Cost-Effective 3D Land Administration for Climate Adaptation in Developing Regions

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Keywords: 3D Cadastral Mapping, Open-Source Technology, Climate Resilience, UAV-GNSS Integration, Sustainable Land Administration

SUMMARY

The increasing challenges posed by climate change, urban expansion, and the imperative for sustainable land management highlight the critical need for efficient, accessible, and cost-effective 3D cadastral systems. Traditional high-cost techniques have historically limited the adoption of 3D land administration in developing regions, creating a significant barrier to leveraging its full potential for sustainable development and climate adaptation. This study addresses these limitations by exploring the application of open-source and affordable tools for 3D cadastre mapping to foster climate resilience and sustainable development, using Erifun Community, Ado-Ekiti, Nigeria, as a case study. The research integrates low-cost Unmanned Aerial Vehicles (UAVs) and open-source GNSS solutions for 3D cadastral mapping. A DJI Mavic Pro Platinum UAV was employed for aerial photogrammetry, conducting flights at a consistent height of 145m with 80% forward and 72% side overlaps. Emlid RS+ GNSS receivers provided high-precision ground control points. Processing involved QGIS for spatial analysis and Agisoft Metashape 1.5.5 for photogrammetric processing and 3D model generation after initial attempts with OpenDroneMap faced limitations. Spatial accuracy assessment compared GNSS-derived coordinates with digitised points from imagery within QGIS, calculating Root Mean Square Error (RMSE) in X, Y, and Z dimensions. The study successfully generated high-precision 3D cadastral maps for Erifun Community at a fraction of the cost compared to conventional techniques, demonstrating significant affordability, accuracy, and efficiency. Critically, the research demonstrated how 3D land administration systems support climate adaptation strategies through flood susceptibility analysis integrated into the cadastral dataset using the Digital Surface Model (DSM) from UAV flights. This provides valuable data-driven insights for urban planning, infrastructure development, and disaster risk reduction, enhancing community resilience. The findings emphasise the potential of open-source and affordable technologies in democratizing access to 3D cadastre technology, empowering local governments and fostering transparency and participation in land governance. Recommendations advocate for scaling up UAV-GNSS integration, enhancing open-source software capabilities, and developing policy frameworks that recognise 3D land administration models in climate resilience strategies.

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1. INTRODUCTION

1.1. Background: Global Challenges in Land Administration and Climate Change

The intersection of climate change, rapid urban expansion, and the imperative for sustainable land management presents a formidable global challenge. Climate change manifests through phenomena such as rising sea levels, increased frequency and intensity of extreme weather events, and altered precipitation patterns, all of which significantly impact land use and human settlements (Enoguanbhor, Gollnow, Walker, Nielsen, & Lakes, 2022; Taiwo, Mwesigye, & Buxton, 2021; Williamson, Enemark, Wallace, & Rajabifard, 2010). Concurrently, the accelerating pace of urbanisation, particularly in developing regions, places immense pressure on existing land administration systems. This often leads to informal settlements, land disputes, and inadequate infrastructure, further exacerbating vulnerabilities to climate-related hazards (Anierobi et al., 2023; Fundisha, 2022). Effective land administration is crucial for managing these complex interactions, ensuring equitable land access, promoting sustainable development, and building resilience against environmental shifts.

1.2. The Imperative for Cost-Effective and Accessible 3D Cadastral Systems

Traditional 2D cadastral systems, while foundational, are increasingly insufficient to address the complexities of modern land tenure, especially in densely populated urban areas and regions prone to climate impacts. The need for a more comprehensive and accurate representation of land rights, including vertical dimensions, has led to the growing recognition of 3D cadastral systems (Skondras et al., 2022; Taiwo, Ibitoye, & Oladejo, 2023). These systems offer a more precise understanding of property boundaries, subsurface rights, and airspace, which are vital for urban planning, infrastructure development, and disaster risk reduction. However, the high costs associated with conventional 3D cadastral mapping techniques have historically limited their adoption, particularly in developing regions where resources are often constrained(Griffith-Charles & Sutherland, 2013). This limitation creates a significant barrier to leveraging the full potential of 3D land administration for sustainable development and climate adaptation.

1.3. Current Limitations and Adoption Barriers of 3D Land Administration in Developing Regions

Despite the clear advantages, the widespread implementation of 3D land administration in developing regions faces substantial hurdles. The cost, in addition to the technical complexity, is a significant reason for limited success in the adoption of 3D LA models in developing regions." The reliance on expensive proprietary software, specialised equipment, and highly trained personnel often renders these systems economically unfeasible for many local governments and small-scale land administrators. Furthermore, a lack of robust policy frameworks, limited institutional capacity, and insufficient technical expertise contribute to these adoption barriers (Atazadeh, Rajabifard, & Olfat, 2023; Paul van der Molen, 2003)These limitations hinder efforts to establish comprehensive and accurate land records, which are essential for effective land governance and climate resilience planning.

1.4. Research Objectives: Bridging the Gap with Open-Source and Affordable Solutions

This study aims to address the limitations above by exploring the application of open-source and affordable tools for 3D cadastre mapping. Our primary objective is to demonstrate how these accessible technologies can foster climate resilience and sustainable development in developing regions. Specifically, this research seeks to:

- Evaluate the effectiveness and accuracy of low-cost Unmanned Aerial Vehicles (UAVs) and open-source GNSS solutions for 3D cadastral mapping.
- Conduct a cost-benefit analysis comparing the proposed low-cost approach with conventional surveying techniques.
- Assess the accuracy, efficiency, and scalability of the integrated UAV-GNSS and open-source software methodology.
- Demonstrate the integration of climate resilience metrics, such as flood susceptibility analysis, into the cadastral dataset to support climate adaptation strategies.
- Propose policy recommendations for the widespread adoption of cost-effective 3D land administration models in developing countries.

1.5. Case Study Context: Erifun Community, Ado-Ekiti, Nigeria

To demonstrate the viability of our proposed approach, this study utilises Erifun Community, Ado-Ekiti, Nigeria, as a case study. This community, like many others in developing regions, faces challenges related to rapid urbanisation, informal land tenure, and vulnerability to climate change impacts (Adeleke et al., 2024). The selection of Erifun Community provides a relevant and representative setting to evaluate the effectiveness of open-source and affordable 3D cadastral solutions in a real-world context, thereby offering valuable insights for similar regions globally.

2. METHODS

2.1. Study Area: Geographical and Socio-Economic Context of Erifun Community

The study was conducted at the Erifun community, a peri-urban settlement located in Ado-Ekiti, Ekiti State, Nigeria. It covers roughly 2 km² and is situated between 7°36′30″N and 7°36′50″N latitude and 5°15′40″E and 5°16′10″E longitude (Taiwo et al., 2024). The climate is tropical savanna, characterised by higher temperatures during the dry season (November–March) and an average of about 1,200 mm of rainfall during the wet season (April–October). The terrain is primarily low-lying and gently sloping, which facilitates rapid runoff and floodwater buildup, a problem exacerbated by poorly drained soils. Land use in the community includes residential neighbourhoods, farms, businesses, and institutions. Unplanned growth and encroachment on waterways have further increased the area's vulnerability to flooding (Abass, 2022). Figure 1 shows the study area.

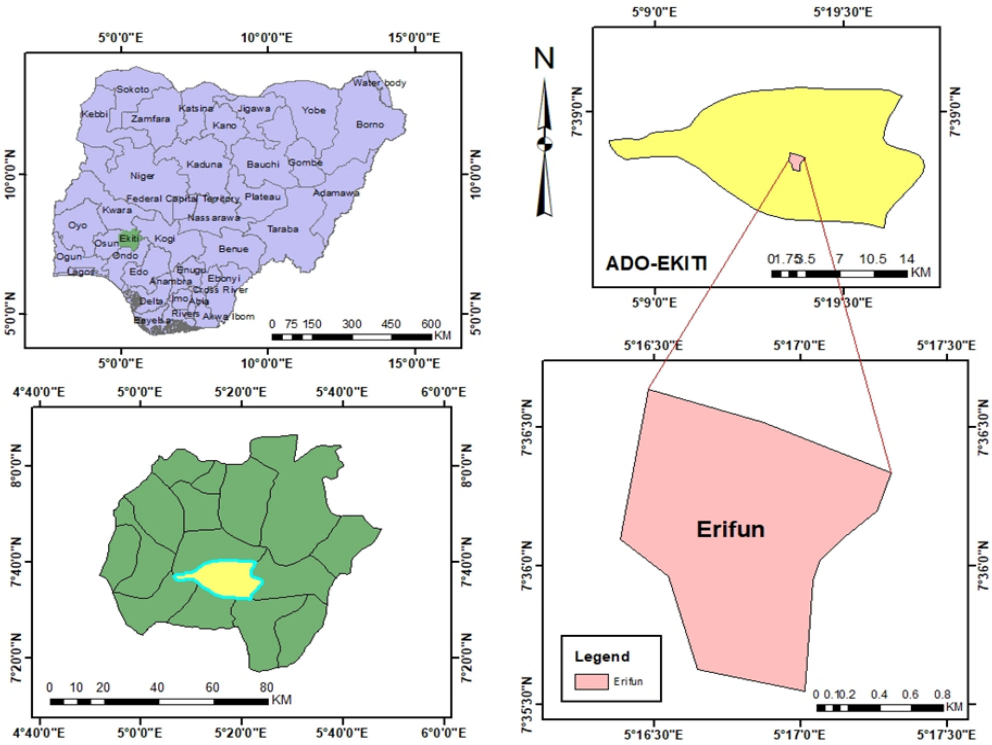

Figure 1. Study Area Map

2.2. Data Acquisition Strategies

Relevant datasets were acquired from both primary and secondary sources to support the 3D cadastral mapping and climate resilience analysis. Table 1 shows the tools used and the rationale behind their use

Table 1. Tools used and rationale behind usage

S/No.	Equipment	Rationale	Description
1.	Mavic Pro Platinum	Low-Cost	Deprecated but easily accessible for rentage or purchase in most developing regions
2.	OpenDroneMap	Semi Open Source	Considered for use, but dropped because of limitations in the number of images based on available licence.
3.	Agisoft Metashape 1.5.5	Proprietary	Used in order to overcome the challenges of processing 790 images at once owing to inadequate fixed coordinates of GCPs
4.	Emlid RS+	Low-cost	Helped to achieve some fixed points
5.	QGIS	Open Source	Used for spatial analysis and flood susceptibility mapping.

2.2.1. Low-Cost Unmanned Aerial Vehicle (UAV) Photogrammetry: Equipment and Flight Planning (Mavic Pro Platinum)

A DJI Mavic Pro Platinum UAV, equipped with a 10-megapixel resolution camera, was employed for aerial photogrammetry. To effectively capture 3D features, five flights were conducted at an average height of 145m above the take-off points, acquiring a total of 790 images. These images were captured with forward and side overlaps of 80% and 72% respectively, and a 70% camera angle. DJI Mavic Pro Platinum was used because of its low cost.

2.2.2. Low-Cost GNSS for High-Precision Ground Control Points (Emlid RS+ Receivers)

Emlid RS+ GNSS receivers provided high-precision ground control points, crucial for enhancing the accuracy of the aerial photogrammetry. For each flight, five well-distributed Ground Coordinate Points (GCPs) were acquired. In instances where a GPS Fix was not achieved within 5 minutes of using the Emlid RS+ GNSS receiver in Real Time Kinematic (RTK) mode, the GNSS data was collected in the available mode (float) with the intention of using any five well-distributed fixed points to process the entire image set.

2.2.3. Spatial Accuracy Assessment Protocols

Ground Control Points (GCPs) were collected using GNSS, with corresponding points digitised from the processed aerial imagery within the QGIS environment. The same identifiable features used for GNSS data collection were carefully digitized from the orthomosaic and 3D model generated from the UAV imagery. The coordinates of these digitised points were then extracted from QGIS. The coordinates obtained from the GNSS measurements were compared with the coordinates of the digitised points from the imagery. This comparison allows for the calculation of discrepancies, typically expressed as Root Mean Square Error (RMSE) in X, Y, and Z dimensions.

2.3. Data Processing and 3D Modelling

The collected datasets were processed using a combination of open-source and proprietary software.

2.3.1. Photogrammetric Processing and 3D Model Generation.

Attempts were initially made to use OpenDroneMap, an open-source software for photogrammetry-based 3D modelling. The OpenDroneMap could only process not more than 200 images at a time. Considering the insufficiency of 5 well-distributed fixed coordinate points across each flights, it became necessary to process all 790 images once. The processing and 3D modelling were eventually carried out using Agisoft Metashape 1.5.5.
By adding photos, aligning the photos, introducing GCP points, building a DEM and building an Orthomosaic, the photogrammetry processing was conducted. Lower options capable of producing fast results that could deliver useful results were selected during the photogrammetric processing.

2.3.2. Open-Source Software for Spatial Analysis and Data Management

Further processing was conducted using open-source QGIS software for spatial analysis and data management. This was used for digitising points for accuracy assessment and parcels for cadastral database creation. This was also used for spatial analysis towards flood susceptibility mapping.

2.4. Integration of Climate Resilience Metrics: Flood Susceptibility Analysis Methodology

The integration of climate resilience metrics, specifically flood susceptibility analysis, was a key component of this study. The methodology for flood risk assessment in Erifun Community involved using the Digital Surface Model acquired from the UAV to generate Hypsographic features, and stream flow lines. WorldClim precipitation data, and pre-existing Land Use/Land Cover maps were integrated. Flood risk zones were identified using a Weighted Overlay (Multi-Criteria Evaluation – MCE) approach, where each factor was assigned a weight based on its relative influence on flooding: Rainfall – 35%, Drainage – 30%, Slope – 15%, Elevation – 10%, and LULC – 10%. This integration produced a Flood Risk Map classifying the community into five categories: very low, low, moderate, high, and very high risk zones. This approach enabled the identification of vulnerable areas and supported data-driven decision-making for flood mitigation.

3. RESULTS

3.1. Generation of High-Precision 3D Cadastral Maps for Erifun Community

In the study, high-precision 2D maps and 3D cadastral data for Erifun Community, Ado-Ekiti, Nigeria, were produced. Figure 2 is the Orthomosaic generated from the UAV mapping process. These maps were developed through the integration of low-cost, open source and proprietary tehnologies. The processing, including spatial analysis, was primarily conducted using open-source QGIS software. The resulting cadastral maps provide a representation of land rights, including vertical dimensions, crucial for modern land tenure systems in developing regions. Figure 3 represents cadastral boundaries extracted from the northern part of the Erifun Community.

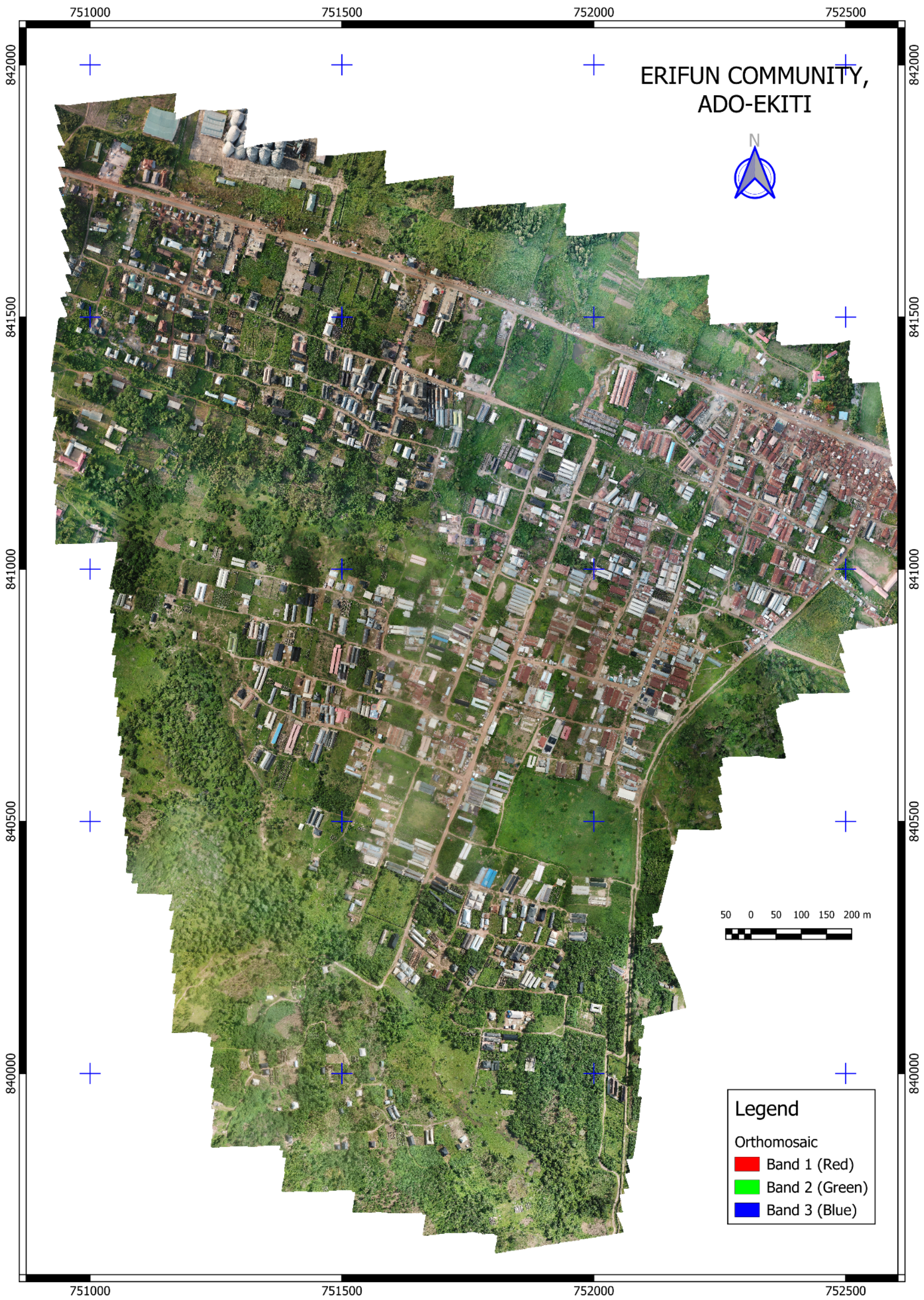

Figure 2. Orthomosaic of Erifun Community

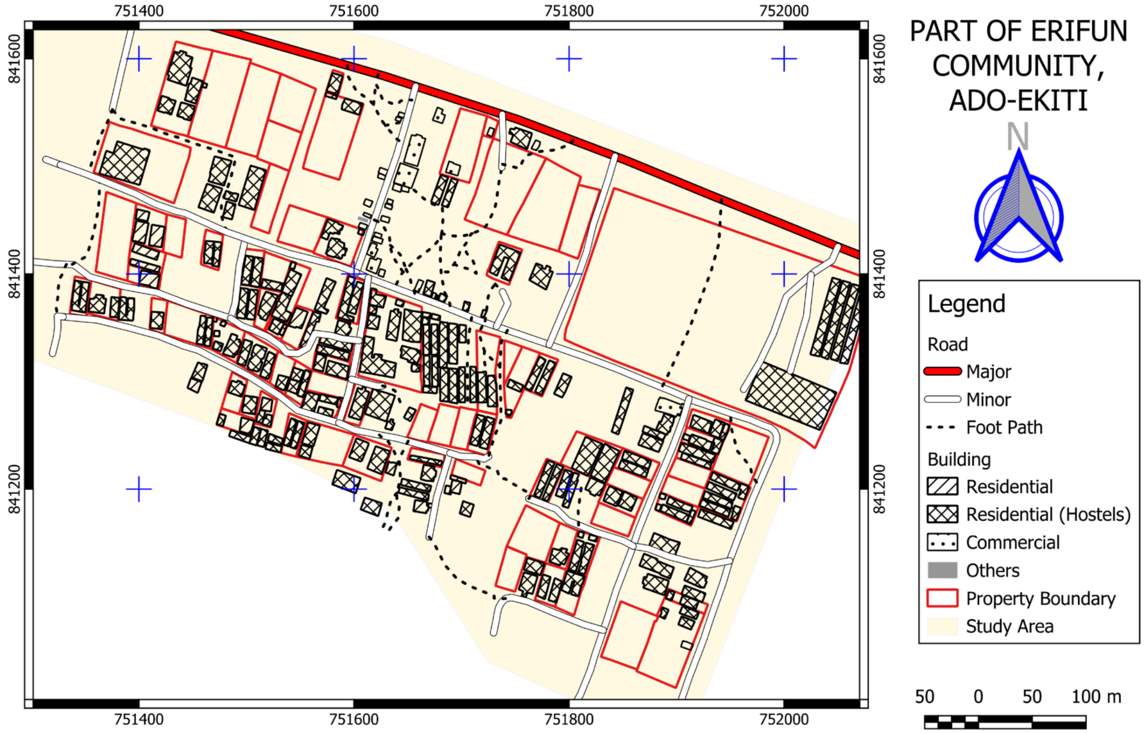

Figure 3. Sample Digitized Cadastral parcels and buildings digitized from orthomosaic

The DSM is shown in Figure 4. DSM of Erifun CommunityFigure 4.
The accuracy comparison between the GNSS derived coordinates and coordinates digitised from the orthomosaic follow after (Taiwo, 2023).

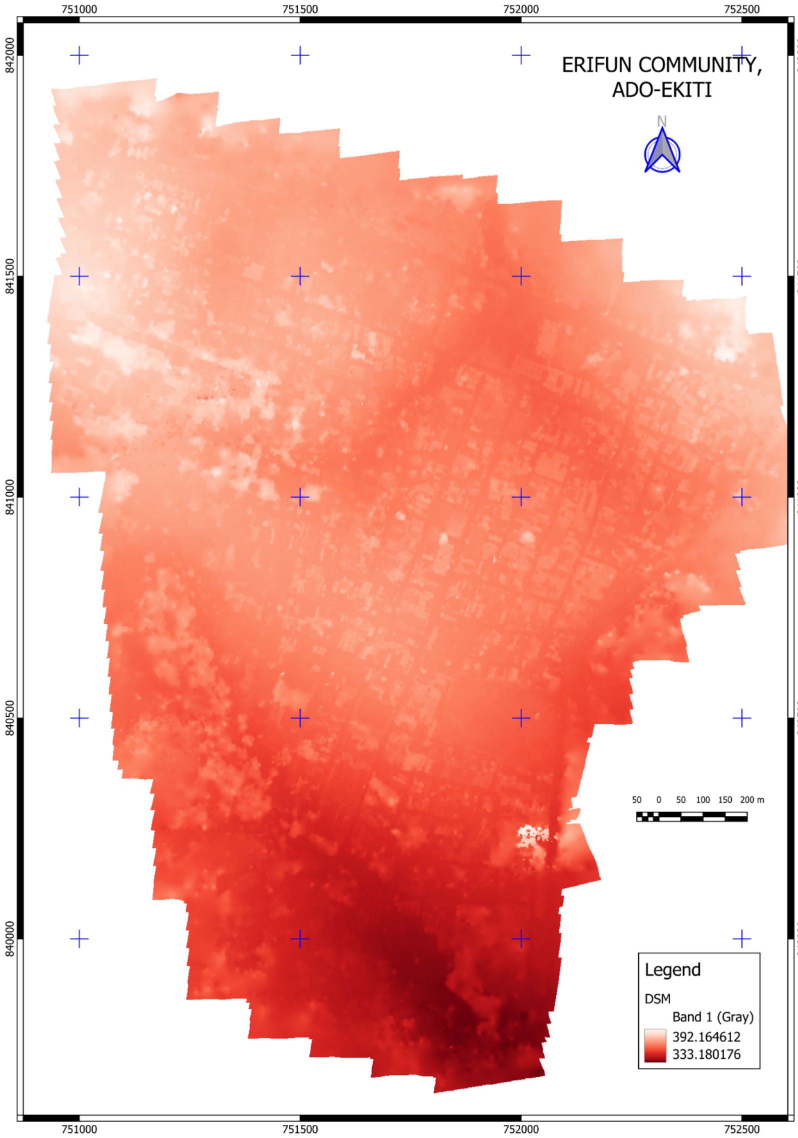

Figure 4. DSM of Erifun Community

3.2. Cost-Benefit Analysis: Comparing Low-Cost Solutions with Conventional Techniques

A finding of the research is the affordability of the approach. The study successfully generated 3D cadastral maps with XYZ data using a combination of low-cost, open-source and proprietary tools at a fraction of the cost compared to leveraging proprietary technologies alone. This cost-effectiveness addresses a major barrier to the adoption of 3D land administration in developing regions. The use of readily available and low-cost, open-source and some proprietary tools significantly reduces the financial component of land administration, making 3D cadastre technology more accessible to local governments and small-scale land administrators.
Table shows the prevalent cost identified by readily available vendors online.

Table 2. Prevalent cost of tools used

S/No.	Equipment	Cost	Vendor
1.	Mavic Pro Platinum	600USD	https://www.ebay.com/
2.	OpenDroneMap	Open Source	
3.	Agisoft Metashape 1.5.5	Proprietary	
4.	Emlid RS+	1000 USD	
5.	QGIS	Open Source	

3.3. Assessment of Accuracy, Efficiency, and Scalability of the Proposed Approach

The integrated UAV-GNSS and open-source software methodology demonstrated high accuracy and efficiency. Scalability is an issue when considering the approach, as observed in the limitation with processing more than 200 images using OpenDroneMap owing to the available lincence. If a fix was achieved in all the GNSS coordinates, the images would have been processed in chunks of less than 200 images and then merged. The spatial accuracy assessment protocols, involving the comparison of GNSS data with digitised points in a QGIS environment, confirmed the reliability of the generated data. The efficiency was evident in the streamlined data acquisition and processing workflows. Integrating available resources, i.e., low-cost, open source and proprietary, will ultimately produce a better, more accurate, efficient and cost-effectve solution for 3D cadastral mapping. Thus, availability is paramount. The scalability of this approach depends on the availability of suitable tools, which will enable wider implementation across various communities facing similar challenges in developing countries, offering a practical solution for sustainable land administration.

3.4. Demonstration of 3D Land Administration Systems in Supporting Climate Adaptation Strategies

The study examines how the 3D mapping approach supports climate adaptation strategies through the integration of climate resilience metrics. Specifically, flood susceptibility analysis was incorporated into the cadastral dataset. This involved using the Digital Surface Model (DSM) from UAV flights, combined with other geospatial data, to identify flood risk zones within the Erifun Community. This integration provides insights for urban planning, infrastructure development, and disaster risk reduction, thereby enhancing the community's resilience against climate-related hazards. Figure 5 shows the flood susceptibility maps.

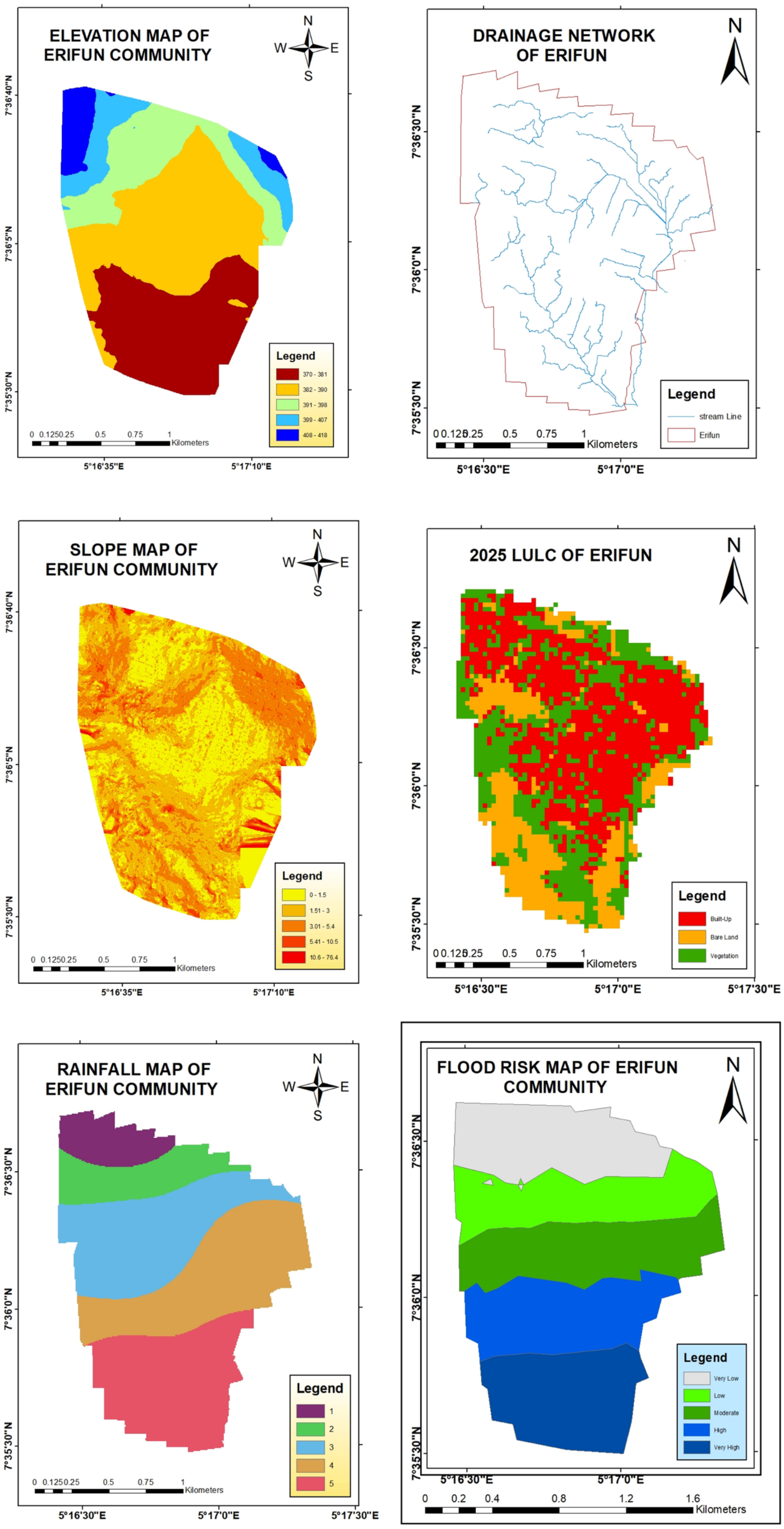

Figure 5. Flood Susceptibility Maps

4. DISCUSSION

4.1. The Role of Open-Source and Affordable Technology in Democratising 3D Cadastre Access

The findings of this study underscore the potential of open-source and affordable technologies in democratizing access to 3D cadastre systems. By demonstrating the successful integration of low-cost UAVs, GNSS solutions, open-source and proprietary software, this research effectively addresses the economic barriers that have historically limited the adoption of 3D land administration in developing regions. This approach enables local governments and small-scale land administrators to create comprehensive and accurate land records, particularly in resource-constrained areas, thereby promoting greater equity and inclusion in land governance.

The practical implications of this study are significant for local governments and small-scale land administrators in developing countries. The demonstrated methodology provides a viable and cost-effective pathway for implementing 3D cadastral systems, which are crucial for effective urban planning, infrastructure development, and disaster risk reduction. The efficiency and accuracy achieved through the integrated approach offer a compelling alternative to conventional methods, enabling these entities to better manage land resources, resolve disputes, and enhance their capacity for sustainable development and climate adaptation.

4.2. How 3D Cadastre Supports Climate Adaptation Strategies

This study elucidates the crucial connection between 3D cadastre systems and climate adaptation strategies. By integrating flood susceptibility analysis into the 3D cadastral dataset, the research demonstrates how these systems can provide invaluable data-driven insights for identifying vulnerable areas and informing targeted interventions. The detailed 3D representation of land and property allows for a more precise understanding of flood risk zones, enabling urban planners and policymakers to develop effective mitigation strategies, such as resilient infrastructure development, land-use zoning, and early warning systems, thereby enhancing community resilience against climate-related hazards.

4.5. Comparison with Existing 3D Land Administration Models and Techniques

While the tools and resources required to build a 3D cadastral database could run into thousands or hundreds of thousands of dollars, this study demonstrates that comparable levels of accuracy and precision can be achieved using affordable UAVs, open-source GNSS, and a combination of open-source and strategically selected proprietary software (Agisoft Metashape 1.5.5 for image processing). This highlights the potential for democratizing access to 3D cadastre technology without compromising on data quality, making it a viable option for regions with limited financial resources.

4.6. Policy Recommendations for Sustainable and Climate-Resilient Land Administration

Based on the findings of this study, some policy recommendations are proposed to advance sustainable and climate-resilient land administration in developing countries:

1. Advocating for Capacity Building in UAV-GNSS Integration in Developing Countries: Stakeholders should actively promote and support the integration of UAV and GNSS technologies for 3D cadastral mapping. This includes providing training, technical assistance, and financial incentives to local governments and land administration agencies.
2. Enhancing Open-Source Software Capabilities for Automated Cadastral Processing: Investment in research and development is needed to further enhance the capabilities of open-source software for automated cadastral processing. This will streamline workflows and improve efficiency,
3. Developing Policy Frameworks Recognising 3D Land Administration Models in Climate Resilience: Governments should develop and implement robust policy frameworks that explicitly recognise and integrate 3D land administration models into national and sub-national climate resilience strategies. This includes incorporating 3D cadastral data into urban planning, disaster risk reduction, and environmental management policies.

4.7. Future Research Directions

This study opens several avenues for future research. Further investigation could explore:

- The long-term sustainability and maintenance of open-source 3D cadastral systems in diverse socio-economic contexts.
- The development of standardised protocols for integrating various open-source tools to create seamless 3D cadastral workflows.
- The potential for community-based participatory approaches in 3D cadastral data collection and validation using accessible technologies.
- Deeper exploration of the socio-economic impacts of implementing cost-effective 3D cadastre systems on land tenure security and local economies.
- Research into the legal and institutional frameworks required to fully support and leverage 3D cadastral data for climate adaptation and sustainable development.

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