Improving Cadastral Accuracy for Disaster Management: The Role of Segment Anything Model (SAM) in Digitizing Historical Cadastral Maps

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SUMMARY

Up-to-date cadastral maps with detailed land ownership, boundaries, and values, are crucial in disaster-prone regions like Nepal, where accurate land data significantly impact disaster risk management for efficient resource allocation, response planning, and so on. Given the challenges associated with updating cadastral mapping, there is a pressing need to digitize existing maps to establish an up-to-date cadastral database. The digitization of old cadastral maps faces challenges like inconsistent skill levels, human errors, and data quality issues, making the process time-consuming and prone to inaccuracies. Hence, automating the process is essential to create an accurate and up-to-date cadastral database.

This study explores the application of the Segment Anything Model (SAM) for automating the digitization of historical cadastral maps, specifically focussing on land parcel boundary extraction, specifically in the context of Nepal. Using a diverse dataset of scanned cadastral maps, the study evaluates SAM’s zero-shot segmentation performance under different prompting conditions, including bounding box, multi-point prompts, and their combinations. Key factors such as parcel size, shape, eccentricity, clarity of boundaries, and noise levels of the cadastral map were analyzed. SAM demonstrated promising results, particularly when employing combined prompts, but challenges arose in handling noisy data near parcel boundaries and complex configurations within the parcel. Moreover, false positives between segmented parcels continue to be significant challenges, and increasing the scanning resolution also did not noticeably improve segmentation accuracy.

The study concludes that SAM provides promising solutions for enhancing cadastral digitization in Nepal. The challenges faced highlight the need for integrating Geographic Information Systems (GIS) with SAM, along with human oversight, to ensure the creation of accurate and complete cadastral databases. Future research should focus on fine-tuning SAM for one-shot learning or using SAM-2 model and integrating it with diverse remote sensing data to further improve segmentation accuracy and resilience in land administration systems.

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1. INTRODUCTION

Nepal is highly vulnerable to various natural disasters, including earthquakes, floods, landslides, and more recently, glacial lake outburst floods (GLOFs). These disasters not only destroy lives and properties but also adversely affect land administration by erasing physical land boundaries and destroying land records (Lukman Syahid, 2011). In the event of a natural disaster, land tenure will only remain secure if adequate land administration records exist or if landowners possess legal documentation proving their rights to the land (Mitchell, 2009). The adverse effects of disasters can be minimized by linking efficient land administration with disaster risk management. Cadastral maps are foundational to land administration systems as they provide detailed records of land parcels, ownership, boundaries, and legal rights. These maps are essential for managing land-related activities, including land registration, property taxation, and land use planning. Up-to-date cadastral information is essential for disaster risk management as it facilitates efficient resource allocation, improves response planning, ensures accurate damage assessment, and provides legal and administrative clarity (Lukman Syahid, 2011). It also enables informed decision-making and improves environmental and risk management strategies.

In the context of cadastral records of Nepal, the initial cadastral survey, completed in 1995 A.D., provided analog cadastral maps for all of Nepal but excluded densely populated areas such as village blocks and public lands (Sapkota, 2012). As demands grew for accurate and easily accessible land records, the Department of Land Information and Archive (DoLIA) was established in 2000 A.D. to implement a Land Information System (LIS) aimed at efficient land management. DoLIA began archiving cadastral records and developing software systems for acquiring spatial data from hard copies of cadastral sheets through digitization and their attribute data as well (Sapkota, 2012). Despite these advancements, significant challenges persist in the scanning and digitization of old maps, including susceptibility to human errors, variability in interpretation and digitization skills among personnel, and inconsistencies in data quality. The digitization process remains time-consuming and error-prone due to differing skill levels and interpretations among individuals working on different map sections, resulting in edge problems and data inconsistencies. Additionally, not all personnel are proficient in digital technology, further complicating the digitization efforts. Given the challenges associated with digitizing cadastral records, there is a pressing need to automate the process to establish an up-to-date cadastral database.

Several studies have been conducted since a long time on developing automatic map interpretation systems and methods for the automatic extraction of cadastral records, aiming to streamline and improve the efficiency of cadastral map digitization and analysis. One of the earliest studies used a baseline automatic cadastral map interpretation method that employed processes including noise removal and skeletonization of scanned maps, vectorization, parcel detection, and interpretation (Janssen, Duin, & Vossepoel, 2002). Among the recent studies, a study used a segmentation method that combined four steps of image processing algorithms to extract land regions automatically from historical cadastral maps and demonstrated that the method extracted land boundaries with an average error of 0.62% with a standard deviation of ± 0.61% (Kim, Lee, Lee, & Seo, 2014). The results imply that while the average error is low, there are some fluctuations in accuracy across different maps. The study also acknowledges limitations in the approach, particularly when dealing with maps that lack clear delineations or contain ambiguities. Another study overviewed the use of deep learning techniques including convolutional neural networks (CNN) and semantic segmentation methods, to automate the digitization of historical cadastral maps (Ignjatić, Nikolić, Rikalović, & Ćulibrk, 2018). The study addressed the limitations of the deep learning algorithms that they require large, high-quality training datasets and the models' struggle with generalizing across different map types. Moreover, accuracy concerns persist, particularly with faded or complex map features, necessitating ongoing human oversight to correct errors. Furthermore, another study assessed the application of Object-Based Image Analysis (OBIA) procedures for the semi-automatic digitalization of heritage maps including historical cadaster maps which demonstrated OBIA techniuqe is viable approach to digitalization over classical pixel based classification methods (Gobbi et al., 2019). The limitations observed in previous studies are either lengthy procedures involved in the case of pixel-based and object-based classifications and complex (combination of) image processing algorithms or the unavailability of large training datasets for deep neural networks such as CNN to perform efficiently.

Segment Anything Model (SAM), recently released by Meta AI Research, is a foundational model in the field of artificial intelligence. SAM has been trained on a massive dataset, consisting of 11 million images and 1.1 billion masks, and it demonstrates impressive zero-shot performance across a wide range of segmentation tasks (Kirillov et al., 2023). Foundation models like SAM, which have made significant strides in both natural language processing (NLP) and more recently in computer vision, are capable of zero-shot learning. This means they can adapt to new datasets and perform unfamiliar tasks using 'prompting' techniques, even with little or no prior training. This capability has the potential to reduce human efforts during the digitization and annotation process and presents an opportunity to alleviate time-intensive tasks. A recent study demonstrated promising adaptability to segmentation of various remote sensing data (satellite, airborne, and UAV) and its analysis and recommended further research models to improve the model's performance by integrating it with additional fine-tuning techniques and other network architectures (Osco et al., 2023).

This study explores the potential of the Segment Anything Model (SAM) for the automatic digitalization of historical cadastral maps, with a specific focus on land parcel boundary extraction. The primary objective is to assess the feasibility and effectiveness of SAM in automating the segmentation of land parcels from scanned cadastral maps into GIS databases. The model's robustness and adaptability were evaluated under varying scenarios and complexities of cadastral parcels in the context of Nepal. A Zero-shot segmentation technique, based on SAM, was employed throughout the study to examine its performance across diverse conditions.

2. MATERIALS AND METHODS

The study has investigated SAM's segmentation capacity with different scanned cadastral maps under different prompting conditions. Figure 1 shows the schematic representation of the overall workflow of the study.

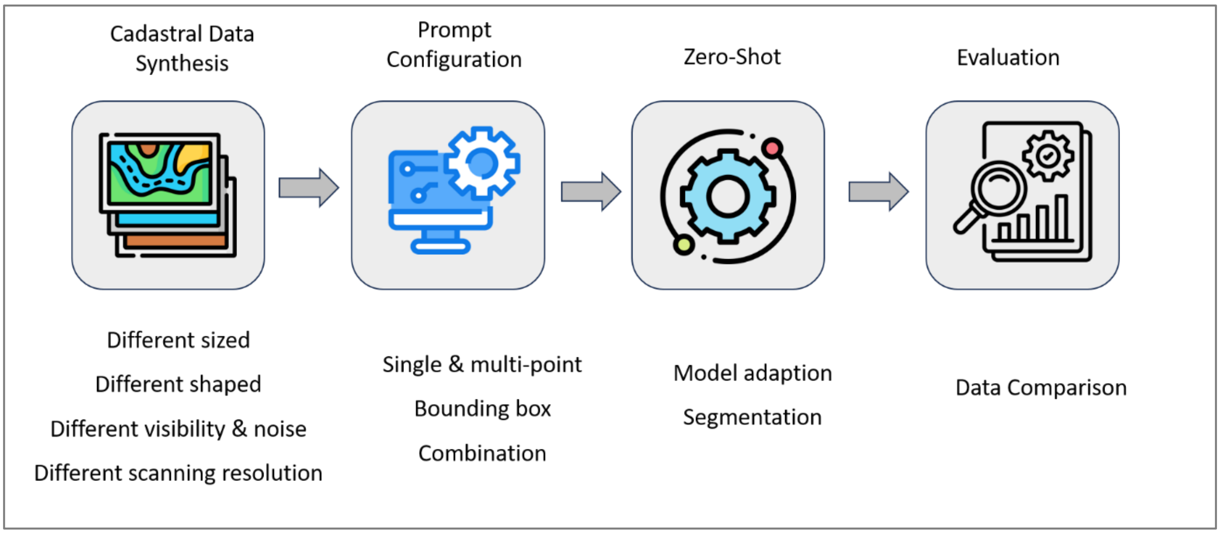

Figure 1: Schematic representation of a step-wise process for evaluating the efficacy of SAM

2.1 Cadastral Data Synthesis

The dataset for this study comprises a diverse array of scanned cadastral images, providing a broad foundation for evaluating the Segment Anything Model (SAM) in terms of robustness and adaptability across a wide range of conditions (Table 1). The georeferenced analog cadastral maps were systematically categorized into five key attributes: size, shape, visual clarity, noise condition, and scanning resolution, allowing for a detailed exploration of SAM's capabilities. Regarding size, the dataset included images of uniform, large, and small dimensions, facilitating the assessment of SAM's performance across varying parcel sizes. For shape, the dataset covered both regular parcels and those with significant eccentricity, enabling the model's adaptability to irregular geometries to be tested. Visual clarity was addressed by comparing parcels with clear and blurred boundaries, which provided insight into SAM's ability to handle imperfect or degraded imagery. Noise conditions were evaluated by including both noisy and noise-free images, simulating issues like scanning defects. All images were initially scanned at a resolution of 300 DPI to standardize the evaluation. To further explore the effect of resolution, the same cadastral maps were scanned at 300, 400, 500, 600, and 800 DPI, allowing an additional layer of analysis on SAM's performance in response to varying image quality and detail. This multi-dimensional dataset serves as a rigorous test bed for assessing SAM's versatility and effectiveness in automating land parcel boundary segmentation under diverse conditions.

Table 1: Diverse cadastral datasets and prompting conditions

S.N.	Condition	Scenario	Scanning Resolution	Target	Box	Point	Combination
1	Size	Equal size	300	Parcel	Yes	Yes	Yes
2		Big sized	300	Parcel	Yes	Yes	Yes
3		Small size	300	Parcel	Yes	Yes	Yes
4	Shape	regular	300	Parcel	Yes	Yes	Yes
5		Large eccentricity	300	Parcel	Yes	Yes	Yes
6	Visual clarity	Clear	300	Parcel	Yes	Yes	Yes
7		Blur	300	Parcel	Yes	Yes	Yes
8	Noise condition	Noise-free	300	Parcel	Yes	Yes	Yes
9		Noisy	300	Parcel	Yes	Yes	Yes
10	Scanning resolution		300	Parcel	No	No	Yes
11			400	Parcel	No	No	Yes
12			500	Parcel	No	No	Yes
13			600	Parcel	No	No	Yes
14			800	Parcel	No	No	Yes

2.2 Prompt Configuration

The study particularly investigated SAM's segmentation capacity in the context of automatic extraction of parcels from scanned analog cadastral maps under different prompting conditions, focusing on zero-shot segmentation. Multi-point and bounding box prompts were provided as a baseline. Bounding boxes (rectangular areas) highlight specific areas within the image restricting SAM's segmentation per object (in our case each parcel) for the sake of segmentation. Moreover, multi-point prompts are a series of specific foreground and background points within the image to guide SAM's processing. We also experimented with combining point-based and bounding box prompts in the segmentation process. This combined approach was intended to harness the strengths of both methods and enhance SAM's adaptability for automated cadastral segmentation.

2.3 Zero-Shot

This section outlines the process of adapting the SAM for automatic cadastral segmentation. The QGIS plugin "GeoSAM" was used to perform zero-shot segmentation(Zhao, Fan, & Liu, 2023). Initially, image features were extracted and saved using SAM’s image encoder through the plugin's encoding module. SAM offers various models, including ViT-H, ViT-L, and ViT-B, each with different computational requirements and architectural complexities (Kirillov et al., 2023). For this study, we employed the ViT-L model, which offers a balance between high accuracy and manageable computational demand. Using the saved image features and prompt encoder i.e. bounding boxes, multi-point, and combined approach, valid masks representing individual land parcels were generated and subsequently converted into polygon shapefiles.

2.4 Model Evaluation

The performance of adopted zero-shot models was evaluated by simply inspecting the visual quality of the segmentation. The segmentation result from each prompt action on each scanned image scenario was inspected visually and inference was made. This is because individual scenarios for cadastral parcels that are considered for the analysis are not present ideally within a scanned parcel image. There is the presence of a combination of multiple scenarios within an image scene, making it difficult to evaluate using quantitative metrics.

3. RESULTS AND ANALYSIS

This section explains the results obtained from various prompt configurations used for diverse cadastral datasets and analyzes the results through visual inspection and comparison of the outputs. For this, representative areas were selected for analysis, focusing on the unique characteristics of parcels in the context of Nepal.

The variation in parcel size and shape in Nepal is primarily due to the differing map scales and the geographic diversity of land parcels. Figure 2(i) illustrates the results of parcel extraction using SAM’s selected base prompts (multi-point and bounding box) and their combinations for areas with varying parcel densities. The figure demonstrates that for equally sized parcels, all base prompts performed comparably well, producing high accuracy, except at parcel boundaries where false negatives were observed. However, for areas with dense parcel configurations, a noticeable decline in accuracy was evident compared to the performance on equally sized parcels. In such dense areas, false negatives were observed not only at the parcel boundaries but also within the parcel interior when using base prompts. This underestimation was mitigated to some extent by employing a combination of the base prompts. The underestimation of dense parcels can be attributed to the complexity of closely packed parcels, which increases the challenge of accurately delineating boundaries. In these scenarios, the proximity of adjacent parcels may cause the model to struggle with distinguishing between them, leading to boundary confusion and misclassification. Additionally, the limited resolution of the base prompts in high-density areas may contribute to the difficulty in accurately capturing finer details within tightly clustered parcels.

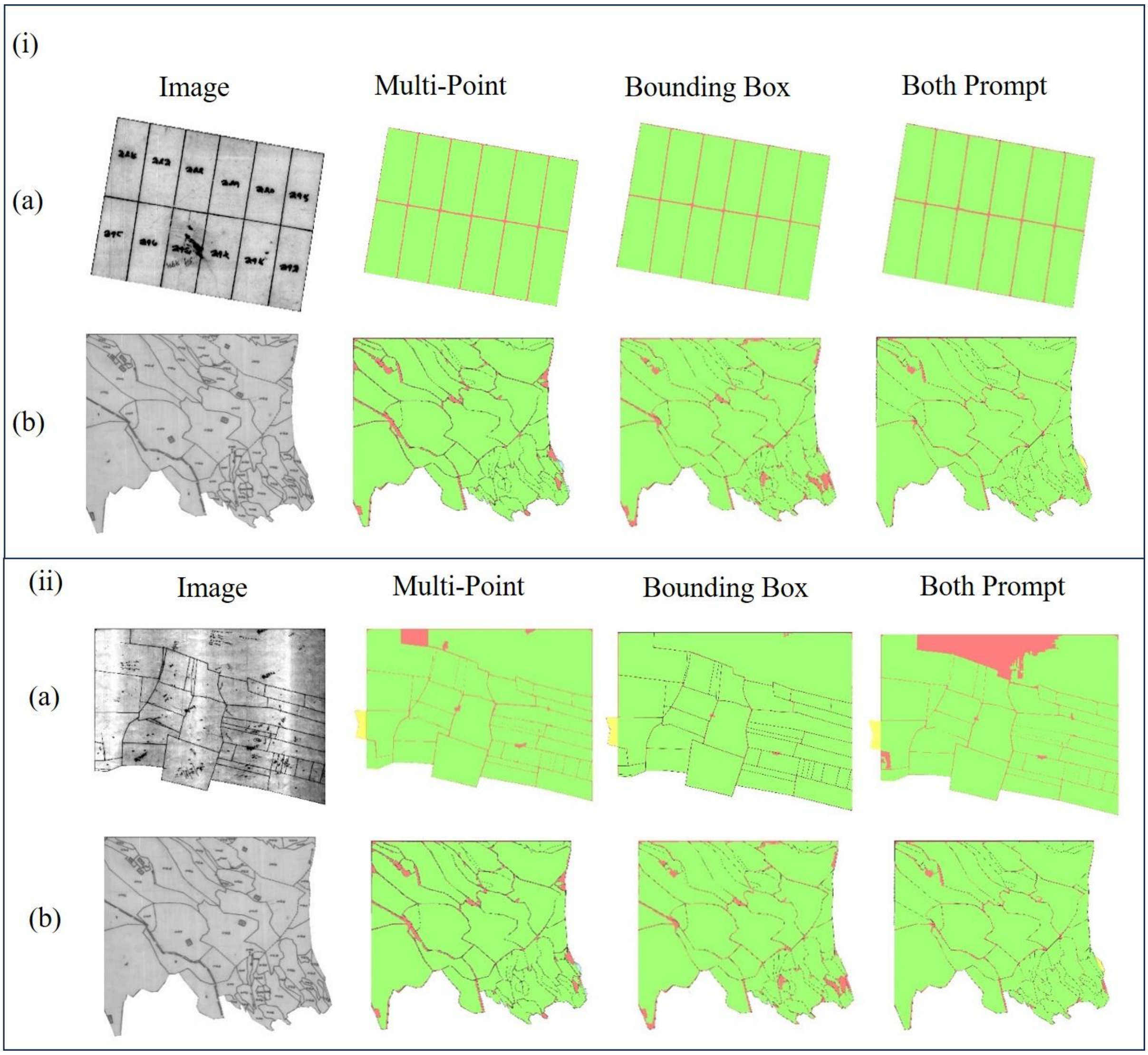

Figure 2: Visualization of prediction of three variations of prompts of zero-shot segmentation of SAM on cadastral parcel extraction task from historical scanned cadastral images (i) based on parcel density (a) equally sized; (b) dense and variety of pixel; and (ii) based on combination of parcel size and its eccentricity. Green pixels are True Positive; red pixels are False Negative, and yellow pixels are False Positive.

Additionally, the capability of zero-shot segmentation was evaluated for all sizes of parcels, as presented in Figure 2(ii). Across all parcel sizes, the mixed prompt approach outperformed individual base prompts. In Figure 2-ii(a), both large and small parcels were accurately extracted using all prompt types, particularly when the parcel shape closely matched well-defined geometric forms, with an eccentricity value near one. However, there was an observed underestimation in delineating larger parcels with high eccentricity (i.e., where the length is significantly greater than the width). Figure 2-ii(b) further demonstrates that as parcel eccentricity increases, the performance of zero-shot segmentation declines, irrespective of parcel size. This finding suggests that the segmentation accuracy for parcels of different sizes is strongly correlated with their eccentricity. The increase in eccentricity introduces greater heterogeneity within the parcel shape, which poses a challenge to SAM's segmentation capability.

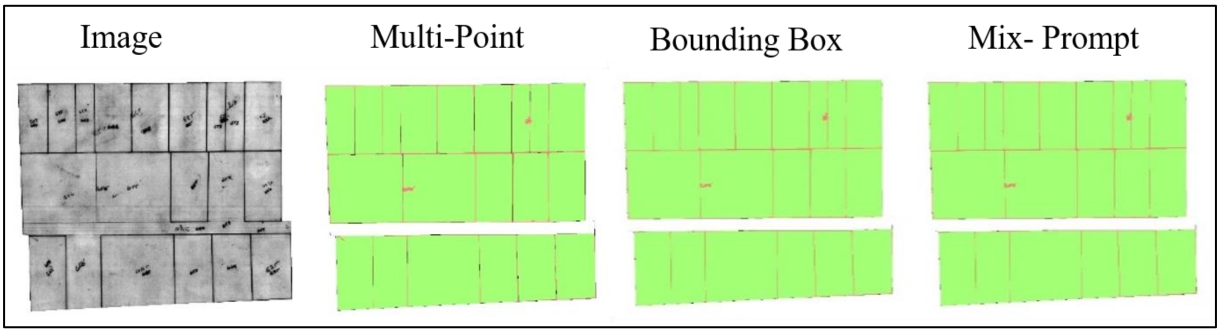

Figure 3: Visualization of prediction of three variations of prompts of zero-shot segmentation of SAM on cadastral parcel extraction task from historical scanned cadastral images based on different visibility of parcel boundary. Green pixels are True Positive; red pixels are False Negative, and yellow pixels are False Positive.

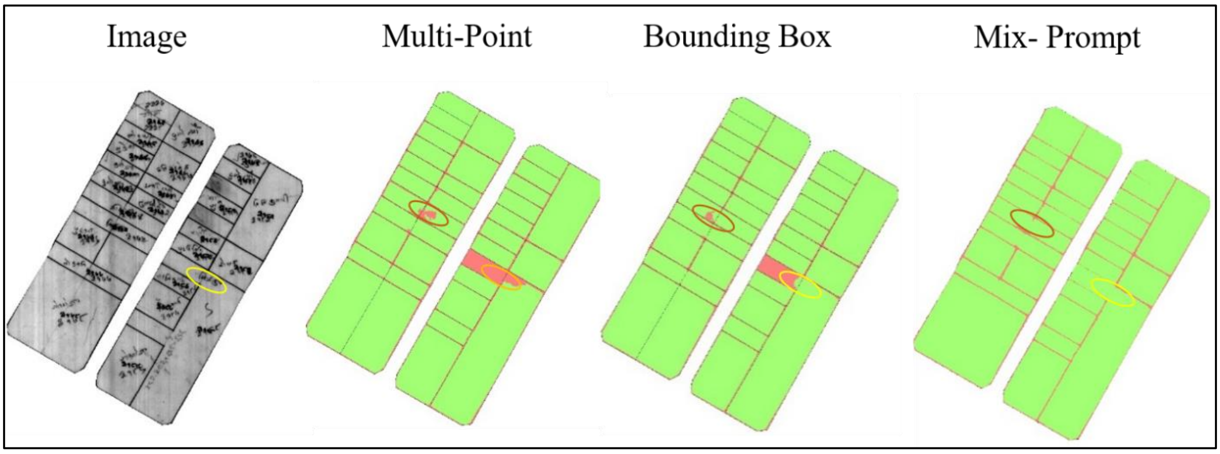

Figure 4: Visualization of prediction of three variations of prompts of zero-shot segmentation of SAM on cadastral parcel extraction task from historical scanned cadastral images based on different noise levels. Green pixels are True Positive; red pixels are False Negative, and yellow pixels are False Positive.

In the case of scanned images with a lack of clarity in the parcel boundaries primarily due to suboptimal scanning processes and the use of pencil marks during parcel subdivision, the results obtained are shown in Figure 3. The clarity of parcel boundaries is a critical factor in accurate delineation. To assess the impact of boundary clarity, the zero-shot segmentation capability was tested across different levels of line clarity in the scanned images. Notably, all prompt types produced promising results in delineating parcels, even under varying degrees of boundary clarity or ambiguity.

Some representative scanned cadastral map images exhibited significant noise, both within and adjacent to parcel boundaries. Noise within the boundary, excluding parcel numbers, did not negatively impact the performance of SAM's zero-shot segmentation, as illustrated in Figure 4. In these cases, the model was able to delineate parcels accurately despite the internal noise. However, noise located adjacent to parcel boundaries significantly reduced the accuracy of segmentation, as shown by the red box in Figure 4. This adjacent noise interfered with the model's ability to precisely delineate parcel boundaries. Additionally, when faint boundary lines were accompanied by adjacent noise, the segmentation was further compromised. In such cases, illustrated by the yellow box in Figure 4, the model either failed to properly delineate the parcels or mistakenly merged two adjacent parcels into one. This highlights the negative impact of adjacent noise on segmentation accuracy and the importance of clear boundary delineation in scanned images.

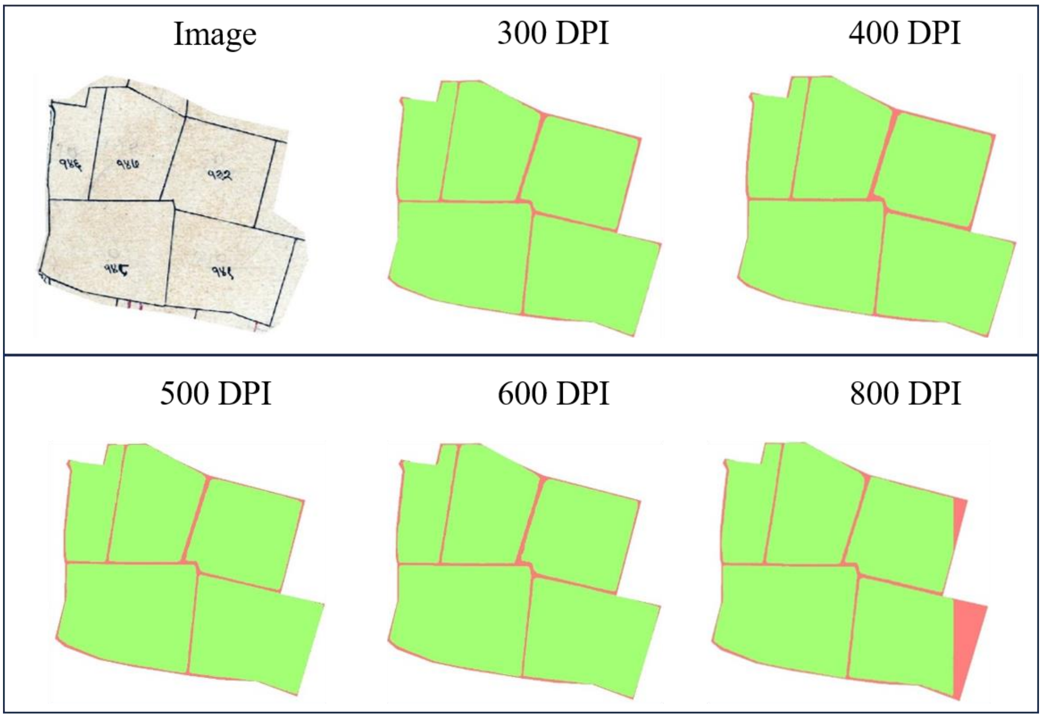

Figure 5: Visualization of prediction of zero-shot segmentation of SAM on cadastral parcel extraction task from historical scanned cadastral images scanned at different scanning resolution levels. Green pixels are True Positive; red pixels are False Negative, and yellow pixels are False Positive.

A common issue across all the experiments was the occurrence of false negatives between parcels. This can be attributed to the fact that the cadastral maps were scanned at a relatively low resolution (300 DPI), where parcel boundary lines occupied only a few pixels, leading to segmentation errors. To address this, the same cadastral map was scanned at higher resolutions to assess the impact on mitigating boundary underestimation. Surprisingly, increasing the scanning resolution did not significantly reduce the occurrence of false negatives between parcels, as shown in Figure 5. In fact, the delineation capability of SAM further decreased with higher scanning resolutions. This reduction in performance can be attributed to the increased heterogeneity introduced by higher resolutions, which likely introduced more noise and finer details, complicating SAM's ability to accurately segment parcel boundaries.

In summary, our findings indicate that the combination of base prompts consistently outperforms individual base prompts in the zero-shot learning approach across all datasets. However, SAM's zero-shot approach faces challenges when handling noisy data near boundaries and areas with complex parcel configurations. Additionally, the occurrence of false positives between segmented parcels remains a persistent issue. These challenges highlight the need for integrating Geographic Information Systems (GIS) with SAM, along with human oversight, to ensure the creation of accurate and complete cadastral databases.

4. Conclusion

In this study, we conducted a comprehensive analysis of the zero-shot segmentation capabilities of the Segment Anything Model (SAM) for cadastral data extraction from scanned historical cadastral maps under various scenarios and complexities. Our analysis revealed that SAM's different prompting methods (points, bounding boxes, and combinations) performed notably well in most cases, except when dealing with noisy data near boundaries and areas with complex parcel configurations. The model demonstrated the potential to significantly reduce human workload and error with minimal or no supervision. However, this initial experiment was limited to exploring SAM's zero-shot capabilities. Future research should focus on evaluating SAM's one-shot segmentation capabilities as well as SAM-2 model, which may further enhance its performance. Additionally, SAM has the potential to integrate with diverse remote sensing data, such as UAV imagery, to quickly generate segmentation outputs without the need for extensive training. This makes SAM particularly well-suited for Nepal's varied geographic conditions, especially in post-disaster scenarios like earthquakes or floods. By incorporating SAM into existing GIS platforms and remote sensing workflows, Nepal's cadastral system can be made more resilient to natural disasters and ongoing land use challenges.

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BIOGRAPHICAL NOTES

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