the year. Moreover, it is possible to acquire high-resolution aerial images, free from atmospheric interference like clouds and gases. Other advantageous factors are cited by Malta *et al*. (2017), such as the identification of leachate and biogas drains, the determination of contour levels, the deposit volume used for covering the waste cell, and assessment of the operational advance.

Considering the circumstances, the aim of this study is to use an orthomosaic and digital surface model generated by aerial survey and photogrammetry as tools to investigate the situation of the landfill in Cuiabá, contributing to its diagnostic, management, and future planning.

2. Methods

The landfill object of this study is in Cuiabá-MT, along Balneário Letícia Road, in the Novo Paraíso neighborhood, northwest region of Cuiabá semi-urban area (Figure 1). The site was the solid waste disposal center for 26 years (1997 to 2023), being closed by the Cuiabá Council in March 2023 as it was unfeasible to adequate with the NSWP (FERREIRA, 2023).

2.1 Background

Over the last four decades, the solid waste disposal facility of Cuiabá changed twice (Figure 1). The abandoned areas left a socio-environmental liability history that still is not in accordance with the current legislation (KNECHTEL *et al*., 2013; RIBEIRO; CANTÓIA, 2020; SHIRAIWA *et al*., 2002).

Between 1982 and 1997, the site was located in the north region of the Cuiabá semi-urban area, along the highway MT 251 (Figure 1). The site worked as the open dump of the city, and it was closed by a court decision due to its high saturation situation. In this period of 15 years, it accumulated about 700 thousand tons of municipal solid waste, generating environmental liabilities such as frequent fires with toxic smoke and groundwater contamination plume by leachate, exposing the surrounding population to health risks (KNECHTEL *et al*., 2013; RIBEIRO; CANTÓIA, 2020; SHIRAIWA *et al*., 2002).

After the closure of the open dump, the waste disposal center of Cuiabá became the site studied in this research. It was an area of 50 hectares in the surroundings of an abandoned gold mine along Balneário Letícia Road (CARVALHO; SILVA, 2011; CUIABÁ, 2013). This waste disposal facility was not licensed to be a landfill but to be a sorting, recycling, and compostable plant, which would be operated by a collector's cooperative. However, in the second year, this project failed (CUIABÁ, 2013; RIBEIRO; CANTÓIA, 2020). Both the technology and the processing capacity were undersized, and the solid waste came to be disposed of without any treatment in the surrounding of the primary area, becoming a controlled dump (CARVALHO; SILVA, 2011. CUIABÁ, 2013; RIBEIRO; CANTÓIA, 2020).

In 26 years in operation (1997-2023), the environmental planning and management were never satisfactory. It operated with emergency authorizations from the State Environmental Secretary of Mato Grosso (SEMA-MT) for the construction of new waste cells attached to the initial place where the waste was disposed in poor environmental conditions. These cells were rapidly saturated, with waste spread in the surrounding area. There was frequent change of management companies (CUIABÁ, 2013; CUIABÁ, 2020), as well as persistence of socio-environmental problems related to unhealthy work conditions of collectors (REIBEIRO; CANTÓIA, 2020). Even though collected, the leachate used to be thrown into the river without adequate treatment, generating a groundwater contamination plume (LAUREANO; SHIRAIWA, 2008; SHIRAIWA *et al*., 2002).

Only in 2016, when 600 tons of untreated waste were disposed of daily in the controlled dump and projections estimated an additional 4 million tons by 2036 (CUIABÁ, 2016a), the council presented the Environmental Impact Assessment and Report (EIA/RIMA) aiming to obtain the landfill's operation license. This license was a requirement of the Mato Grosso State Public Prosecutor's Office, which had not been fulfilled since 2013 (CAETANO, 2016; CUIABÁ, 2020; SANFORD, 2013).

Although the council had acknowledged the significant environmental damage to the site, they proposed adding more waste cells in the waste mass with improvements to the environmental control system. The new waste disposal facility, called the new landfill of Cuiabá, was supposed to be in accordance with the NSWP, including measurements to support the recycling executed by the local collectors (CUIABÁ, 2016b; CUIABÁ, 2020). Nonetheless, these measurements were not sufficient to avoid the unsanitary conditions and premature saturation of the controlled dump (ALMEIDA, 2018; RIBEIRO; CANTÓIA, 2020), and finally the site was permanently closed in 2023.

The study area encompassed the waste mass, consisting of the waste cells constructed between 1997 and 2017, the year after the EIA/RIMA was submitted for landfill licensing, which occurred 19 years after operations began. Until its permanent closure in 2023, the waste mass had increased by an additional 10% since 2017, the year when this aerial survey was carried out (Figure 2).

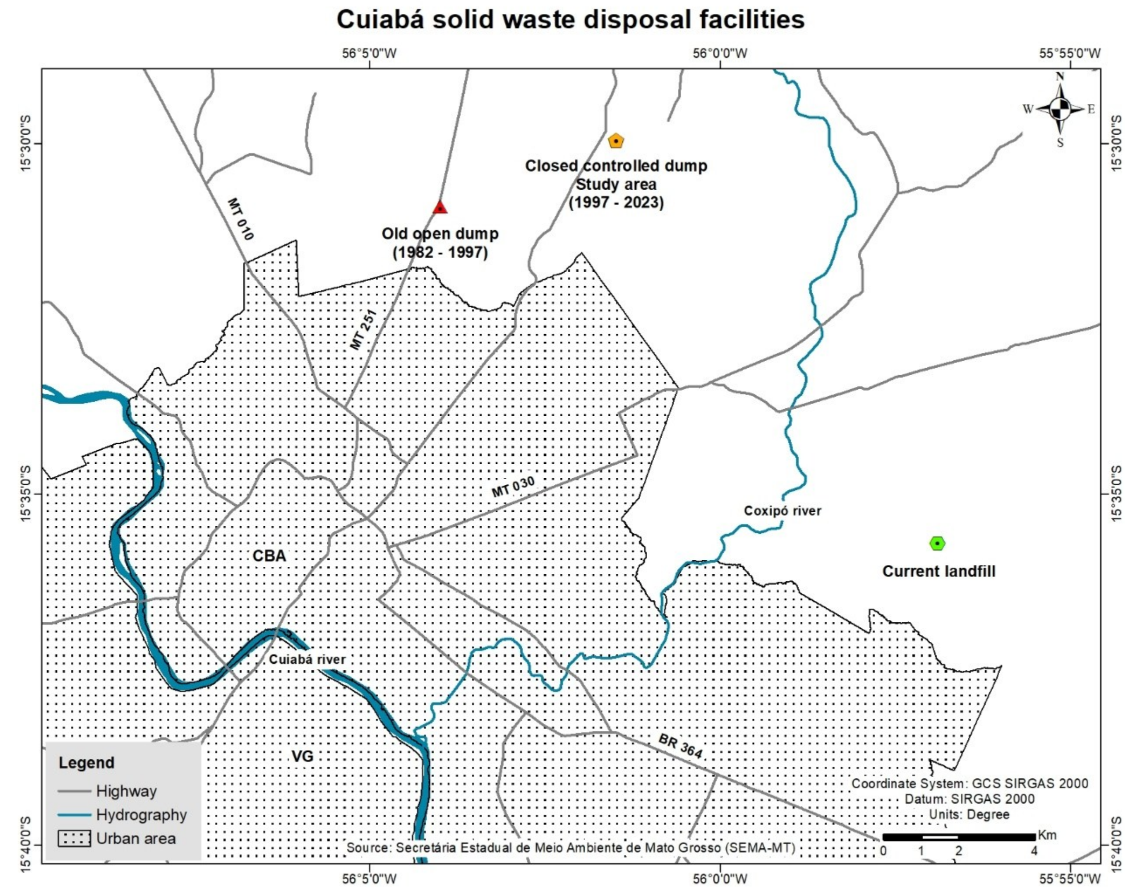

Figure 1 – Cuiabá solid waste disposal facilities between 1982 and 2025. 1) Period between 1982 and 1997 – open dump along MT-251; 2) Period between 1997 and 2023 – controlled dump along Balneário Letícia Road; 3) From 2023 – sanitary landfill Ecoparque Pantanal.
Source: Authors (2025).

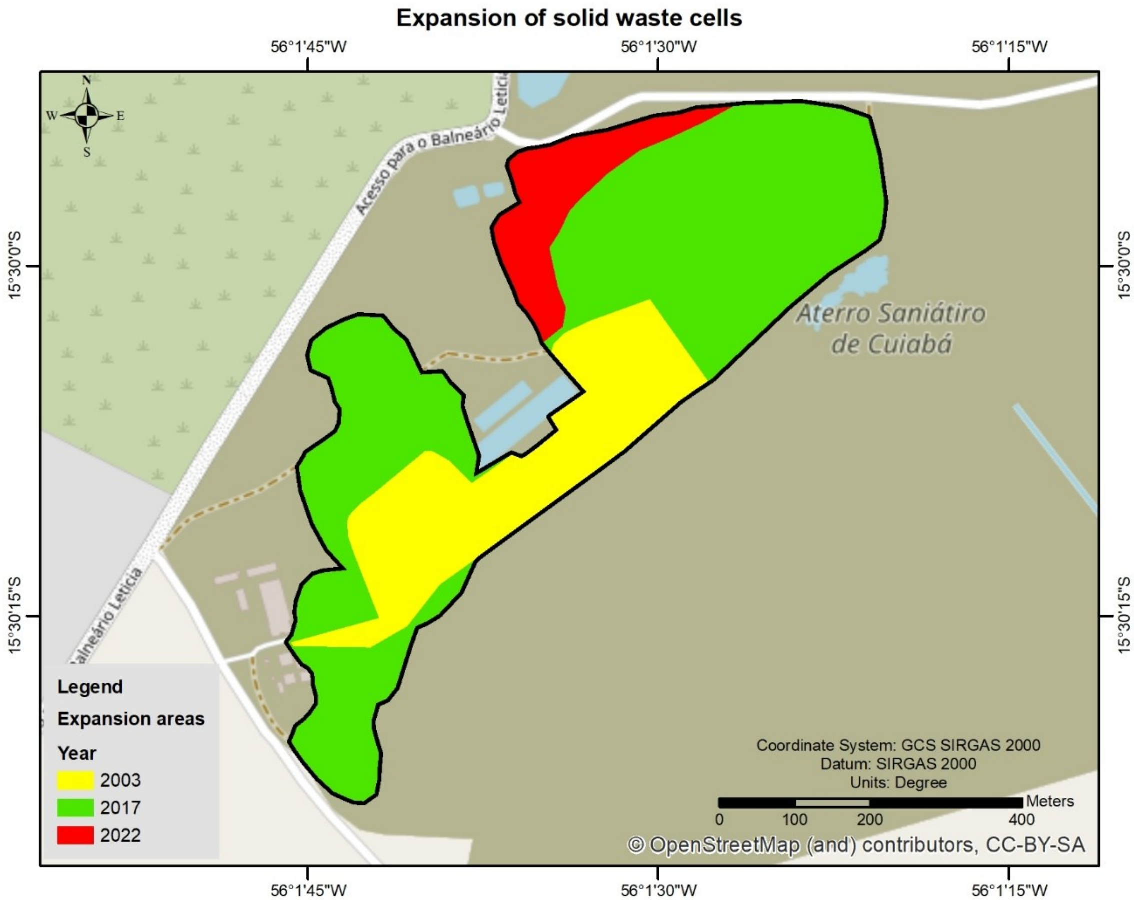

Figure 2 – Expansion of the solid waste cells boundaries at the controlled dump along Balneário Letícia Road between 2002 and 2023. The aerial survey was conducted in 2017, when the waste mass corresponded to the yellow and green areas. Source: Authors (2025).

2.2 Procedures

The approach of this research consists of the following eight steps: 1) planning of the aerial survey; 2) image acquisition; 3) pre-processing; 4) processing of the Digital Surface Model (DSM); 5) processing of orthomosaic; 6) validation; 7) documentation; 8) assessment of landfill conditions.

2.2.1 Planning of the aerial survey

Flight planning is crucial for any aerial survey that utilizes RPAS. For that, the eMotion software, version 4 (AGEAGLE, 2023), was used to plan the flight.

The aerial survey was conducted on 4th August 2017, with a cover of 136,638 hectares. The senseFly eBee RPAS was used in conjunction with the IXUS 127 HS camera (EGEAGLE, 2022), featuring a resolution of 4608x3456 pixels. The flight reached an altitude of 253.53 meters, achieving an average Ground Sampling Distance (GSD) of 7.78 cm.

Flight paths were planned with sufficient overlap (generally 60-80% between consecutive images) to ensure adequate correlation between the images and allow the three-dimensional reconstruction of the surface. The digital aerial images were processed using Pix4Dmapper Pro software, version 3.1.22 (PIX4D, 2024).

2.2.2 Image acquisition

A total of 159 images were captured, all calibrated and georeferenced using five ground control points (GCP). The GCP coordinates were obtained using a dual-frequency GNSS receiver using RTX technology, Trimble R10 (TRIMBLE, 2014). These coordinates were used to correct the image position, ensuring that all the data were properly aligned with the SIRGAS 2000/UTM 21S coordinate system.

2.2.3 Pre-processing

During the initial processing, the internal parameters of the camera, such as focal distance and distortion coefficient, were adjusted to correct any optical distortion and ensure measurement accuracy. Table 1 shows the details about the camera calibration.

Table 1 – Internal camera parameter.

	Focal length	**Principal point X**	**Principal point Y**	**R1**	**R2**	**R3**	**T1**	**T2**
Initial values	3,270.924 (pixel) 4.380 (mm)	2,303.999 (pixel) 3.085 (mm)	1,728.000 (pixel) 2.314 (mm)	-0.049	0.059	-0.036	0.000	-0.003
Optimized values	3,297.160 (pixel) 4.415 (mm)	2,235.585 (pixel) 2.993 (mm)	1,787.972 (pixel) 2.394 (mm)	-0.038	0.041	-0.020	0.004	-0.004
Uncertainties (Sigma)	1.169 (pixel) 0.002 (mm)	0.408 (pixel) 0.001 (mm)	0.380 (pixel) 0.001 (mm)	0.001	0.002	0.001	0.000	0.000

Source: Authors (2025), adapted from Pix4Dmapper (2017).

Additionally, the images were aligned with each other through a block adjustment, which minimized the position and orientation errors by optimizing the relative position of the camera and the captured points.

2.2.4 Processing of the Digital Surface Model (DSM)

From the initial sparse point cloud (generated by the block adjustment), the software densified the cloud using multi-image matching techniques. The densified cloud contained 15,991,307 3D points with an average density of 5.62 3D points per cubic meter.

The densified points were interpolated to generate the DSM, using the Inverse Distance Weighting (IDW) method to smooth the surface and correct minor inconsistencies. Next, noise removal and surface smoothing filters ("Sharp" type) were applied to improve visual quality and reduce imperfections in the DSM.

The IDW interpolation technique was adopted in this study due to the dense point cloud generated through photogrammetry and its uniform distribution across large features with clear edges. IDW is a direct deterministic method that is simple to execute and computationally efficient, making it suitable for large datasets (KANG; SUH, 2021; LI; HEAP, 2014). In addition, it maintains discontinuities and sharp transitions in the terrain, such as the edges of the landfill (MOUSSA; ABBOUD, 2024). Another advantage of IDW is that it considers local spatial influences without assuming any prior stochastic autocorrelation, which helps prevent distortions in areas where spatial variability is inconsistent or anisotropic (AMADU *et al*., 2022). This characteristic was especially important for the Cuiabá landfill, where the surface shows significant heterogeneities, including cells of varying ages and sizes.

In contrast, geostatistical techniques such as kriging involve variogram modeling and are better suited for sparse datasets where estimating uncertainty is key (AMADU *et al*., 2022; LI; HEAP, 2014). Although kriging is powerful for scenarios that require uncertainty estimation, these conditions did not apply to the present study, which relied on a dense and uniformly distributed point cloud. Compared to kriging, IDW captures slope and contour variations with greater precision and avoids over-smoothing (KANG; SUH, 2021). This is crucial for accurately representing the boundaries and topographic profiles of the waste cells.

2.2.5 Processing of the orthomosaic

The aerial images were geometrically corrected to eliminate perspective distortions and scale variations caused by the topography and the inclination of the camera during the flight. Subsequently, the orthorectified images were merged to create a continuous mosaic, representing the surface of the mapped area in a flat projection. The final resolution of the orthomosaic was kept equal to the GSD (7.78 cm/pixel), ensuring that the details captured in the individual images were preserved.

2.2.6 Validation

The average errors of the GCP coordinates were analyzed to validate the accuracy of the georeferencing and the model. The orthomosaic and the DSM were visually revised to identify any potential stitching errors or distortions. Also, the consistency of the data was checked throughout the entire mapped area.

The assessment of the DSM accuracy was conducted in accordance with the Cartographic Accuracy Standard (PEC), regulated by Decree-Law No. 89.817/1984. The procedure involved comparing the coordinates of the GCP with the corresponding coordinates derived from the photogrammetric model. The analysis included the calculation of mean planimetric and altimetric errors, as well as the Positional Standard Error (PSE), to verify compliance with the accuracy class limits defined by the PEC.

2.2.7 Documentation

All processing steps were documented, including details about the calibration parameters, adjustments made, and specifications of the final products. Complete metadata was generated to ensure traceability and the reuse of the geospatial data.

2.2.8 Analysis of landfill conditions

Finally, an analysis was conducted through visual interpretation of the orthomosaic, highlighting the main critical points of the waste disposal facility. This step aimed to identify anomalies and operational failures that could compromise the environmentally adequate operation of the site. The interpretation included the assessment of the waste disposal patterns, identification of areas with lack of cover or compaction, potential points of inadequate drainage, and signs of leachate accumulation. In addition, the visual analysis aimed to identify any signs of irregularities, such as burning, and evaluate the structural conditions of the leachate treatment ponds.

3. Results and discussion

The orthomosaic and DSM (Figure 3) generated by the aerial photogrammetry showed a GSD of 7.78 centimeters, with an average reprojection error of only 0.161 pixels, indicating that the block adjustment, positional adjusting, and image orientation were well aligned, with the calculated positions of the camera and GCPs very similar to the real position. The GCP were measured with high accuracy (0.020 m accuracy in XY/Z) (Table 2), being essential for the georeferencing and positional adjustment of the images.

Table 2 – Localization accuracy per GCP and mean errors in the three coordinate directions. The last column counts the number of calibrated images where the GCP has been automatically verified vs. manually marked.

GCP Name	Accuracy XY/Z [m]	Error X [m]	Error Y [m]	Error Z [m]	Projection Error [pixel]	Verified/ Marked
PC1 (3D)	0.020/ 0.020	0.031	-0.053	0.009	0.801	11 / 11
PC2 (3D)	0.020/ 0.020	-0.009	0.022	-0.011	0.605	14 / 14
PC3 (3D)	0.020/ 0.020	-0.005	0.012	0.027	0.798	15 / 15
PC4 (3D)	0.020/ 0.020	0.010	0.007	-0.021	0.844	17 / 17
PC5 (3D)	0.020/ 0.020	-0.038	0.002	0.042	0.645	12 / 12
Mean (m)		-0.002316	-0.002035	0.009352		
Sigma (m)		0.022521	0.026401	0.023253		

RMS error (m)		0.022640	0.026479	0.025063		

Source: Pix4Dmapper report (2017), authors (2025).

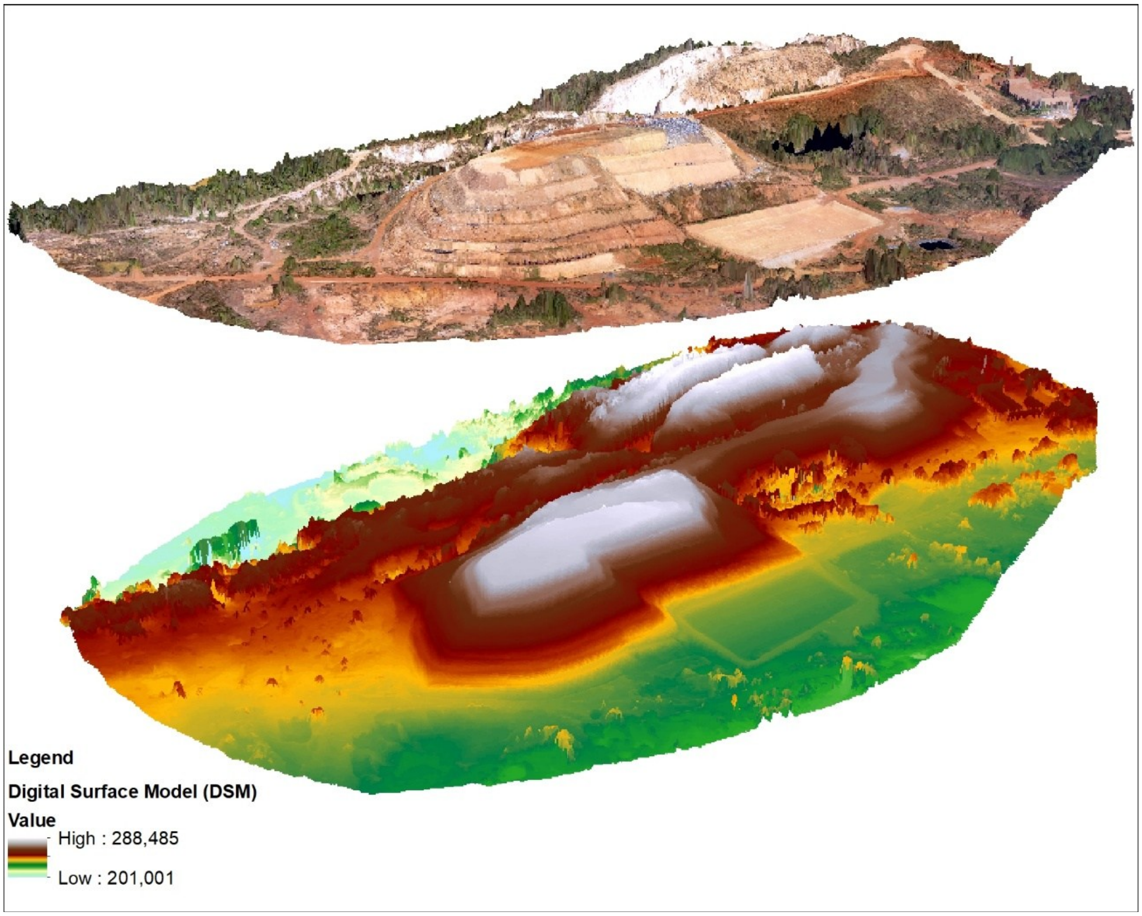

Figure 3 – Visualization in 3D perspective of the orthomosaic and MDS.
Source: Authors (2025).

The results of the DSM cartographic accuracy evaluation showed Root Mean Square (RMS) errors of 0.0226 meters in X, 0.0265 meters in Y, and 0.0251 meters in Z, with an average three-dimensional PSE of 0.0248 meters. These values meet the limits for Accuracy Class A at 1:1,000 scale, according to PEC, which allows a maximum admissible error of 0.5 meters and RMS errors up to 0.3 meters for planimetry. For altimetry, Decree-Law No. 89.817/1984 stipulates that the standard error must not exceed one-third of the contour interval. Given the vertical RMS error of 0.0251 meter, a minimum contour interval of 7.5 centimeter is required. Thus, the use of 10 centimeter contours is appropriate, ensuring compliance with Class A standards. It illustrates that the products are suitable for high-precision applications, including spatial analysis and environmental monitoring, highlighting the quality and accuracy of the photogrammetric model used.

The average PSE of 0.024 meters illustrates the high level of accuracy both horizontally and vertically (Table 2). The relative accuracy of the camera positions was 0.111 meters on the X axis, 0.118 meters on the Y axis, and 0.095 meters on the Z axis. Furthermore, the relative differences between the initial and optimized internal parameters of the cameras were only 0.8%, indicating that the aerial survey has adequate accuracy for applications that require high-fidelity detail.

In view of that, it seems that the orthomosaic and DSM have sufficient planialtimetric resolution to detail the condition of the landfill. According to Filkin *et al*. (2022), the accuracy is higher on terrains with low complexity, where the waste cell overlap is minimal, and the waste mass has distinct lateral and basal edges, enabling clear differentiating from the surrounding terrain. In this study, these characteristics are evident, with the waste mass being visually prominent due to its height relative to the surrounding terrain. This allowed a clear identification of the base level on which the waste is deposited.

The creation of a high altimetric resolution DSM corresponds to a new way of approaching the problem of designing, implementing, and monitoring landfill projects (FILKIN *et al*., 2022). From models with adequate scale, it is possible to calculate a set of parameters such as volumes, areas, and perimeters, as well as derivative products including topographic profiles, shaded images, slope and aspect maps, hypsometric intervals, and three-dimensional perspectives.

Based on the DSM obtained through photogrammetry, topographic profiles of the waste cells were generated (Figure 5) using cross-sections of the landfill (Figure 4).

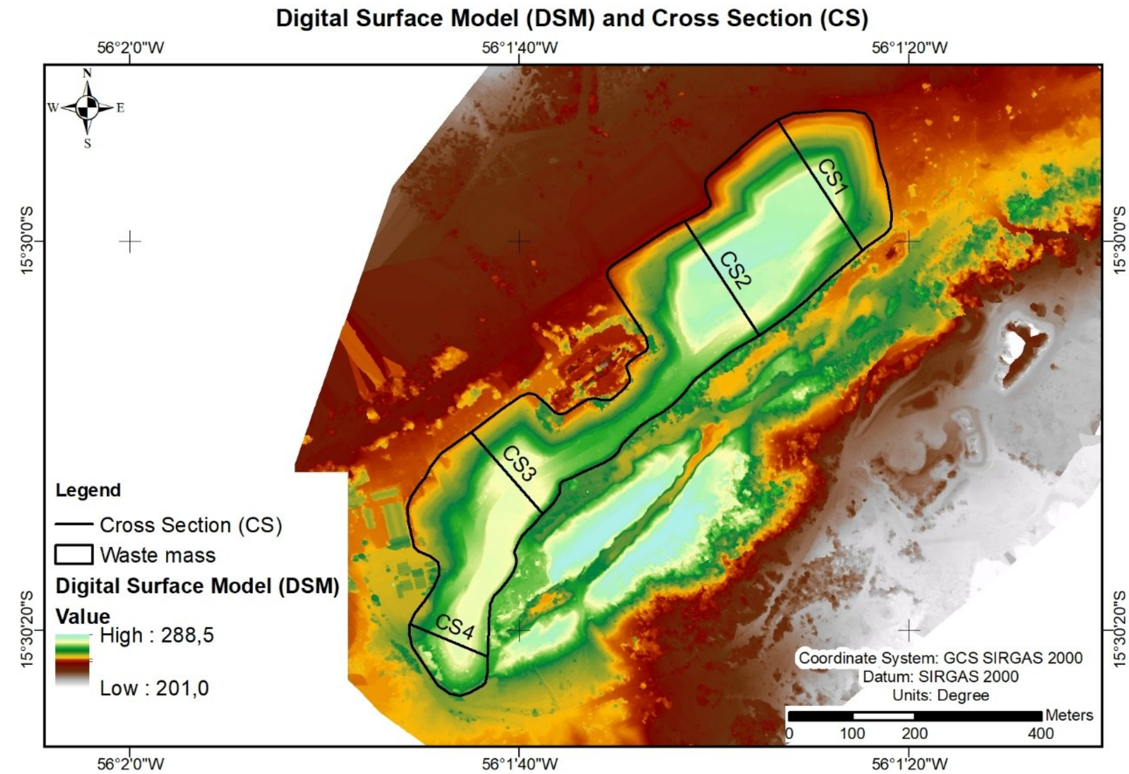

Figure 4 – Digital Surface Model (DSM) DSM and Cross-Sections (CS) of the Cuiabá landfill.
Source: Authors (2024).

The cross-sections CS1 and CS2 refer to the waste cell that was active in 2017, the year the survey was conducted, while the sections CS3 and CS4 are the first cell used for waste disposal, which was deactivated in 2017 (Figure 4).

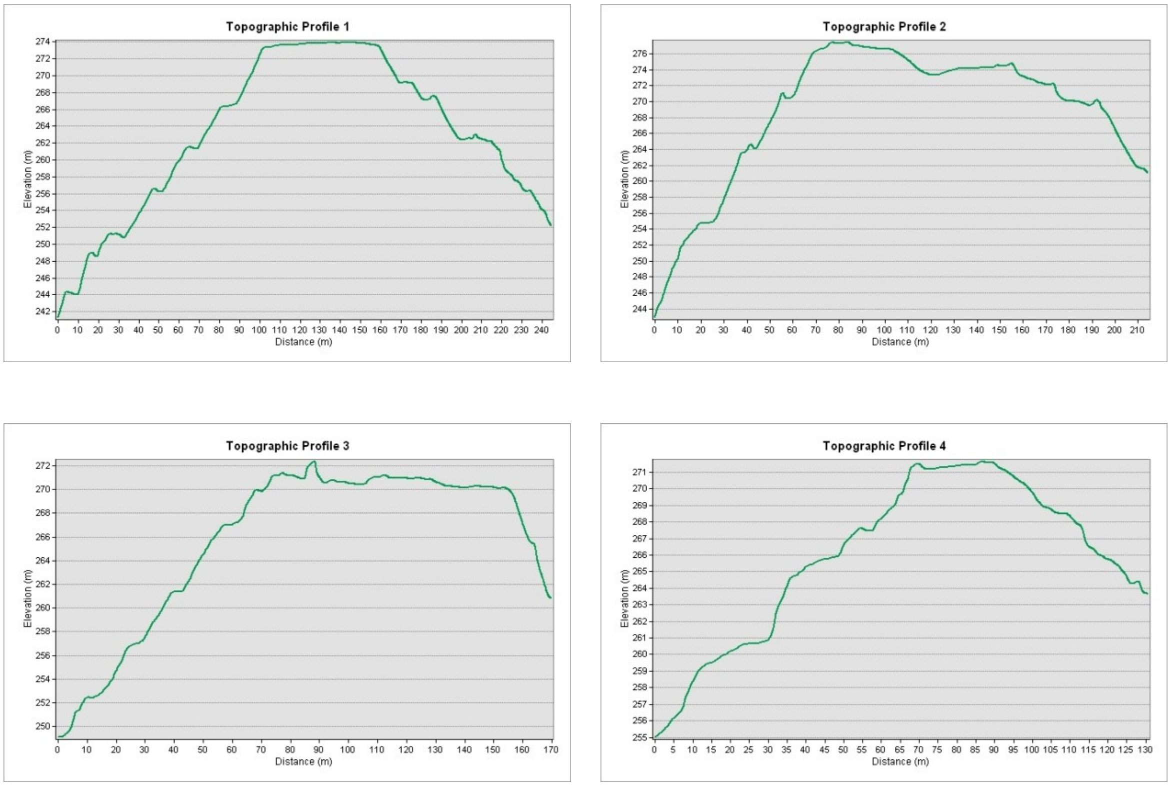

Figure 5 – topographic profiles.
Source: Esri (2016).

Through the topographic profiles, it was possible to determine the height and base of the waste cell. It was found that the tallest active cell in 2017 was approximately 33 meters (S1) and 29 meters (S2) in height, as well as 250 meters (S1) and 220 meters (S2) in width. Meanwhile, the lowest cell showed heights ranging from 23 meters (S3) to 16 meters (S4) and widths ranging from 170 meters (S3) to 135 meters (S4), corresponding to the oldest deactivated cell.

3.1 Visual analysis and field investigation

The visual analysis of the aerial images indicated that the solid waste disposal was not in compliance with certain minimum requirements established by the NSWP. The main issues observed both in the orthomosaic and through field investigation on the day of the aerial survey were improper waste disposal, leachate leakage over the cell, abandonment of leachate treatment ponds, and signs of possible solid waste burning.

3.1.1 Improper waste disposal

Proper solid waste disposal in sanitary landfills requires soil, air, and water protection. Brazilian Regulatory Standard (NBR) No. 8419 of 1992 establishes that the waste disposal must be accompanied by covering and compaction at the end of operations, daily. Nonetheless, the absence of covering and compaction of the disposed waste was observed (Figure 6A), which can lead to the attraction of micro and macro vectors to the landfill, expose the waste to the weather conditions, and intensify the organic matter degradation, increasing leachate and gas production, as well as dispersing waste beyond the waste cell or waste mass.

3.1.2 Leachate leakage

The visual analysis of the orthomosaic allowed the identification and localization of several points of leachate leakage (Figures 6B and 6C). Malta *et al*. (2017) argue that it is possible to identify leachate and gas drainage locations through

RPAS. Christensen *et al*. (2001) highlight the impact of leachate presence in the soil, with adverse effects at distances greater than 100 meters from the final disposal site, caused by toxic substances originating in the waste mass. Castilhos Junior *et al*. (2006) reveal the contamination risks to the groundwater and surface waters if leachate reaches local water sources, posing serious environmental damage, including the emission of volatile gases into the atmosphere.

3.1.3 Abandonment of leachate treatment ponds

Another problem observed by visual analysis of the orthomosaic and confirmed by the collectors present on the day of the aerial survey was the abandonment of leachate treatment ponds (Figure 6D), which was originally designed for the treatment of leachate.

Leachate is a highly polluting substance formed by the decomposition and leaching of organic waste. As a result of its low biodegradability, this effluent can cause serious harm to the environment and public health if not properly treated. Environmental damage includes soil and groundwater contamination, leading to a complete cycle of water contamination. Therefore, NBR 8419/1992 outlines the minimum conditions required for the construction of a sanitary landfill, stipulating that the project must include a system for the collection, drainage, and treatment of percolated liquids.

The most used methods for leachate treatment in this case are aerobic or anaerobic biological treatment (activated sludge, lagoons, and biological filters) and physical-chemical treatment processes (dilution, filtration, coagulation, flocculation, precipitation, sedimentation, adsorption, ion exchange, and chemical oxidation) (IWAI, 2005).

In Figure 6D, the neglected appearance of the lagoons is evident, with difficult access due to excessive growth of dense vegetation around them, lack of leachate recirculation, and likely insufficient maintenance and monitoring of the lagoons, contributing to increased leachate contamination.

3.1.4 Solid waste burning

Another aspect evident from visual analysis was the presence of scattered marks of extinguished flames, indicating potential past burning of solid waste (Figure 6E).

Article 47 of the NSWP prohibits the open-air burning of solid waste or in unlicensed containers, facilities, or equipment not licensed for this purpose. Despite that, fires are frequently observed at solid waste disposal sites lacking proper control and monitoring. These fires often result from the decomposition of waste, generating biogas, which is a mixture primarily composed of methane and carbon dioxide (LANDIM; AZEVEDO, 2008).

In such situations, methane accumulates pressure as it forms and migrates along the paths of least resistance within the waste mass. Since methane is lighter than air and highly flammable, if its concentration reaches 5 to 15% of the air present within the voids of the mass or at the surface, a spark or flame can ignite in those areas, potentially causing a severe explosion (LANDIM; AZEVEDO, 2008).

Moreover, the recurrent burning of waste in landfills or abandoned dumps releases particulate matter and atmospheric pollutants. These emissions not only degrade air quality but also extend beyond the disposal areas, adversely affecting nearby populations. (GOUVEIA, 2012).

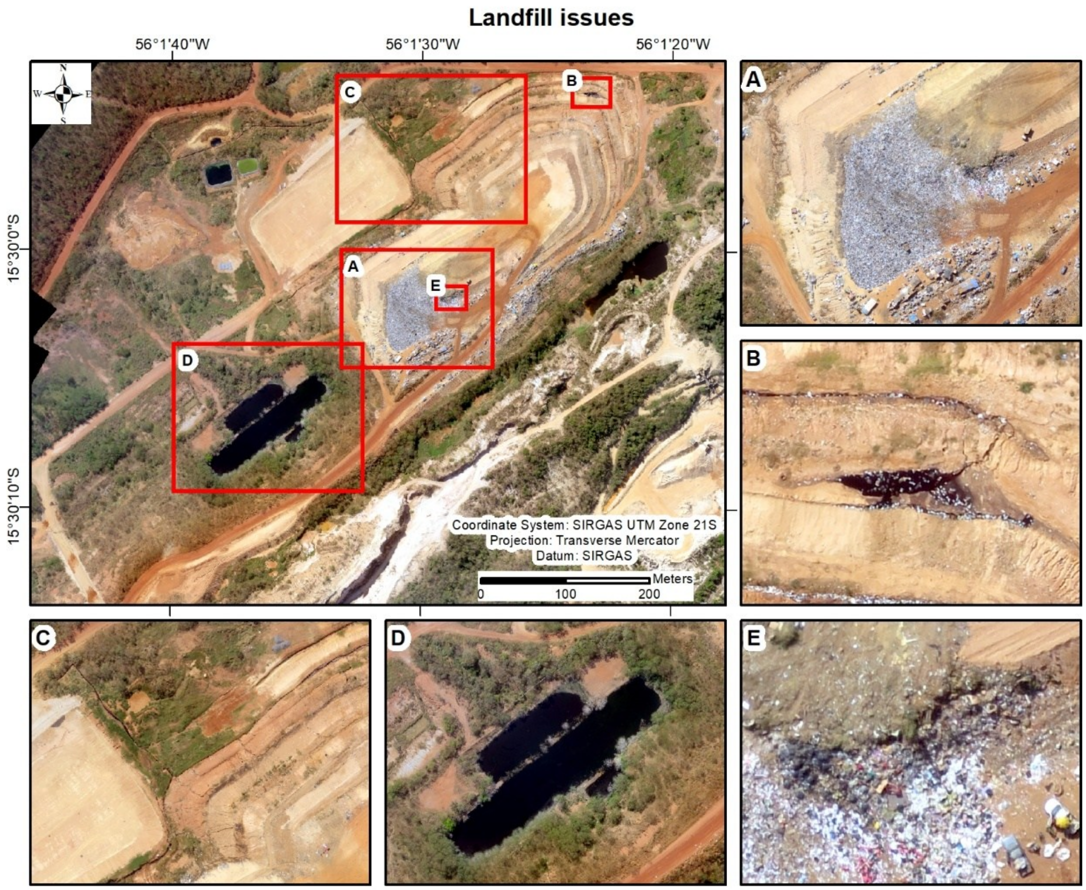

Figure 6 – Issues observed in the Cuiabá Landfill.
Source: Authors (2025).

4. Conclusion

This study demonstrated the effectiveness of orthomosaic and Digital Surface Model (DSM), obtained via Remotely Piloted Aircraft System (RPAS), for fast and accurate environmental monitoring of sanitary landfills. The accuracy of the DSM was comparable with traditional geodetic surveying, exclusively based on field data. This approach also allowed the precise identification of major operational issues at the Cuiabá landfill, including leachate leaks, abandonment of treatment ponds, exposed waste without proper compaction and cover, and signs of improper waste burning. The visual analysis based on the orthomosaic offered a clear view of the waste disposal facility's operational state during the aerial survey. By identifying these issues, it will be possible to improve landfill management's compliance with environmental protection laws.

The findings emphasize the importance of diagnosing and monitoring sanitary landfills with RPAS technologies and recommend these tools to other landfills in Brazil, especially in cases of inadequate operations, such as those observed in Cuiabá.

Acknowledgements

We would like to express our gratitude to Centro Geo Geotecnologias Comercio e Serviços LTDA EPP for providing us with the eBee RPAS from senseFly, equipped with the Canon digital camera, model IXUS 127 HS, as well as the Pix4Dmapper Pro software, version 3.1.22, and the RTX dual-frequency GNSS, Trimble R10. We also extend our thanks to the Federal University of Mato Grosso for supplying the ArcGIS software, version 10.4.1.

References

ABRELPE. *Panorama dos Resíduos Sólidos no Brasil 2020*. São Paulo: ABRELPE, 2020. Available: https://abrelpe.org.br/panorama/. Access on: Jan 25, 2024

AGEAGLE. *Sensors*. Available: https://ageagle.com/solutions/sensors/. Access on: Mar 20, 2024.

AGEAGLE. *eBee X mapping drone - Drones*. Available: https://ageagle.com/drones/ebee-x/. Access on: Mar 20, 2024.

ALMEIDA, A. Número de catadores cresce 200% no "lixão a céu aberto". *Gazeta Digital*. Available: https://www.gazetadigital.com.br/editorias/cidades/numero-de-catadores-cresce-200-no-lixao-a-ceu-aberto/554886. Access on: Jan 24, 2024.

AMADU, C. C.; OWUSU, S.; FOLI, G.; BRAKO, B. A.; ABANYIE, S. K. COMPARISON OF ORDINARY KRIGING (OK) AND INVERSE DISTANCE WEIGHTING (IDW) METHODS FOR THE ESTIMATION OF A MODIFIED PALAEOPLACER GOLD DEPOSIT: A CASE STUDY OF THE TEBEREBIE GOLD DEPOSIT, SW GHANA. *Malaysian Journal of Geosciences (MJG)*, v. 6, n. 1, p. 19-28, 2022. http://doi.org/10.26480/mjg.01.2022.19.28

BEZERRA, J. P. P. Gestão de resíduos sólidos e geotecnologias: considerações elementares. *Periódico Eletrônico Fórum Ambiental da Alta Paulista*, v. 10, n. 4, p. 75–91, 12 nov. 2014.

BRASIL. *Law No. 12,305, of August 2, 2010***.** Establishes the National Policy on Solid Waste and other measures. Available: https://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/lei/l12305.htm. Access on: Sep 17, 2024.

CAETANO, R. G. Prefeitura apresenta Estudo de Impacto Ambiental do novo aterro sanitário ao Ministério Público. *Prefeitura de Cuiabá*. Available: http://www.cuiaba.mt.gov.br/procuradoria-geral/prefeitura-apresenta-estudo-de-impacto-ambiental-do-novo-aterro-sanitario-ao-ministerio-publico/13509. Access on: Jan 24, 2024.

CARVALHO, E. M. A.; SILVA, I. A. F. Análise Diagnóstica sobre a Gestão dos Resíduos Sólidos: um Estudo de Caso no Aterro Sanitário de Cuiabá - MT. In: *VIII SIMPÓSIO DE EXCELÊNCIA EM GESTÃO E TECNOLOGIA***,** 2011 Resende, Rio de Janeiro. Anais [...]. Resende: AEDB, 2011. Available: https://www.aedb.br/seget/arquivos/artigos11/26114223.pdf. Access on: Sep 17, 2024.

CASTILHOS JUNIOR, A. B. DE; PROJETOS (BRASIL) (FINEP), F. DE E. E; PROJETOS (BRASIL) (FINEP), F. DE E. E. *Gerenciamento de resíduos sólidos urbanos com ênfase na proteção de corpos d'água: prevenção, geração e tratamento de lixiviados de aterros sanitários*. [s.l.] Associação Brasileira de Engenharia Sanitária e Ambiental, 2006. Available: https://repositorio.mcti.gov.br/handle/mctic/5582. Access on: Sep 17, 2024.

CHRISTENSEN, T. H.; KJELDSEN, P.; BJERG, P. L.; JENSEN, D. L.; CHRISTENSEN, J. B.; BAUN, A.; ALBRECHTSEN, H.-J.; HERON, G. Biogeochemistry of landfill leachate plumes. *Applied Geochemistry*, v. 16, n. 7, p. 659–718, 1 jun. 2001. https://doi.org/10.1016/S0883-2927(00)00082-2

CUIABÁ. *Plano municipal de saneamento básico*. Prefeitura de Cuiabá, 2013. Available: http://www.cuiaba.mt.gov.br/upload/arquivo/planosaneamentobasico.pdf. Access on: Sep 17, 2024.

CUIABÁ. *Estudo de Impacto Ambiental – EIA*. Prefeitura Municipal de Cuiabá, 2016a. Available: https://www.cuiaba.mt.gov.br/download.php?id=34789.. Access on: Sep 17, 2024.

CUIABÁ. *Novo aterro sanitário de Cuiabá relatório de impacto ambiental – RIMA*. Prefeitura Municipal de Cuiabá, 2016b. Available: https://www.cuiaba.mt.gov.br/download.php?id=34788. Access on: Sep 17, 2024.

CUIABÁ. *Plano Municipal de Gestão Integrada de Resíduos Sólidos de Cuiabá/MT*. Prefeitura Municipal de Cuiabá, 2020. Available: https://cae8e92f-fad0-4b7a-b2de-69a8ad2088f9.filesusr.com/ugd/7f0fbc_b1802fa0ac5c4361ad26ef09abd9b162.pdf. Access on: Sep 17, 2024.

ESRI. *ArcGIS 10.4.1 for (Desktop, Engine, Server) Geocoding General Maintenance Patch*. Available: https://support.esri.com/en-us/patches-updates/2016/arcgis-10-4-1-for-desktop-engine-server-geocoding-gener-7382. Access on: Mar 20, 2024.

FERREIRA, A. M. *Cuiabá "enterra" lixão e passa a operar Ecoparque Pantanal com licitação de R$ 25 milhões***.** Repórter MT. Available: https://www.reportermt.com/entrevista/cuiaba-enterra-lixao-e-passa-a-operar-ecoparque-pantanal-com-licitacao-de-r-25-milhoes/188672. Access on: Jan 24, 2024.

FILKIN, T.; SLIUSAR, N.; HUBER-HUMER, M.; RITZKOWSKI, M.; KOROTAEV, V. Estimation of dump and landfill waste volumes using unmanned aerial systems. *Waste Management*, v. 139, p. 301–308, 15 fev. 2022. https://doi.org/10.1016/j.wasman.2021.12.029

GALIN, E.; GUÉRIN, E.; PEYTAVIE, A.; CORDONNIER, G.; CANI, M.-P.; BENES, B.; GAIN, J. A Review of Digital Terrain Modeling. *Computer Graphics Forum*, v. 38, n. 2, p. 553–577, 2019. https://doi.org/10.1111/cgf.13657

GOUVEIA, N. Resíduos sólidos urbanos: impactos socioambientais e perspectiva de manejo sustentável com inclusão social. *Ciência & Saúde Coletiva*, v. 17, p. 1503–1510, jun. 2012. https://doi.org/10.1590/S1413-81232012000600014

HASSAN, S. Z.; SUN, P.; GOKGOZ, M.; CHEN, J.; REINHART, D. R.; GUSTITUS-GRAHAM, S. UAV-based approach for municipal solid waste landfill monitoring and water ponding issue detection using sensor fusion. *Journal of Hydroinformatics*, v. 25, n. 6, p. 2107–2127, 10 out. 2023. https://doi.org/10.2166/hydro.2023.195

IWAI, C. K. *Tratamento de chorume através de percolação em solos empregados como material de cobertura de aterros para resíduos sólidos urbanos*. [s.l.] Dissertação (Mestrado em Engenharia Industrial) - Faculdade de Engenharia, Universidade Estadual Paulista. Bauru - SP., 14 jan. 2005. Available: http://hdl.handle.net/11449/90805. Access on: Sep 17,2024.

KANG, T.; SUH, M. Retrieval of High-Resolution Grid Type Visibility Data in South Korea Using Inverse Distance Weighting and Kriging. *Korean Journal of Remote Sensing*, v. 37, n. 1, p. 97-110, 2021. https://doi.org/10.7780/kjrs.2021.37.1.8

KNECHTEL, R.; PAULA, R. B.; SILVA, M. A.; SILVA, C. R. M.; SANTOS, C. C. B.; COELHO, A. C.; RIGOTTI, V. L.; PEREIRA, P. T.; CUTRIM, A. O. Avaliação da dispersão da pluma de contaminação do antigo lixão da cidade de Cuiabá-MT, usando sondagem elétrica vertical e caminhamento elétrico. In: *13TH INTERNATIONAL CONGRESS OF THE BRAZILIAN GEOPHYSICAL SOCIETY & EXPOGEF*, 2013, Rio de Janeiro. Anais […]. Rio de Janeiro: 29 ago. 2013. Available: https://library.seg.org/doi/10.1190/sbgf2013-114. Access on: Jan 24, 2024

LANDIM, A. L. P. F.; AZEVEDO, L. P. DE. O aproveitamento energético do biogás em aterros sanitários: unindo o inútil ao sustentável. *BNDES Setorial*, n. 27, p. 59–99, mar. 2008. http://web.bndes.gov.br/bib/jspui/handle/1408/2433

LAUREANO, A. T.; SHIRAIWA, S. Ensaios geofísicos no aterro sanitário de Cuiabá-MT. *Revista Brasileira de Geofísica*, v. 26, p. 173–180, jun. 2008. https://doi.org/10.1590/S0102-261X2008000200005

LI, J.; HEAP, A. D. Spatial interpolation methods applied in the environmental sciences: A review. *Environmental Modelling & Software*, v. 53, p. 173-189, 2014. https://doi.org/10.1016/j.envsoft.2013.12.008

LIMA, L. M. Q. *Remediação de lixões municipais (aplicações da biotecnologia)*. São Paulo: Hemus, 2005.

LINDSAY, J. B. Efficient hybrid breaching-filling sink removal methods for flow path enforcement in digital elevation models. *Hydrological Processes*, v. 30, n. 6, p. 846–857, 2016. https://doi.org/10.1002/hyp.10648

MALTA, L.; BARROS, J.; CANDEIAS, A. Projeto aerofotogramétrico para RPA's (VANT) no aterro sanitário no município de escada. In: *XIX SEMANA DE ENGENHARIA FLORESTAL DA UFRPE*, 2017, Recife. Anais [...]. Recife: UFRPE, 2017. Available: https://www.researchgate.net/publication/317348735_PROJETO_AEROFOTOGRAMETRICO_PARA_RPA'S_VANT_NO_ATERRO_SANITARIO_NO_MUNICIPIO_DE_ESCADA. Access on: Sep 17,2024.

MELLO, C.; SIMÕES, G. Aerofotogrametria com VANT aplicada ao monitoramento volumétrico de aterros sanitários. In: *IX CONGRESSO BRASILEIRO DE GEOTECNIA AMBIENTAL (REGEO 2019) VIII CONGRESSO BRASILEIRO DE GEOSSINTÉTICOS (GEOSSINTÉTICOS 2019)*, 2019, São Carlos. Anais [...]. São Carlos: REGEO, 2019. Available: https://www.researchgate.net/profile/Caio-Mello-3/publication/340315988_Aerofotogrametria_com_VANT_aplicada_ao_monitoramento_volumetrico_de_aterros_sanitarios/links/5e83d68c299bf130796dbca0/Aerofotogrametria-com-VANT-aplicada-ao-monitoramento-volumetrico-de-aterros-sanitarios.pdf. Access on: Sep 17,2024.

MOUSSA, H; ABBOUD, M. The Methodology of Applying Inverse Distance Weighting Interpolation Method in Determining Normal Heights. *Proceedings of Science and Technology*, v. 4, n. 1, 2024. https://doi.org/10.21625/resourceedings.v4i1.1068

PARENTE, D. C. *Utilização de veículo aéreo não tripulado (VANT) na identificação de resíduos de construção civil (RCC) dispostos em locais inadequados*. Dissertação (Mestrado em Engenharia Ambiental) - Programa de Pós-Graduação em Engenharia Ambiental, Universidade Federal do Tocantins, Palmas, 9 nov. 2016. Available: http://hdl.handle.net/11612/364. Access on: Sep 17,2024.

PIX4D. *Professional photogrammetry and drone mapping software*. Available: <https://www.pix4d.com/>. Access on: 20 mar. 2024.

PIX4DMAPPER. *Quality Report*. Available: https://support.pix4d.com/hc/en-us/articles/202558689-Quality-Report-Help-PIX4Dmapper. Access on: 20 mar. 2024.

RIBEIRO, N. L. D.; CANTÓIA, S. F. O lixão de Cuiabá e a geração de impactos socioambientais. *Geosaberes*, Fortaleza, v. 11, p. 100–115, jan. 2020. http://www.repositorio.ufc.br/handle/riufc/53500

SANFORD, C. *Prefeitura faz acordo judicial e recebe licença para o funcionamento do Aterro Sanitário*. Prefeitura de Cuiabá. Available: http://www.cuiaba.mt.gov.br/secretarias/empresa-cuiabana-de-zeladoria-e-servicos-urbanos/prefeitura-faz-acordo-judicial-e-recebe-licenca-para-o-funcionamento-do-aterro-sanitario/6536. Access on: Jan 26, 2024.

SHIRAIWA, S.; LISOVSKY, S. P.; ELIS, V. R.; PORSANI, J. L.; BORGES, W. R. Estudos geofísicos integrados no lixão de Cuiabá, MT, Brasil: resultados preliminares. *Revista Brasileira de Geofísica*, v. 20, p. 181–186, dez. 2002. https://doi.org/10.1590/S0102-261X2002000300004

SILVA, C. A. DA; SOUTO, M. V. S.; DUARTE, C. R.; BICHO, C. P.; & SABADIA, J. A. B. Avaliação da acurácia dos ortomosaicos e modelos digitais do terreno gerados pelo MVANT/DNPM. *Revista Brasileira de Cartografia*, v. 67, n. 7, p. 1479–1495, 2015. http://www.repositorio.ufc.br/handle/riufc/64400

TRIMBLE. *User guide-Trimble R10 GNSS reciver*. Available: https://www.trimble.com/ls_receiverhelp/v5.11/en/r10userguide.pdf. Access on: Mar 20, 2024.

WYARD, C.; BEAUMONT, B.; GRIPPA, T.; HALLOT, E. UAV-Based Landfill Land Cover Mapping: Optimizing Data Acquisition and Open-Source Processing Protocols. *Drones*, v. 6, n. 5, p. 123, maio 2022. https://doi.org/10.3390/drones6050123