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LAND SUBSIDENCE DYNAMICS IN MALAYSIA BASED ON TIME-SERIES VERTICAL DEFORMATION USING MODIFIED D-INSAR SENTINEL-1

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Abstract

Land subsidence in urban areas is geohazard that can be caused by tectonic movements, changes in aquifer networks, or anthropogenic activities such as excessive groundwater extraction, mining, tunnelling, and plantations. The degree of land subsidence can be monitored using time-series vertical deformation data extracted from Sentinel-1 satellite imagery using the modified D-InSAR method. This study aims to determine the land subsidence dynamics of 16 cities in Malaysia based on time-series vertical deformation data, including Kota Bahru, Kuala Terengganu, George Town and Butterworth, Alor Setar, Kangar, Ipoh, Seremban, Malacca, Kuala Lumpur, Putra Jaya, Shah Alam, Kuantan, Johor Bahru, Kinabalu, Bandar Labuan (Victoria), and Kuching. The time-series vertical deformation data used in this study were extracted between 2014-2022. Negative values of vertical deformation indicate that land subsidence is occurring, while positive values of vertical deformation are indicative of regional uplift. The overall rate of land subsidence in Malaysia is between -0.5 cm to -6.0 cm, while the average uplift rate is between +0.5 cm to +4.5 cm. An analysis of the data extracted reveals that the city that is most vulnerable to land subsidence is Johor Bahru, followed by Kuala Terengganu, Seremban, Kuala Lumpur, Shah Alam, Malacca, and Kuantan, while the city that has the lowest risk of land subsidence is Kangar. In contrast, cities that are vulnerable to regional uplift are Kinabalu and Bandar Labuan (Victoria). The results of this study can be used to guide urban planning initiatives, allowing them to consider any threats that might be posed by land subsidence.

Keywords: Land Subsidence, Time-Series Vertical Deformation, Modified D-InSAR, 16 cities of Malaysia

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INTRODUCTION

Malaysia is a Southeast Asian country that has undergone significant urban development in recent years. The development of cities has been characterized by the addition of residential districts, increased population density, increasingly accessible transportation services, and topographical changes. One of the major geohazards that large cities face is land subsidence. Land subsidence is a geological hazard phenomenon (Motagh et al., 2017; Zhu et al., 2015). Land subsidence is becoming an increasingly important problem in Malaysia, with several cities experiencing some form of land subsidence (Muhammad et al., 2021). Land subsidence is most commonly caused by active tectonic movement but can also be due to anthropogenic activities (Julzarika et al., 2021). Excessive groundwater extraction, tunnelling, excessive infrastructural development, and mining activities that may disrupt aquifers are the example of anthropogenic activities (Ardha et al., 2021; Julzarika et al., 2022; Muhammad et al., 2021).

The Malaysian area less experienced land subsidence due to the tectonic movement. Land subsidence in large cities in Malaysia is more likely to be caused by groundwater extraction. Cities such as Kuala Lumpur and Johor Bahru have undergone a significant degree of residential development as well as an increase in population density, while regions such as Kota Bahru (Kelantan) represent approximately 38 % of the national groundwater demand. These factors have resulted in an increase in groundwater consumption from 1990 to 2010 (Suratman, 2012). Rates of land subsidence in Malaysia are still relatively low, especially when compared to regions such as the northern Java, California, and the northern Africa (Ardha et al., 2021; Mohamed & Gonçalvès, 2021; Stampoulis et al., 2019). This phenomenon is still concerning to local governments and residents, and the steps should be taken to ensure that future incidents do not occur. Consequently, land subsidence monitoring is key in areas that encompass fault boundaries or in large, dynamic cities (Suhadha et al., 2021). Land subsidence can impact a community's economy, disrupt regional and urban planning, and damage existing infrastructure, such as by disrupting underground utility lines, allowing for seawater intrusion, damaging the foundations of buildings, and increasing the risk of tidal flooding. The primary concerns are the impact on the environment as well as the impacts on the urban economy associated with asset loss. This study aims to analyse the land subsidence dynamics in Malaysia based on modified Differential Interferometry Synthetic Aperture Radar (D-InSAR) from Sentinel-1.

RESEARCH METHODOLOGY

Study Area

This research area is located in 16 cities of Malaysia. The selection of these 16 cities was based on regional administrative conditions (state capital), population density, and groundwater consumption potential. Population density has a linear correlation with groundwater consumption potential. The 16 cities referred to in this study can be seen in Figure 1. The 16 cities include (1) Kota Bahru, (2) Kuala Terengganu, (3) George Town and Butterworth, (4) Alor Setar; (5) Kangar, (6) Ipoh, (7) Seremban, (8) Malacca, (9) Kuala Lumpur, (10) Putra Jaya, (11) Shah Alam, (12) Kuantan, (13) Johor Bahru, (14) Kinabalu, (15) Bandar Labuan (Victoria), and (16) Kuching.

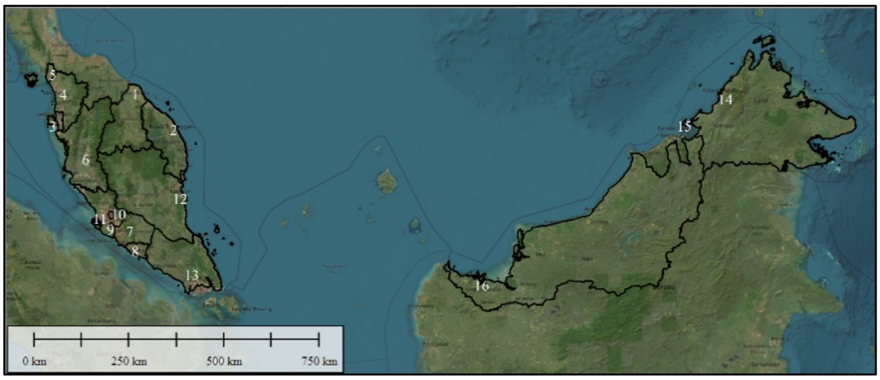

Figure 1: Study Area in 16 Cities of Malaysia
Source: Author modification from World Imagery

D-InSAR and Sentinel-1

D-InSAR is an active remote sensing technique based on the principle of analysing paired and co-registered SAR images with different acquisition times to detect displacements down to subcentimeter along the sensor's line of sight to the target or Line of Sight (LOS) (Suhadha & Julzarika, 2022). It is similar to terrain motion measurement. This method can be used for efficient and effective mapping and to complement the deficiencies of existing field survey data (Devanthéry et al., 2016). Sentinel-1 imageries are used to extract the vertical deformation using modified D-InSAR. The Sentinel-1 is a radar satellite (C band sensor) with a spatial resolution of 5 to 10 m and a temporal resolution of 6 to 12 days (ESA, 2019).

The modified D-InSAR method is a modified method of the traditional D-InSAR, P-SBAS, and PS-InSAR, which has taken into account the error propagation in the model and data used and has changed the final result of vertical deformation LOS to vertical deformation (true) (Julzarika et al., 2022; Suhadha et al., 2021). The result of vertical deformation is still in the form of LOS, so it is necessary to make nadir corrections or vertical deformation (true). LOS vertical deformation means that the oblique vertical deformation value corresponds to the direction of the satellite's viewing angle to the ground surface, see equation (1) (Ferretti et al., 2007; Rucci et al., 2012). Vertical deformation (true) means that the resulting vertical deformation value has been nadir corrected or perpendicular to the nadir. The vertical deformation value (true) is close to the actual value in the field; see equation (2) (Suhadha et al., 2021).

Vertical deformation (LoS) $= 2\pi\Delta r / \lambda = (4\pi * B * q) / (\lambda * R)$ *……………… equation (1)*

Vertical deformation (true) = vertical deformation (LoS) $* \cos\theta$ *…….. equation (2)*
θ = incidence angle; B = the perpendicular baseline; q = the displacement between the resolution cell along the perpendicular to the slant range; R = the radar target distance; λ = SAR wavelength

The D-InSAR results still have low vertical accuracy, so it is necessary to integrate with several field measurement points. Measurements with D-InSAR focus on results in precise vertical deformation (Julzarika et al., 2022; Rucci et al., 2012). Field data brings the value of vertical deformation according to the existing reference plane on the earth's surface. This method can complement the need for more available field survey data. The D-InSAR and field data integration results will produce high-precision and high-accuracy vertical deformation measurements over a wide area. Vertical deformation monitoring is critical to support security and regional planning, especially in areas with dynamic land use changes and cities like Malaysia.

RESULTS AND DISCUSSION

The results of this study are the time-series vertical deformations across Malaysia between 2014-2022. The results were analysed using accuracy and profile tests. The results of the vertical deformation analysis can be used to determine whether the city is experiencing land subsidence or uplift. Vertical deformation on the Earth's surface geodynamics can be categorised into land subsidence and uplift. Land subsidence is a vertical deformation with a negative value, while uplift is a vertical deformation with a positive value. This negative value means a decrease in the surface, while a positive value means an increase in the surface.

Our analysis revealed a significant global vertical deformation anomaly in 2020-2021. This anomaly refers to abnormal changes in vertical deformations, such as the occurrence of extremely rapid rates of land subsidence or instances of extreme uplift. More simply, the global vertical deformation anomaly can be described as the opposite of previous vertical deformation patterns. The impact of the global vertical deformation anomaly causes irregularities in the geodynamic movements. It is away from the equilibrium point of tectonic movements and changes the composition pattern of land 29% and water 71%. Figure 2 is the global vertical deformation anomaly. In 2020, there was a significant negative vertical deformation anomaly that affected most of Malaysia.

Several areas experienced uplift during the global vertical deformation anomaly, especially in areas where subsidence had occurred before 2020.

In addition, there was an episode of vertical deformation in 2021-2022 in the opposite direction of the deformation observed during 2020-2021 anomaly. For example, if extreme subsidence had occurred in 2020-2021, then the same area would have experienced extreme uplift during 2021-2022, effectively returning the regions to the equilibrium (balance movements) conditions experienced prior to the 2020 anomaly. Similarly, areas that experienced extreme uplift during the 2020-2021 anomaly experienced extreme subsidence 2021-2022. The following are the results of the vertical deformation dynamics and cross-section profile patterns in 16 cities in Malaysia. The locations of these 16 cities are grouped into the west coast of Peninsular Malaysia, the east coast of Peninsular Malaysia, and East Malaysia.

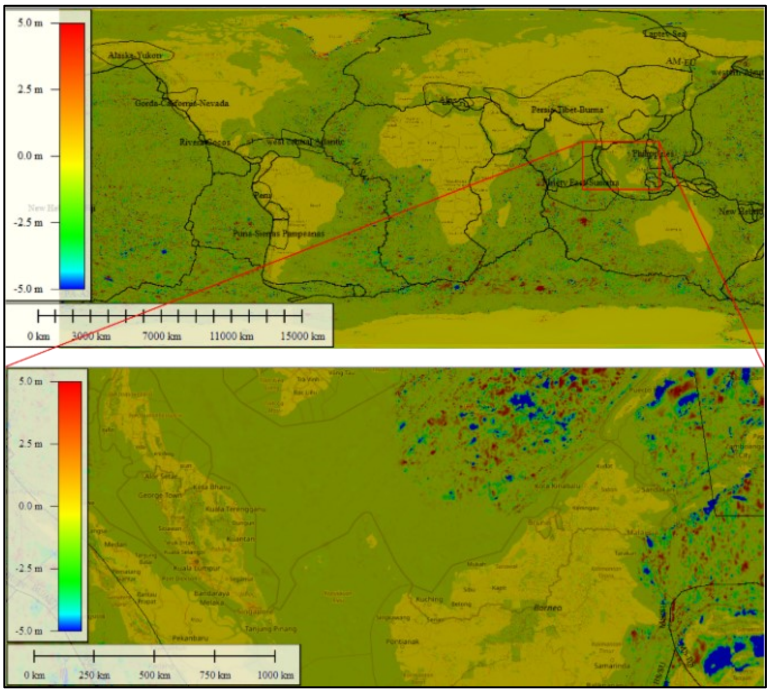

Figure 2: Global Vertical Deformation Anomaly 2020-2021
Source: Author calculation (2020-2022)

(1) West Coast of Peninsular Malaysia

The west coast of Peninsular Malaysia includes Kangar, Alor Setar, George Town and Butterworth, Ipoh, Seremban, Kuala Lumpur, Putra Jaya, Shah Alam, and Malacca. Kangar is a city near the Thailand border that experiences lower land subsidence, see Figure 3(A). In 2014-2020, there was a subsidence of -0.5 cm. In 2020, this region was affected by the effects of the global vertical deformation anomaly. Kangar experienced an extreme uplift of +10.0 cm. This uplift condition is due to the area around Kangar experiencing a subsidence movement so that the city is surrounded and affected by a balancing movement towards the surrounding area. There will be a subsidence of -0.5 cm in 2021, but this region has yet to reach equilibrium after the global vertical deformation anomaly. The impact of the 2021 subsidence will cause more significant subsidence in 2022. The 2022 subsidence value is -9.0 cm. In addition to natural balance factors, it can also be caused by groundwater extraction or changes in the aquifer networks. Overall, Kangar did not experience any significant vertical deformation during the 2020-2022 period. In 2022, the vertical position of Kangar will be almost the same as the vertical position in 2020. Some areas in Kangar will experience land subsidence of -0.5 cm, and some areas in Kangar will experience an uplift of +0.5 cm. Kangar is an example of an ideal area in Malaysia that experiences a balance of tectonic movements and moderate consumption of groundwater.

Alor Setar is the capital of the state of Kedah. Alor Setar is located in the northern part of Peninsular Malaysia. The Alor Setar area has soft soil conditions, and the large Kedah River crosses it. Parts of Alor Setar are river deltas and are prone to sedimentation. Soft soil conditions cause vulnerability to land subsidence, while sedimentation causes vulnerability to uplift. In 2014-2020, Alor Setar was dominated by land subsidence of -0.5 cm, see Figure 3(B). In 2020, Alor Setar was affected by a global vertical deformation anomaly, which caused an uplift of +2.5 cm. Likewise, in 2021, Alor Setar will experience another uplift of +3.0 cm. High sedimentation also affects the uplift value in 2020-2021. In 2022, a tectonic equilibrium occurred and caused Alor Setar to experience a subsidence of -7.0 cm. These conditions are close to the vertical position as before 2020. In the 2020-2022 period, Alor Setar experienced land subsidence of -1.5 cm. The condition of the vertical deformation movement, which sometimes subsides and sometimes uplifts, is also influenced by anthropogenic activities and the major flood that hit Alor Setar. For example, floods in 2022 will occur in a wide area, and extended inundation is caused by high land subsidence. Another factor that caused the uplift in 2020-2021 and high subsidence (-7.0 cm) in soft soil is the aquifer networks changes, and surface water from rain becomes easily stagnant on the surface.

George Town is the state capital of Pulau Pinang. It is located on an island and is separated from Peninsular Malaysia. The opposite side east of George Town is Butterworth. In 2014-2020, George Town and Butterworth experienced land subsidence of -2.0 cm, see Figure 3(C). In 2020, these two cities experienced an uplift of +2.0 cm. Then, in 2021, these two cities will be dominated by an uplift movement of +5.5 cm. Geodynamic equilibrium in this area will occur in 2022. The dominance of subsidence of -13.0 cm causes tectonic movement towards conditions before 2020. George Town and Butterworth experienced land subsidence of -5.5 cm in 2020-2022. Infrastructure development, groundwater consumption, land cover changes, and aquifer dynamics can cause high land subsidence in George Town and Butterworth.

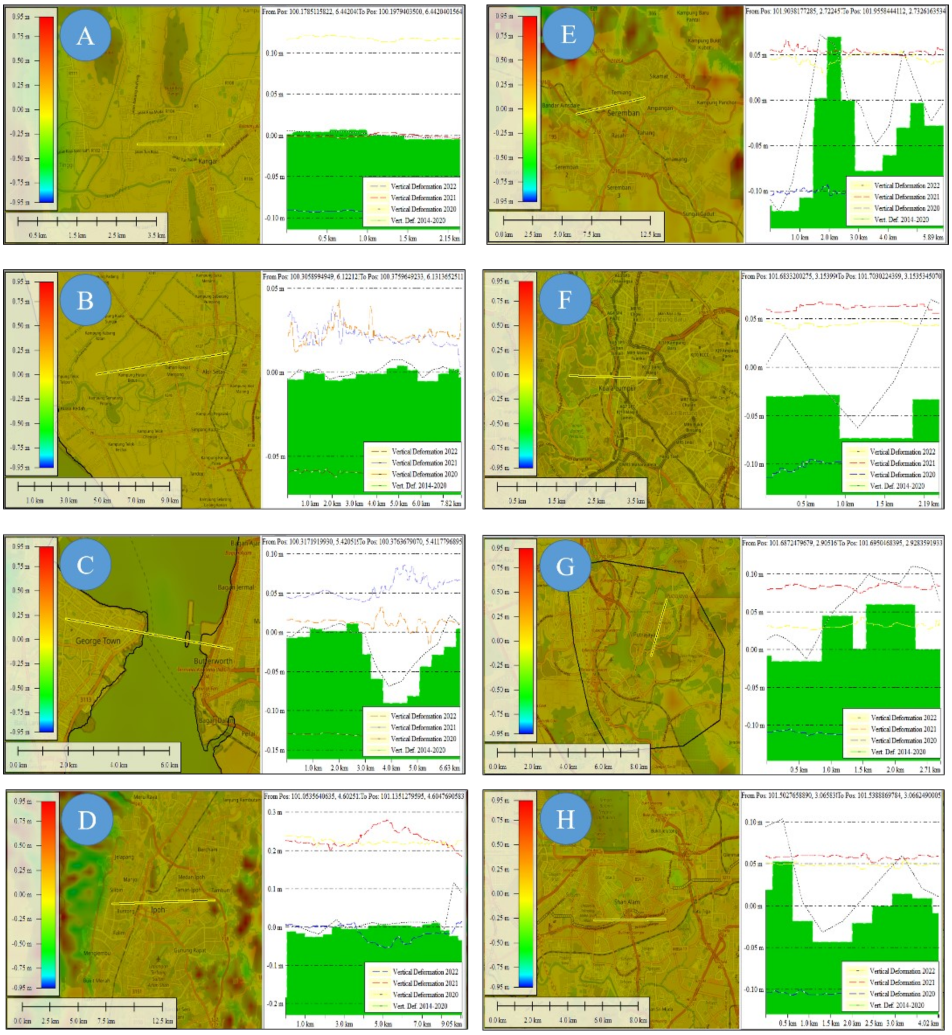

Figure 3: Time-Series Vertical Deformation in the West Coast of Peninsular Malaysia (2014-2022). A. Kangar; B. Alor Setar; C. George Town and Butterworth; D. Ipoh; E. Seremban; F. Kuala Lumpur; G. Putra Jaya; H. Shah Alam

Ipoh is the capital of the state of Perak. It is located in the central part of Peninsular Malaysia or north of Kuala Lumpur. In 2014-2024, Ipoh is dominated by land subsidence with a value of -1.0 cm, see Figure 3(D). Then, in 2020 and 2021, Ipoh will be affected by a global vertical deformation anomaly, which causes an extreme uplift. Another factor that caused the uplift was landslides and significant floods in 2020-2021. The 2020 uplift value is +21.0 cm, and the 2021 uplift value is +22.0 cm. A landslide causes the formation of piles of soil (uplift) with a broader area, but the landslide point causes subsidence in a smaller area. Major floods cause sedimentation and mineral displacement to form new land or increase the thickness of the soil (uplift). In 2022, Ipoh experience a land subsidence of -1.0 cm. Ipoh is a geological area that experiences high dynamics. Uplift and subsidence can occur one after another, depending on natural conditions, and anthropogenic activities. Fault movements cause natural conditions. Anthropogenic activities include excess groundwater extraction, plantation and mining activities, and infrastructure development. Ipoh is dominated by an uplift in 2020-2022.

The Seremban is located on the south side of Kuala Lumpur. It is the capital state of Negeri Sembilan. Seremban is one of the cities affected by subsidence due to the surrounding area experiencing uplift and the use of groundwater, which is quite large. In 2014-2020, Seremban experienced an uplift of -5.0 cm, see Figure 3(E). In 2020, this region will experience subsidence of -10.0 cm. Global vertical deformation anomaly factors groundwater use and infrastructure development can cause high subsidence. Natural equilibrium occurs in 2021 and 2022. In this period, the geodynamic movement is uplifting at +5.0 cm/year. There will be almost no subsidence in 2021-2022 in Seremban. Overall, in 2020-2022, there will be low subsidence and uplift. The vertical position in 2022 is close to the vertical position in 2020. The potential for land subsidence in Seremban is still threatening for the next few years if excessive groundwater use and infrastructure development occur.

Kuala Lumpur is the capital city of Malaysia. This city is located in Peninsular Malaysia. Kuala Lumpur is vulnerable to land subsidence. Based on the results of observations in 2014-2020, Kuala Lumpur is dominated by subsidence with an average value of -5.0 cm, see Figure 3 (F). In 2020, subsidence will reach -10 cm caused by various factors such as global vertical deformation anomaly, infrastructure development, and high groundwater consumption. In 2021 and 2022, uplift will be more dominant compared to subsidence. The uplift value in 2021 is +5.5 cm, and in 2022 it is +5.0 cm. In 2020-2022, the subsidence predominate in Kuala Lumpur at -0.5 to 1.0 cm each year. Groundwater consumption and infrastructure development will be the main factors of future land subsidence in Kuala Lumpur. Consumption of groundwater will be high along with the increase in the number and density of residents in Kuala Lumpur.

Putra Jaya is the capital of the Malaysian government. It is located on the south side of Kuala Lumpur. Before 2020, an uplift of +2.0 cm dominated Putra Jaya, see Figure 3(G). Then, 2020 subsidence will dominate due to the influence of a global vertical deformation anomaly of -10.0 cm. In 2021, Putra Jaya experienced a geodynamic equilibrium with a movement of +7.0 cm. The end of the equilibrium movement will occur in 2022. In 2022, there will be an uplift dominance of +3.0 cm. These conditions have caused Putra Jaya to return to its vertical position as it was before 2020. Putra Jaya is dominated by the uplift of +0.5 to +1.0 cm, and several areas will experience subsidence of -0.5 cm in 2020-2022. Infrastructure development and groundwater consumption are the main factors causing land subsidence in Putra Jaya. The potential for land subsidence in Putra Jaya is still smaller than the potential for land subsidence in Kuala Lumpur.

Shah Alam is located on the west side of Kuala Lumpur. Shah Alam is one of the cities in Malaysia that experienced subsidence in 2014-2020, see Figure 3(H). Shah Alam's subsidence value in that period was -3.5 cm. Infrastructure development and high groundwater consumption are one of the causes of land subsidence in this region. Shah Alam also has many settlements and potentially high population densities. The coastal area also has soft soil and is prone to subsidence. The influence of the global vertical deformation anomaly in 2020 will also have an impact on subsidence in Shah Alam, with a value of -10.0 cm. In 2021 and 2022, an uplift of +5.5 cm and +5.0 cm will be dominated. The uplift conditions during these two years have impacted the geodynamic equilibrium in Shah Alam. The subsidence dominated in Shah Alam for the 2020-2022 period (-1 cm). The potential for land subsidence could increase in the future due to the rapid development of infrastructure in this region and the increasing number and density of the population. Land subsidence in Shah Alam is still in the normal category today.

Malacca is located in the southern part of Kuala Lumpur. Malacca experienced land subsidence of -5.0 cm in 2014-2020, see Figure 4(D). In 2020, a high subsidence of -10.0 cm was observed. The consumption and use of groundwater, relatively unstable soil types, and the effects of global vertical deformation influence this high subsidence value. In 2021, Malacca will be dominated by an uplift of +5.0 cm. Malacca will also be dominated by an uplift of +4.5 cm in 2022. Overall, Malacca is dominated by subsidence in 2020-2022. The subsidence value is -0.5 to -1 cm. The potential for land subsidence in the following years could also threaten Malacca. The value of land subsidence in Malacca is still classified as low to moderate because it is still around 0 to -5.0 cm/year.

(2) East Coast of Peninsular Malaysia

The east coast of Peninsular Malaysia includes Kota Bahru, Kuala Terengganu, and Kuantan. Kota Bahru is located near the Thailand border. Kota Bahru experiences relatively high dynamics of vertical deformation. In 2014-2020, the vertical deformation in this city is more towards subsidence, see Figure 4(A). The average subsidence value in 2014-2020 is -1 cm. This condition is still stable and indicates that subsidence in Kota Bahru is caused by slow tectonic movements and groundwater extraction with a relatively equal amount each year. Groundwater extraction in Kota Bahru may be high in terms of consumption in Malaysia, but it is less extreme than on the northern coast of Java and Africa. A global deformation anomaly occurred in 2020, resulting in higher subsidence in Kota Bahru. The subsidence value in 2020 is -8.5 cm. In 2021, there will be a high uplift of +5.0 cm. This uplift process is part of the tectonic movement to balance the post-anomaly region of global vertical deformation. In 2022, there will be another subsidence of -6.0 cm. This condition can be caused by tectonic movements to balance the geodynamics of the region. It can also be caused by the effect of groundwater withdrawal, which is starting to increase. Kota Bahru has experienced subsidence of -3.2 cm (2020-2022).

Kuala Terengganu is the capital state of Terengganu. It is located at the mouth of the Terengganu River. Kuala Terengganu is one of the cities in Malaysia that has the potential to experience land subsidence. In 2014-2020, subsidence was observed with an average of -3.0 cm, see Figure 4(B). Then, in 2020, Kuala Terengganu was affected by a global vertical deformation anomaly and experienced an uplift of +4.5 cm. In 2021, the geodynamic process to balance the area will be carried out naturally, and this area will experience subsidence of -12.0 cm. The factor of high groundwater withdrawal can also be the cause of the high subsidence rate in 2021. In 2022, Kuala Terengganu will experience an uplift of +4.0 cm. One of the causes of this area experiencing uplift is sedimentation around the river mouth and flooding that occurs in this area. Sedimentation and flooding are more dominant than high groundwater withdrawal, so the uplift effect is more dominant than subsidence in 2022. Kuala Terengganu experienced land subsidence of -4.2 cm in the 2020-2022.

Kuantan is the capital of the state of Pahang. Kuantan is a city vulnerable to land subsidence, see Figure 4(C). In 2014-2020, the subsidence value in Kuantan was -4.0 cm. This condition is higher than in other areas around Pahang. Subsidence in Kuantan is slightly lower than in Johor Bahru, Kuala Terengganu, Kuala Lumpur, Seremban, and Malacca. This quaternary is not too affected by the global vertical deformation anomaly. Land subsidence in Kuantan is dominated by groundwater use and infrastructure development. In 2020, the subsidence value in Kuantan is -1.0 cm. In 2021, Kuantan will also be dominated by subsidence with a value of -0.5 cm. Another condition in 2022, Kuantan, is more dominated by uplift with a value of +2.0 cm. One of the factors causing the uplift in 2022 is caused by the major flood that hit Kuantan. It causes sedimentation and the addition of minerals or soil erosion brought by the flood from upstream. Kuantan is located in the coastal and estuary parts of the river so that the range of sedimentation occurs. In 2022, there will be land subsidence in several areas in Kuantan, but uplift will dominate this area.

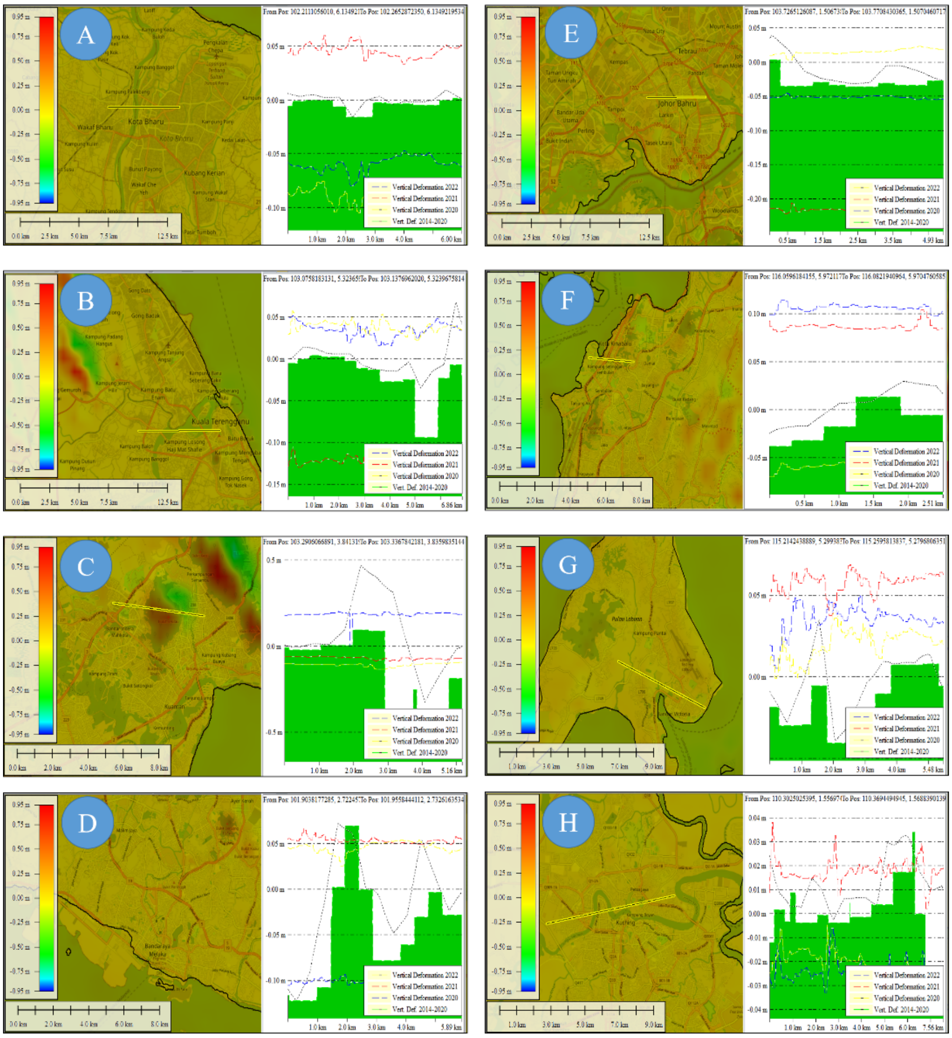

Figure 4: Time-Series Vertical Deformation in Malacca, East Coast of Peninsular Malaysia, East Malaysia (2014-2022). A. Kota Bahru; B. Kuala Terengganu; C. Kuantan; D. Malacca; E. Johor Bahru; F. Kinabalu; G. Bandar Labuan (Victoria); H. Kuching

Johor Bahru is the capital of the state of Johor. Johor Bahru is located on the southern side of Peninsular Malaysia and borders Singapore. Johor Bahru has a high population, making it the second-largest city in Malaysia. This high population number causes the demand for water to be high. Consumption of groundwater is one way to fulfil its needs. Johor Bahru is an area with high land subsidence potential. The city experienced a land subsidence of -4.0 cm in 2014-2020, see Figure 4(E). In 2020, Johor Bahru will also experience subsidence of -5.0 cm. The increase in the potential for land subsidence also impacts other disasters such as major floods, which stagnant water for a long time. This major flood comes from the upstream area and tidal floods at the highest tide. In 2021, a high potential for land subsidence was detected in this region. Some areas reach -21.0 cm. The significant subsidence value was caused by landslides, soil eroded by flood waters, excessive groundwater, drastic changes in topography, or drastic changes in aquifer networks. There were major floods in Johor in 2021. Many factors are causing land subsidence in 2021. In 2022, the Johor Bahru area will be dominated by uplifts. It was caused by a lot of sedimentation and major floods that exceeded 2021. Even though land subsidence will still occur in 2022, the uplift value has become more dominant this year. The uplift value in 2022 is +1.5 cm. Johor Bahru is dominated by land subsidence of -24.5 cm in 2020-2022.

(3) East Malaysia

East Malaysia include Kinabalu, Bandar Labuan (Victoria), and Kuching. Kinabalu is the capital of the state of Sabah. It is located on Borneo Island and the northern coast of East Malaysia. Kinabalu is a coastal area prone to major and tidal floods. Kinabalu is located on soft soil and is prone to potential land subsidence. In 2014-2020, Kinabalu experienced a land subsidence of -3.0 cm, see Figure 4(F). Then 2020, there will also be a subsidence of -5.5 cm. Subsidence will also occur in 2021 and 2022, but uplift will dominate Kinabalu. Significant floods, high sedimentation, and high erosion upstream caused the dominant uplift condition. The major flood in 2021 led to an uplift dominance of +8.0 cm. Likewise, the major floods in 2022 led to an uplift dominance of +10.5 cm. Overall, Kinabalu experienced an uplift of +13.0 cm. The potential for significant floods and sedimentation in the coming years can cause a high uplift, causing the addition of new land on the coast of Kinabalu. Land subsidence will continue, especially in peat areas, swamps, and densely populated settlements.

Bandar Labuan (Victoria) is the capital of the Labuan federal region. It is located adjacent to Kinabalu. Bandar Labuan (Victoria) experienced land subsidence in 2014-2020 with a value of -1.5 cm, see Figure 4(G). However, in 2020-2022, uplift will be more dominant than land subsidence. The increase in uplift value can be caused by sedimentation coming from upstream and accretion from ocean currents that carry mineral sediments. In 2020, the uplift value at

Bandar Labuan (Victoria) was +2.0 cm. In 2021, there will be an additional uplift value of +6.0 cm. In 2023, the uplift value at Bandar Labuan (Victoria) is +3.5 cm, while in 2020-2022, the uplift was +11.3 cm.

Kuching is the capital of the state of Sarawak. It is located on the northern coast of East Malaysia and Borneo Island. Kuching is a lowland city located on the river banks. The soil in Kuching is also classified as soft, unstable, and dominated by peat and swamps. Kuching is an area that has the potential for land subsidence, see Figure 4(H). In 2014-2020, the subsidence value is -0.5 cm. Likewise, in 2020, there has been a subsidence of -2.0 cm. In 2021, uplift is more dominant in Kuching compared to land subsidence. The uplift value is +2.0 cm. One of the causes of the uplift in 2021 is that significant floods will bring lots of minerals and sedimentation. Land subsidence in Kuching is caused more by natural factors and anthropogenic activities. These natural factors are the dynamics of peat and swamp lands. The change in land cover is in the form of forests converted to oil palm plantations so that water absorption becomes less in the upstream part. Land subsidence in 2022 is more dominant in Kuching, with a value of -2.5 cm. It is caused by the dynamics of peat and swamp lands in Kuching, which are more dominant than sedimentation and soil erosion. Kuching is dominated by land subsidence in 2020-2022 with a value of -2.5 cm.

Land Subsidence Dynamics in 16 Cities in Malaysia

The vertical deformation results of the 16 cities have been tested using height different tests. We use 25 height points to create the polygon test in all study areas. All vertical deformation has no blunder error, no systematic error, and minimum random error (less than 1.96σ in a confidence level of 95 %). The result of the height difference test is ~ 0 m. It means that all vertical deformation results are in the same height reference plane and have high precise relative vertical accuracy. Based on the 2014-2022 vertical deformation analysis results, which cities are more vulnerable to land subsidence can be seen, see Table 1. The city most vulnerable to potential land subsidence is Johor Bahru. Then followed by Kuala Terengganu, Seremban, Kuala Lumpur, Shah Alam, Malacca, and Kuantan. The city that has the lowest risk of land subsidence is Kangar. Cities that have a high risk of uplift are Kinabalu and Bandar Labuan (Victoria).

Kota Bahru, George Town and Butterworth, Alor Setar, Ipoh, Putra Jaya, and Kuching are cities with moderate levels of land subsidence and uplift vulnerability. The results of this study can be used for further study of urban planning that is safe from the threat of land subsidence, especially in Johor Bahru, Kuala Terengganu, Seremban, Kuala Lumpur, Shah Alam, Malacca, and Kuantan. Overall, Malaysia's value rate of land subsidence is -0.5 cm to -6.0 cm. The uplift value rate in Malaysia is in the range of +0.5 cm to +4.5 cm. According to research (Yong et al., 2018), the northern Kelantan subsides at a maximum rate of 4.22 ± 0.17 mm/year (1σ confidence level). It shows higher ground deformation rates than the other parts of Peninsular Malaysia (0.22 ppm/year). This condition is similar to the results from the D-InSAR that the Kota Bahru area has experienced subsidence of -3.2 cm in 2020-2022. Although the study location in Kelantan is slightly different, it still has similarities in regional tectonic movements.

Table 1: The Vertical Deformation in 16 Cities of Malaysia during 2014-2022

No	City Name	Mean of Vertical Deformation 2022 (cm)	Mean of Vertical Deformation 2021 (cm)	Mean of Vertical Deformation 2020 (cm)	Mean of Vertical Deformation 2014-2020 (cm)
1.	Kota Bahru	-6.0	+5.0	-8.5	-1.0
2.	Kuala Terengganu	+4.0	-12.0	+4.5	-3.0
3.	George Town and Butterworth	-13.0	+5.5	+2.0	-2.0
4.	Alor Setar	-7.0	+3.0	+3.5	-0.5
5.	Kangar	-9.0	-0.5	+10.0	-0.5
6.	Ipoh	-1.0	+22.0	+21.0	-0.5
7.	Seremban	+5.0	+5.0	-10.0	-5.0
8.	Malacca	+4.5	+5.0	-10.0	-5.0
9.	Kuala Lumpur	+5.0	+5.5	-10.0	-5.0
10.	Putra Jaya	+3.0	+7.0	-10.0	+2.0
11.	Shah Alam	+5.0	+5.5	-11.0	-3.5
12.	Kuantan	+2.0	-0.5	-1.0	-4.0
13.	Johor Bahru	+1.5	-21.0	-5.0	-4.0
14.	Kinabalu	+10.5	+8.0	-5.5	-3.0
15.	Bandar Labuan (Victoria)	+3.5	+6.0	+2.0	-1.5
16.	Kuching	-2.5	+2.0	-2.0	-0.5

Value (+) = uplift; value (-) = land subsidence

Research by Gao et al., 2021 concluded that Pulau Pinang experienced an indication of land subsidence that would increase 2.0% and 5.9% of the inundated area based on the different scenarios by 2100 projections. In this study, George Town and Butterworth experienced land subsidence of -5.5 cm in 2020-2022. Land subsidence in this city has increased compared to the 2014-2020 period. One way to minimise land subsidence is by regulating groundwater use, building balanced infrastructure, minimising tunnels, mining and plantations, and monitoring groundwater aquifer networks. Regional and urban development needs to apply disaster mitigation-based planning such as land subsidence, sedimentation, land erosion, abrasion, and coastal accretion. The D-InSAR method on Sentinel-1 (free data) can be used widely (area), efficiently (mapping costs), and effectively (work time) to monitor large areas and time series.

CONCLUSION

The land subsidence dynamics of 16 cities in Malaysia were monitored by collecting time-series vertical deformation data between 2014-2022. We use Sentinel-1 imagery data and a modified D-InSAR method for extracting the vertical deformation. The results of the vertical deformation analysis 2014-2022 were used to identify the cities that were most vulnerable to land subsidence and uplift. The city that has the lowest risk of land subsidence is Kangar, while the city most vulnerable to potential land subsidence is Johor Bahru. The other cities vulnerable to land subsidence are Kuala Terengganu, Seremban, Kuala Lumpur, Shah Alam, Malacca, and Kuantan. Kota Bahru, George Town and Butterworth, Alor Setar, Ipoh, Putra Jaya, and Kuching are cities with moderate levels of land subsidence and uplift vulnerability. The cities that are vulnerable to uplift are Kinabalu and Bandar Labuan (Victoria). Malaysia's value rate of land subsidence is between -0.5 cm to -6.0 cm, while the uplift value rate in Malaysia is between +0.5 cm to +4.5 cm.

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