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City Development and Land Succes Problems in River Delta Areas

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Abstract

In recent years, the decrease in swamp land has been observed in both urban and rural areas. This phenomenon is land hoarding to the deliberate drainage practices which focused on rendering the land suitable for residential and infrastructure purposes and facilitating economic growth. The landfilling causes oxidation of the peatlands due to the influence of oxygen, which causes soil subsidence. Land subsidence poses a significant risk to buildings and residents in affected zones. This study aims to investigate and understand the spatiotemporal patterns of land subsidence in sub-optimal terrain, particularly in areas affected by drainage and human activities. Mapping and monitoring the impact of land subsidence on infrastructure plays a crucial role in identifying vulnerable areas prone to threats. The observation of land subsidence was conducted using two methods. The first involved the utilization of the Global Positioning System (GPS), which was a standard and dependable technique for monitoring deformation. The second method employed the Interferometric Synthetic Aperture Radar (InSAR), which provided precise detection of subsidence over expansive areas. To map spatiotemporal land subsidence phenomena in Palembang City, a combination of research utilizing the InSAR time-series analysis and various data sources such as JERS-1, Radarsat, Sentinel-1, and ALOS PALSAR with high spatial and temporal resolution, along with GPS observations was conducted. Analysis of a ten-year InSAR time-series data (October 10,2014 - August 31, 2023) showed a decrease of approximately 53,2 cm. These findings are expected to provide insights into the relationship between subsidence-prone areas, nearby rivers, and landslide phenomena.

Keywords: *Alluvial, Deltaic Plan, Geohazard, InSAR, Land Subsidence*

INTRODUCTION

Background

Previous research on land subsidence was primarily focused on examining variations in decline magnitude within specific time frames. It is crucial to recognize that land subsidence occurs over extended durations, with changes and deformations taking place at small scales, even down to millimeter fractions (Raspini et al, 2018). Numerous studies in various countries, including urban areas, have explored the mechanisms, prediction, and control of land subsidence. This geological hazard arises from regional elevation reduction caused by natural factors and human activities. Construction engineering practices, such as building size, volume ratio, and dispersion, have contributed to land subsidence, impacting the environment and sustainable urban development (Xiong et al, 2021).

In China, over 70 cities or regions have experienced land subsidence, leading to substantial economic losses (Xu et al, 2016). The consequences extend to urban construction projects and economic advancement, which led to damaged buildings, underground pipe cracks, increased flood control maintenance costs, seawater intrusion, and soil salinity (Hu et al,2019; Bernike et al, 2020).

Recent studies have also highlighted the severe implications of land subsidence for lowland areas (Andriani et al, 2018), including inundation and potential flooding risks (Marfai et al, 2008). Palembang City, a major town in Indonesia, is characterized by its lowland topography, composed of alluvial soil and situated on the delta plain of the Musi River, with an average elevation ranging from 4-16 m above sea level (Dinar et al, 2018). Certain areas still experience water-logging from swamps, rainfall, and Musi River runoff.

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Research Significance

Cities developed on alluvial or river delta land have the potential to experience faster subsidence including Jakarta, Semarang, and Palembang. In Palembang, extensive development had been undertaken by filling in large swampy areas in Seberang Ulu to develop the Jakabaring Sport Center Area. This supported the National and International Sports activities such as the Sea and Asian Games. Similarly, the development of Special Economic Zone (SEZ) extended towards Tanjung Api-Api and Tanjung Carat Ports in the Musi Delta area. In recent years, waterlogging at several points around these development areas had increased leading to more frequent flooding. Therefore, research needed to be conducted to analyze the potential for land subsidence which could intensify flooding and damage infrastructure in the area. The results served as a basis for spatial planning and setting limits on land use at specific levels. The availability of InSAR satellite data allowed for accurate and large-scale monitoring of land subsidence in urban and rural areas.

LITERATURE REVIEW

Land Subsidence Mechanism

There are diverse perspectives regarding land subsidence in many cities, primarily attributed to excessive groundwater extraction, which involves the principle of effective stress and dynamic consolidation of water. As water head decreases and effective stress increases, soil deformation occurs leading to land subsidence (Ardha et al, 2021; Chen et al, 2021). However, in urban areas of Shanghai, research conducted since the 1990s showed a significant increase in soil depreciation despite no change in groundwater levels. This coincided with extensive urban development projects carried out until the end of 2009 (Hors et al, 2018).

Extensive research has established a correlation between urban land subsidence and engineering construction, highlighting that accelerated soil deformation is associated with urbanization and developmental activities (Luo et al, 2022). Various factors contribute to land subsidence during the urbanization process, including the imposition of construction and traffic loads, soil compression from excavation, intense rainfall, and tunnel construction. These factors collectively reduced groundwater infiltration from the surrounding area, which led to the ongoing acceleration of land subsidence caused by water-related effects in building blocks (Luca et al, 2018; Suhada, 2022).The conclusion reached was that groundwater exploitation was not the primary cause of land subsidence. Instead, the significant role in accelerating land subsidence was attributed to large-scale urban construction and development (Yan et al,2021).

Engineering activities are responsible for approximately 30-40% of land subsidence (Putranto et al, 2020). As urbanization progresses in major cities, there are concern that the proportion of land subsidence attributed to engineering will persistently rise, underscoring the imperative for effective measures to curtail its impact.

In 2018, Andriani et al., initiated research on land subsidence in Palembang City, specifically focusing on the lowland region of the Tanjung Api-api Special Economic Zone (SEZ). The study employed the Landsat Image Interpretation ETM-8 method, combining soil sample collection and laboratory testing. The results showed that the undergoing infrastructure development for industrial and residential purposes had a potential land subsidence of 0.38 cm, while the existing conditions indicated a decline of 0.169 cm. Analysis of the primary factors contributing to land subsidence identified problematic soil types such as inorganic silt or diatomaceous fine sand, elastic silt (MH), organic clays with moderate to high plasticity (OH), inorganic silts and very fine sands, carmine powder or silty or loamy fine sands (ML), and organic silt and organic silt clay with low plasticity (OL) at a depth of 20-30m above mean sea level, where infrastructure buildings were situated.

The causes of land subsidence originated from individual factors, natural or anthropogenic triggers, or a combination of both (Chaussard et al, 2013). Geological factors, such as tectonic movements and sediment compaction influenced by overlying pressure or normally consolidated sediments, contribute to naturally occurring land subsidence (hu et al, 2019; Chaussard et al, 2013; Ciampalini, 2019; Solari et al, 2018; Miranda et al, 2018;Du et al, 2018). However, anthropogenic factors also play a role in influencing the

phenomenon (Setan et al, 2001). Detecting land subsidence in built-up areas presents intriguing research, as the consequences of this phenomenon pose risks to human safety (Khoulali, 2016; Gallicofa et al, 2021).

Liu et al (2022) conducted research on monitoring the phenomenon of ground movement with SAR imagery. Their findings demonstrated that InSAR was a straightforward method for detecting groundwater and regional deformation. To validate the InSAR findings, Global Positioning System (GPS) measurements were utilized. Similarly, de Luca et al. conducted a study focusing on displacement analysis using InSAR Sentinel-1A data. The research emphasized that dual-pair measurements, particularly the latest vertical displacement extraction, were beneficial for D-InSAR and precision displacement methods. The utilization of dual-pair measurements enhanced the vertical accuracy test. The subsidence parameter was characterized by a negative vertical displacement (Castelazzi et al, 2016).

By integrating remote sensing, geodesy, geology, and geotechnical science, the collaboration enabled the detection of land subsidence phenomena and their impact on building construction. Therefore, this study focused on discussing the utilization of a combination of InSAR and GNSS-Levelling survey methods in relatively flat lowland areas such as Palembang City. The GNSS-Levelling survey was employed for evaluating height differences.

Land subsidence manifested in localized or extensive areas, exhibiting both linear and nonlinear rates (Gumilar et al, 2016). Geodetic measurements provided a high reference for monitoring this phenomenon. Various technologies were employed to detect land subsidence phenomena, each with its strengths and limitations.

These technologies encompass leveling (Xu et al, 2016), GNSS (Gumilar et al, 2016). Interferometric Synthetic Aperture Radar (InSAR) (Ruiz et al, 2018; 2018), and gravity. The InSAR method proved effective in accurately detecting and mapping land subsidence over large areas with high precision.

METHODOLOGY

Research Location

The research area was designed along a three-point path in an area developed into a built-up zone. The first point was the Bukit Sejahtera Housing area developed by filling in swamps for large-scale housing projects. The second point was the Jakabaring Sport Center Area Point, which was developed by filling in swamps with material partly sourced through dredging sediment from the Musi River. Furthermore, the third point was the Airport Area, developed towards Tanjung Api-Api port by filling in several swamp areas. Fig. 1 showed the three control points of the network area which were analyzed for subsidence levels using D-InSAR method with Sentinel 1A image data from 2014 to 2023.

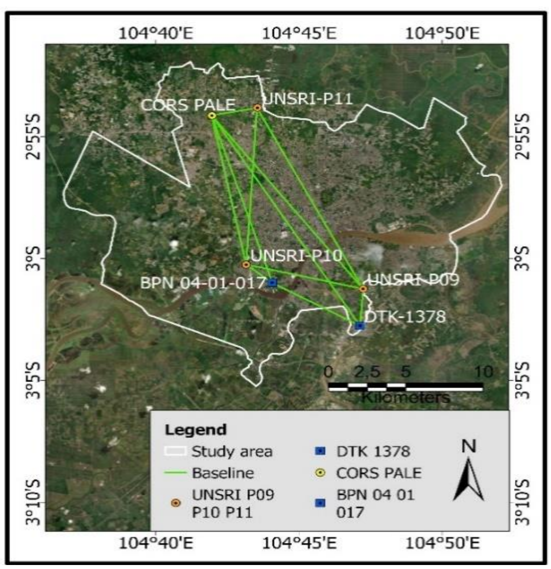

Figure 1: Area of the path around the Installed Vertical and Horizontal Control Point for Land Subsidence Observation using Geodetic and D-InSAR methods

The land around the research points in Palembang City remained surrounded by water from swamps, rainwater, and overflow from the Musi River. Geographically, the research area was located between 2°59'27.99"S to 3° 5'S latitude and 104°35'24.24" to 104° 52'30" East longitude.

The topography of Palembang City was generally flat and low with swamps along the Musi River and the tributaries extending in the City.

Data Used

European Space Agency (ESA) was used in the research, downloaded from the Alaska website (https://search.asf.alaska.edu/) for the period 2014 to 2024. The master and slave images used were of the Single Look Complex (SLC) type with a C-band sensor. The selection of images was based on the similarity of orbit numbers, areas, perpendicular line lengths, and time intervals between the two images. Higher perpendicular lines led to more accurate topography and displacement results. Table 1 showed the baseline length measured on two pairs of images consisting of five master and slave images each. The highest perpendicular baseline among the five pairs of images was 34 m, which was found in the slave image on March 10, 2024. The shortest time interval which was 576 days was between the master and the slave image from May 27, 2016.

Table 1: Perpendicular baseline length and time interval of the image

Master Image ID Scene and Polarization	Slave Image ID Scene and Polarization	Acquisition Time	Baseline Perpendicular(m)	Time Interval (days)
Sentinel 1-A Oct 29, 2014 VV	Sentinel 1-A Mei 27, 2016 VV	Mei 27, 2016	-19	576
Sentinel 1-A July 14, 2016 VV	Sentinel 1-A July 28, 2018 VV+VH	July 28, 2018	-8	744
Sentinel 1-A June 10, 2018 VV+VH	Sentinel 1-A June 11, 2020 VV+VH	June 11, 2020	-7	744
Sentinel 1-A Sept 15, 2020 VV+VH	Sentinel 1-A Sept 17, 2022 VV+VH	Sept 17, 2022	-14	732
Sentinel 1-A April 4, 2022 VV+VH	Sentinel 1-A March 10,2024 VV+VH	March 10, 2024	34	696

Source: Design by Researchers

Research Methods

InSAR has a working principle, namely that phase change information is taken from the image recorded at the time of the master image, namely the reference image and the subsequent recording in the form of a slave image (Ruiz et al, 2018). To obtain high category information, the next process is phase difference processing. In addition to this information, changes and movements that occur on the Earth's surface can also be obtained after processing the phase data (Constain, 2018). The illustration of the recording time of the master and slave images in Figure 2 can be said to be a result of surface movement. So that the equation regarding the interferogram phase can be explained, namely in the following equation 1.

$$\Delta\emptyset = \emptyset_{1} - \emptyset_{2}$$

$$\Delta\emptyset = \frac{4\pi}{\lambda} (R_{1} + R_{2})$$

$$\Delta\emptyset = \frac{4\pi}{\lambda} \Delta R \qquad (1)$$

In equation 1, the interferogram phase difference is denoted by $\Delta\emptyset$. The wavelength is denoted by λ. While the relative difference in Line of Sight (LoS) is denoted by ΔR. Differences in the position of satellite observers on the same object can cause differences in LoS. Differences in LoS can also be caused by changes in the position of objects on the Earth's surface, namely those recorded by the same satellite.

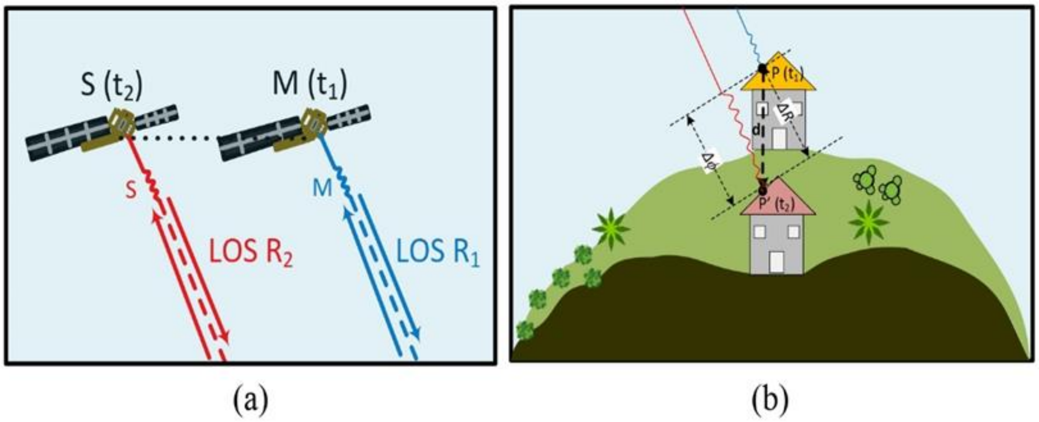

Figure 2: (a) Illustration of the recording of master and slave images; (b). Illustration of phase differences as a result of the phenomenon of ground surface movement.

Source: Design by Researchers (2024)

In SAR image processing, phase to displacement is a phase change from refinement and re-flattening to a LoS displacement value (Ruiz et al, 2018). The displacement results are in millimeter to centimeter fractions (Visalli et al, 2022). After the refinement and re-flattening process (phase unwrapping results) changes to displacement, there are two options. First, phase to displacement, which is the process of changing the phase to vertical displacement in LoS. The result is displacement information that is still in the form of LoS. Second, phase to vertical displacement, which is changing the phase difference to vertical displacement (true). The result is actual displacement information. The calculation of the phase to vertical displacement (true) uses equation 2 (Suhadha and Zulsankha, 2022).

$$Displacement\ vertical\ (true) = \frac{fase\ unwrapped.0{,}056}{-4\pi\ Cos\ \theta} \quad (2)$$

From equation 2, the angle formed between the wave beam and the line perpendicular to the surface of the object on the Earth's surface is denoted by θ (incidence angle). Information about the incidence angle is found in the metadata of each SAR image. If the SAR image processing already has LoS displacement, then the actual vertical displacement can be obtained with the following equation 3.

$$Displacement\ vertical\ (true) = \frac{LoS}{Cos\ \theta} \quad (3)$$

From equation 3, the LoS displacement is only compared with the cos incidence angle value and without involving other parameters of the InSAR image (Bernike et al, 2020). The flowchart of the research on INSAR and D-InSAR is shown in Fig. 3.

Ground Control Point Observation using GNSS

The basic Land Control point data was observed using the distribution of City Planning Service (DTK) control points that have been installed since 1994 for the Palembang City Region. The area covered by the network covers the entire administrative area of Palembang City. The distance between each leveling point is around 1 - 3 km in the city center. Leveling is checked using a thorough GPS GNSS survey to ensure the accuracy of land subsidence data. All land deformation data is extracted from DTK points, each consisting of Concrete BM and planted into the ground 4 m deep with a sondir tool, as a basic land control point as well as to monitor Land Deformation in Palembang City.

The basic land control point measurement method is combined using InSAR time-series analysis of ALOS L-band SAR data (Ferreti et al, 2007; Chausard, 2013; Hu et al, 2017), with high spatial and temporal resolution. Meanwhile, time-series analysis of InSAR data from various images is used to determine the conditions of changes in land subsidence and land use in the research area since 2014-2024.

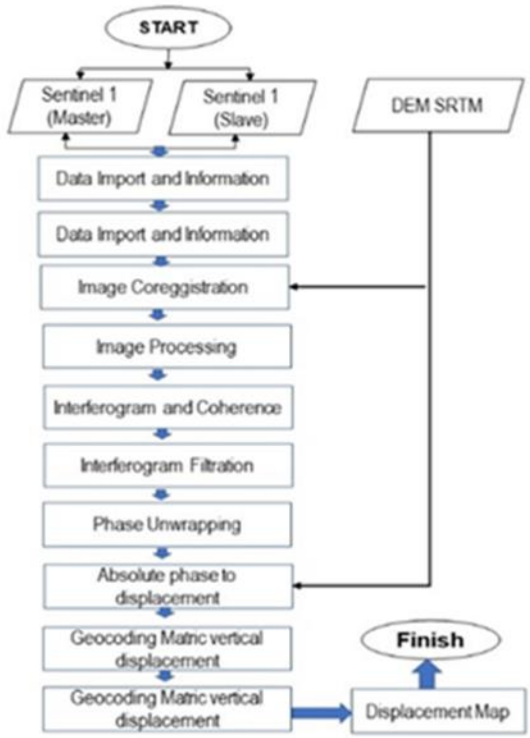

Figure 3: Research Flowchart

Source: Design by Researchers

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RESULT AND DISCUSSION

Phase Interferogram

The interferogram phase (phase VV) indicates that a region has a land subsidence phenomenon. However, the phase still contains an ambiguity phase. This is because it is still in the phase unit +2phi to -2phi. The interpretation of this interferogram phase shows a change in surface elevation in Palembang City.

The interferogram phase value shown in Fig. 4 is -3.0 to 3.0 phi. The interferogram phase value can of course vary. This can be caused by seasonal changes in the study area. In terms of obtaining accuracy and precision, differences in interferogram phase values can also be caused by the type of data or the quality of the input data.

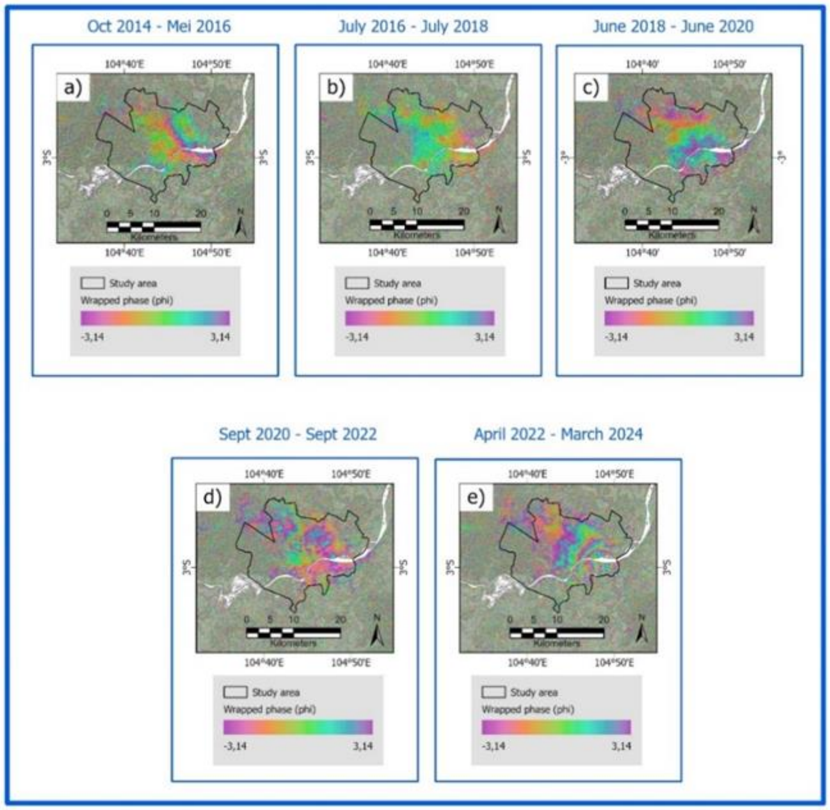

Figure 4: Phase Interferogram 2014 – 2024

Source: Results of Interpretation Analysis by Researchers

Vertical Displacement Extraction Period

In the SAR Image data processing stage, the phase to displacement uses files, namely coherence, unwrapped phase, and DEM. In the phase to displacement stage, the basic parameters used are product coherence threshold (0.2), vertical displacement, slope displacement, displacement custom direction, X dimension (5 m), Y dimension (5 m), window size interpolation (7), and dummy removal.

Based on Figure 5(a), the vertical displacement value in Palembang City in the period from October 2014 to May 2016 is around -14.1 to 4.0 cm. This area experienced maximum subsidence of -14.1 cm and uplift of up to 4 cm. In the period from July 2016 to July 2018, Palembang City experienced negative vertical displacement, namely experiencing the largest subsidence of -11.4 cm and uplift of up to 9 cm. In the period from June 2018 to June 2020, the largest subsidence value was -14.7 cm while the uplift value was 3 cm per two years.

In the period of September 2020 to September 2022, the vertical displacement value generally ranged from -13.1 cm to 10.0 cm. And in the period of April 2022 to March 2024, the largest subsidence value was -28.1 cm and during this period the city of Palembang did not experience uplift or topographic increase. More details can be seen in Table 2 below.

Based on Table 2, it can be seen that the maximum subsidence of -28.1 cm occurred in the period of 2024, namely since April 2022. This is indicated by a color that tends to be dark red. The minimum subsidence occurred in the period of 2016 to 2018, namely -11.4 cm. Not only did subsidence occur, the city of Palembang also experienced an uplift or maximum topographic increase, namely in the period of September 2020 to September 2022, amounting to +10.0 cm, which is indicated by a purplish blue color. This topographic increase occurred within a period of two years, namely since September 2020.

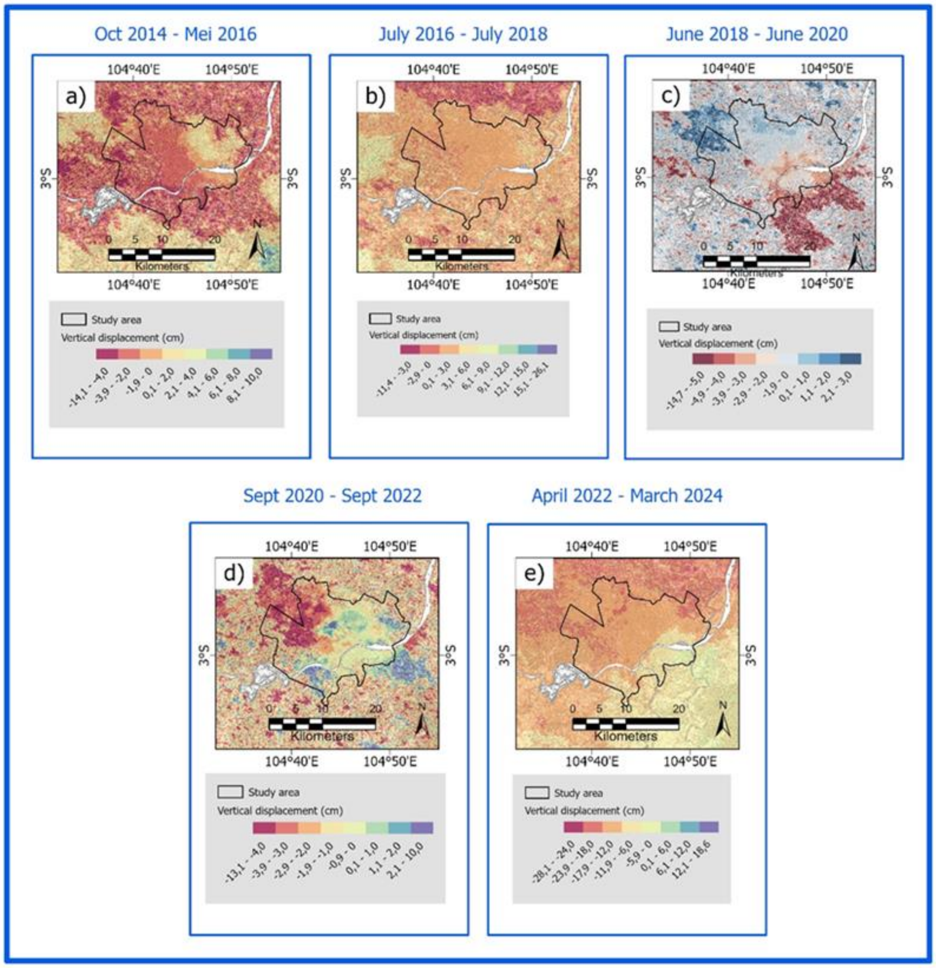

Figure 5 : Vertical *Displacement* (2014 - 2024)

Source: Results of Interpretation Analysis

Table 2: Vertical Displacement Values of Palembang City for the Period 2014 to 2014

Period	Vertical Displacement Palembang City (cm)				Vertical Displacement Palembang City and Surrounding Area (cm)
	Subsidence		Uplift		
	Min	Max	Min	Max	
2014-2016	0	-14.1	0	+4.0	-14.1 – 10.0
2016-2018	0	-11.4	0	+9.0	-11.4 – 26.1
2018-2020	0	-14.7	0	+3.0	-14.7 – 3.0
2020-2022	0	-13.1	0	+10.0	-13.1 – 10.0
2022-2024	0	-28.1	0	+6.0	-28.1 – 18.6

Source: Results of Interpretation Analysis

GNSS Survey Analysis

Table 3 presented the variation in average cumulative subsidence in Palembang City based on observations of the height of the BM points installed by the City Planning Agency since 2000. These points served as the basis for issuing Building Permits (IMB) and were re-measured in 2004, 2014, and 2024. Three key areas were observed to track the development of the city correlating with the three development points. The points included (1) P10 located in the Residential and Office Development Area near the Palembang - Jambi Outer Cross Road. (2) P09 in the Palembang Sports Center development area which included New Office and Residential Centers, and (3) P11 in Tanjung Api-Api Port SEZ Infrastructure Development Area. These points were monitored using GNSS to determine the level of subsidence.

Table 3: Results of GNSS observations at BM points in three locations in the land subsidence observation path area

Year	P-09	ΔH(P09-P10)	P10	ΔH(P10-11)	P-11	ΔH(P11-P09)	P09
2000	1,9	-1,08	2,98	-1,56	4,54	2,64	1,9
dh	0,6	0,44	0,16	-0,15	0,31	-0,37	0,68
dh/year	0,15	0,11	0,04	-0,0375	0,0775	-0,0925	0,17
2004	2,5	-0,64	3,14	-1,71	4,85	2,27	2,58
dh	0,74	0,32	0,42	0,76	-0,34	-1	-0,66
dh/year	0,074	0,032	0,042	0,076	-0,034	-0,1	-0,066
2014	3,24	-0,32	3,56	-0,95	4,51	1,27	3,24
dh	-0,28	0,3	-0,58	0,06	-0,64	-0,36	-0,28
dh/Year	-0,028	0,03	-0,058	0,006	-0,064	-0,036	-0,028
2024	2,96	-0,02	2,98	-0,89	3,87	0,91	2,96

P09-Jakabaring Sport Center Area

P10-Setlement Area, Outer Ringroad Palembang-Jambi
P-11- Road to Tanjung Api-Api SEZ Area

Source: Results of Interpretation Analysis

The average land subsidence was 0.04 m per year from 2000 to 2004, 0.042 m from 2004 to 2014, and -0.036 m from 2014 to 2024. This closely correlated with the average land subsidence analysis conducted using imagery at the same areas for the period 2014-2024 (Table 2 and Fig. 6, log section profile).

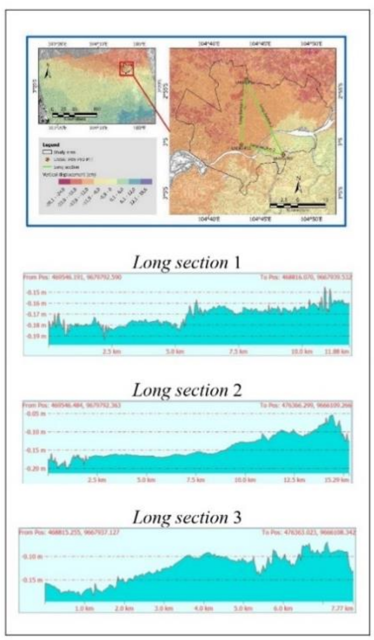

Figure 6: Long section profile of vertical displacement around the monitoring point during the period March 2024 in Palembang City

Source: Interpretation Analysis results

Subsidence and City Infrastructure Development

The longitudinal cross-sectional line connecting points P09, P10, and P11 along with surrounding areas was interpreted for subsidence using Imagery (Fig. 6).

The annual rate of land subsidence in each period is as follows, 3,84 Cm/year in 1994–2004 (vd1), 9.97 Cm /year in 2005–2014 (vd2), and 12.09 Cm/year in 2015–2023 (rd3). The rates of increase in floor area were 0.58, 2.30, and 13.17 Ha/year, respectively. Notably, vd2 and vd3 values are two and three times higher than vd1. Analysis showed that both the length of the roadway and the total floor area contributed to the acceleration of land subsidence. However, it is noteworthy that prior to 1994.

Based on this analysis, the development of urban infrastructure, such as the urban road network, emerged as a significant factor contributing to the intensified land subsidence in Palembang City since 2004.

Since 2004, since the development of the city of Palembang was directed across Ulu and towards Tanjung Api-Api Harbor, which is a swamp area or Musi River flood runoff, by filling in the swamp, the cumulative Vd (Vertical displacement) has decreased.

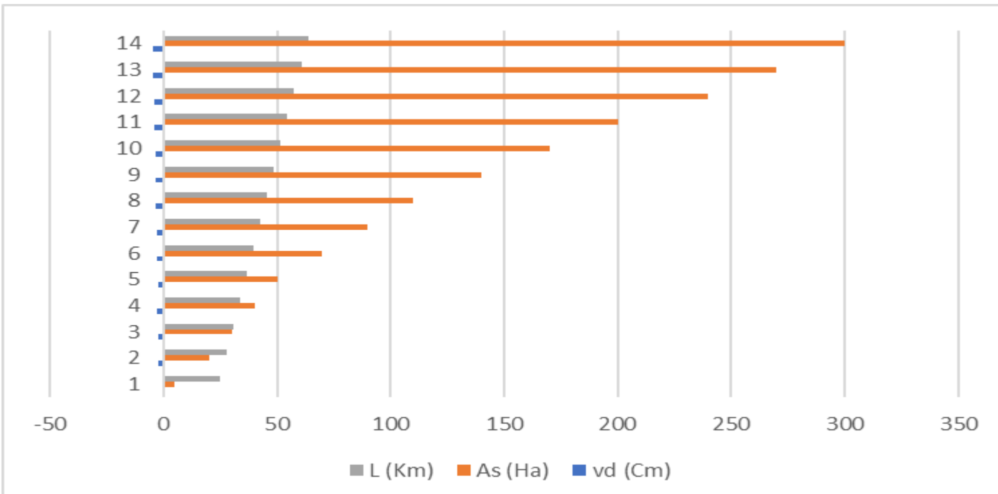

Figure 7: Graph of the relationship between the addition of road sections, the increase in building infrastructure, and cumulative land subsidence in Palembang City

Source: Interpretation Analysis results

Even when Vd decreases, the rate of land subsidence begins to increase, rather than decrease, as had occurred in previous periods. If Vd exceeds the critical value, it will show no correlation with variations in soil settlement.

The analysis implies that the level of land development on marshlands may be the most critical factor controlling land subsidence. Therefore, it is important to study the reasons for the decline and the mechanism of continuous subsidence of the land surface, especially in urban development areas carried out by reclamation of swamp land.

CONCLUSION

In conclusion, the following observations were made in this research.

During the period before significant city development (2000-2004), no subsidence was observed. The outer ring road area of Palembang City, particularly the Settlement Development area (P10) experienced an uplift of 4 cm per year from 2000 to 2004, which increased to 4.2 cm per year from 2004 to 2014. In the Jakabaring Sport City Center area (P09), the uplift was 15 cm per year during 2000-2004 which slowed to 4.2 cm per year from 2004 to 2014. Furthermore, the area near Tanjung Api-Api SEZ (P11) observed an uplift of 7.75 cm per year from 2000 to 2004, followed by a decrease of -3.4 cm per year from 2004 to 2014. Between October 2014 and August 2019, Palembang City around the North Musi River (Downstream Across the Area) experienced subsidence ranging from -19.9 to -4.9 cm.

The highest subsidence occurred in the areas surrounding the Musi River with declines ranging from -19.9 to -10.0 cm.

Despite the subsidence, Palembang City also experienced vertical uplift or positive displacement ranging from 0.1 to 5 cm over 5 years, specifically between October 2014 and August 2019.

The subsidence in urban areas could be attributed to the increased construction loads due to the rapid development of multi-story buildings exceeding five floors. Based on the results, it was essential to identify new constructions and specific built-up areas to determine the subsidence figures statistically over time.

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