Land subsidence analysis using DInSAR and GNSS survey in Medan-Belawan City, North Sumatera, Indonesia

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Abstract. Rapid land subsidence is a major threat to coastal megacities in Indonesia. However, spatially detailed information on subsidence rates remains limited in Indonesia, particularly for Medan-Belawan. This study aimed to quantify land subsidence rates in Medan-Belawan and assess the consistency between ground-based and satellite-based measurements. Land subsidence was measured using Global Navigation Satellite System (GNSS) observations at 10 benchmark (BM) points and Differential Interferometric Synthetic Aperture Radar (DInSAR) analysis using Sentinel-1A imagery. Both methods consistently indicated substantial subsidence across the city. GNSS-derived subsidence rates ranged from -0.84 to -8.76 cm/year, while DInSAR-derived rates ranged from -6.18 to -13.56 cm/year. The overall mean subsidence rate was -6.41 cm/year, with an RMSE of 6.57 cm between the two approaches. The highest subsidence rates were concentrated in districts with very high population densities. Medan-Belawan is experiencing significant land subsidence, and GNSS and Sentinel-1A DInSAR provide broadly consistent estimates. The spatial concentration of high subsidence in densely populated districts highlights the need for targeted monitoring and mitigation strategies.

Keywords: Land subsidence, Medan-Belawan, DInSAR, GNSS

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1 Introduction

The Medan-Belawan region, located in North Sumatera, Indonesia, forms a critical urban–coastal corridor that connects Medan City, the provincial capital, to Belawan Port, one of Indonesia's busiest international trade gateways. This low-lying area, situated along the Deli River delta and coastal alluvial plains, is characterized by soft Holocene clay and silt deposits, extensive groundwater-dependent industries, and rapid urbanization and reclamation activities. Such geomorphological and anthropogenic conditions make Medan-Belawan highly susceptible to ground deformation and land subsidence. Land subsidence, driven by both anthropogenic and natural factors, has become a serious problem in Medan-Belawan City, Indonesia, threatening the livelihoods of the local communities. This phenomenon is primarily associated with rapid urbanization, particularly in large cities where excessive groundwater extraction has led to significant land subsidence [1].

Land subsidence poses major risks to infrastructure and heightens the vulnerability of Medan-Belawan to tidal flooding, especially during periods of high rainfall and rising sea levels [2]. The main purpose of this research was to analyze and quantify land subsidence in the Medan-Belawan coastal region by integrating Differential Interferometric Synthetic Aperture Radar (DInSAR) and Global Navigation Satellite System (GNSS) techniques.

Urbanization in Medan-Belawan has greatly influenced both population growth and infrastructure development. A geometric population growth model predicts a sharp increase in the population of Medan from 2,301,101 people in 2020 to 2,501,069 people in 2029, reflecting substantial growth [3]. Urban expansion has also spurred major infrastructure projects, such as the construction of an underpass at the Jalan Gatot Subroto-Jalan Gagak Hitam intersection, aimed at reducing traffic congestion caused by the rapid increase in vehicle numbers [4]. However, this rapid urbanization and population growth have led to widespread land conversion, environmental degradation, and insufficient green space, falling short of the legally mandated 30% [5, 6]. While urbanization in Medan fosters economic growth and infrastructure development, it also presents challenges in environmental sustainability and resource management.

The rapid development of the city, compounded by construction pressure, has increased the load on land and worsened land subsidence. The high compressibility of soil under building loads exacerbates this issue [7]. Excessive groundwater extraction further accelerated subsidence. Aquifer depletion reduces pore pressure, causing soil compaction and ground sinking [8]. In Medan City, land subsidence rates range from -48.6 mm/year to -54.1 mm/year [1, 9]. The relevance of studying land subsidence in this region lies in its implications for urban planning and environmental management as well as its contribution to understanding broader subsidence patterns in Indonesia.

Medan-Belawan City is also highly susceptible to tidal flooding because of its low elevation of approximately 3 m above the sea level. These floods are primarily triggered by high sea levels during tidal events and frequently affect large areas, including Sicanang and Belawan Bahagia Villages [10]. The use of Sentinel-1 SAR data and the GNNS technique has been instrumental in monitoring land subsidence in Northern Sumatra, including Medan and Belawan. This technology allows for precise measurement of subsidence rates and patterns over time [11-12]. GNSS provides high-precision vertical deformation measurements (mm to sub-centimeter level) but at discrete locations. Key uncertainties arise from multipath interference (±3-5 mm), antenna height errors or local monument instability (±1-2 mm), atmospheric delay residuals (±2-3 mm), and reference-frame realization errors (±1-2 mm). The resulting total vertical uncertainty, typically (±3-7 mm) per station, depends on the observation duration and environment.

The impact of tidal flooding is worsening in Medan-Belawan, largely because of land subsidence [2]. However, comprehensive studies on land subsidence in this region remain limited. Therefore, this study seeks to provide detailed insights into land subsidence rates in Medan-Belawan City, serving as a scientific basis for efforts to mitigate tidal flood disasters. The novelty of this research is the integration of multitemporal DInSAR (Sentinel-1) and GNSS data to significantly enhance the accuracy of land subsidence measurements in urban areas such as Medan-Belawan City.

2 Methods

2.1 Study area

This research was conducted in the coastal waters of Eastern North Sumatra, which are directly connected to the city of Medan-Belawan, within the geographical coordinates of 3°27′N-3°47′N and 98°35′E-98°44′E (**Fig. 1**).

The method used to determine land subsidence in Medan-Belawan City combines Real-Time Kinematic Global Navigation Satellite System (RTK-GNSS) and Differential Interferometric Synthetic Aperture Radar (DInSAR). The procedure for land subsidence measurement using RTK-GNSS comprises several stages, including raw data acquisition at benchmark (BM) points, quality assessment of the collected data, orbit verification, instrument calibration and correction, atmospheric and instrumental error correction, reference system determination, data filtering, and final data processing.

2.2 Materials and data processing

The research materials comprised land subsidence data derived from the RTK-GNSS measurements. The GNSS survey equipment, positioned at the BM point as the measurement target, is shown in **Fig. 2**. Sentinel-1A SLC data, Sentinel-2A L2A imagery, and the Indonesian National Digital Elevation Model (DEMNAS).

Land subsidence analysis was conducted using Sentinel-1A data. Data processing was performed using the SNAP software with SNAPHU extension. The dataset consisted of a master (2023) and slave (2025) image pair, which were co-registered using the S1 TOPS co-registration method with the SRTM 1 Sec HGT DEM as a reference. The initial steps included interferogram generation and coherence estimation, applying a minimum coherence threshold of 0.2, followed by burst merging using the TOPSAR Deburst tool. Subsequently, the topographic phase was removed to isolate the deformation phase, and Goldstein filtering combined with multi-looking filtering was applied to enhance the image quality. The filtered phase was unwrapped in SNAPHU and converted from radians to metres. Geometric correction was then performed using range-Doppler terrain correction with the same DEM. Finally, the results were visualized in ArcMap to generate a subsidence map representing the elevation changes in the study area. Equation 1 shows the phase difference (Δφ) resulting from InSAR. The SAR Interferometry (InSAR) process used to obtain the deformation phase value is called Differential Interferometry Synthetic Aperture Radar (DInSAR).

$$\Delta\varphi = \Delta\varphi d + \Delta\varphi topo + \Delta\varphi orb + \Delta\varphi atm + \Delta\varphi n, \quad (1)$$

Where:

$\Delta\varphi d$ accounts for the possible displacement of the scatterer between observations.
$\Delta\varphi topo$ represents the residual topography-induced phase owing to the imperfect knowledge of the height profile (i.e., DEM errors).
$\Delta\varphi orb$ accounts for inaccurate orbital information during the synthesis of the topographic phase.

$\Delta\varphi atm$ denotes the phase components owing to changes in the atmospheric and ionospheric dielectric constants between the master/slave acquisitions.
$\Delta\varphi n$ accounts for decorrelation phenomena (e.g., spatial, temporal, and thermal).

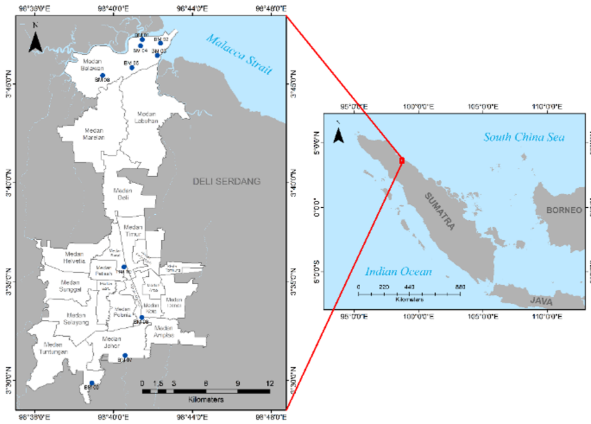

Fig. 1. Research area and benchmark (BM) measurement locations in Medan-Belawan City, North Sumatra, Indonesia.

Fig. 2. The GNSS receiver installed at a benchmark point used for monitoring land subsidence in Medan–Belawan City, North Sumatra, Indonesia. The setup illustrates the field observation configuration and the fixed reference employed to obtain precise vertical displacement measurements.

Sentinel-1A ascending images acquired between March 2023 and 2025 were processed using the PS InSAR technique at SNAP. The mean incidence angle was 39° and the temporal baseline threshold was set at 24 days. Precise orbit files and Goldstein filtering were applied to enhance the interferometric coherence.

Land Subsidence is calculated to predict flooding and coastal inundation risks; monitoring supports engineering maintenance and mitigation planning, helping regulate extraction rates and protecting aquifers, identifying vulnerable zones and adjusting land-use or zoning policies, and environmental protection, such as wetland loss, saltwater intrusion, and ecosystem degradation. The RMSE provides a numerical measure of the average deviation between the DInSAR and GNSS datasets (Form 2).

$$RMSE = \sqrt{\frac{1}{N}\sum_i^n (H_{DInSAR,i} - H_{GNNS,i})^2} \qquad (2)$$

N is the number of observation points (collocated DInSAR-GNSS stations), $H_{DInSAR,i}$ represents the subsidence value from DInSAR (mm or cm), and $H_{GNNS,i}$ is the subsidence value from GNSS (mm or cm).

3 Results and discussion

3.1 Land subsidence using satellite data

Sentinel-1A data from 2023 to 2025, processed using the DInSAR method (**Fig. 3**), indicates land deformation with subsidence rates ranging from 0 to 14 cm/year. The deformation rates at benchmark points BM1–BM10 are presented in **Table 1**. The Southern part of Medan exhibits relatively low deformation (-1.2 cm/year), whereas the highest rates, reaching from -6 to -14 cm/year, are concentrated in Helvetia District, Medan Perjuangan, and the eastern region, particularly in the Medan-Belawan Port area.

The natural consolidation of alluvial soils in Medan is another factor contributing to land subsidence. This process represents a geological phenomenon that develops over time and occurs independently of human activities [6, 7, 11].

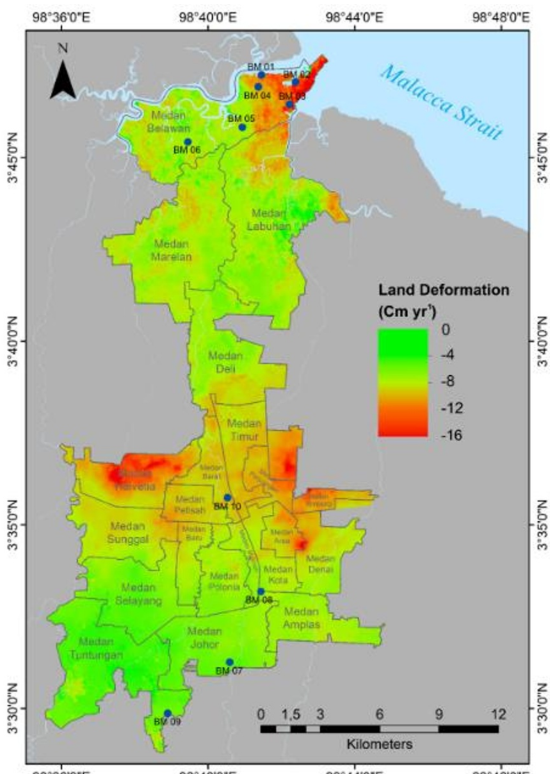

Fig. 3. Land subsidence map in Medan-Belawan City, North Sumatra, Indonesia. The map presents the spatial distribution of land subsidence rates in Medan–Belawan City derived from DInSAR analysis of Sentinel-1A imagery during 2023-2025.

3.2 Land subsidence using GNSS survey

Land subsidence measurements in Belawan City using the GNSS method during 2023-2024 (**Table 1)** [1] recorded the highest rate at BM02 (IKD Pelindo) with -8.76 cm/year, and the lowest at BM05 (Belawan Bahagia) with -1.80 cm/year. In August 2025, the land subsidence was measured using the same method. As only a single measurement was available for that year, subsidence values for each BM point in Medan City were supplemented with land subsidence data from the Indonesian Geospatial Information Agency (BIG) (**Table 1**).

Table 1. Land Subsidence in Medan-Belawan City Using DInSAR and GNSS Methods. The comparison highlights the level of agreement between satellite-based and ground-based observations in detecting spatial patterns of subsidence.

BM	Latitude	Longitude	Subsidence DInSAR (cm/year)	Subsidence GNSS (cm/year)
BM 01	03°47′15.355″N	098°41′27.601″E	-12.66	-8.40
BM 02	03°47′03.891″N	098°42′22.901″E	-13.56	-8.76
BM 03	03°46′27.030″N	098°42′13.472″E	-13.04	-3.84
BM 04	03°46′55.729″N	098°41′22.497″E	-11.24	-3.72
BM 05	03°45′49.754″N	098°40′55.638″E	-7.58	-1.80
BM 06	03°45′25.873″N	098°39′26.864″E	-7.05	-0.84
BM 07	03°31′15.679″N	098°40′35.460″E	-6.18	-1.20
BM 08	03°33′10.987″N	098°41′26.632″E	-7.58	-1.30
BM 09	03°29′52.016″N	098°38′54.082″E	-6.89	-1.20
BM 10	03°35′44.564″N	098°40′31.547″E	-10.17	-1.20

The integration of the DInSAR and GNSS methods provides more comprehensive and reliable information on land subsidence in Medan-Belawan City. Although DInSAR offers broad spatial coverage, GNSS supplies precise and continuous point-based measurements. The combination of these approaches helps overcome the limitations of each technique and enhances the overall accuracy of land subsidence monitoring.

Medan-Belawan City is among the ten most densely populated cities in Indonesia. A high population density contributes to excessive groundwater extraction, which is a major driver of land subsidence and accounts for up to 67% [13, 14]. Similar conditions were observed in Medan-Belawan, where groundwater exploitation significantly influenced the subsidence patterns [15]. The highest rates of land subsidence in the area occur in the Medan Perjuangan District, which has a population density of 25,533 inhabitants per square kilometer. The resulting demand for housing has driven land use changes, with 97.67% of the district now allocated for residential and community activities [16].

Medan Baru District, recognized as a commercial center, also faces critical spatial pressure. The extent of public green open space in this district is only 18.78 hectares, or 3.48%, far below the 20% requirement mandated by Law No. 26 of 2007 on Spatial Planning [17]. Such reductions in green space alter the hydrological cycle and exacerbate subsidence, particularly in urban areas where groundwater extraction is intensified to meet water demands [18, 19].

The most severe subsidence is observed in the Medan-Belawan District, with rates ranging from 12 to 15 cm/year during 2023-2024 (**Fig. 3**). This condition is linked to a population density of 3,380 inhabitants per square kilometer [20, 21]. Excessive groundwater extraction is one of the primary causes of subsidence in port extraction [22].

The RMSE value was 6.57 cm. In other words, if the value of RMSE is more than 10 mm/year, it requires an evaluation of the source of error from the orbit, atmosphere, or reference.

4 Conclusion

Calculating land subsidence is essential for understanding, predicting, and mitigating environmental and structural hazards in Medan-Belawan. The rate of land subsidence in the Medan-Belawan region, based on the DInSAR and GNSS methods, ranges from -1.2 cm/year to -15 cm/year. The lowest rates were observed in Medan Tuntungan, Medan Johor, and Medan Selayang Districts, whereas the highest occurred in Medan Helvetia, Medan Perjuangan, and Medan-Belawan Districts, particularly in the Belawan Port area. The primary contributing factors include high population density driven by urbanization, intensive land use, large-scale groundwater extraction, and vertical building loads. Both the DInSAR and GNSS methods yielded consistent results, with the broad spatial coverage of DInSAR complementing the point-based precision of the GNSS. However, owing to the limited number of GNSS measurements, further studies are required to validate and refine the accuracy of land subsidence estimates derived from the DInSAR method. The integration of DInSAR and GNSS provided essential baseline data for developing urban resilience and sustainable groundwater extraction strategies. This study provides a validated geospatial framework that supports sustainable urban development, enhances flood resilience, and informs future policy decisions for the Medan-Belawan region.

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References

1. D.Z. Randani, A.P.M. Tarigan, E.P. Bangun, G.C.R. Hasibuan, Land subsidence analysis in Medan Belawan using the GNSS survey, in Proceedings of the 3rd International Conference on Natural Resources and Sustainable Development, Medan, Indonesia, September 4 (2024). https://doi.org/10.1088/1755-1315/1452/1/012033
2. J. Lumban-Gaol, J.T.S. Sumantyo, E. Tambunan, D. Situmorang, I.M.O.G. Antara, M.E. Sinurat, N.P.A.R. Suhita, T. Osawa, R.E. Arhatin, Sea level rise, land subsidence, and flood disaster vulnerability assessment: A case study in Medan City, Indonesia. Remote Sens. **16**, 865 (2024). https://doi.org/10.3390/rs16050865
3. S. Syahfitri, D. Deasy, A. Sugarda, R. Aprilia, Penggunaan model aritmatik dan geometrik dalam laju pertumbuhan penduduk di Kota Medan pada tahun 2029. AKSIOMA: J. Sains Ekon. Eduk. **2,** 180–189 (2025). https://doi.org/10.62335/2xnt8c71
4. A.F.E. Panggabean, M. Lubis, R.H.T. Simbolon, Analysis of the impact of traffic on the construction of the Jl. Underpass Gatot Subroto, Medan City. Jurnal Pendidikan Amartha **3**, 1616–1523 (2024). https://doi.org/10.57235/qistina.v3i2.4242
5. M.R.P. Putra, The analysis of the impact of population growth and economic development on urban land conversion: Case study of Gresik Regency. J. Econ. Dev. Issues **7**, 30–45 (2024). https://doi.org/10.33005/jedi.v7i2.163

6. H.Z. Abidin, H. Andreas, I. Gumilar, B.D. Yuwono, D. Murdohardono, S. Supriyadi, On integration of geodetic observation results for assessment of land subsidence hazard risk in urban areas of Indonesia, (Springer, Cham, 2015). https://doi.org/10.1007/1345_2015_82
7. E. Chaussard, F. Amelung, H. Abidin, S.-H. Hong, Sinking cities in Indonesia: ALOS PALSAR detects rapid subsidence due to groundwater and gas extraction. Remote Sens. Environ. **128**, 150–161 (2013). https://doi.org/10.1016/j.rse.2012.10.015
8. Z.D. Cui, Theoretical analysis of land subsidence caused by the engineering-environmental effect, (Springer, Singapore, 2018). https://doi.org/10.1007/978-981-10-8040-1_2
9. S. Al Fatah, T.A. Aththorick, R. Rahmawaty, M.K. Hamzah, Management strategy for public green open spaces in Medan City using SWOT analysis. J. Environ. Dev. Stud. **5**, 61–72 (2024). https://doi.org/10.32734/jeds.v5i02.18179
10. H. Frederick, A.A. Dwi S., H. Hariadi, Pemetaan banjir rob terhadap pasang tertinggi di wilayah pesisir Kecamatan Medan Belawan, Sumatera Utara. J. Oceanogr. **5,** 334–339 (2016)
11. R.S. Perdana, O. Anggara, A.G. Suhadha, D.M. Pangestika, A.T. Atmojo, M.N. Al Attar, P. Sonya, S.M. Alif, Assessing land subsidence from anthropogenic activity in Northern Sumatra, Indonesia revealed using SAR interferometry. J. Degrad. Min. Lands Manag. **12,** 7235–7245 (2025). https://doi.org/10.15243/jdmlm.2025.122.7235
12. A.M. Lubis, Y. Fukuda, H.Z. Abidin, Extreme flood event analysis in Indonesia based on rainfall intensity and recharge capacity, in Proceedings of the Global Colloquium on GeoSciences and Engineering, Bandung, Indonesia, October 18–19 (2017), 012045. https://doi.org/10.1088/1755-1315/118/1/012045
13. Q. Cao, Y. Zhang, L. Yang, J. Chen, C. Hou, Unveiling the driving factors of urban land subsidence in Beijing, China. Sci. Total Environ. **916**, 170134 (2024). https://doi.org/10.1016/j.scitotenv.2024.170134
14. H. Gong, Y. Pan, L. Zheng, *et al.*, Long-term groundwater storage changes and land subsidence development in the North China Plain (1971–2015). Hydrogeol. J. **26**, 1417–1427 (2018). https://doi.org/10.1007/s10040-018-1768-4
15. S.N. Mohamad Deros, N. Md Din, S.M. Norzeli, R.C. Omar, F. Usman, S.A. Hamim, Land subsidence susceptibility projection for Palembang slum area by complex MCDM-AHP technique. J. Eng. Technol. Sci. **54,** 220104 (2022). https://doi.org/10.5614/j.eng.technol.sci.2022.54.1.4
16. https://medankota.bps.go.id/id/publication/2021/02/26/695922e9701d335f2207cf74/kota-medan-dalam-angka-2021.html
17. C. Utami, D.T. Septiningtyas, I. Fauzi, M. Alfiani, R. Mulyani, E. Rita, G. Siregar, Evaluation of laboratory waste management at Medan State Polytechnic. Int. J. Res. Vocat. Stud. , 34–39 (2024). https://doi.org/10.53893/ijrvocas.v3i4.209
18. T. Davydzenka, P. Tahmasebi, N. Shokri, Unveiling the global extent of land subsidence: The sinking crisis. Geophys. Res. Lett. **51**, e2023GL104497 (2024). https://doi.org/10.1029/2023GL104497
19. V. Agarwal, A. Kumar, Z. Qin, R.L. Gomes, S. Marsh, Lessons for sustainable urban development: Interplay of construction, groundwater withdrawal, and land subsidence at Battersea, London. Remote Sens. **15**, 3798 (2023). https://doi.org/10.3390/rs15153798
20. https://medankota.bps.go.id/id/publication/2023/02/28/fd2c9f972ff3f33b1289067a/kota-medan-dalam-angka-2023.html

21. Y.K. Firmansyah, Analisis settlement timbunan causeway dan container yard pada pembangunan terminal multipurpose Labuhan Bajo di Manggarai Barat, Nusa Tenggara Timur. Jurnal TESLINK. **5,** 35–43 (2023). https://doi.org/10.52005/teslink.v5i2.276
22. M. Esteban, H. Takagi, D. Fatma, T. Mikami, P. Valenzuela, E. Avelino, R. Crichton, L. Jamero, C. Chadwick, M. Onuki, Port adaptation to sea level rise: Lessons from present examples of land subsidence, in Proceedings of the 36th International Conference on Coastal Engineering, Baltimore, Maryland, USA, July 30–August 3 (2018), risk. 59. https://doi.org/10.9753/icce.v36.risk.59