Morphotectonic Evaluation and Land Surface Deformation Changes in the Western Segment of the Lembang Fault

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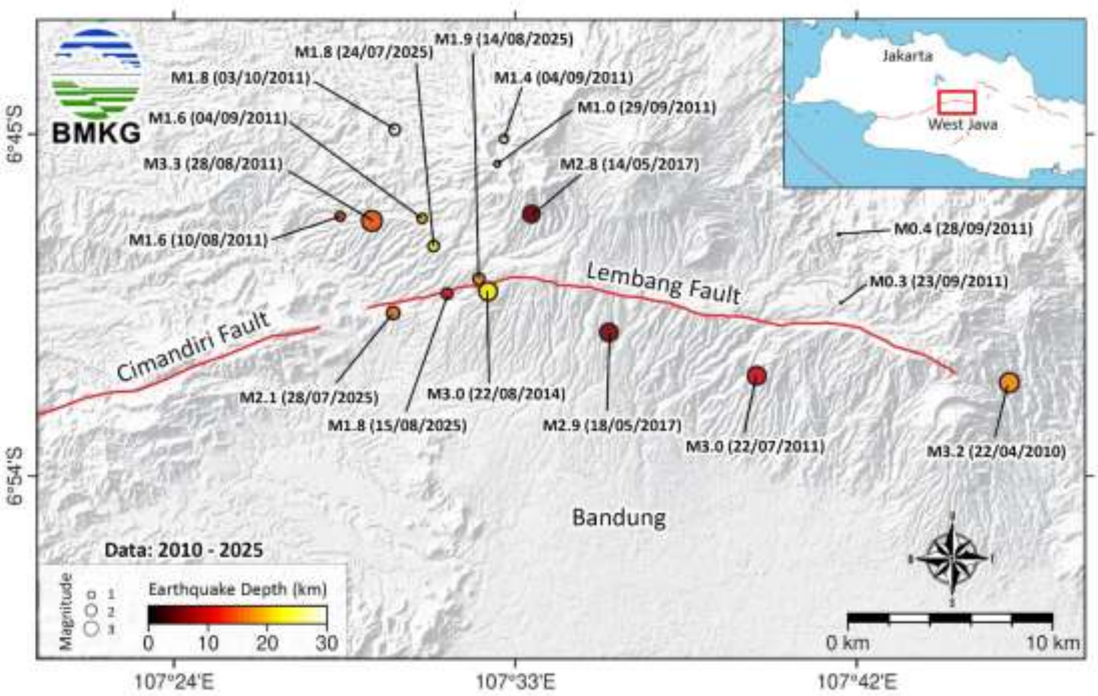
Abstract The Lembang Fault in West Java is an active horizontal fault that can cause surface deformation, especially in the western segment of the Cisarua region. The lack of information to the public increases the risk of casualties, so mitigation is needed through deformation monitoring. This study aims to detect and analyze deformation in Cisarua District using active remote sensing technology, specifically DinSAR based on Sentinel-1 imagery (2017 and 2025). Data is processed through pre-processing, filtering, and correction stages, followed by deformation analysis (phase conversion, pattern mapping, classification). The results are used to link deformation with fault activity, identify potential geological hazards, and analyze deformation dynamics temporally. The results show that land deformation in the Western Segment of the Lembang Fault for the period 2017-2025 shows active dynamics with varying uplift and subsidence patterns, where 2017 is characterized by contrasting deformation and 2025 is dominated by broad uplift. DInSAR technology has proven effective in detecting millimeter-scale displacements and mapping the spatial distribution of deformation that is closely correlated with earthquake events. The spatial and temporal patterns in Cisarua District confirm that this area is experiencing dynamic deformation and has a high level of geological vulnerability, thus requiring continuous monitoring.

Keywords: Deformation, Lembang Fault, Remote Sensing, Sentinel-1a, DInSAR

Introduction

The Lembang Fault is a geological phenomenon that has important urgency in the North Bandung area, this fault is located on the slopes of the active Tangkubanparahu volcano which is a clear geomorphological expression of neotectonics in the north of the Bandung basin (Brahmantyo, 2011). This fault is known as one of the active faults in West Java with horizontal movement (strike-slip) which can cause surface deformation, such as cracks or land subsidence (Meilano, et al., 2012). The Lembang Fault stretches from east to west, where the eastern part has experienced more visible subsidence compared to the western part (Firdaus , Setyawan , & Yusuf, 2016) (Daryono M. R., Natawidjaja, Sapiie, & Cummins, 2018) (Tjia, 1968). Fault movement can occur as long as the fault is active. The sudden release of energy along the fault line is called an earthquake. The Lembang fault experienced movement of 22 to 29 km from 2009 to 2015, increasing the risk of disaster (Rumadan & Darwin, 2016) (Aji, Prasetyo, &

Awaluddin, 2018). The Lembang Fault has experienced increased movement in the last ten years, namely in 2017 with a magnitude of 2.8 and 2.9 (Ferdian, 2021). In addition, BMKG recorded an increase in seismic activity in the Cimeta segment, BMKG indicated that earthquakes around the Lembang Fault in 2025 would be of small magnitude, ranging from M 1.7 to M 2.3 (Warsudi, 2025). Predictions for the strength of the earthquake caused by the Lembang Fault are that the largest magnitude could reach 6.5 to 7 if all segments move.(Widodo, Hepta, & Fairuz, 2017).



Source: Dr. Pepen S (2025).

Figure 1. Map of the distribution of earthquake epicenters in the Lembang Fault area, showing an increase in the western segment in the last 10 years.

The presence of sagponds in the Cimeta segment indicates an active fault zone, featuring a basin-like shape filled with loose material, sediment, and water. This morphology also serves as an accumulation area for landslide material and produces surface deformation. One such morphology is observed in the Muril village area, which is also traversed by the Lembang Fault (Aliyan, Pamungkas, Susanto, & Ayesha, 2023) (Aliyan, et al., 2025). The Cimeta segment of the Lembang Fault is part of an active fault dominated by pyroclastic breccia, lava, and tuff rocks, reflecting volcanic activity associated with the fault. Structurally, the Cimeta segment exhibits normal faulting with block uplift in the south and block subsidence in the north, forming a landscape of hills and valleys typical of tectonic activity (Daryono M. , Natawidjaja, Sapiie, & Cummins, 2019). This fault has the potential for earthquakes with magnitudes up to 7, making it an important focus for geological studies and disaster risk mitigation in the

Bandung area. This research was conducted to analyze morphotectonic features and deformation using remote sensing methods to examine geological phenomena related to the activity of the Lembang fault.

Literature Review

a. Geological Setting

The research area is included in part of the Bandung Regional Geological Map (Silitonga, 1973). This area is dominated by Quaternary-aged materials which are the result of young volcanic deposits in the form of pyroclastic materials and lava flows. The following is an explanation of several formations that make up the research area from younger to older units, including; Young volcanic products (Qyd), namely sand tuff; Young volcanic products (Qyt), namely pumice tuff; Old volcanic products (Qvu), namely undecomposed volcanic rocks; Old volcanic products (Qob), namely older volcanic products (volcanic materials). Muril Village is located on a geological map sheet composed of young volcanic products consisting of sand tuff material (Qyd).

Regionally, the research location is in the Cimeta section, part of the Lembang Fault which is one of the main faults in West Java which has sinistral-lateral strike-slip characteristics, based on its interpretation of the main order offset (Tjia, 1968) (PUSGEN, 2017). The Lembang Fault has a length of 29 km and can produce a dominant sinistral Mw of 6.5-7.0 with a shear rate of 1.95 – 3.45 mm/year (Daryono M. , Natawidjaja, Sapiie, & Cummins, 2019). Based on the geodetic study of Meilano et al. (2012). The estimated shear rate of the Lembang Fault is 6 mm/year. Seismologically, the Lembang Fault is still active and produces earthquakes, although they are of small magnitude. The earthquakes are concentrated at the fault's extremities, both at the western and eastern ends (Rasmid, 2014). Earthquake vibrations can also trigger landslides, rock falls, ground movements, and destructive landslides.

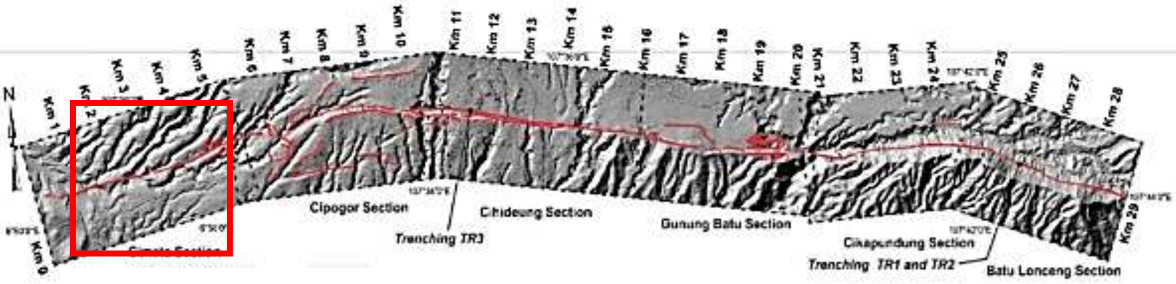


Figure 2. Map showing the traces of active faults and the general morphology of the Lembang Fault. (Daryono M. R., Natawidjaja, Sapiie, & Cummins, 2018). The research location, which is part of the western segment of the Lembang fault, is indicated by the area boundary (red).

b. Morphotectonic

Morphotectonic and morphometric analysis is part of quantitative geomorphological studies that utilize various geomorphic indices to reveal the processes of landform formation and evolution. Morphotectonics emphasizes the relationship between geological structures and geomorphological aspects, thus providing an indication of tectonic activity that influences the shape of the Earth's surface. In this study, a morphotectonic approach was applied with reference to the method proposed by (Edward & Nicholas , 2002) (Jannah, Pamumpuni, & Sadisun, 2024) (Asfar, et al., 2022).

c. *Differential Interferometric SAR* (DInSAR)

Differential InSAR (DISAR) is a radar imaging method that utilizes the phase difference between two or more SAR images taken at different times. This method is used to analyze surface topography and deformation. If a reference surface topography model is available or three or more radar images are available, surface changes can be identified using differential InSAR. (Al Akbar, Prasetyo, & Wijaya, 2015; Al Akbar, Prasetyo, & Wijaya, 2015). The phase information contained in the interferogram from the results of 2 SAR observations at different times contains elements of topography, orbital shift, surface deformation, and atmospheric effects (Castaneda, Pourthie, & Souyris , 2011). The phase difference value can be formulated using the following equation:

$$\Delta\theta = 4\pi\delta R/\lambda \quad (1)$$

$$\Delta\theta = \Delta\theta topo + \Delta\theta defo + \Delta\theta atm + \Delta\theta orb \quad (2)$$

In radar interferometry analysis, $\Delta\theta$ represents the measured phase difference between two radar images and is influenced by the wavelength λ of the Sentinel-1 satellite and the distance from the sensor to the object, denoted by R**.** The total phase of observation is a combination of several components, namely θtopo which comes from topography or surface elevation, θdefo which reflects surface deformation such as tectonic movement or land subsidence, θatm which is influenced by atmospheric conditions such as humidity and air pressure, and θorb which is caused by inaccuracies or changes in the satellite orbit position. Understanding all these variables allows the separation of the effects of topography, deformation, atmosphere, and orbit so that surface deformation estimates can be obtained more accurately. Analysis with the DInSAR method is carried out to observe ground movement or ground deformation using the repeat-pass interferometry technique. The difference from this Phase interferometry contains some information from the topographic profile, orbital trajectory, deformation, atmosphere, and phase noise. So this DInSAR method is used to minimize noise and eliminate the influence of topography and atmosphere. (Hanssen, 2001).

Methodology

a. Research Location

The research location is in the Cimeta Sub-Das which is located in the western segment of the Lembang Fault, precisely in part of the administrative area of Cisarua, Ngamprah, Cikalongwetan and Padalarang districts. Geographically, it is located at 107o 26’6.5"E - 107o 34’48"E and 6o 45’40"S - 6o 49’55"S, with an area of ±79 Km2. The location of this research is shown in Figure 1.

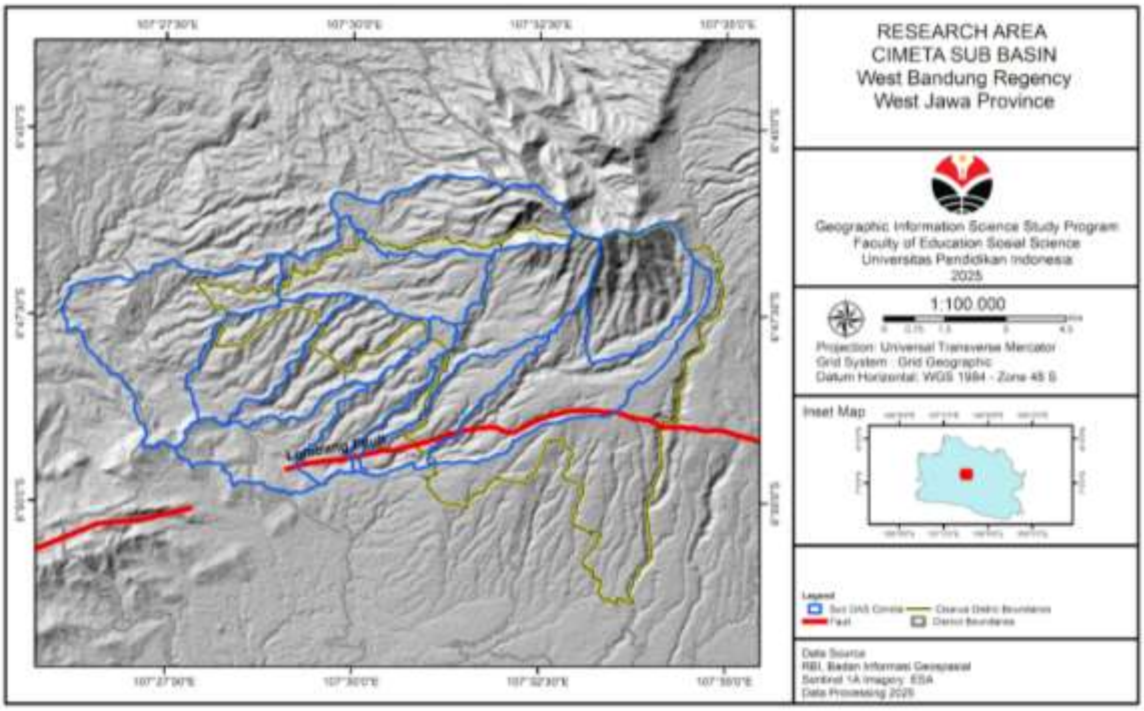


Figure 3. Research Area

b. Research Method

This study uses Sentinel-1 radar imagery data as the primary source for deformation analysis, a digital elevation model (DEM) for topographic correction, and morphometric extraction. The next stage includes data processing and core analysis. Radar interferometry (InSAR) processing involves preparing Sentinel-1 image pairs, performing co-registration, interferogram generation, topographic phase removal, and atmospheric and orbital corrections to produce a map of surface deformation and movement rates in millimeters per year.

Table 1. Sentinel-1 satellite imagery used

Image Data	Acquisition Time
S1_210449_IW2_20170505T111445_VV_19DD-BURST	5 May 2017

S1_210450_IW2_20170517T111449_VV_6EA6-BURST	17 May 2017
S1_210448_IW3_20250429T111517_VV_A01B-BURST	29 April 2025
S1_210449_IW2_20250511T111519_VV_8526-BURST	05 May 2025

In parallel, DEM-based morphotectonic analysis was carried out using three main parameters, namely Basin Form Index (Bs), Drainage Density (Dd), and Mountain Front Sinuosity (Smf). (Nugraha, Almira, Sukiyah, Helmi, & Fahira, 2023) untuk menilai tingkat pengaruh tektonik terhadap morfologi wilayah kajian. The classification criteria for each parameter are as follows:

Table 2. Classification of Values for Parameter Bs.

Class	Bs Range	Basin Shape Index (Bs)
Class 1	> 4	High Tectonic
Class 2	4-3	Moderate Tectonic
Class 3	< 3	Low Tectonic

Source: (El Hamdouni, Irigaray, Fernandez, Chacón, & Keller, 2008)

Table 3. Classification of Values for Parameter Dd.

Class	Dd Range	Drainage Density (Dd)
Class 1	5.5 - 8.2	High Tectonic
Class 2	4.14 - 5.5	Moderate Tectonic
Class 3	< 4.14	Low Tectonic

Source: (Pristiwantoro, Widiarso, Moechtar, & Cita, 2025)

Table 3. Classification of Values for Parameter Smf.

Class	Smf Range	Mountain Front Sinuosity (Smf)
Class 1	< 1.1	High Tectonic
Class 2	1.1 - 1.5	Moderate Tectonic
Class 3	> 1.5	Low Tectonic

Source: (El Hamdouni, Irigaray, Fernandez, Chacón, & Keller, 2008)

Based on research conducted by (Pristiwantoro, Widiarso, Moechtar, & Cita, 2025) shows that the averaged class values of the three parameters Bs, Dd, and Smf are used to obtain the Relative Tectonic Activity Index (IATR). IATR is calculated using the formula: IATR = (Bs value + Dd value + Smf value) / number of parameters used. The resulting IATR values are then categorized into four classes based on the level of tectonic activity as follows:

Table 4. Classification of Values for Index of Relative Tectonic Activity (IATR)

Class	IATR Range	Index of Relative Tectonic Activity (IATR).
Class 1	1.0 – 1.5	Very High Tectonic Activity
Class 2	1.5 – 2.0	High Tectonic Activity
Class 3	2.0 – 2.5	Moderate Tectonic Activity
Class 4	> 2.5	Low Tectonic Activity

Source: (Pristiwantoro, Widiarso, Moechtar, & Cita, 2025)

The InSAR processing results were then integrated with morphotectonic index maps to assess the relationship between deformation patterns and geomorphological features controlled by fault activity. Deformation data were then verified using field observations. The study area was then classified based on its level of tectonic activity using the Relative Tectonic Activity Index (IATR) scheme, which divides areas into very high, high, medium, and low classes. The final results include an integrated deformation and morphotectonic map, statistical tables for each parameter, and recommendations for follow-up monitoring of the Lembang Fault activity.

Results and Discussion

a. Morphotectonic Analysis

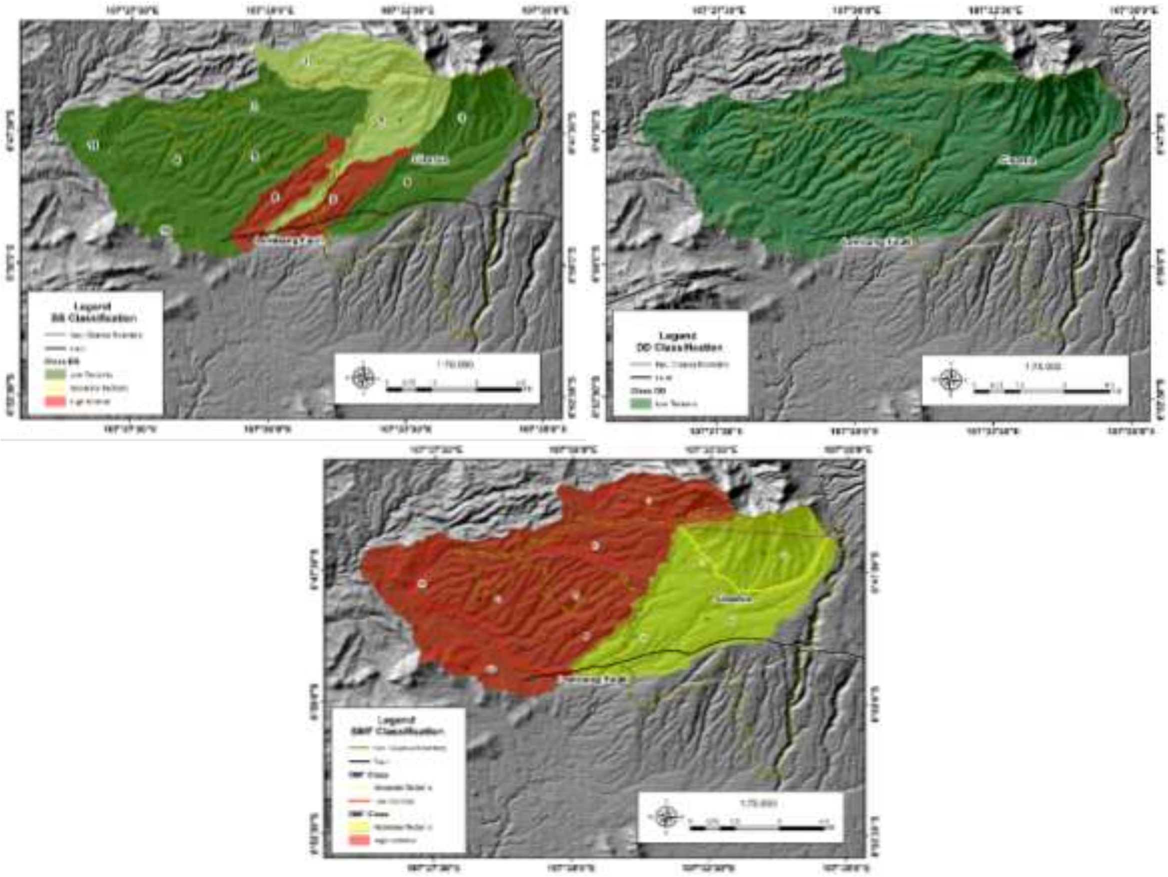


Figure 2: View of three maps of active tectonic parameters (Basin Shape (Bs), Drainage Density (Dd), and Sinuosity Mountain Front (Smf)) in the Cimeta Sub-DAS.

1. Basin Shape Index (Bs)

The basin shape index value can reflect tectonic activity. Elongated watershed/sub-basin geometric shapes are generally associated with high tectonic activity, while circular watershed/sub-basin shapes are generally associated with low levels of tectonic activity. The results of the basin shape index calculation can then be classified into high, medium, and low tectonic activity levels.(Hidayat, Muslim, Zakaria, Permana, & Wibowo, 2021). From the data processing (Figure 2), it was obtained: two sub-watersheds that are categorized as high tectonic class, namely in the southern sub-watershed (numbers 8 and 9), two sub-watersheds that are categorized as medium tectonic class, namely in the northern sub-watershed (numbers 1 and 7) and other sub-watersheds that are included in the low tectonic category.

2. Drainage density (Dd)

The Dd value can describe the density of each river segment within a watershed/sub-watershed. The Dd value can reflect geological conditions, climate parameters, geomorphology, vegetation, and the strength of rocks and soil against erosion acting in the area (Tawil, Baldan, Botjing, & Djainal, 2023). From the results of processing the Dd value data in the research area, all sub-watersheds are categorized as areas with a low tectonic activity class (Figure 2).

3. Sinuosity Mountain Front (Smf)

The Smf value is a geomorphic index parameter that can reflect the balance between erosion forces and which tends to cut along the curve of the mountain surface and tectonic forces/strengths that directly produce mountain faces and produce irregularities (sinusities) in the mountain face that coincide with active fault zones (active tectonics) vertically so that they produce a straight mountain face shape (Hidayat, Muslim, Zakaria, Permana, & Wibowo, 2021). Classification of Smf values can be classified with high, medium and low tectonic activity values. The findings in the research area are divided into two values; medium tectonic activity in the eastern part and high tectonic activity in the western part of the Cimeta sub-DAS.

4. Index of Relative Tectonic Activity (IATR)

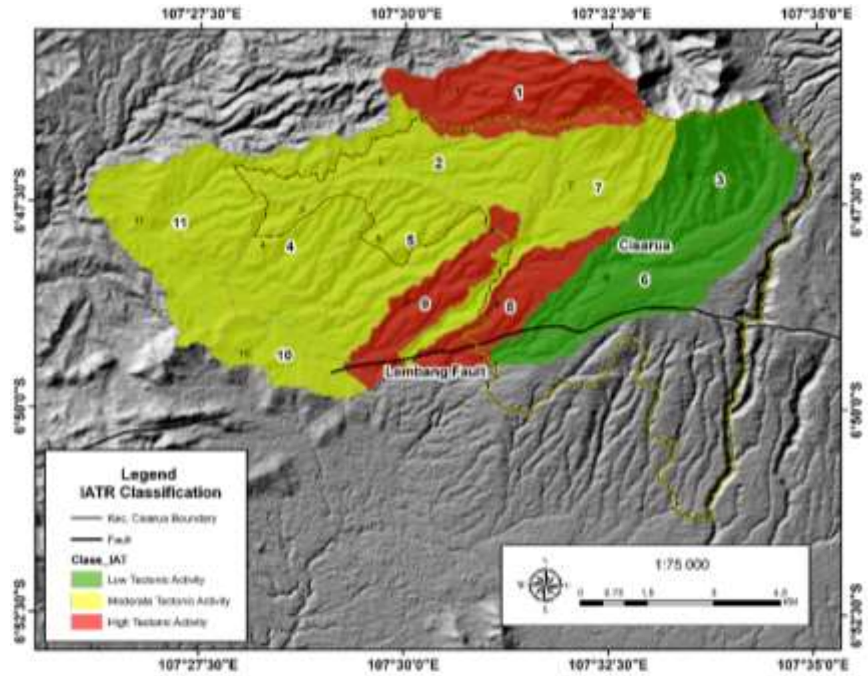


Figure 3: Index of Relative Tectonic Activity (IATR) map in in the Cimeta Sub-DAS.

Based on the results of the IATR value processing displayed in Figure 3, there are 2 sub-watersheds that are included in the low tectonic activity class, namely sub-watersheds number 3 and 6, then there are 6 sub-watersheds that are included in the middle class including sub-watersheds number 2, 4, 5, 7, 10, and 11, while the other 3 sub-watersheds are included in the high class including sub-watersheds number 1, 8, and 9.

b. Surface Deformation Value of the West Segment Area of the Lembang Fault

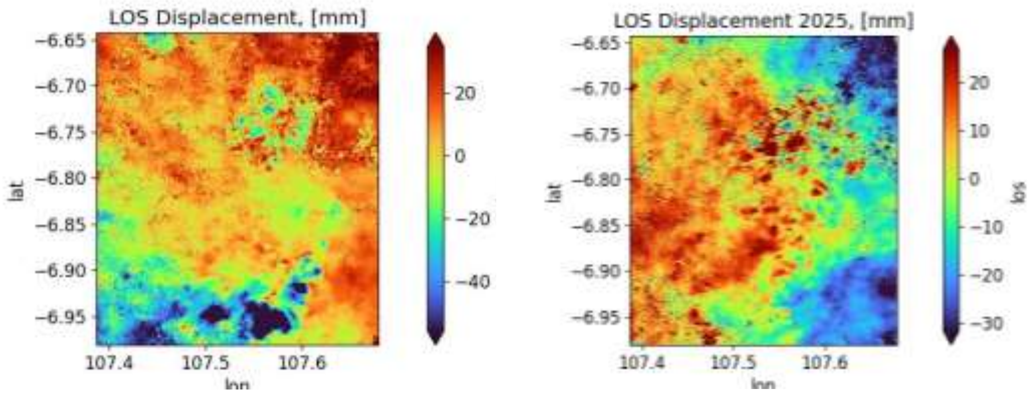


Figure 4. LOS Displacement in 2017 and 2025.

In 2017, LOS displacement results showed deformation variations ranging from uplift > +20 mm to subsidence < –40 mm. Red-brown colors dominated the north-east (uplift), while dark blue dominated the south-southwest (subsidence). This demonstrates a sharp contrast in deformation, with extreme deformation distributed across two distinct zones. Meanwhile, in 2025, the deformation range remained significant, ranging from uplift > +20 mm to subsidence < –30 mm. However, uplift appeared more widespread and evenly distributed in the west-central part of the region, while subsidence tended to be concentrated in the east-southeast. This pattern indicates that uplift was becoming increasingly dominant, while subsidence was concentrated in a few specific pockets.

The 2017 deformation exhibited a strong north-south gradient, with uplift in the north and subsidence in the south. A green-yellow transition zone is clearly visible in the center, indicating the location of an active fault line. This pattern demonstrates sharp differences in block movement, making the area around the fault highly dynamic. The year 2025 showed a different pattern: uplift was more evenly distributed in the west-central region, while strong subsidence occurred only in the east-southeast. A transition zone was visible in the central-eastern region, indicating a more concentrated distribution of deformation to one side. This pattern suggests that fault activity tends to be concentrated in a specific area compared to the broader distribution in 2017.

In 2017, several significant earthquakes were recorded along the Lembang Fault. For example, the M2.9 (May 18, 2017) and M2.8 (May 14, 2017) earthquakes were located along the western segment of the fault. The presence of these earthquakes aligns with the contrasting deformation pattern of 2017, where the sharp uplift-subsidence difference reflects the accumulation and release of tectonic energy. The extreme LOS displacement pattern reinforces the indication of active tectonic activity during that period. Based on LOS data, mapping results and BMKG earthquake data (2025 land subsidence, LOS displacement, and 2017 BMKG earthquake) confirm that the Cisarua area and its surroundings are a critical deformation zone.

c. Morphotectonic and Deformation relate to the West Segment Area of the Lembang Fault

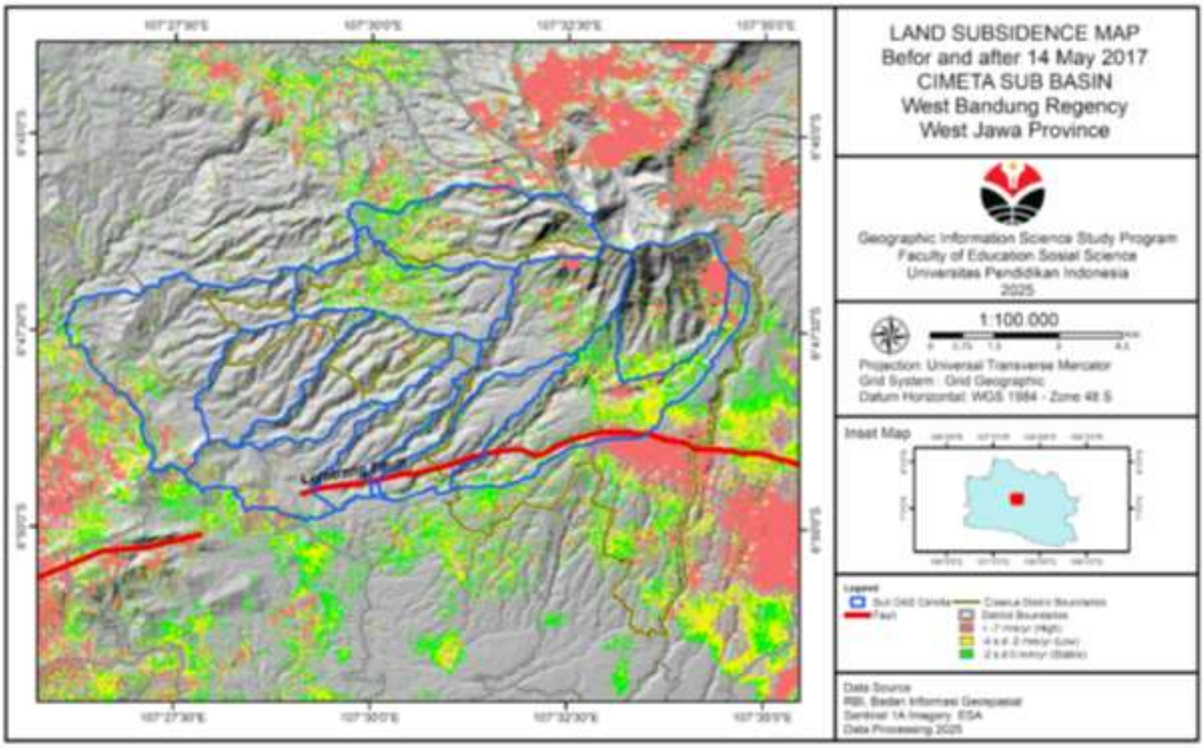


Figure 5. Land subsidence map of Cimeta Sub-DAS in 2017.

The 2017 land subsidence map of the Cimeta Sub-watershed shows a high concentration of subsidence (red, > 7 mm/year), especially in the eastern region around Cisarua District and parts of Parongpong. Furthermore, moderate subsidence (orange, -7 to -4 mm/year) is spread across the central to western parts, while stable areas (green) dominate most of the region. This pattern aligns with the 2017 LOS displacement results, where contrasting deformation occurred with significant uplift in the northeast and substantial subsidence in the southwest.

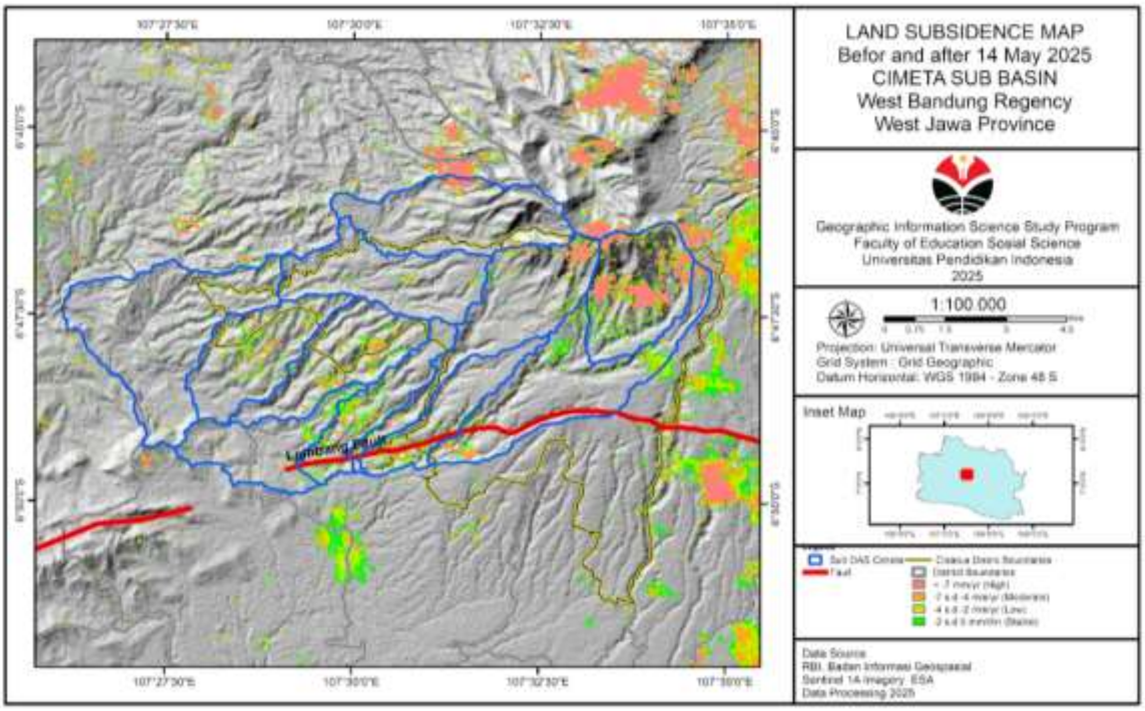


Figure 6. Land subsidence map of Cimeta Sub-DAS in 2025.

Based on the 2025 map, pockets of land subsidence (red-orange, >4 to <-7 mm/year) are concentrated in the east-northeast of the Cimeta Sub-watershed—around Cisarua to the Parongpong border—while most of the west-central region remains relatively stable (green). This pattern aligns with the 2025 LOS map: dominant and extensive uplift occurs in the west-central region (>+20 mm), while strong subsidence is concentrated in the east-southeast (<-30 mm). This spatial consistency indicates that the eastern area is a zone of deformation tending towards the west-central region while recurring, active, and more evenly distributed surface rise.

Conclusion and Recommendation

Morphotectonic analysis shows that the Cimeta Sub-watershed exhibits varying levels of tectonic activity. Basin Shape, Drainage Density, and Sinuosity Mountain Front values indicate high tectonic activity in the south and west, while others are moderate to low. The IATR results also confirm three high-activity sub-watersheds, six moderate-activity sub-watersheds, and two low-activity sub-watersheds, demonstrating the heterogeneity of tectonic dynamics in this region. Surface deformation data based on LOS displacement for 2017 and 2025 show significant shifts in the form of uplift and subsidence. In 2017, a north-south gradient pattern was clearly visible, with sharp differences in block movement. In 2025, uplift became increasingly dominant in the west-central region, and subsidence was concentrated in the east-southeast. This indicates a concentration of tectonic activity that is increasingly concentrated in certain areas. The 2017 and 2025 subsidence maps reinforce these findings, with the Cisarua to Parongpong area being a critical zone experiencing repeated subsidence, while the west-central part remains relatively stable. Consistent deformation patterns and seismic activity indicate that the western segment of the Lembang Fault remains active and poses a potential geological hazard. Therefore, the northeastern Cimeta Sub-watershed is a priority area for disaster mitigation based on geospatial monitoring and spatial planning.

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