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Spatiotemporal Analysis of Land Subsidence in Sumatra Island, Indonesia, Based on SuGAr and InaCORS GNSS Observations

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Abstract

The Earth's surface is a dynamic system where natural and anthropogenic processes can alter its physical form, including land subsidence. In Indonesia, land subsidence has been widely reported in major urban areas; however, its occurrence in Sumatra Island remains less comprehensively quantified. This study investigates land subsidence across Sumatra Island for the period 2010–2023 using continuous GNSS observations from InaCORS and SuGAr stations processed with the AUSPOS service. The results indicate cumulative subsidence ranging from 1.10 to 41.40 cm, with average annual rates between 0 and 8.80 cm/year. Over the last three years, cumulative subsidence ranged from 0.30 to 21.50 cm. Subsidence along the eastern coastal region is primarily associated with intensive land use and groundwater extraction, while in the western region it is influenced by tectonic activity and complex geophysical conditions. These findings highlight the necessity of continuous geodetic monitoring to support mitigation and sustainable development planning in Sumatra.

Keywords: Land Subsidence; Sumatera Island ; GNSS Data Observation

1. Introduction

Land subsidence is a geodynamic phenomenon characterized by the gradual downward displacement of the Earth's surface relative to a reference datum. It may result from natural processes such as tectonic activity and sediment compaction, as well as anthropogenic factors including excessive groundwater extraction, infrastructure loading, and hydrocarbon exploitation. In Indonesia, land subsidence has been extensively documented in major urban areas such as Bandung, Jakarta, Medan and Semarang, where subsidence rates have reached several centimeters per year and have caused significant environmental and infrastructural impacts (Andreas et al., 2017; Abidin et al., 2011; Chaussard et al., 2013; Perdana et al., 2025 ; Anggara et al., 2025 ; Manan et al., 2025).

While previous studies have primarily focused on Java Island, the potential for land subsidence in Sumatra Island has received comparatively less comprehensive investigation. Sumatra is located along an active tectonic margin influenced by the Sunda megathrust system, making it susceptible to both tectonic deformation and surface instability. In addition to tectonic influences, rapid urbanization and increasing groundwater extraction in several coastal regions of Sumatra may contribute to vertical ground deformation. Therefore, continuous and systematic monitoring is essential to understand its spatial and temporal characteristics (Alif et al., 2024 ; Nurhamidah et al., 2018 ; Susilo et al., 2023; Perdana et al., 2022; Perdana et al., 2025)

Various geodetic techniques have been employed to monitor land subsidence, including GNSS surveys, InSAR, leveling, and gravity observations. Among these, GNSS provides high-precision three-dimensional positioning with millimeter-level accuracy and enables long-term continuous monitoring independent of weather conditions. Continuous GNSS networks such as InaCORS and the Sumatran GPS Array (SuGAr) provide valuable datasets for analyzing vertical deformation across Sumatra (Suhandri, 2017; Perdana et al., 2025).

Previous GNSS-based studies in Sumatra reported annual subsidence rates ranging from approximately 0.15 to 3.98 cm/year (Chaussard et al., 2013; Anggara et al., 2025). However, updated assessments covering longer observation periods are necessary to evaluate recent deformation trends. This study aims to quantify cumulative and annual land subsidence across Sumatra Island during the 2010–2023 period using GNSS observations from InaCORS and SuGAr stations processed with the AUSPOS service. The results are expected to contribute to improved geodetic monitoring and support hazard mitigation and infrastructure planning in Sumatra.

2. Materials and Methods

2.1 Study Area

The study was conducted across Sumatra Island, Indonesia, geographically located between 95°E–105°E and 6°N–6°S, covering an area of approximately 473,481 km². Sumatra lies along the active Sunda subduction zone, where the Indo-Australian Plate converges with the Eurasian Plate. This tectonic setting, combined with sedimentary basins and rapidly developing coastal urban areas, makes the region susceptible to vertical ground deformation.

2.2 GNSS Observation Data

This study utilized continuous GNSS observation data from two permanent networks:

1. InaCORS (Indonesia Continuously Operating Reference Stations) operated by the Geospatial Information Agency (BIG);

2. SuGAr (Sumatran GPS Array) operated by the Earth Observatory of Singapore in collaboration with Indonesian institutions.

A total of 71 InaCORS stations and 45 SuGAR stations distributed across Sumatra were analyzed. The observation period spans from 2010 to 2023, depending on data availability at each station. The datasets consisted of daily RINEX files containing dual-frequency GNSS observations.

2.3 GNSS Data Processing

GNSS data were processed using the Australian Online GPS Processing Service (AUSPOS) developed by Geoscience Australia. AUSPOS employs a differential processing strategy based on International GNSS Service (IGS) reference stations and utilizes the Bernese GNSS software (v5.2) for precise positioning.

Each RINEX file was submitted to AUSPOS with antenna type and antenna height information. The processing output provided station coordinates in the International Terrestrial Reference Frame (ITRF), including ellipsoidal height and orthometric height values.

In this study, orthometric heights were used for vertical displacement analysis. The cumulative subsidence for each station was calculated as the difference between the earliest and latest available orthometric height :

$$\mathbf{S_c = H_{initial} - H_{final}}$$

where:
Sc = cumulative subsidence (cm),
Hinitial = initial orthometric height,
Hfinal = final orthometric height.
The average annual subsidence rate was computed as:

$$\mathbf{S_r = S_c \,/\, \Delta_t}$$

where:

Sr = annual subsidence rate (cm/year),
Δt = observation period (years).

Additionally, cumulative subsidence over the last three years (2020–2023) was calculated to evaluate recent deformation trends. Stations showing uplift were assigned a subsidence value of zero for the purpose of spatial interpolation.

2.4 Spatial Interpolation

To analyze the spatial distribution of land subsidence across Sumatra, the station-based results were interpolated using the Inverse Distance Weighted (IDW) method in ArcGIS 10.8. IDW estimates unknown values based on surrounding sample points with weights inversely proportional to distance:

$$u(\mathrm{X}) = \sum_{i=0}^{N} \frac{w_i(\mathrm{X})u_i}{\sum_{j=0}^{N} w_j(X)}$$

where:
ui : u(Xi), where i = 0,1,2,......, N

X : interpolation point
Xi : known data point
d : distance between X and Xi
N : total number of known points

The interpolation results were classified into seven subsidence categories to facilitate visualization and spatial interpretation.

3. Results

3.1 Cumulative Land Subsidence

Analysis of vertical GNSS from InaCORS and SuGAr stations indicates that land subsidence occurred in several regions of Sumatra during the 2010–2023 period. The estimated cumulative subsidence ranges from 1.10 to 41.40 cm, depending on station location and data availability. The highest subsidence values during the 2020–2023 period were recorded at NGNG station (Mentawai Islands, West Sumatra) with 21.5 cm, followed by HNKO station (West Nias, North Sumatra) with 17.8 cm, and NIAN station (Nias, North Sumatra) with 17.6 cm (Figure 1). The significant deformation observed at these stations is primarily associated with tectonic processes, particularly frequent seismic activity along the western coast of Sumatra. High rainfall intensity combined with complex geographical and topographical conditions in this region may further enhance ground instability and vertical deformation.

Overall, higher cumulative subsidence values were predominantly observed along the eastern coastal region of Sumatra, especially in low-lying sedimentary basins and rapidly urbanizing areas (Figure 2). These regions are characterized by intensive land use, infrastructure development, and substantial groundwater extraction, which may accelerate soil compaction and anthropogenic subsidence. In contrast, several stations in the central and western parts of Sumatra exhibited relatively lower cumulative subsidence or stable vertical trends, although localized deformation was detected in tectonically active zones, indicating the influence of crustal dynamics.

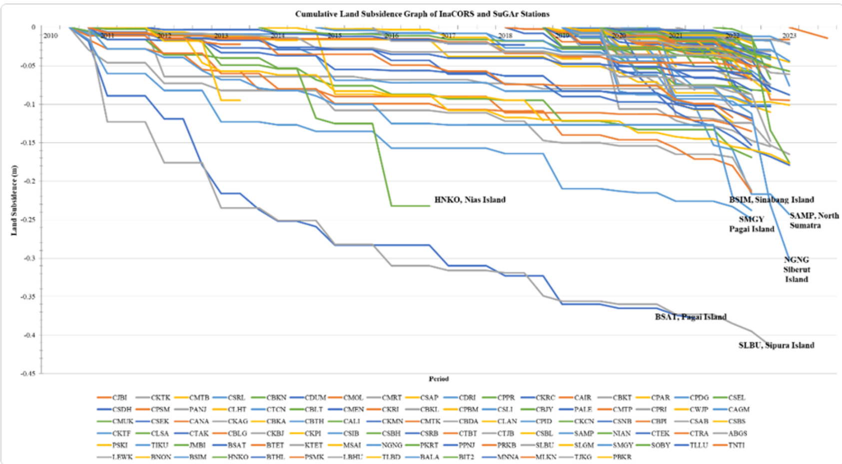

Figure 1. Cumulative Land Subsidence Graph of GNSS point in Sumatra

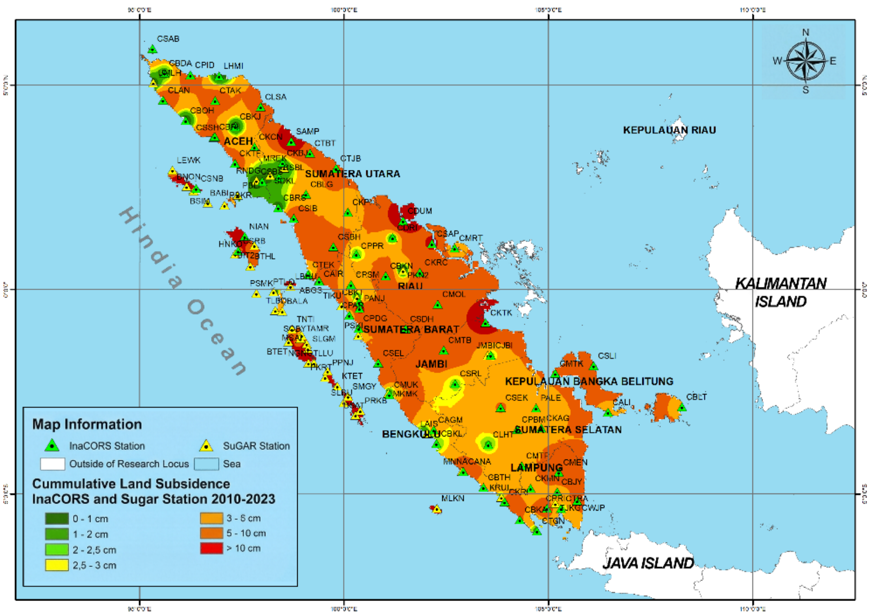

Figure 2. Cumulative Land Subsidence Map of Sumatra Island

3.2 Annual Subsidence Rate

The computed average annual subsidence rates vary between 0 and 8.80 cm/year. The highest annual rates were identified in coastal areas with high anthropogenic pressure. Rates exceeding 5 cm/year indicate a potentially critical condition that may significantly affect infrastructure stability and flood vulnerability, especially in low-elevation regions.

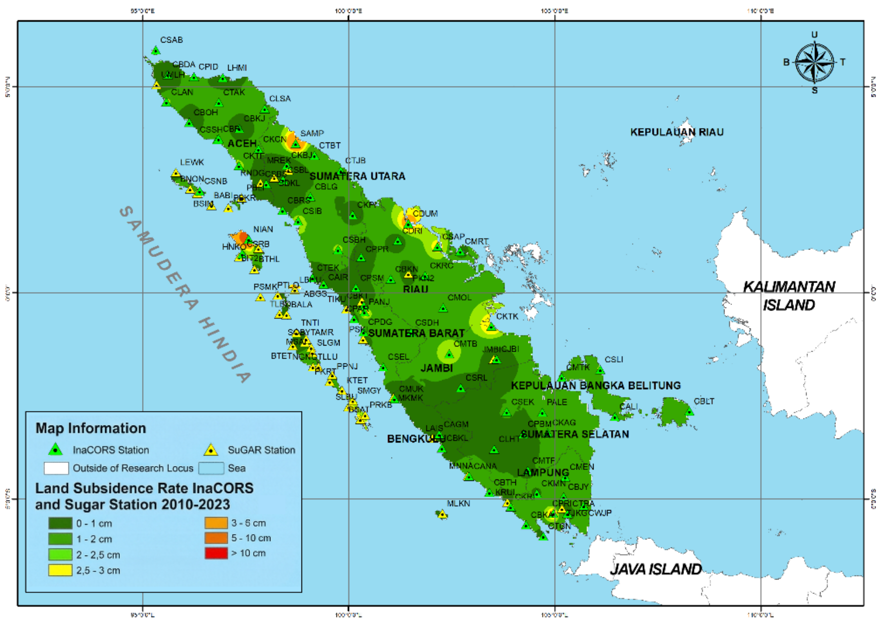

Figure 3. Spatial Distribution of Average Land Subsidence in Sumatra Island

Figure 3 presents the spatial distribution of the average land subsidence derived from InaCORS and SuGAr stations across Sumatra during 2010–2023. The highest average subsidence rate was observed at NIAN station (Nias, North Sumatra) with 8.8 cm/year, followed by SAMP station (Deli Serdang, North Sumatra) with 4.86 cm/year, and PANJ station (Padang Panjang, West Sumatra) with 3.875 cm/year.

The significant subsidence at NIAN is likely associated with tectonic activity, particularly frequent seismic events along the western coast of Sumatra, as well as high rainfall intensity influenced by complex topographic conditions. In contrast, subsidence at SAMP and PANJ may be associated with anthropogenic influences, particularly intensive land use and population pressure. For instance, Sampali Village has a population density of approximately 1047.26 inhabitants/km², while Padang Panjang City reaches about 2756 inhabitants/km², indicating relatively high land utilization in both areas. Such conditions are commonly linked to increased soil compaction and groundwater extraction, although further quantitative investigation is required to confirm this relationship.

3.4 Impact for Hazard Mitigation

The identified subsidence rates, particularly in densely populated coastal regions, pose significant risks to infrastructure, drainage systems, and long-term urban sustainability. Persistent land subsidence may exacerbate coastal flooding, compromise structural integrity, and increase maintenance and adaptation costs. These impacts are especially critical in low-lying coastal environments where relative sea-level rise can be amplified by ongoing vertical ground deformation (Figure 4).

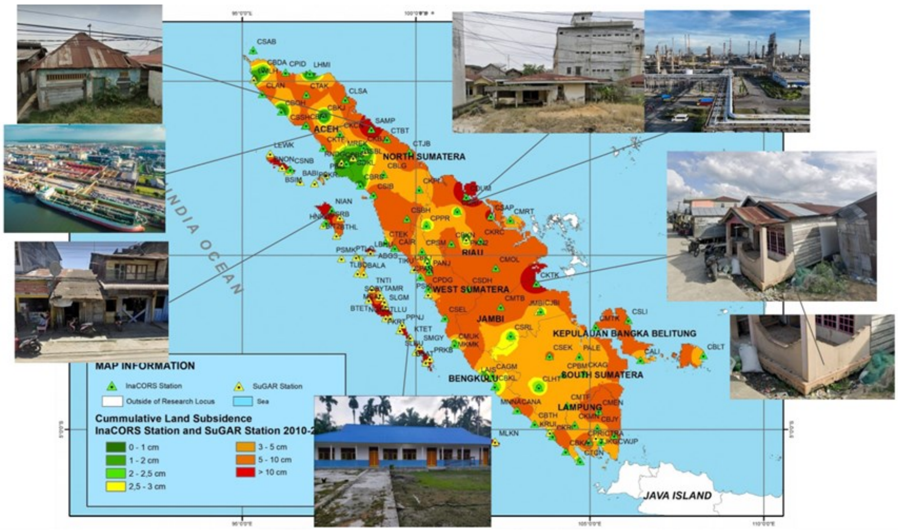

Figure 4. Causes of land subsidence in Sumatra

Observations indicate that substantial subsidence occurs in industrialized and densely populated areas along the eastern coast of Sumatra, including North Sumatra, Riau, and Jambi. In North Sumatra, Medan City and Deli Serdang have experienced land subsidence of up to 24.3 cm over a five-year period. These areas also represent the highest population density in the province, with approximately two million residents, intensifying pressure on land and groundwater resources. Similarly, Dumai City recorded subsidence of 17.9 cm over five years. The average annual population growth rate in Dumai reached 2.87% during the last five years, exceeding the previous period (1.66% per year). As an industrial hub characterized by oil refining, natural gas processing, and port activities, Dumai likely experiences substantial groundwater extraction, which may lead to aquifer compaction and gradual surface subsidence.

These findings suggest that anthropogenic factors, particularly groundwater withdrawal and rapid urban–industrial expansion play a critical role in accelerating land subsidence in eastern Sumatra. Therefore, continuous GNSS monitoring, integrated groundwater management, and stricter spatial planning policies are essential to mitigate future risks. The incorporation of geodetic observations into regional development planning and disaster risk reduction frameworks is strongly recommended to enhance environmental resilience and ensure sustainable coastal management.

4. Conclusions

This study analyzed land subsidence across Sumatra Island during the 2010–2023 period using continuous GNSS observations from InaCORS and SuGAr stations processed through the AUSPOS service. The results indicate that cumulative subsidence ranges from 1.10 to 41.40 cm, with average annual rates between 0 and 8.80 cm/year. Over the most recent three-year period (2020–2023), cumulative subsidence reached up to 21.50 cm at several stations, indicating ongoing vertical deformation in specific regions.

Spatial analysis reveals a contrasting deformation pattern across Sumatra. Subsidence along the eastern coastal region is predominantly associated with anthropogenic factors such as intensive land use, infrastructure development, and groundwater extraction in sedimentary environments. In contrast, deformation along the western region is strongly influenced by tectonic activity related to the Sunda subduction system, with localized high subsidence values linked to seismic processes.

These findings demonstrate that land subsidence in Sumatra is controlled by both anthropogenic and tectonic mechanisms. Continuous GNSS monitoring is therefore essential to support hazard mitigation, sustainable infrastructure planning, and long-term geodynamic assessment in the region.

5. Declaration of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

6. Acknowledgement

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