Fusing Sentinel-2 and Sentinel-1 Data in Google Earth Engine for Road Infrastructure Mapping in Data-Scarce and Conflict Environments

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Abstract

Accurate road infrastructure data is vital for planning, mobility analysis, and disaster response, yet in conflict-affected and data-scarce environments such as South Sudan, authoritative sources are scarce, fragmented and often outdated. Traditional field surveys remain difficult due to insecurity and cost, while optical imagery is frequently obscured by persistent cloud cover. This study presents a cloud-resilient, low-cost workflow for road mapping in Juba County that fuses Sentinel-1 Synthetic Aperture Radar (SAR) and Sentinel-2 optical imagery within Google Earth Engine (GEE). Imagery from December 2024 to March 2025 (Sentinel-2) and the full 2024 year (Sentinel-1) was composited using pixel-wise median stacking with selected bands (B2, B3, B4, B8, B11, B12). Four fused tiles were exported to QGIS for marging, visualization, digitization, and comparison with OpenStreetMap (OSM), Geofabrik, and Google Satellite data. A Select–Zoomed-In road network visibility analysis (RNVA) demonstrated enhanced detection of paved and unpaved roads compared to single-source data. Results revealed numerous unmapped segments and outdated classifications in existing datasets. The integration of Informed Volunteered Geographic Information (IVGI), derived from the researcher's local knowledge of Juba roads, further improved classification accuracy. The outputs provide a GeoAI-ready dataset for future automated road surface detection, contributing to closing data gaps in fragile regions.

Keywords: Data-scarce environments, GeoAI, Informed Volunteered Geographic Information, Road mapping, Sentinel fusion

1. Introduction

Road networks are critical for socio-economic development, humanitarian access, and resilience planning(Randhawa et al., 2025). In South Sudan, however, comprehensive road datasets are lacking due to decades of conflict, limited institutional capacity, financial constraint and persistent cloud cover that hampers optical remote sensing(Dagne et al., 2023). Global open sources such as Geofabrik and OSM provide partial coverage, but many segments are missing or outdated, especially in peri-urban and informal settlement areas (See et al., 2025).

Juba County, the administrative hub of South Sudan, was selected as the study area due to its strategic importance and highly dynamic road network. The county has experienced rapid urban growth in recent years, yet it remains severely underrepresented in authoritative geospatial databases. Road data are either outdated, incomplete, or fragmented, particularly in peri-urban areas where informal settlements expand without planned infrastructure. Moreover, lack of funds, persistent insecurity and logistical challenges make conventional field-based road surveys impractical(Paul, 2023). The unique combination of conflict, rapid urban change, and lack of reliable datasets makes Juba County a critical and challenging AOI for testing remote sensing-based mapping approaches.

2. Methodology

This step started by bench-marking potential data sources and tools. A hybrid approach, leveraging open-access remote sensing archives, institutionally licensed software, and curated datasets from humanitarian and volunteered geographic information (VGI) platforms, was adopted. A schematic representation of this workflow is shown in **Figure 1** below.

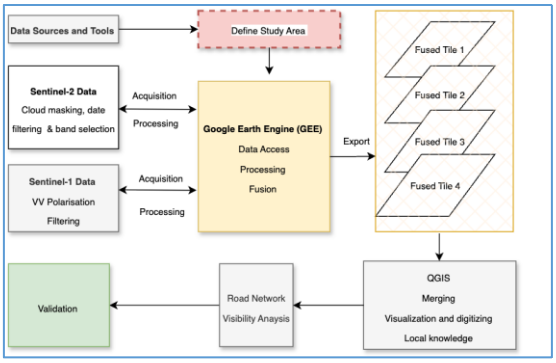

Figure 1: Methodology workflow diagram

2.1 Data Sources and Processing Tools

The data sources and tools were carefully selected for the acquisition of up-to-date and comprehensive road boundary datasets for detecting road infrastructures in Juba County based on availability, reliability, spatial coverage, and suitability. **Table 1** describes the data sources, types, time frame, and their applications in the study, and **Table 2** highlights the tools and their roles in the study.

Table 1. Data sources used in the study

Data Source	Data Type	Time Frame	Study Application
ESA Copernicus Open Access Hub	Sentinel-1 (SAR)	January – Dec 2024	Cloud-independent detection of road surfaces
ESA Copernicus Open Access Hub	Sentinel-2 optical	Dec 1,2024-March 31,2025	Visual enhancement and spectral feature detection
Humanitarian Data Exchange (HDX)	Administrative boundaries (ADM0-2)	Accessed April 2025	Defining area of interest (AOI), spatial extent, and map layout
Geofabrik (OSM extracts)	Vector roads data (paved /unpaved)	Accessed April 2025	Baseline road dataset for comparison and validation
Google Satellite Imagery	High-resolution imagery	Accessed February – April 2025	Visual validation of fused imagery and road interpretation
Researcher's VGI Input	Locally digitized road segments	April- July 2025	Supplementing missing roads based on local knowledge of Juba County

Table 2: Software and Platforms Used

Tool / Software	Type	Purpose in the Study
Google Earth Engine (GEE)	Cloud-based geospatial platform	Satellite data access, median compositing, band stacking (SAR + optical fusion)
QGIS	Desktop GIS software	Manual road digitization, map layout, validation overlays, and export
Draw.io	Diagram and layout tools	Illustration of methodology and workflow charts
Microsoft edge / Google Chrome and Plugins	Web browser and GEE access	Platform for accessing GEE and downloading maps and data

2.2 Study Area

Geographically, the county lies along the White Nile at latitude and longitude 31.571 and 4.859 respectively, and is characterized by seasonal rivers, wetlands, and expansive drylands. Juba county has an approximated total area of 18366.5248 Sqkm. The map of the area of interest described is shown in **Figure 2**.

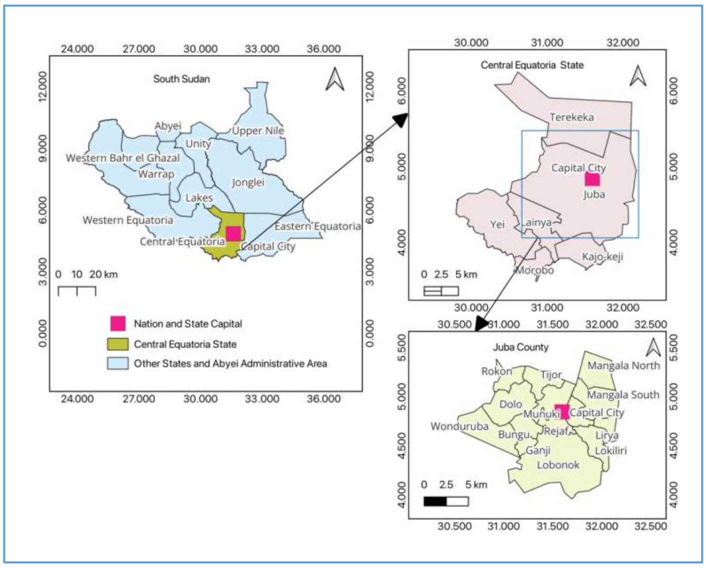

Figure 2: Map showing the location of Juba County Central Equatoria State South Sudan

2.3 Data Acquisition and Processing

Sentinel-2 imagery from the dry season (December 2024–March 2025) was selected to minimize seasonal obstructions, while Sentinel-1 SAR data covering all of 2024 provided cloud-independent backscatter. The data were accessed and processed in GEE, where pixel-wise median composites were generated and bands B2, B3, B4, B8, B11, and B12 were stacked with SAR layers to enhance road feature visibility(Gargiulo et al., 2020).

The fused imagery was exported in four tiles to QGIS, merged and ready for visualization. Road features were digitized using a Select–Zoomed-In approach at 1:5,000 scale, enabling identification of linear features not present in OSM or Geofabrik datasets. Local knowledge of the road network served as Informed VGI, ensuring that ambiguous or newly upgraded roads were correctly interpreted. Validation was performed through overlays with Geofabrik, OSM, and high-resolution Google Satellite imagery.

3. Results

The Road Network Visibility Analysis (RNVA) produced three illustrative cases:

3.1 Case 1

The fused imagery revealed improved clarity of both paved and unpaved roads compared to single-sensor data. In peri-urban areas, unpaved feeder roads previously obscured by vegetation became visible, while in Juba city, paved roads were distinguishable despite clutter from built-up areas as shown in **Figure 3** below.

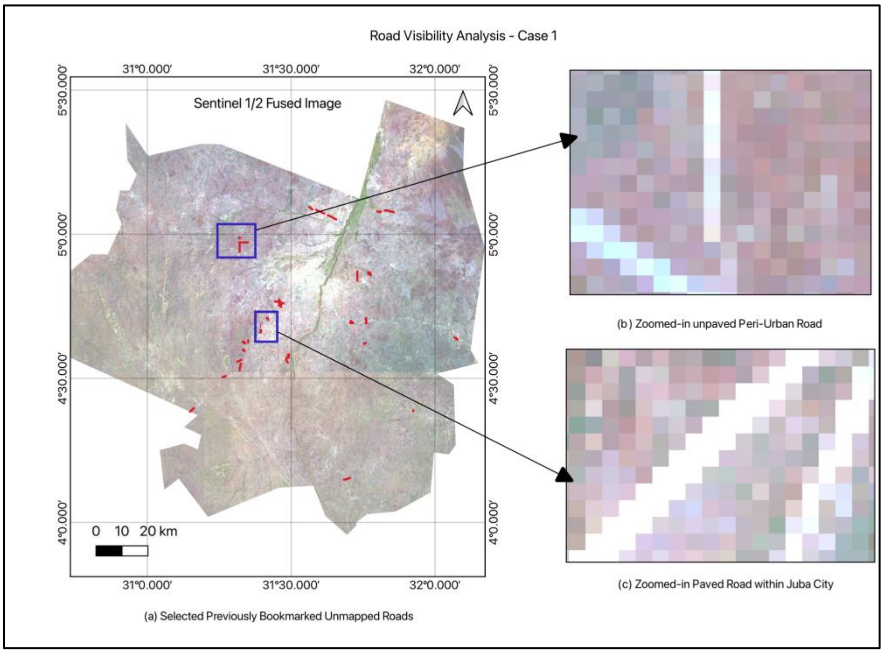

Figure 3: Visibility enhancement of missing unpaved peri-urban and paved urban roads

3.2. Case 2

Overlay with Geofabrik data exposed significant omissions. Several paved and unpaved roads visible in the fused imagery had no representation in the reference datasets, as shown in **Figure 4**. These gaps highlight the incompleteness of open-source coverage in Juba County South Sudan.

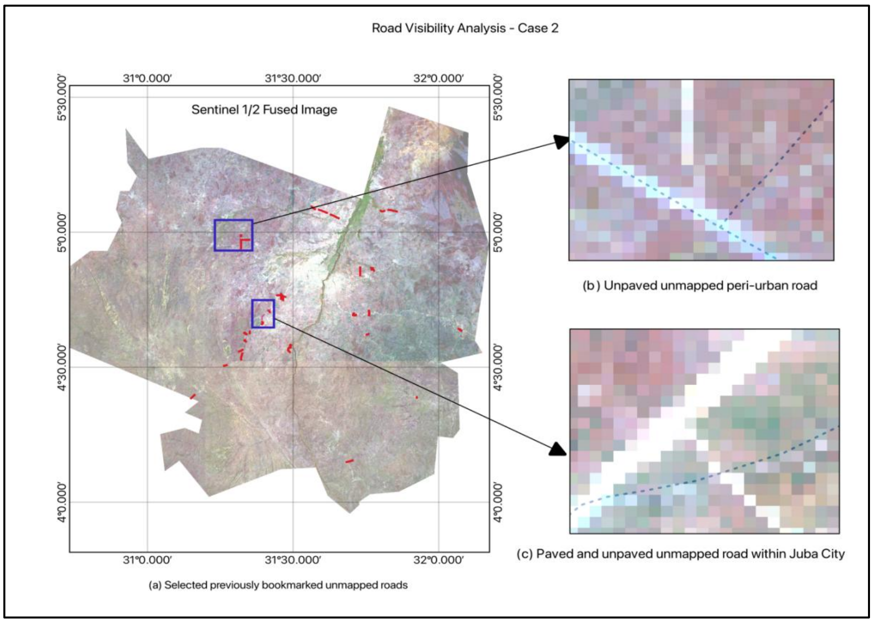

Figure 4: Geofabrik overlay reveals unmapped roads

3.3 Case 3

A zoomed-in comparison with Google Satellite confirmed the presence and alignment of the newly digitized roads as revealed in F**igure 5**. Surface characteristics, such as texture and brightness, enabled classification of paved versus unpaved roads, validating the fusion-based mapping outputs.

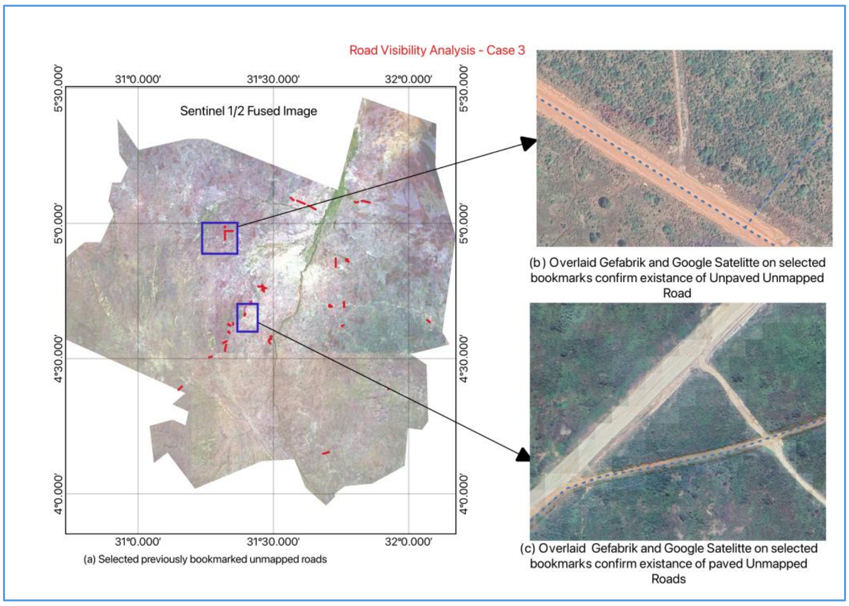

Figure 5: Overlay of Google Satellite for validation of unmapped roads

In addition, the integration of IVGI proved particularly valuable in detecting roads that had been recently upgraded from unpaved to paved but were still misclassified in Geofabrik. **Figure 6** demonstrates the critical role of local expertise in complementing remote sensing for infrastructure mapping (Opach et al., 2023)

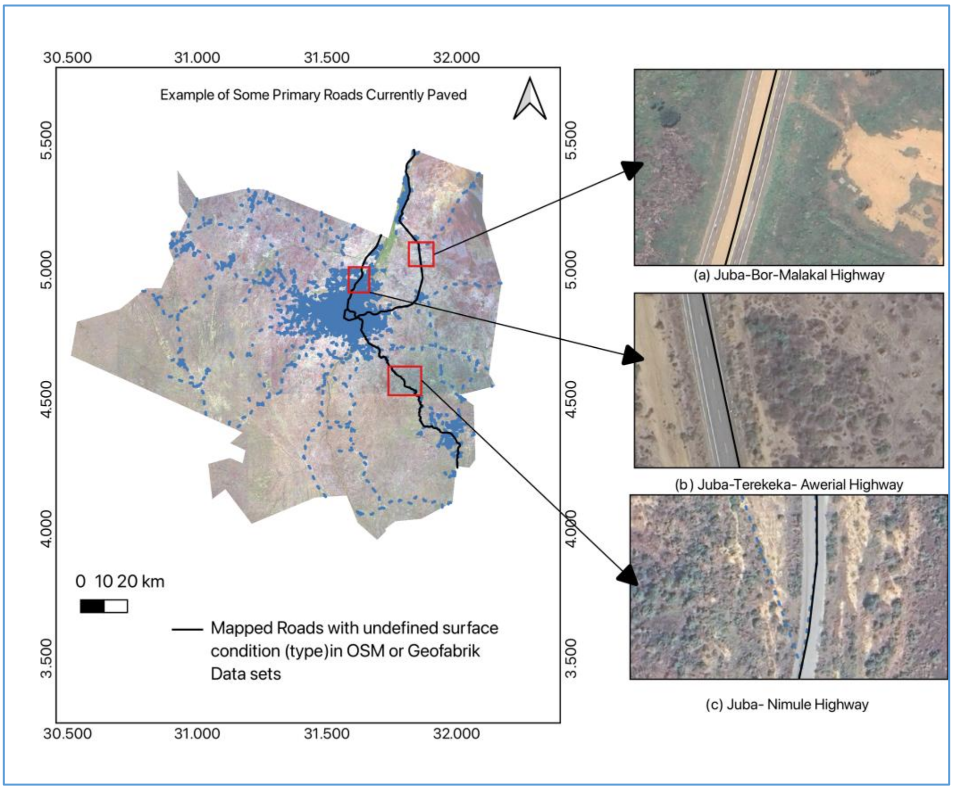

Figure 6: Upgraded Road type revealed during validation

4. Conclusion

This study demonstrates that fusing Sentinel-1 SAR and Sentinel-2 optical imagery provides a practical, cloud-resilient approach for road infrastructure mapping in Juba County, South Sudan. The workflow enhances road visibility, identifies unmapped segments, and corrects outdated classifications in existing datasets. By incorporating local knowledge as IVGI, the study contributes contextual accuracy often lacking in automated mapping.

The outputs provide a GeoAI - ready baseline for future work on automated road classification and surface type detection. More broadly, the workflow is adaptable to other fragile or under-mapped regions where conventional surveys and authoritative datasets are unavailable.

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