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Landslide Area Mapping in Dampit Subdistrict, Malang District, East Java Province Using Satellite Imagery of Gravity Data for Disaster Mitigation

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Abstract

Research using satellite imagery of gravity data has been conducted in the Dampit District, Malang Regency, East Java Province. This research was conducted to identify areas vulnerable to landslides. The results of this research can serve as a basis for the government to develop effective landslide disaster mitigation policies, thereby minimizing the losses incurred. The data used is TOPEX satellite gravity data in the form of Free Air Correction data, and supported by landslide vulnerable areas data from the InaRisk satellite. The research area is 23 km x 16 km with 2 km spacing between points and 184 measurement points. Furthermore, the research area is divided into four areas: Area A1, Area A2, Area A3, and Area A4. The residual anomaly value in the study area is between -13.6 mGal to 7.3 mGal. The residual anomalies are more variable due to the local nature of the anomalies. The correlation between the residual anomaly value and InaRisk satellite image data shows that Area A4 is the most vulnerable to landslides, especially if there is a trigger such as an earthquake. This is because Area A4 has a low-density value, a large fault, and is the contact area between the Mandalika Formation and Wuni Formation.

Introduction

Natural disasters are caused by natural and human activities that can cause major damage to the environment and infrastructure [1]. Natural disasters in Indonesia often occur due to the meeting of 3 tectonic plates: the Indo-Pacific plate, the Indo-Australian plate, and the Eurasian plate [2]. This has resulted in natural disasters such as volcanoes, tsunamis, floods, and landslides. One area that often experiences landslides is East Java Province, precisely in Malang Regency. Based on the Indonesian Disaster Risk Index in 2023, Malang Regency is ranked 7th in East Java with 132 landslides in one year [3]. Landslides in this area are caused by slope instability [4]. Malang Regency has varying slopes of hills and valleys, creating ideal locations for landslides to occur [5]. Specifically, the area where landslides often occur in Malang Regency is Dampit Subdistrict.

Landslides in the Dampit Subdistrict are very detrimental to the community because they have a considerable social impact, such as damage to road infrastructure, bridges, houses, and fatalities. [6]. The Malang District Government has made various mitigation efforts, such as concrete installation, cliff strengthening, and research using the resistivity method [7]. The wide coverage area is one of the inhibiting factors in mitigation distribution, therefore, this research was conducted to know the areas with the highest landslide vulnerability level based on the distribution of rock density. Factors of landslide occurrence in this area vary from high rainfall, slope, faults, and a soft soil type [8]. The principle of landslides occurs when the retaining force is smaller than the driving force, resulting in soil movement in the direction of gravity [9]. Generally, the strength of the retaining force of a soil layer in a landslide area is influenced by several things, such as the density of the layer [10], Slope [11], Rainfall [12], and the type of vegetation [13].

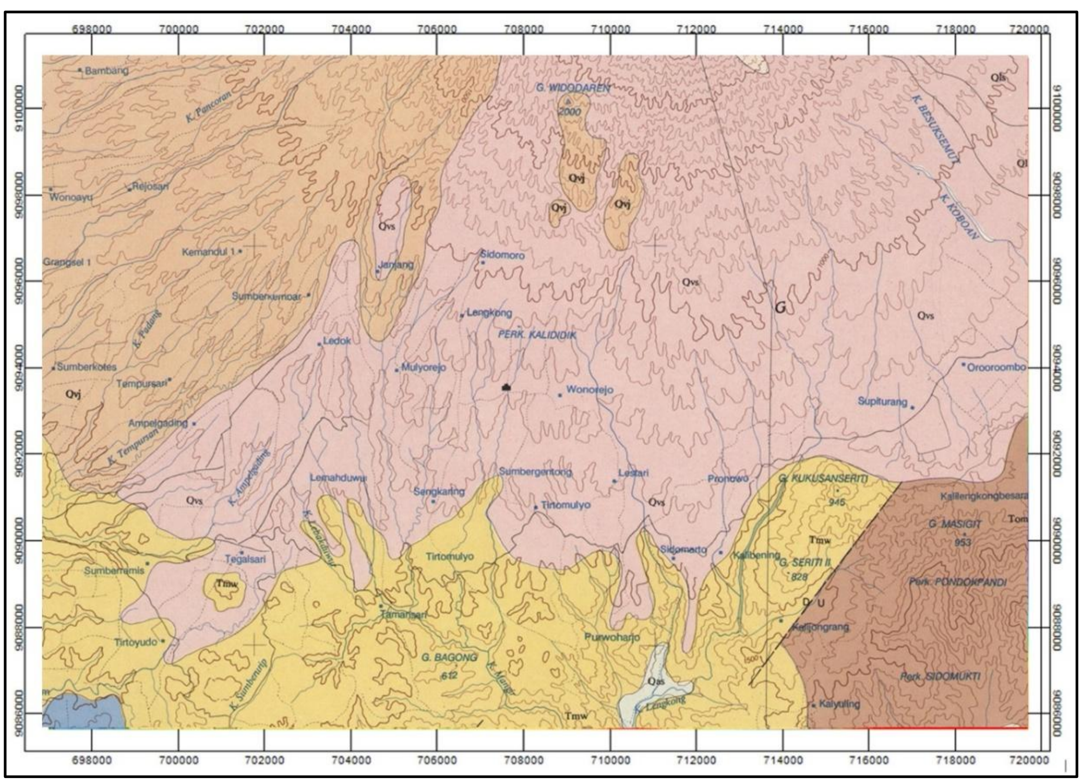
Rock density is one of the geological parameters that cause landslides [14]. Rock density describes the density of the rock. Rock density is measured in kilograms per cubic meter (kg/m^3) or grams per cubic centimeter (g/cm^3) [15]. Rocks with high porosity have low density compared to rocks with low porosity, indicating that porosity and density are inversely proportional. An area dominated by low-density and high-porosity rock layers such as tuff, sand, and pumice has the highest landslide vulnerability. Landslides, besides occurring due to low density, can also occur due to other factors such as slope and rainfall [16]. Variations in rock density value can provide information about geological structures, faults, and rock types [17]. The variation of rock density in an area can be measured by the gravity method [17] [18]. The gravity method has some drawbacks, such as high ambiguity due to differences in altitude and the Earth's atmosphere, but this can be minimized by corrections that aim to eliminate other effects. The advantages of the gravity method are that it covers a large area, matches density distribution mapping, and is low-cost.

Previous research using the gravity method in Batu City [19] showed that the distribution of gravity anomalies can be used as a reference in determining landslide-prone areas. This is due to the low densities scattered in the region [19]. Another research using the resistivity geoelectric method with dipole-dipole configuration [20] in Srimulyo, Dampit Subdistrict, Malang District, and research using Microtremor [21] showed that the Dampit area, especially Srimulyo Village, has high landslide vulnerability. This is due to the soft rock layer on the surface that creates a sliding plane [20]. The high landslide rate in Malang Regency indicates the need for appropriate mitigation efforts. Since the area is vast, research is needed to identify the areas with the highest landslide vulnerability. This preliminary research uses the gravity method with data taken from the TOPEX Satellite. TOPEX satellite data and other data from satellite imagery like GGMPlus are commonly used in subsurface structure research such as fault identification [22] [23], identification of hydrocarbon basins [24], and identification of rock layer contact between sediment and volcanic rock [17], and mapping of potential landslide area [19]. The advantage of research using TOPEX satellite data is that it is cheaper than measuring data directly in the field [25]. This research aims to determine the landslide-prone areas in Dampit and its surroundings, and the results can be used as recommendations for determining government policies in disaster mitigation efforts.

Field Site Study

Based on the Turen Geologic Map (Figure 1), the study area consists of 4 different formations, namely Semeru Volcano Deposits (Qvs) formed during the Quaternary, Jembangan Volcano Deposits (Qvj) formed during the Quaternary, Wuni Formation (Tmw) formed during the late early Miocene, and Mandalika Formation (Tomm) formed during the late Oligocene [26]

The youngest to oldest formations are Semeru Volcano Deposits, Jambangan Volcano Deposits, Wuni Formation, and Mandalika Formation. The oldest formations are more consolidated, and the youngest are less consolidated [27].



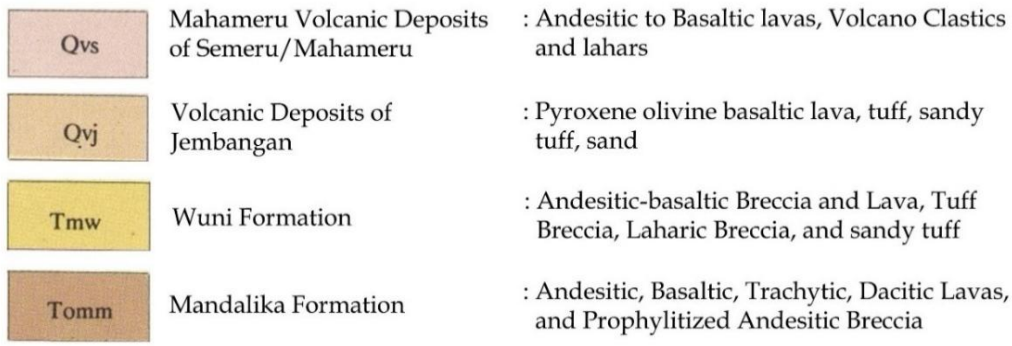


Figure 1. Geological Map of Research Area [26]

Based on rock types, Volcanic deposits of Semeru (Qvs) are the most dominant and consist of andesitic to basaltic lavas, volcano clastics, and lahars. The Wuni Formation (Tmw) consists of laharic breccia, Lava, tuff breccia, andesitic-basaltic breccia, and sandy tuff. Volcanic Deposits of Jembangan (Qvj) consist of pyroxene olivine basaltic lava, tuff, sandy tuff, and sand. Then, the last formation is the Mandalika Formation (Tomm), which consists of andesitic, basaltic, trachytic, and dacitic lavas, as well as prophylitized andesitic breccia.

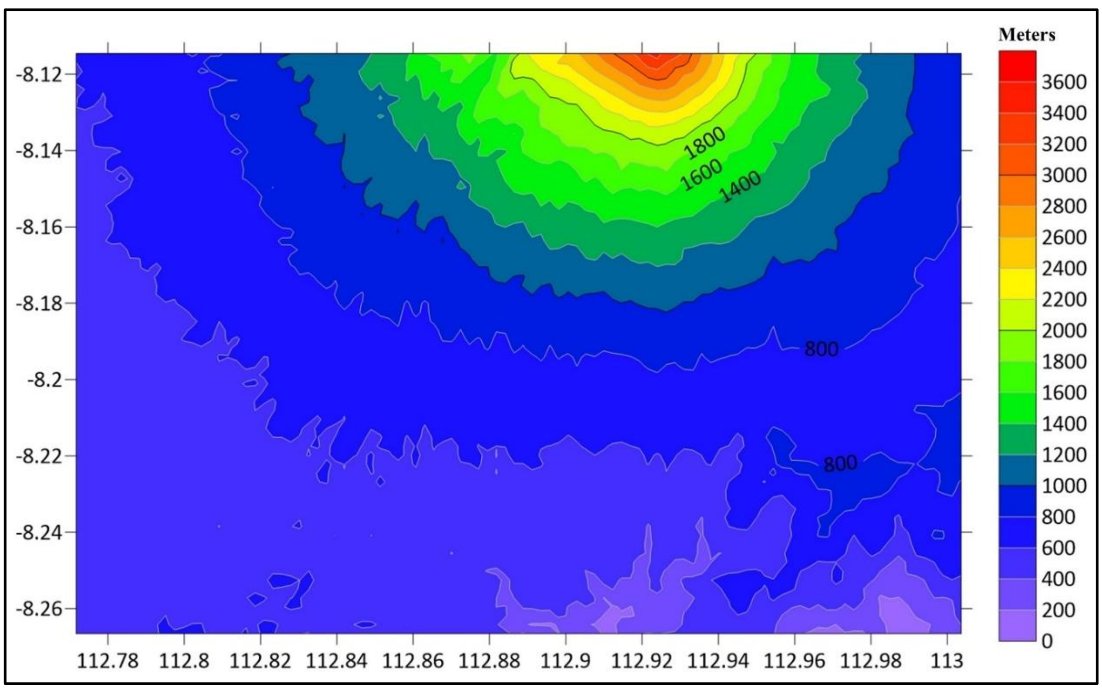


Figure 2. Topography Map

Based on the topography map (Figure 2), the study area has a landscape dominated by mountains and valleys. The highest point is 3800 meters above sea level, located on Mount Semeru, and the lowest point is 0 meters above sea level.

Methodology

Research data was taken from TOPEX satellite gravity data in the form of Free Air Anomaly (FAA) data. The study area is located in Dampit District, Malang Regency, East Java Province.

The study area is 23 km x 16 km with a spacing of 2 km and 184 measurement points (Figure 3). The distance used is quite far because the research aims to map the coverage of a large area or region. This is to obtain a regional distribution of rock density.

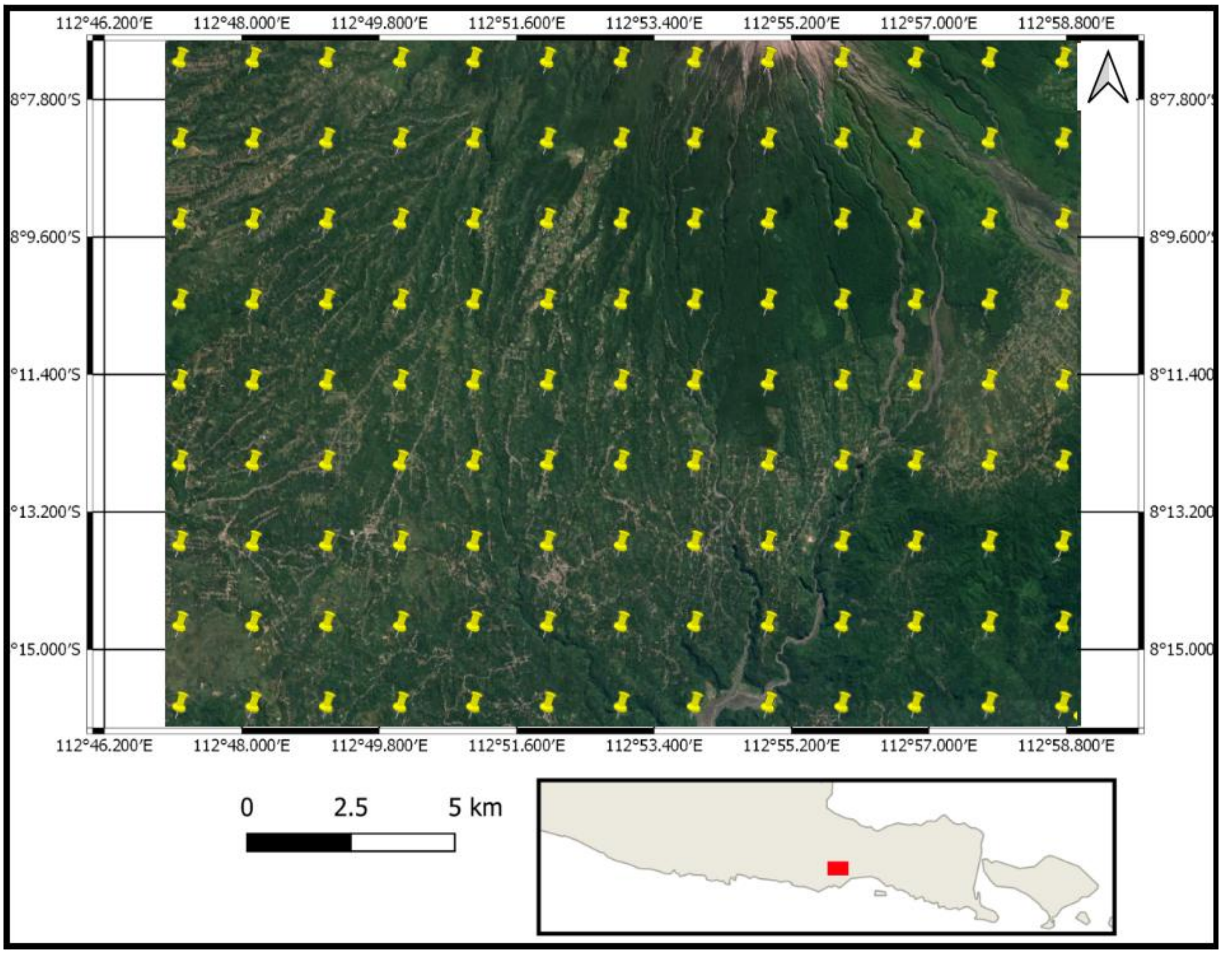


Figure 3. Survey Design of the Study Area

The basis of the gravity method is based on Newton's Law, which states that the amount of gravitational force is directly proportional to the mass of the object and inversely proportional to the square of the distance between the two masses. Thus, the magnitude of the force of attraction (gravity) between the mass of the Earth (M1) and the mass of the object (M2) on the surface of the Earth at a distance of R can be seen in equation 1 [28]:

$$\vec{\boldsymbol{F}} = G\frac{M1M2}{R^2}\,\hat{\boldsymbol{r}} \tag{1}$$

Where $\vec{\boldsymbol{F}}$ is the gravitational force that has units of Newton (N) that occurs between the mass of the earth (M1) and the mass of the object (M2) which has units of kilograms (kg), then R is the radius of the earth with units of meters (m), G is the value of the universal gravitational constant whose value is 6.6732 x 10^{11} N m^2/kg^2, and $\hat{r}$ is the unit vector R. In determining the acceleration of gravity, equation 2 is used:

$$\vec{\boldsymbol{g}} = G\frac{M1}{R^2}\hat{\boldsymbol{r}} \tag{2}$$

Where $\vec{g}$ is known as the acceleration or gravitational field of the Earth felt by a mass (M2) or at a point outside the Earth. Because the unit of the Earth's gravitational field is m/s². The ambiguity in the gravity values measured at the surface is very high, so it is necessary to make several corrections to eliminate this influence, namely latitude correction, tide correction, drift correction, free air correction, and Bouguer Correction [28]. The gravity data downloaded from the TOPEX satellite is FAA (Free Air Anomaly) data. This causes the Free Air Correction (FAC) and correction due to daily activity to be ignored [29], but requires the Bouguer Correction (BC). The Bouguer Correction removes elevation differences by not ignoring the mass below the surface of the measurement point [30]. The Bouguer Correction equation can be expressed by the equation:

$$BC = 0.04192\rho h \tag{3}$$

where ρ is the rock density (gram/cm³), and h is the elevation. Furthermore, terrain correction is carried out using data obtained from the computer application program. Terrain correction aims to eliminate the effects of topographic differences in the research area. The terrain correction process is carried out using a computer application program by entering the elevation of the study area and obtaining the terrain-corrected value. The DEM value entered is the research area (Inside) and outside the research area (Outside). This is because the outer radius is used as a reference for terrain correction, for the equation can be written:

$$TC = \frac{2\pi G\rho}{n}(r_L - r_D) + \left(\sqrt{{r_L}^2 - Z^2}\right) - \left(\sqrt{{r_D}^2 - Z^2}\right) mGal \tag{4}$$

Where r_L and r_D are the outer radius and inner radius, r_D is the average difference in elevation, and n is the number of segments in the area. Furthermore, after obtaining the terrain correction value, it is necessary to get the Complete Bouguer Anomaly (CBA). CBA is a disturbance in the Earth's gravitational field caused by a mass zone below the Earth's surface. The CBA equation is based on the equation below:

$$CBA = FAA - BC + TC \tag{5}$$

where FAA is the free air corrected gravity value (mGal), and BC is the Bouguer Correction, and TC is the terrain correction. Furthermore, the CBA values will be projected onto a flat plane with a Butterworth filter to obtain regional anomaly values and residual anomalies [17]. Regional anomalies indicate deep subsurface structures, and residual anomalies indicate shallow subsurface structures. The residual anomaly values will be compared with the landslide vulnerability map from InaRisk to determine the vulnerable areas. InaRISK is a portal formed based on the risk assessment results that utilizes the ArcGIS server as the source data. ArcGIS Server source data includes disaster-threatened areas, potential physical losses, affected communities, potential economic losses, and potential environmental damage. It is integrated with achievements to minimize disaster risk and is used as a tool to assess the disaster risk index [3]. InaRisk was launched by the National Agency for Disaster Countermeasure (BNPB).

Result and Discussion

The complete Bouguer anomaly (Figure 4) has an anomaly range from 82.7 mGal to 142.4 mGal for the highest to lowest color scale shown by blue-pink. The anomalous value shows the density in an area. The blue color scale indicates that the area has a low density, and the pink color indicates that the density value of the area is high. The complete Bouguer anomaly needs to be separated to get the local anomaly and the residual anomaly.

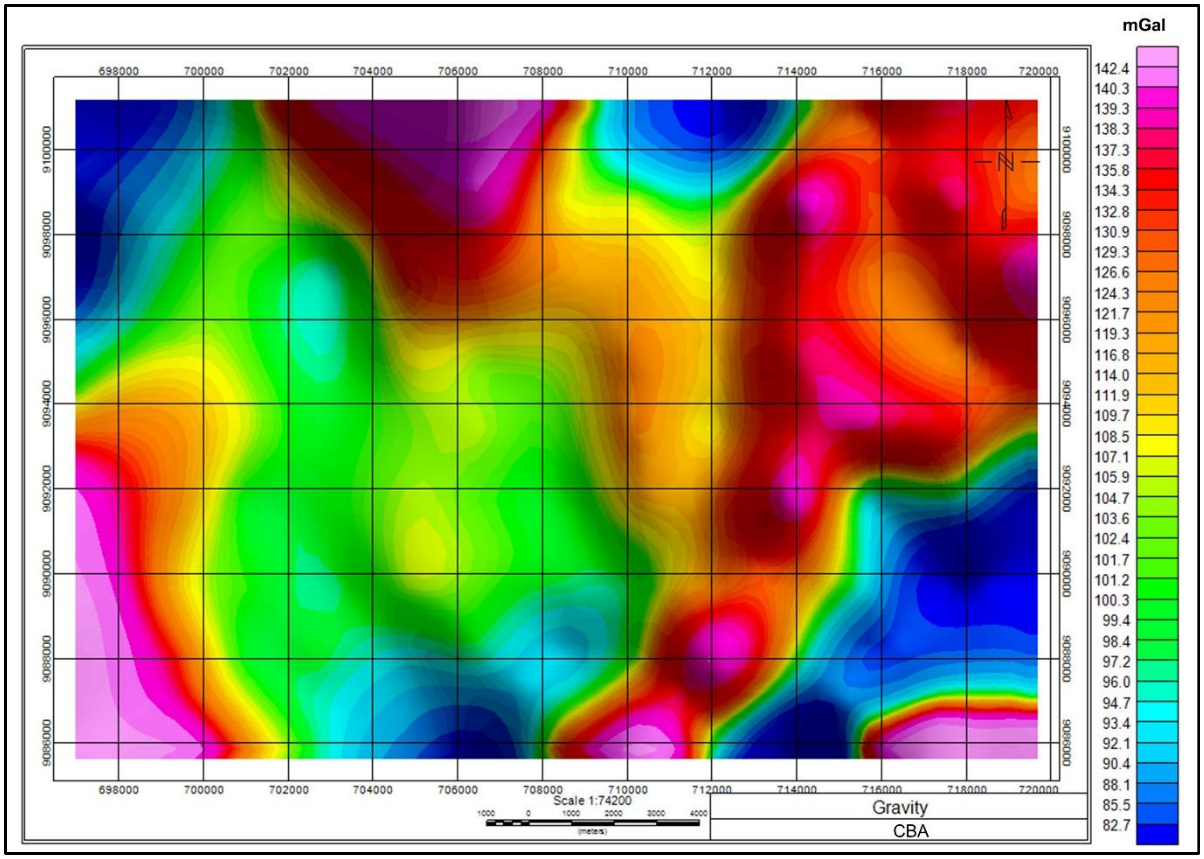
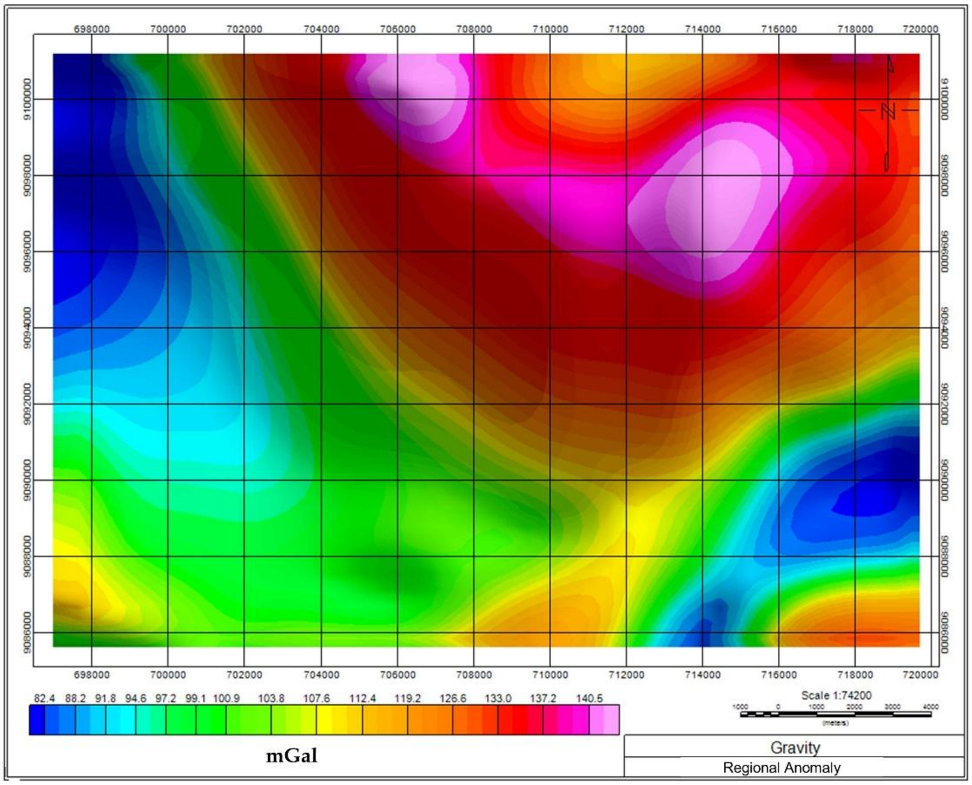


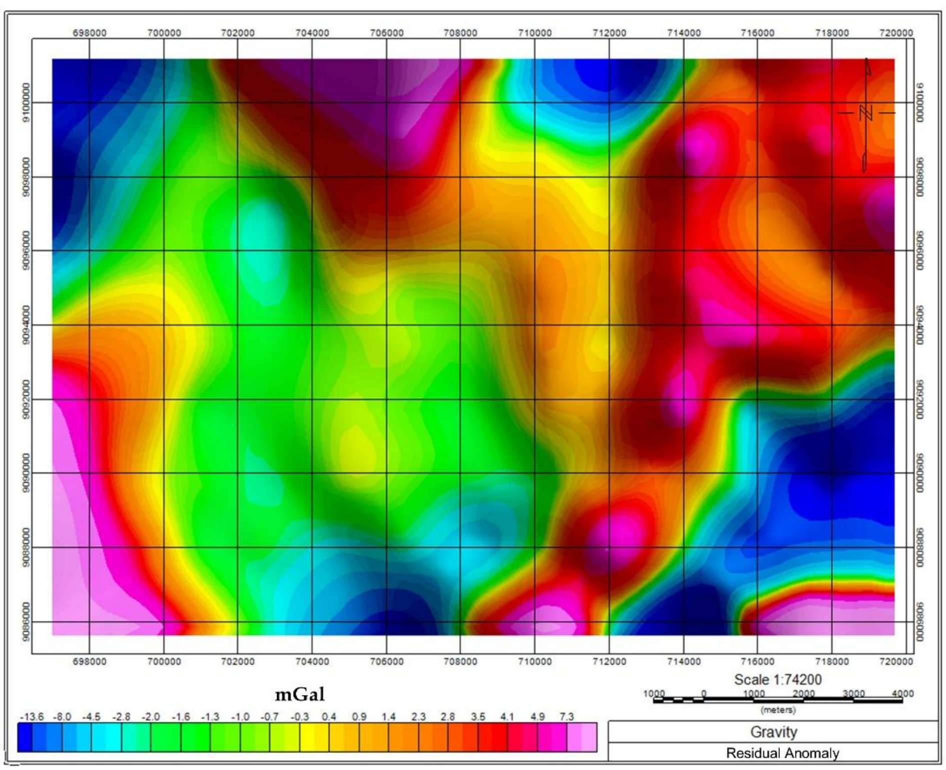
Figure 4. Complete Bouguer Anomaly (CBA)

Anomaly separation to obtain residual anomaly and regional anomaly is done using Butterworth filters in the computer application program. The Butterworth filter has a flat frequency response in the passband and a good frequency drop at blocked frequencies. It is very suitable for the separation of regional and residual anomalies.

Based on the regional anomaly (Figure 5a) and residual anomaly (Figure 5b), there are differences between the two anomalies. The regional anomaly has a nearly similar color range as the Complete Bouguer Anomaly because it is regional and shows deep subsurface structures. The residual anomaly is more variable because it is local and shows shallow subsurface structures. The regional anomaly values range from 82.4 mGal to 140.5 mGal, and the residual anomaly ranges from -13.6 mGal to 7.3 mGal. The residual anomaly provides more specific information about the subsurface structure. This is because the residual anomaly removes the effects of larger factors, such as the distribution of mass in the subsurface and gravity fluctuations caused by superficial topographic effects. Residual anomaly can indicate smaller local anomalies, such as the determination of geological structures, rock types, and mineral deposits.



(a)

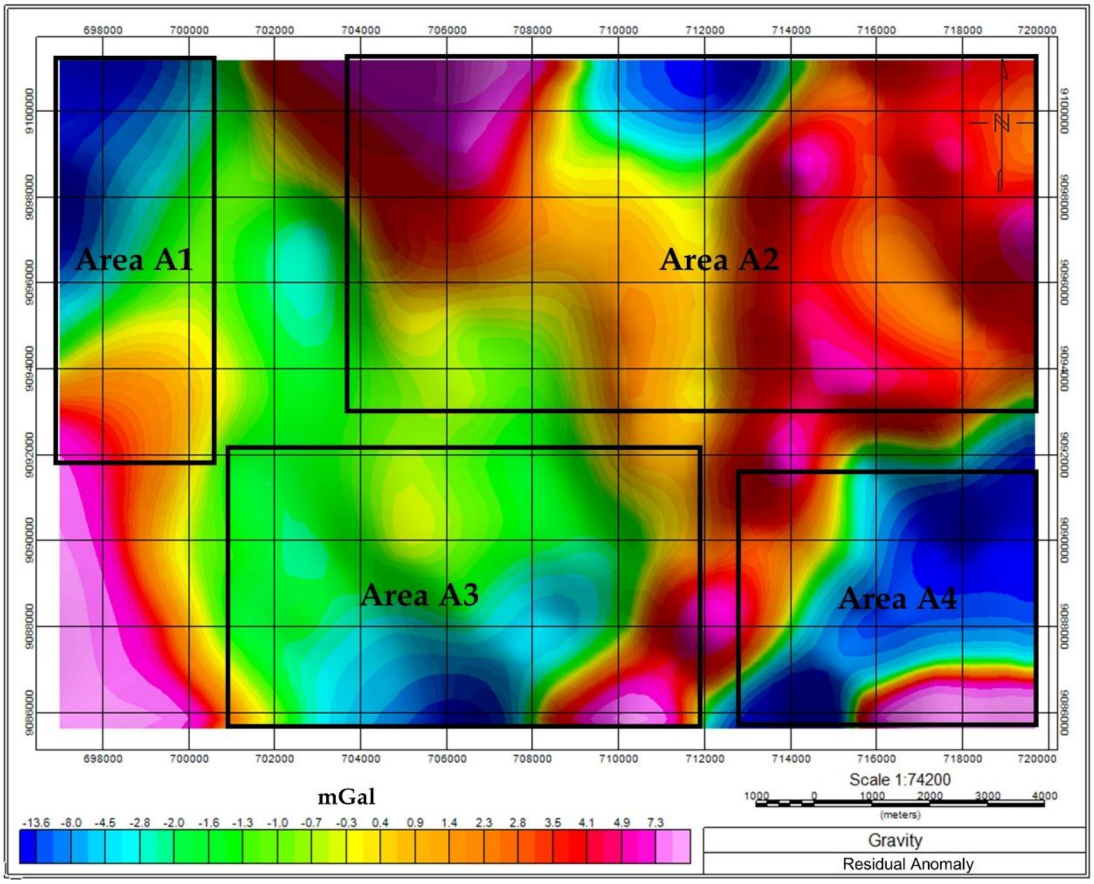


(b)

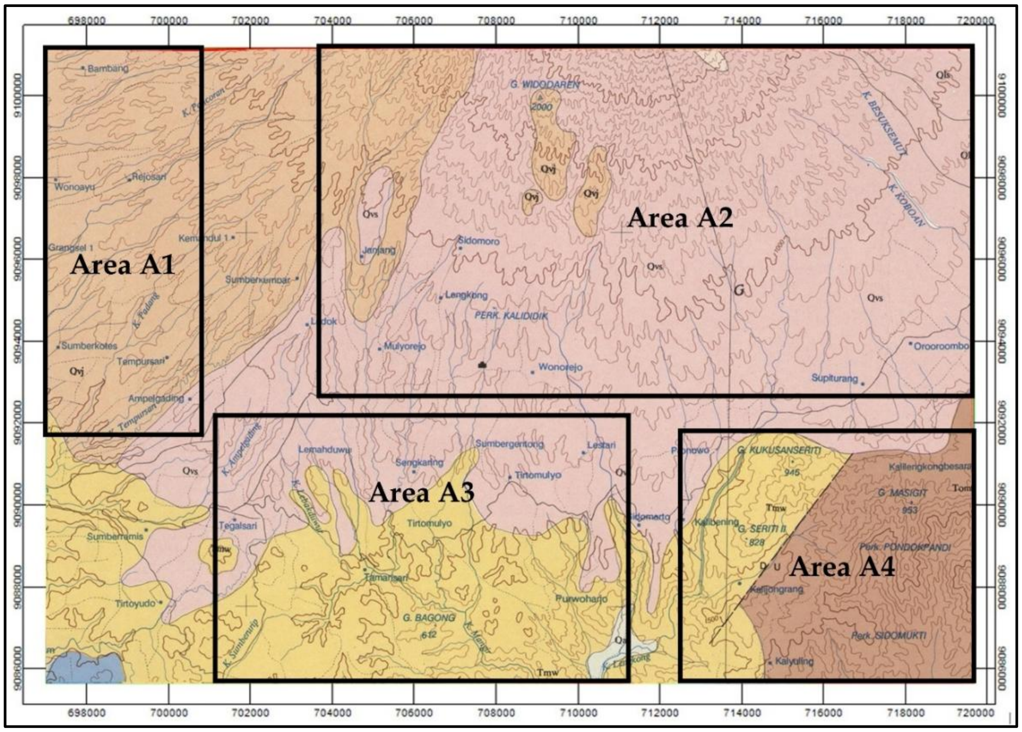
Figure 5. (a) Regional Anomaly (b) Residual Anomaly

Correlation of Geological Map of Research Area and Residual Anomaly

The correlation of residual anomaly with geological maps is necessary to determine the relationship between the anomaly map and the geological area. This is to determine the lithology of the area. Residual gravity anomalies can provide information on subsurface density variations in combination with geologic maps. This will provide information on the relationship between the residual gravity anomaly and the geological map of the research area.



(a)



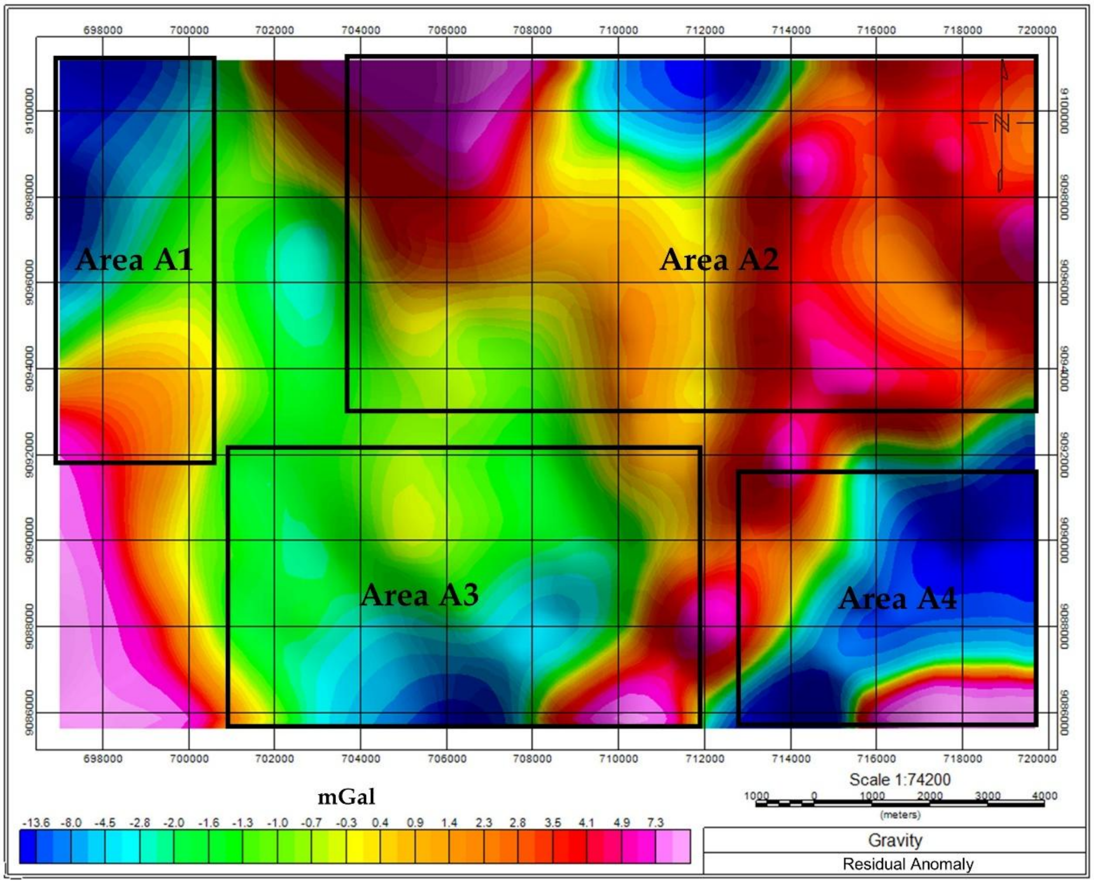
(b)

Figure 6. (a) Residual Anomaly (b) Geological Map

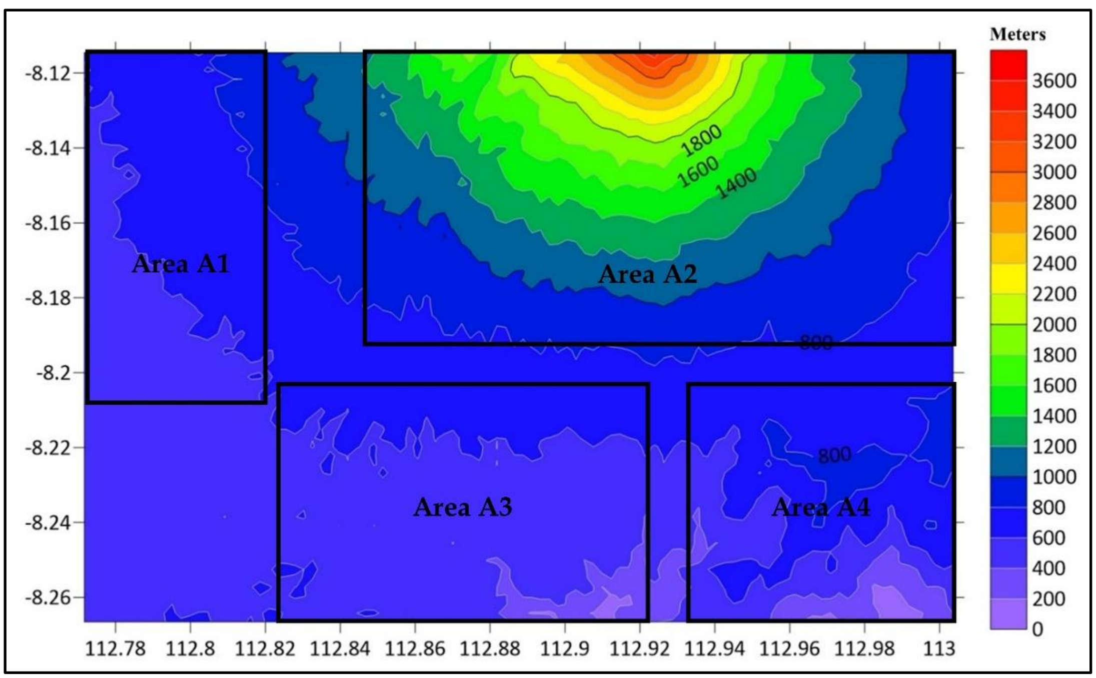
The correlation between the residual anomaly (Figure 6a) and the geological map (Figure 6b) can be divided into 4 areas: Area A1, Area A2, Area A3, and Area A4 (Figure 6). In Area A1, the residual gravity anomaly shows a small value. This indicates that Area A1 has low density. Based on the geological map, Area A1 is located in the Volcanic Deposits of Jembangan (Qvj), consisting of pyroxene olivine basaltic lava, tuff, sandy tuff, and sand. Area A2 has the largest gravity anomaly, so this area has the highest density, and the geology of this area consists of the Volcano deposits of Semeru consist of basaltic lavas, volcano clastics, and lahars. Area A3 shows a medium gravity anomaly, meaning the density value is medium. The lithology of Area A3 is in the Wuni formation, which consists of laharic breccia, Lava, tuff breccia, andesitic-basaltic breccia, and sandy tuff. The last area, Area A4, has a low gravity anomaly value, so this area has a low density. The regional geology of this area is in the Mandalika formation, which consists of andesitic, basaltic, trachytic, dacitic lavas, and prophylitized andesitic breccia. In addition, in Area A4, there are huge faults. This will cause this area to be more vulnerable to landslides, especially if there is a trigger such as an earthquake.

Correlation of Residual Anomaly, Topography Map, and Landslide Hazard Map from InaRisk

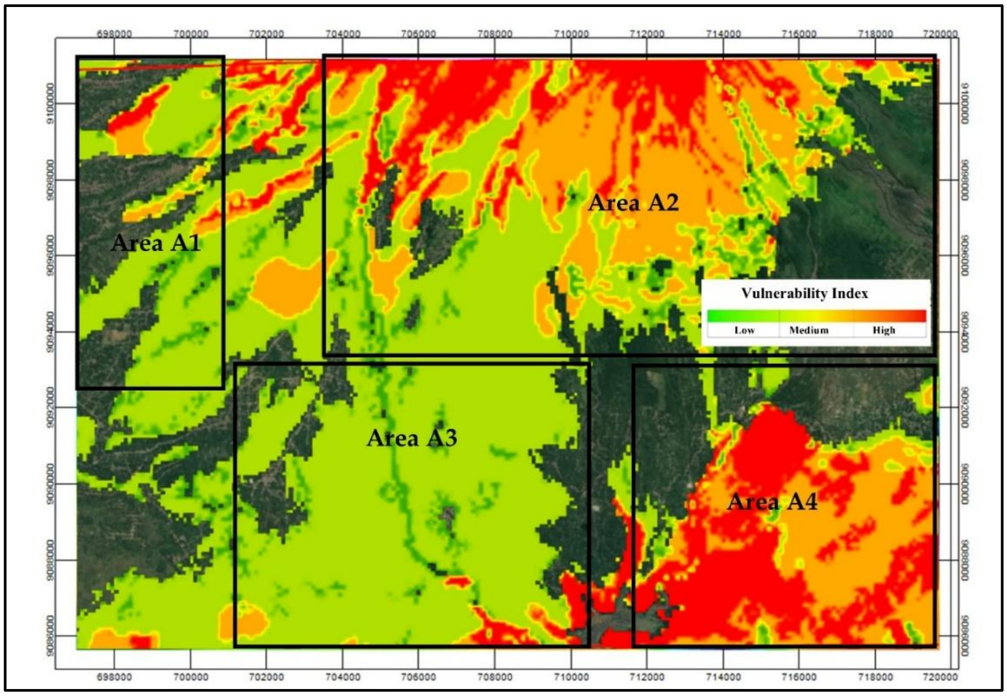
The residual anomaly (Figure 7a) is compared with the Topography Map (Figure 7b), and the landslide hazard map from InaRisk (Figure 7c) to determine the correlation between the three. Based on the Landslide Hazard Map from InaRisk, the landslide hazard level consists of three-color scales: low landslide hazard shown in green, medium landslide hazard shown in orange, and high landslide hazard shown in red.


Area A1
Area A2
Area A3
Area A4
mGal
Scale 1:74200
(meters)
Gravity
Residual Anomaly

(a)


Meters
Area A1
Area A2
Area A3
Area A4
1800
1600
1400
800
800

(b)



(c)

Figure 7. (a) Residual Anomaly, (b) Topography Map, (c) Landslide Hazard Map

The correlation between the landslide hazard map, the Topography map, and residual gravity anomaly can be divided into 4 different areas: Area A1, Area A2, Area A3, and Area A4 (Figure 7). This area division is based on the gravity anomaly value and the landslide hazard level. In Area A1, the residual anomaly value is low, so the density value is low. Based on the landslide hazard map from InaRisk, Area A1 has a low landslide hazard level. This is because the topography in Area A1 is between 400 and 800 meters above sea level, so the landslide hazard level is low, even though it has a low density. Area A2 is an area that is not at risk of landslide, although on the InaRisk Landslide Hazard Map, this area has a high landslide hazard level. This is because the rock density in Area A2 has a high value and has protected vegetation because it is located around Mount Semeru. The altitude of Area A2 is between 1200 and 3600 meters above sea level. The rock type in Area A2 consists of lava rock, which is a member of the Semeru Volcanic Deposits. Area A3 has a medium gravity anomaly value, so the density value is medium. Based on the InaRisk Landslide Hazard map, this area has a low to medium landslide hazard level, and its elevation is between 400 to 800 meters above sea level. Finally, Area A4 is the area with the highest landslide probability. This is because this area has a low-density value. Based on the InaRisk Landslide Hazard Map, this area has a high landslide hazard level, and its elevation is between 400 to 1000 meters above sea level. The landslide hazard level in this area is due to the presence of a very large fault and is the contact area between the Wuni Formation and the Mandalika Formation. The contact layer of these two formations tends to be unconsolidated. This will cause this area to be more vulnerable to landslides, especially if there is a trigger such as an earthquake. Malang Regency itself is included in a Regency with a high class of Earthquake Risk Index with a score of 12.0 [31]. Based on previous research using the resistivity method, the Dampit Subdistrict is vulnerable to landslides [7]. It is because this area has many local faults [32]. In addition, this area is also heavily populated and is located between the boundaries of Malang Regency and Lumajang

Regency, which is indeed a landslide-vulnerable area because it has a factor of safety below 1.25, and landslides often occur [33]. The results of this research can be used as a preliminary study for the government. The government still needs to conduct further research using other geophysical methods to obtain a comprehensive conclusion, especially in Area 4, which has a high vulnerability. Besides that, the results can be used as recommendations for determining government policies in disaster mitigation efforts.

Conclusion

The satellite imagery of gravity data combined with InaRisk landslide vulnerability map data can provide good information about landslide potential areas. The complete Bouguer anomaly value is 82.7 to 142.4 mGal. The gravity anomaly value obtained from the regional anomaly is 82.4 mGal to 140.5 mGal. The residual anomaly value is -13.6 mGal to 7.3 mGal. The research area is dominated by volcanic rocks that have high-density values. The results of the correlation of the residual anomaly with the geological map show that the distribution of density is in line with the type of rock in the research area. This indicates that the satellite image gravity data in the study has accurate results. The correlation between the residual anomaly and the InaRisk landslide vulnerability map is divided into 4 areas: Area A1, Area A2, Area A3, and Area A4. The correlation shows that Area A4 is the area with the highest possibility of a landslide. This is because this area has low-density values and high landslide hazard levels. The results of this study can be used as data for the government in determining policies on landslide mitigation. It is expected that the government will pay more attention to Area A4.

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