# Integration of Low-Cost Sensor Technologies and Open Geospatial Data for Comprehensive 3D Cadastral Modeling of Terrain

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**Key words**: Geospatial data integration, Multisource-based terrain modeling, Low-cost sensors, Land administration from low-cost data, 3D cadastre

**SUMMARY**

This manuscript presents a methodology for 3D cadastral modeling by integrating low-cost sensor technologies, such as drone-based photogrammetry, with authoritative geospatial datasets. The approach is designed to overcome the limits of conventional 3D data acquisition, which can be highly resource-consuming. The workflow proposed in this research encompasses multisource data integration, such as data cleaning, georeferencing, and the alignment of 3D geometries with legal parcel boundaries. The resulting models are suitable for visualization and cadastral verification, offering practical tools to enhance land administration practices. It may also be used as the basis of 3D building representation or volumetric cadastre. To demonstrate its applicability, our proposed methodology is applied to a property located on the bank of a river in rural Québec, away from major urban centers.

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## 1. INTRODUCTION

Land administration systems are in significant transformation with the emergence of 3 D cadastres. In contrast to conventional 2D representations, 3D cadastres provide a more comprehensive approach to define and visualize property rights, restrictions and responsibilities (RRR) particularly in environments where multiple legal parcels overlap vertically (Shiode, 2012; Stoter et al., 2016; Olsen, 2019). This development is related to the increasing demand for precise spatial information in settings such as vertical developments, underground infrastructure, and densely built metropolitan areas (Grifith-Charles and Sutherland, 2020; Gkeli et al., 2021). By incorporating 3D geoinformation, 3D cadastres have the potential to reinforce legal certainty, improve land-use planning, and contribute to more sustainable forms of territorial governance (Coote et al., 2017; Gkeli et al., 2020; da Purificaçao et al., 2022).
In Québec province, Canada, the cadastre remains essentially 2D, limited to parcel numbers and boundary measurements recorded on cadastral plans. The system provides a legal framework for property identification and delimitation, but it does not capture volumetric rights or any 3D terrain modeling for land use. In certain situations where superposed properties exist (e.g. condominium), the cadastral plan is insufficient to represent all the information related to a 3D property. For this reason, Ministry of Natural Resources and Forests (MRNF) instructions include a specific status called ″Cadastre vertical″. In brief, the current 2D cadastral plan refers to external complementary plans (CP). These CPs contain all the information related to the 3D cadastral system, including vertical profiles and information such as width, length, height, surface and volume of the properties. A CP-number could refer to one or several complementary plans, which are managed separately from the cadastral plan (MRNF, 2025). Early work reveals significant challenges in automating the migration from 2D plan of superposed properties to 3D cadastral plan (Pouliot et al., 2010).
Despite their benefits, the large-scale implementation of 3D cadastres has been constrained by diverse issues. High acquisition costs and technical requirements associated with established technologies (e.g. aerial LiDAR, drone-based LiDAR, and mobile mapping systems) remain prohibitive for many land administration agencies. While these methods deliver highly accurate datasets, they remain expensive and difficult to apply in regions where institutional or technical capacities are limited. Consequently, the modernization of cadastral systems has progressed unevenly, leaving gaps in their integration with broader frameworks of land management and territorial planning (Ho et al., 2018; Olsen, 2019).
Recent advances in low-cost geospatial technologies offer promising alternatives to overcome these barriers. Affordable tools such as drones, smartphones, and tablets equipped with advanced sensors now make it possible to capture detailed 3D information with relative ease (Rokhmana and Utomo, 2016; Ramlal et al., 2023; Gonçalves et al., 2024; Dragomir et al.,

2025). Governments are also increasingly releasing high-quality spatial datasets (e.g. digital elevation models, cadastral boundary layers, and orthoimages) that can be combined with sensor-based data. The integration of these complementary resources makes it possible to generate geometrically accurate and legally relevant 3D cadastres at a fraction of the cost of conventional approaches. However, achieving this requires structured workflows capable of ensuring spatial accuracy, legal validity, and interoperability with existing cadastral and land administration systems. Beyond visualization, such workflows must support essential cadastral functions, including property boundary verification, rights delimitation, and regulatory compliance.

This paper proposes a cost-effective and scalable methodology for acquiring and integrating 3D cadastral data by combining different low-cost sensors with governmental open geospatial sources. By addressing issues of accuracy, completeness, and interoperability, the research aims to contribute to the development of practical solutions that can accelerate the adoption of 3D cadastres in diverse contexts. To illustrate its feasibility, the approach is applied to a cabin situated on the bank of a river in rural Québec (Canada), away from major urban centers, where access to updated geospatial information is limited.

## 2. MATERIALS AND METHODS

### 2.1 Study area

The study was conducted in a cabin located in the Portneuf Regional County Municipality (RCM), shown in Figure 1. Unlike urban environments where dense data acquisition infrastructures and geospatial updates are frequent, rural and recreational areas often face challenges such as limited accessibility, heterogeneous land cover, and reduced availability of up-to-date cadastral information. The study site includes typical features of rural properties such as a forested parcel on an uneven terrain, and a main building with attached structures along a river. Figure 1 shows the property chosen for our study.

**Figure 1.** Location of the studied property in a rural area of Québec. The red dot on the upper left shows its position within the province of Québec, highlighting the Portneuf Regional County Municipality (RCM) near the Québec City area.

Figure 2 illustrates the anonymized cadastral parcel (A 123 456) of the study area. Cadastral data was obtained from ″Cadastre du Québec″ provided by the authoritative government (MRNF-Ministère des Ressources naturelles et des Forêts) via the Infolot platform (Infolot, 2025). The study area is subject to the Rv-12 zoning regulation. According to the municipal regulation, the main building on this property is subject to a front margin of 7 meters, a side margin of 2 meters, but with a combined side margin of 9 meters and a rear margin of 10 meters. Similarly, the detached garage on this property is subject to a rear margin of 1 meter, side margins of 1 meter (1.5 meters where an opening exists), and a front margin consistent with that of the main building. These margins are essential for ensuring compliance with land-use planning. For example, they help prevent risks and provide access for emergency vehicles. However, they are never shown in the official cadastral plan, as they vary depending on the municipality and specific zoning regulation within each jurisdiction.


**Figure 2.** Anonymized cadastral parcel of the study area.

The cadastral map only shows the parcel boundaries in 2D. It does not provide any information about the river and the terrain slope. Since the property is located along the river, part of it is included within the riparian strip. The verification of the riparian strip, steep slopes, and other constraints is necessary, as any structure within this strip is subject to additional restrictions to prevent flood risks and erosion. The riparian strip is a 15-meter strip measured from the high-water line (MDDEP and CREL, 2009). Knowing the terrain gradient is also essential because any structure located on a steep slope must comply with geotechnical stability requirements and municipal building codes to mitigate risk such as erosion, landslides, or foundation failure.

### 2.2 Generation of terrain 3D cadastre

The methodology for generating a 3D terrain cadastre proposed in this manuscript and applied to the study site follows three main steps. First, data has been acquired on the field by UAV and GNSS antennas and has been processed to generate a point cloud, DTM and orthoimage. Second, land tenure or cadastral analysis involves gathering legislative and regulatory information, such as margins, steep slopes, flood zones, and agricultural zoning. Essentially any details that may constrain the property under applicable laws and regulations. Third, these datasets are integrated and harmonized within a common reference system to reconcile terrain geometry with legal boundaries aiming to be integrated into a multi-layered 3D cadastre that unites physical terrain with ownership and regulatory information. Figure 3 illustrates the methodology.

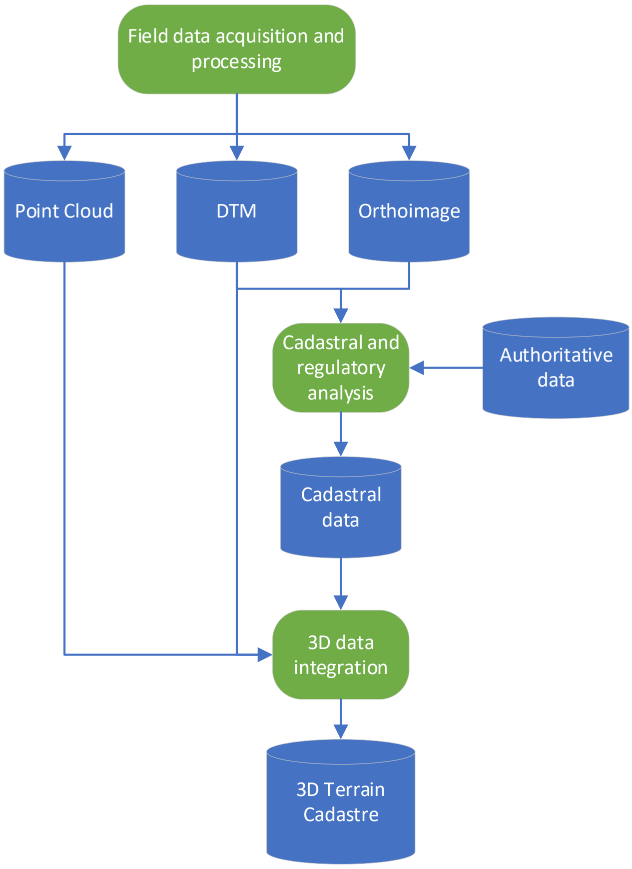


**Figure 3.** Proposed methodology to generate a 3D cadastre of the terrain.

2.2.1 Field data acquisition and processing

The first step consists of the photogrammetric survey that was carried out using a drone DJI Mavic 3E (DJI, 2025) with an onboard 20 MP wide-angle camera (5280x3956 pixels), valued at approximately $8,000 CAD. Flight missions were planned to follow a grid pattern, maintaining constant altitude and systematic coverage of the study area. Longitudinal and lateral overlaps were set, respectively, to 90% and 80% in order to generate dense point clouds with a flight height of 60m and a Ground Sample Distance (GSD) estimated at 1 cm. More than 400 images were acquired within approximately 20 minutes of flight time across the 2450.5 $m^2$ of area. To achieve precise georeferencing, a network of 21 points was used as Ground Control Points (GCPs) and Check Points (CPs) across the study area. Their locations were carefully selected to ensure homogeneous distribution and to account for variations in terrain and land cover, as suggested by ASPRS (2024). Each GCP and CP was measured with a Trimble R12i GNSS receiver operating in RTK mode (Trimble, 2025).
The images were processed using Trimble UASMaster. Automated tie point extraction was performed through aerial triangulation, where distinctive points were detected and matched across overlapping images. This procedure enabled the creation of a robust bundle block adjustment, ensuring that the relative orientation of the imagery was geometrically consistent across the entire dataset. The 3D RMSE of the GCP was 2.9 cm and the CP was 4.5 cm. Once the block adjustment was completed, UASMaster generated a point cloud (cf. Figure 4A) and

an orthoimage (cf. Figures 4B). The point cloud was subsequently filtered to reduce noise using Trimble Business Center, yielding a clean dataset suitable for further modeling. From this segmented and classified point cloud, the Digital Terrain Model (DTM) was derived (cf. Figure 4C), obtained by classifying and removing above-ground objects such as vegetation and buildings with a resolution of 10 cm.

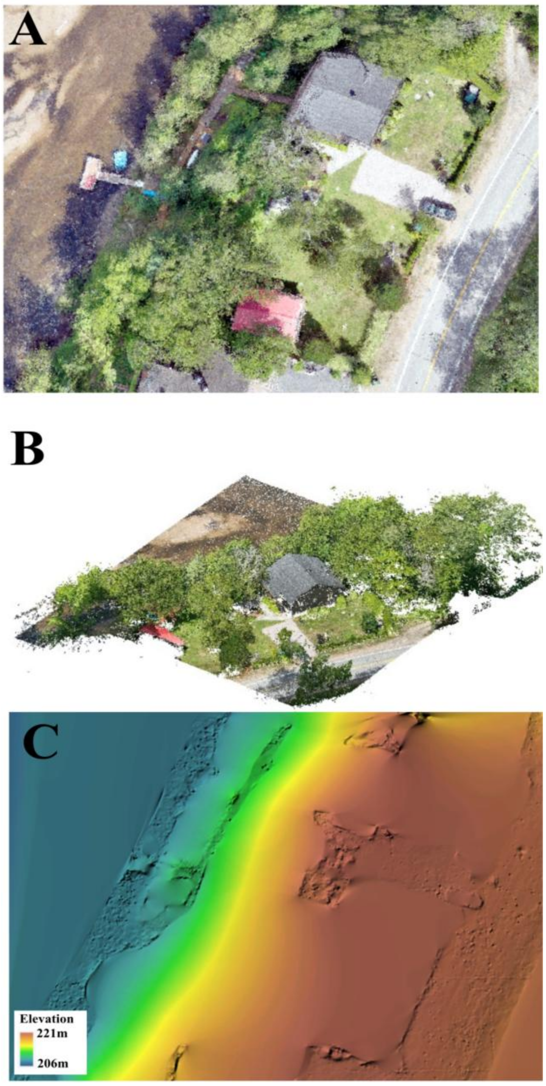


**Figure 4.** Orthoimage with a resolution of 5cm (A), extraction of the point cloud (B) and the DTM with a resolution of 10cm (C) of the studied area.

### 2.2.2 Cadastral and regulatory analysis

The second step involves a cadastral and regulatory analysis that considers both the physical and legal dimensions of the property. The objective is to ensure that the 3D terrain models correspond to the authoritative cadastral boundaries, thereby guaranteeing the accuracy of the 3D model. While this procedure does not replace the exhaustive assessment carried out by a land surveyor, it establishes a solid framework for validation, visualization, and potential future

development. It is important to note that, in the Cadastre du Québec, coordinates have no legal value. Consequently, the lines presented in the case study serve only to illustrate the potential of the proposed framework.
To define the legal constraints, two DTMs were mobilized: the government DTM with a 1 m resolution, and the photogrammetry-based DTM with a 10 cm resolution. Given the limited size of the study area, the higher-resolution photogrammetric DTM was prioritized. However, the government DTM was still used as a reference to visually cross-check the accuracy of the information obtained through low-cost technologies. The riparian strip was delineated using the orthoimage by identifying the high-water line. Along a natural, undeveloped river, the high-water line is characterized by the transition from aquatic to predominantly terrestrial vegetation (MDDEP and CREL, 2009).
In the context of 3D cadastral modeling, steep slopes represent a significant challenge. They complicate both data processing and the demonstration of regulatory compliance. The irregular geometry of steep terrain can lead to distortions or poor image correlation in photogrammetric surveys, thereby affecting the precision of the 3D model. Moreover, such areas are often subject to particular restrictions, such as mandatory setbacks or erosion-control measures, to mitigate risk and adhere to municipal and environmental regulations. In these cases, information is extracted from DTMs generated by photogrammetric products. Depending on the geographic context, the survey methods, and the quality of the resulting datasets, these photogrammetric DTMs can provide sufficiently reliable information to meet the requirements of 3D cadastral modeling.

#### 2.2.3 3D data integration

The third step focused on the integration of multiple datasets into a coherent spatial framework to construct the 3D terrain cadastre. All sources, including the orthoimage, the DTM, the point cloud, and the cadastral/legal layers, were georeferenced within a common coordinate reference system, ensuring geometric consistency between imagery, elevation models, and cadastral boundaries. This alignment was crucial for enabling true three-dimensional interoperability of the datasets. Integration was carried out within a GIS, where QGIS was used for planimetric visualization and ArcGIS Pro for advanced 3D visualization and analysis.
Each dataset contributed a distinct dimension of spatial information. The orthoimage provided a high-resolution two-dimensional backdrop for verifying parcel markers and landscape features. The point cloud supplied dense three-dimensional measurements, supporting the derivation of the DTM and allowing the precise characterization of ground morphology. The DTM itself served as the foundational terrain layer, enabling slope analysis and other elevation-based assessments. Through their integration, these datasets established the geometric framework necessary to connect cadastral information with the physical attributes of each parcel in three dimensions.
Authoritative cadastral and regulatory layers were then incorporated, including official parcel boundaries, watercourse limits, and mandatory setback zones (performed in the previous subsection). Special care was taken to reconcile natural boundaries, such as the riverbank, with their legally defined counterparts in cadastral records. The outcome was a multi-layered 3D dataset that unites terrain geometry, orthoimage context, and cadastral regulations within a single environment. The resulting 3D terrain cadastre enables more than simple overlay: it

supports the visualization and analysis of property extents and restrictions directly in three dimensions. This integration enhances legal verification by grounding cadastral boundaries in the physical reality of the terrain, while simultaneously offering a powerful spatial planning tool for future development and environmental management.

## 3. RESULTS

The integration of drone photogrammetry, GNSS measurements, and authoritative cadastral datasets produced a coherent 3D representation of the study parcel. The orthoimage at 5 cm resolution, combined with the classified point cloud and derived DTM, enabled the identification of parcel delimitation, vegetation, building footprints, and terrain variations relevant to legal conformity. The resulting multi-layered 3D cadastre shows how physical terrain and legal information can be reconciled in a single framework. By linking geometry, parcel boundaries, zoning margins, and environmental constraints, the model provides a practical tool for property rights validation and land-use planning (cf. Figures 5 and 6). Figure 5 illustrates this information in a planimetric representation. This representation may help laypeople visualize and understand the constraints on their property. Although it provides more information than a regular cadastral plan, there is still some challenges, particularly in interpreting the lines when trees or other obstacles are present. This is why 3D representation offers more information that laypeople can interpret and use effectively.


**Figure 5.** Planimetric representation of the integrated cadastral information with the orthoimage.

The integration process brought together the orthoimage, point cloud, DTM, and cadastral layers within a unified 3D framework as illustrated in Figure 6. This allowed the physical characteristics of the terrain (e.g. elevation, slope, riverbank limits) to be directly connected with the legal boundaries and zoning constraints defined in the government cadastre. The parcel can even be partitioned into strips where different regulations apply.

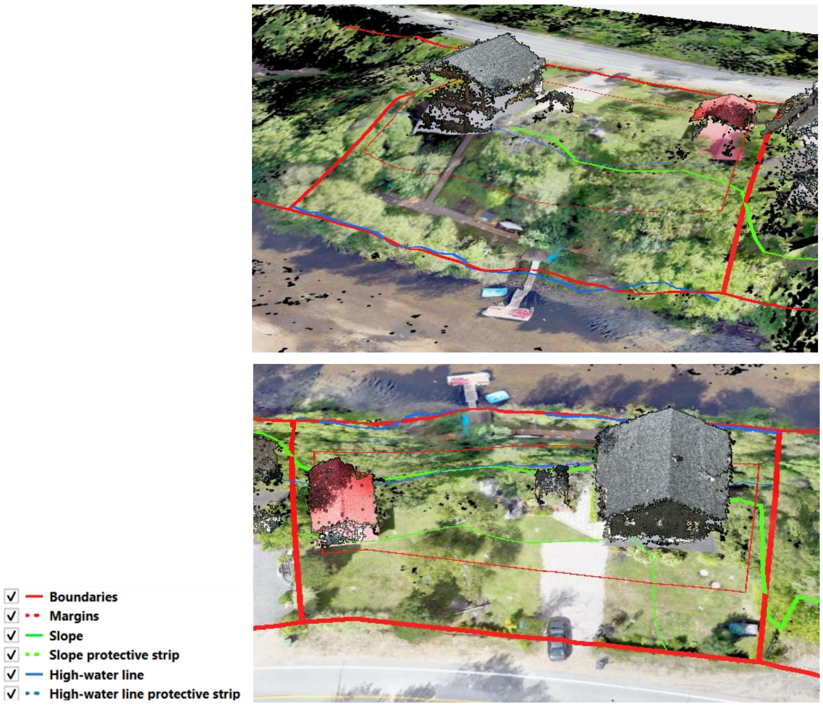


**Figure 6.** Integrated 3D cadastre combining terrain data, cadastral boundaries, and regulatory constraints.

## 4. DISCUSSION

The proposed paper aims to demonstrate that drone photogrammetry, when combined with authoritative data, can produce 3D products with centimetric accuracy that can be used for cadastral analyses. The main advantage of this approach lies in its cost-effectiveness and accessibility, since drones are easier to deploy and require fewer resources compared to advanced equipment. This makes them a realistic option for land administration agencies with limited budgets or technical capacities. The results are consistent with previous work on low-cost surveying (Kersten et al., 2025), and they confirm that the integration of multiple data sources may strengthen the applicability of the resulting models.

Important challenges still remain. While technical alignment between physical and legal data can be achieved, reconciling cadastral information with property law is not straightforward. The Québec cadastral system, as in many jurisdictions, remains essentially two-dimensional, limiting the legal recognition of volumetric models. Thus, even if a technically valid 3D representation can be generated, its operational use in land administration will depend on institutional reform and legal adaptation.

The study also highlights practical limitations inherent to photogrammetry. Image-based methods are sensitive to vegetation, weather conditions, and flight restrictions, and accuracy depends strongly on the distribution and quality of ground control, which requires additional fieldwork. Despite these constraints, the case study confirms the feasibility of low-cost 3D cadastral workflows and illustrates their potential beyond the urban environments that dominate most studies. More broadly, it emphasizes that technical advances must evolve in parallel with institutional and legal frameworks if 3D cadastres are to become fully operational in practice.

## 5. CONCLUSION

This research demonstrates that integrating drone photogrammetry, GNSS measurements, and authoritative cadastral data can generate a coherent 3D terrain modelling that may be insert into a cadastre. The workflow developed, combining low-cost sensors with governmental open data, proved effective for capturing and integrating terrain geometry, parcel boundaries, and regulatory constraints into a single multi-layered 3D environment. The resulting model not only provides a more comprehensive visualization of property rights and restrictions than conventional 2D cadastral plans but also offers practical support for land-use planning, legal verification, and risk management.

Despite these promising results, important challenges remain before such approaches can be mainstreamed into cadastral practice. Technical hurdles include the sensitivity of photogrammetry to vegetation, weather, and control point distribution, while institutional barriers stem from the fundamentally 2D nature of current cadastral systems in Québec and elsewhere. For 3D cadastres to move from demonstration to operational adoption, parallel advances in legal frameworks, institutional practices, and data governance will be necessary. Indeed, the integration of low-cost drone photogrammetry with authoritative data opens a path towards an accessible web-based 3D cadastral system. Recent work on digital twins (La Guardia and Koeva, 2023) highlights the value of combining heterogeneous 3D data within open-source, web-accessible environments. Applying similar principles to the Québec context could support a new generation of cadastral platforms where point clouds, terrain models, and legal boundaries are accessible online to both surveyors and property owners. Such platforms would enhance transparency, enable remote validation of property limits, and foster more inclusive participation in land-use decisions.

Finally, the main challenge lies not only in the technical domain but also in institutional and legal adaptation. While web-based 3D cadastres are technically feasible, their legitimacy depends on the recognition of volumetric rights and responsibilities within property law. In Québec, as elsewhere, cadastral legislation still reflects a two-dimensional conception of land parcels. Moving toward 3D requires both a legal framework that acknowledges volumetric boundaries and operational standards that ensure accuracy, reliability, and data security. Developing such frameworks in parallel with low-cost technical solutions will be essential to move beyond case studies and towards systematic implementation of 3D cadastres in practice.

**ACKNOWLEDGMENT**

The authors thank the property owner (anonymized) for granting access to the study site. We also acknowledge Lina Kokosha for her support in processing the photogrammetric data and generating the DTM.

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**Vicky BINETTE** is a Master student in Geomatics Sciences at Université Laval with extensive professional experience in cadastre and land tenure. Her research focuses on the development and application of 3D cadastre in the Québec context. She is particularly interested in the integration of legal and spatial data to improve property rights management. Her work contributes to advancing innovative approaches for cadastral modernization and territorial governance.

**Sylvie DANIEL** is a Full Professor in the Department of Geomatics Sciences at Université Laval. She has a vast experience in geospatial and hydrospatial research, with expertise in LiDAR and bathymetric point clouds, image processing, 3D modeling, data fusion, and augmented reality. Her work advances the perception and 3D representation of urban and fluvio-marine environments, including city digital twins and seabed morphology.

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