Geospatial Analysis of Karst Features using UAV-Based LiDAR in Sete Lagoas, Minas Gerais, Brazil

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Abstract

This study presents the application of UAV-based LiDAR and aerial photogrammetry for the detailed mapping and morphometric analysis of karst features in the Sete Lagoas region, Brazil. Thirteen karst depressions were identified, including eight caprock dolines and five karst lagoons, based on high-resolution elevation models and structural geological field data. The integration of geomorphological and structural information enabled a precise characterization and volumetric estimation of the features using GIS-based methods. The results provide essential insights into the morphology of the karst system and contribute to the development of thematic cartographic products. These products may support future investigations on groundwater recharge and enhance strategies for sustainable management of water resources in areas strongly reliant on karst aquifers. Beyond the scientific contributions, the datasets generated also provide a valuable foundation for future development of a Spatial Data Infrastructure (SDI), which could facilitate easier access, visualization, and interpretation of karst features for research and sustainable water resource management, , particularly in regions such as Sete Lagoas where karst systems play a vital role in water supply.

Keywords: Karst geomorphology, Dolines, UAV-based LiDAR, Geospatial analysis.

1. Introduction

Karst terrains are distinctive geological landscapes shaped by the dissolution of soluble rocks such as limestone, dolomite, and evaporites, resulting in landforms like dolines, blind valleys, and underground rivers [1] [2]. These environments cover about 15% of the Earth's surface and around 3% of Brazil, especially in carbonate formations like the Bambuí Group [3].

Dolines are closed depressions that play a key role in groundwater recharge. Caprock dolines, in particular, result from the subsidence of overlying material into voids formed beneath insoluble layers and are significant indicators of subsurface karstification [4]. Understanding their morphology is crucial for aquifer protection and land-use planning.

UAV-based LiDAR has significantly advanced the identification of these features, producing high-resolution DEMs even in vegetated areas [5]. Combined with GIS, this data supports the creation of thematic maps that integrate geological and hydrographic information [6].

Recent advancements in UAV-based LiDAR technology, such as higher point density, improved penetration through vegetation, and enhanced integration with GIS platforms, have considerably expanded its application in karst geomorphology [7] [8]. Other studies have demonstrated the usability of UAV LiDAR for analysing karst terrain morphology, specifically for doline detection [9] [10].

Despite their importance, karst features in urban and peri-urban areas in Brazil remain poorly mapped. In Sete Lagoas, Minas Gerais, where much of the municipal water supply depends on karst aquifers, there is a lack of detailed morphometric data. This study aims to identify and characterize caprock dolines and karst lakes in Sete Lagoas using UAV-based LiDAR and geospatial analysis (Figure 1). The objective is to generate thematic maps that support hydroenvironmental understanding and water resource management in the region.

Given the hydrogeological relevance of karst systems for water supply and the risks associated with subsidence in urban areas, the generation of detailed cartographic products goes beyond academic purposes. High-resolution mapping and morphometric characterization of karst features represent key tools for supporting aquifer protection, territorial planning, and sustainable water resource management. In this context, integrating UAV-based LiDAR and photogrammetric datasets offers not only advances in geomorphological analysis but also practical applications for decision-making in regions that depend on karst aquifers, such as Sete Lagoas.

Beyond its immediate scientific objectives, this study was designed with a broader perspective: the geospatial datasets produced could serve as the foundation for the future development of a Spatial Data Infrastructure (SDI) for Sete Lagoas or even contribute to a larger SDI of the Federal University of Minas Gerais (SDI-UFMG). An SDI is a coordinated framework of geographic data, metadata, standards, and tools that enables efficient sharing and use of spatial information. In Brazil, the concept is implemented nationally through the Infraestrutura Nacional de Dados Espaciais (INDE), which aims to integrate and make geospatial data available for diverse applications [11]. Such a system would facilitate the storage, access, and visualization of karst morphometric data, strengthening the ability of researchers, planners, and decision-makers to monitor and manage karst environments in a systematic and integrated manner.

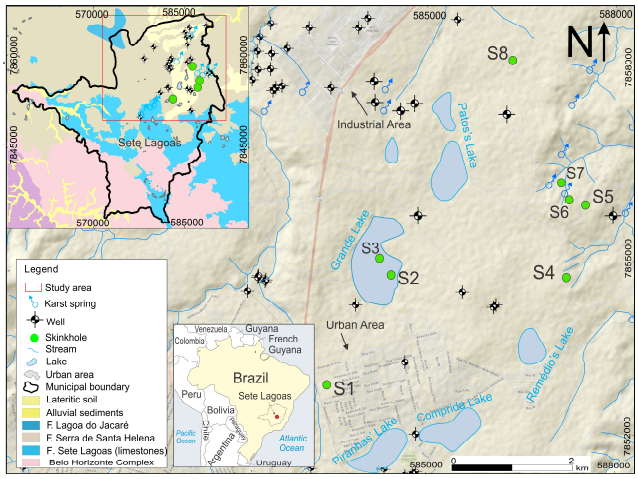

Figure 1. Location map of the study area.

2. Material and Methods

The study was conducted in the northeast region of the municipality of Sete Lagoas, Minas Gerais (Figure 1), a medium-sized city where groundwater from karst aquifers supplies most of the population [12]. The area features carbonate rocks of the Sete Lagoas Formation (Bambuí Group), responsible for the development of typical karst landforms [13].

A UAV equipped with a LiDAR sensor was used to acquire high-resolution topographic data, producing dense point clouds capable of capturing microtopographic variations, even beneath partial vegetation cover. Ground Control Points (GCPs) were surveyed using RTK-GPS to enhance spatial accuracy and ensure precise co-registration between datasets (Figure 2A).

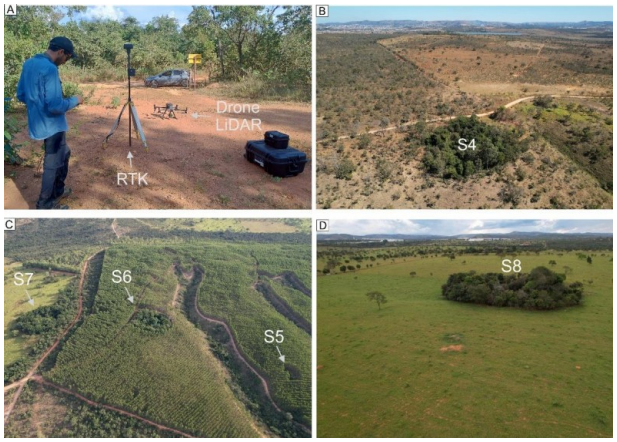

Figure 2. UAV survey and aerial views of dolines: (A) RTK-GPS and LiDAR system coupled to the drone; (B) overflight of sinkhole S4; (C) sinkholes S5–S7 under denser vegetation; (D) sinkhole S8 with dense vegetation.

3. Results

The remote sensing surveys, which integrated UAV-based LiDAR and aerial photogrammetry, successfully allowed for the mapping and characterization of a total of 13 karst features in the Sete Lagoas study area, specifically identifying 8 caprock dolines and 5 karst lakes.

The interpretation of high-resolution Digital Elevation Models (DEMs) derived from LiDAR and the UAV imagery enabled the accurate delineation of these landforms. The detailed morphometric data obtained revealed that the dolines showed depths ranging from 2 to 25 meters and mapped areas from 287 m^2 to 8,416 m^2, with calculated volumes reaching up to 130,075 m^3.

Most dolines exhibited a bowl shape, suggesting gradual subsidence, while one (S4) presented collapse features. The karst lakes, in contrast, were significantly larger in area, ranging from 156,305 m^2 to 794,872 m^2, with average depths between 5 and 10 meters and volumes exceeding 1.2 million m3 (reaching up to 1,222,929 m^3). These lakes likely function as recharge zones and are indicators of aquifer-surface interactions (Figure 4).

The integration of geomorphological and structural information within the GIS environment allowed for a precise characterization and volumetric estimation of the features. As a final product, a thematic map was developed that integrates and correlates dolines, sinkholes, lithological units, contour lines, hydrography, and closed depressions to aid in the identification of karst features. This map serves as an essential foundation for further detailed studies and hydrogeological assessments, with field validation confirming the accurate identification and interpretation of the karst features.

The spatial analysis of the karst features revealed significant patterns: dolines and karst lakes are spatially clustered in specific areas of the study site, mainly near lithological contacts identified in geological maps, evidencing a structural control over the formation of these features, corroborating studies on the conceptual geological model of the region [12]. Furthermore, the overlay of these features with borehole data and hydrogeological maps available in the Spatial Data Infrastructure (SDI) Sisema showed that many coincide with

Photogrammetric processing in Agisoft Metashape generated orthomosaics and 3D point clouds, which were subsequently aligned with the LiDAR-derived products. The LiDAR point cloud was filtered and classified to produce a bare-earth Digital Terrain Model (DTM), while the orthomosaics provided high-resolution visual information for surface feature interpretation. These datasets were then integrated into ArcGIS Pro 3.3 by overlaying raster and vector layers, combining elevation models, contour lines, and geological maps (Figure 3).

This integrated approach enabled morphometric analyses of dolines and karst lakes (Figures B, C, D), including calculations of area, depth, and volume, as well as spatial correlations with lithological units, sinkholes, tubular wells (Sisema Spatial Data Infrastructure – SDI Sisema, the Minas Gerais state platform for spatial data sharing), and hydrological data from The National Water Agency (ANA), supporting a comprehensive geomorphological interpretation.

The datasets generated in this study were developed not only for detailed morphometric analysis but also to provide geospatial products with potential for integration into a Spatial Data Infrastructure (SDI), facilitating future access and analysis by researchers, planners, and decision-makers.

Finally, thematic maps were developed within a GIS environment, and field validation confirmed the accurate identification and interpretation of karst features. By integrating LiDAR-derived DTMs, photogrammetric orthomosaics, geological maps, and hydrological datasets, the thematic maps provide a spatial framework capable of informing groundwater management, aquifer vulnerability assessments, and urban planning in karst terrains.

aquifer recharge zones, reinforcing their role in the local hydrogeological regime and in agreement with studies on recharge sources in the region [11].

These patterns motivated the creation of a thematic map (Figure 5) that integrates dolines, sinkholes, lithological units, contour lines, hydrography, and closed depressions. This map not only supports the geospatial interpretation of karst features but also represents a cartographic product with potential for integration into a SDI for Sete Lagoas or even the Federal University of Minas Gerais (SDI-UFMG), providing a structured base for future hydrogeological studies and water resource management planning.

The results provide essential insights into the morphology of the karst system, revealing structural controls and recharge patterns that are fundamental for hydrogeological understanding. These thematic products can support future investigations on groundwater recharge and contribute to regional strategies for sustainable management of water resources in areas highly dependent on karst aquifers.

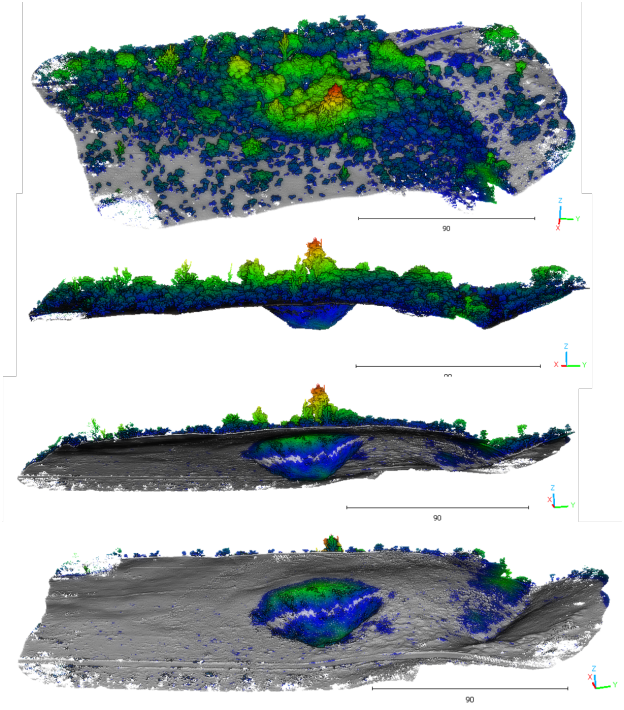

Figure 3. Processing and morphometric analysis of doline S4.

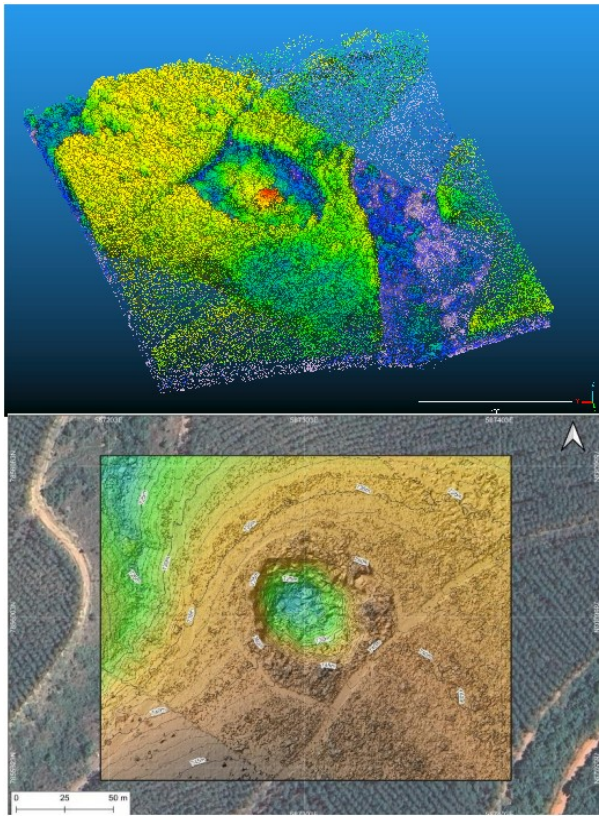

Figure 4. Morphometric analysis of doline S8.

4. Conclusion

This study successfully identified and characterized 13 karst features in Sete Lagoas (8 dolines and 5 karst lakes) using UAV-based LiDAR and photogrammetric point clouds, providing detailed morphometric data on their shape, depth, area, and volume.

Dolines reached depths of up to 25 m and volumes of 130,075 m³, while karst lakes extended over 794,872 m² with volumes exceeding 1.2 million m³, emphasizing their role as recharge zones and indicators of aquifer–surface interactions.

The integration of LiDAR-derived DTMs with photogrammetric point clouds proved effective for delineating karst features even under dense vegetation, highlighting the value of geotechnologies in advancing karst studies and supporting future applications such as hydrodynamic modelling and aquifer vulnerability assessments.

The resulting thematic map integrates geological, hydrological, and structural datasets, offering a validated tool for hydrogeological assessment, aquifer protection, and land-use planning in karst environments. Beyond the scientific contributions, the cartographic products generated in this study hold direct implications for territorial planning and groundwater management in Sete Lagoas. The validated maps of dolines and karst lakes offer essential support for identifying recharge areas, mitigating risks related to subsidence, and ensuring aquifer sustainability in an urban context strongly dependent on karst water resources. Furthermore, the methodological framework developed here can be replicated in other Brazilian karst regions, fostering broader strategies for hydrogeological monitoring, land-use planning, and sustainable management of karst environments.

Finally, the geospatial datasets and thematic maps generated here provide a robust basis for future integration into a Spatial Data Infrastructure (SDI) for Sete Lagoas or the Federal University of Minas Gerais (SDI-UFMG). Such integration would facilitate broader access, interpretation, and management of karst features, strengthening the potential for research, territorial planning, and sustainable water resource management.

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