Changes in Anak Krakatau landscape after December 2018 eruption

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Abstract. The south-western slope of Anak Krakatau collapsed after the eruption on December 22nd, 2018 and reshaped the volcanic island landscape. This work focused on determining the geomorphological features of Mt. Anak Krakatau before and after the eruption. A total of 71 lapilli and 17 volcanic ash samples were collected from Anak Krakatau and Panjang islands on February 23, 2019, and March 14, 2019. Sentinel-2 and Planet Scope images were utilized to monitor thermal activities and the changes of the coastlines. Google Earth Pro was capitalized to determine the rills and gullies formation. After the December 2018 eruption, the height of Anak Krakatau was reduced from 258 to 126 m and, about 76 x 10⁶ m³ of materials were eroded to the sea. The eruption caused Anak Krakatau to be covered by unconsolidated volcanic materials. About 214 of rills (dimension of 380 to 851 m and 30 to 100 cm) and 35 of the gully features (length from 150 to 841 m and width from 0.5 to 13 m) run from the highest peak to the coastline. This work can serve as a reference for predicting potentially disastrous events such as Anak Krakatau, which shows growth and destruction can be observed using remote sensing techniques.

1. Introduction

Strombolian activity of Anak Krakatau volcano raised intensively the beginning of June 2018. As a result, the height of Anak Krakatau and the area of Anak Krakatau Island grew-upped rapidly until mid of December 2018. On December 22, 2018, the highest peak of Anak Krakatau activity occurred, and resulted in a large explosion where its flank in southwest sector collapsed. Moreover, the collapse of flank that fallen into the sea triggered a tsunami disaster in Sunda Strait when hit the western part of Java and the southwest coast of Sumatra [1]. The volcano’s collapsed body reduces the height of the island from 320 to 120 m [1]. It was estimated that the body collapse of Anak Krakatau created a loss of volume of 0.27 km³ [2], 0.1 km³ [3], [1] also estimated the fall volume of 0.202 km³. The collapse of Anak Krakatau resulted in significant morphological changes in the form of Anak Krakatau including material deposition, erosion line formations, changes in coastline areas, and vegetation.
Recently, remote sensing technology is widely used to monitor morphological changes of volcano before and after its eruption. It is supported by various imagery satellite data that have been available freely either from optical sensor such as Sentinel-2, Landsat-8, and MODIS or radar sensors such as Sentinel-1. The use of multi-sensor satellite imagery provides more information and understanding of volcano activities [4].

After the eruption of December 22, 2018, the material on the surface of Anak Krakatau was entirely covered by new volcanic material. The prediction and modeling of growth new volcanic material of Anak Krakatau Island were analyzed in this study using remote sensing technique.

2. Materials and methods

2.1. Research location

Anak Krakatau is an active volcano located in the ancient Krakatau complex. The Krakatau Complex consists of four islands: Sertung, Panjang, Rakata, and Anak Krakatau (Figure 1). After no volcanic activity for less than half a century of the terrible eruption of 1883, it was known that there was an eruption out of the edge of the deep Caldera basin, at the point between the old cones of Danan and Perbuwatan [5]. On 26-27 August 1883, the second-largest eruption of Krakatoa in Asia occurred, collapsed, and triggered tsunami [6]. Frequent eruptions occurred from 1928-1930 so that new cones appeared called Anak Krakatau.

The eruption of Anak Krakatau continued to occur from the Surtseyan eruption style to Vulcanian until 1960 and Strombolian so that it reached a height of 315 m above sea level in 2005 [7]. Anak Krakatau was developed from layers of lava and pyroclastic deposits that have erupted since 1927 [8]. At first, the Anak Krakatau appeared at sea level with an explosive eruption and effusion in 1927 with a maximum value of the Volcanic Explosivity Index (VEI) 2. The composition of Anak Krakatau products has erupted with basaltic, andesitic, and sometimes dacite evolutions [9]; [10]. Anak Krakatau was in an increased stage of activity and began the intense eruption in 2018. Analysis of infrared data recorded by Sentinel-2 showed that Anak Krakatau began intensive eruption on June 19, 2018 for 54 days, until December 22, 2018, when it destroyed and collapsed the western sector of the volcano to the sea, changed the altitude for on 339 m to 110 m and the loss of material volume from 0.22 to 0.30 km$^3$ [1]. According to our survey on the island in 2015 and 2019, the morphology of the Anak Krakatau was changed significantly including material deposition, erosion line formation, changes in coastline area, vegetation, and development of a deposit of new ash material.
2.2. Data collection and methods
Detailed information on Anak Krakatau activities regarding its evolution and morphological changes, various kinds of data have been used. The data and methods used in this study are listed in Table 1 and described in detail in this section.

Table 1. The information of data used to observe lava flow and morphological changes

| Sensor          | Band           | Acquisition date       | Data Source                                                                 |
|-----------------|----------------|------------------------|-----------------------------------------------------------------------------|
| 1. Lava Flows   | B12: SWIR 2,  | 2018 July 12           | https://code.earthengine.google.com/9f291181993494df652bc82e61e787773v     |
| Sentinel-2      | B8: NIR,      |                        |                                                                             |
|                 | B4: Red        |                        |                                                                             |
| Planet Scope    |                | 2018 June              | https://www.planet.com/                                                   |
| Scope Images    |                | 2018 July              |                                                                             |
|                 |                | 2018 September         |                                                                             |
|                 |                | 2018 October           |                                                                             |
|                 |                | 2018 November          |                                                                             |
|                 |                | 2018 December          |                                                                             |
|                 |                | 2018 December 30       |                                                                             |
|                 |                | 2018 March 12          |                                                                             |
|                 |                | 2019 January 07        |                                                                             |
|                 |                | 2019 January 12        |                                                                             |
| Worldview and   | 2018 July 15   | https://www.google.com/intl/id/earth/versions/#earth-pro               |
| Pleiades        |                |                        |                                                                             |
| 2. Morphological changes |        |                        |                                                                             |
| Drone (UAV)     |                | 2019 June 14           | https://www.bppt.go.id/teknologi-hankam-transportasi-manufacturing/3595-bppt-berhasil-lakukan-pemetaan- evaluasi-dampak-kebencanaan-gunung-anak-krakatau |

2.2.1. Detection of lava flows. To determine and analyze the growth of Lava and the size of the island, we collected high-resolution satellite data obtained from Google Earth Pro, Planet Scope images, and Sentinel-2. Various types of data were used to ensure clearly that there were morphological changes in the Anak Krakatau activities before the 2018 collapse. Temporal resolution is very helpful in understanding events that occur. All data used in this study were obtained on the span time between June 19, 2018 to January 12, 2019 covering the period before and after the collapse.

Google Earth Pro is a feature-rich version of Google Earth software that was released in 2005. This application creates a virtual globe by combining several different file formats and imaging methods including aerial photography, satellite imagery, and geographic information system technology (GIS). Google Earth Pro has various spatial resolutions range from moderate to very high resolutions and has time variations from one location to the other (https://www.google.com/earth/). On this study, Google Earth Pro July 15, 2018 and November 01, 2019 were used to obtain information about the activities and evolution of Mount Anak Krakatau when the Planet Scope did not have a clear picture. This method showed changes in the coastline, the growth of lava before the 2018 eruption, changes in morphology, and erosion formation aftermath of volcanic activity.

Google Earth Engine is a web portal that provides satellite imagery and global time series vector data, cloud-based computing, access to software, and algorithms to process data faster and easier [11].
Data collection of more than 40 years of satellite imagery and 391 worldwide catalog data, such as Sentinel 1, 2, 3, Landsat 1, 2, 3, 4, 5, 7, 8, MODIS (Aqua and Terra), DMSP, and NOAA AVHRR. Sentinel 2 is a multispectral, high-resolution optical image mission, with a global 5 days temporal time. Data available on Sentinel-2 from June 23, 2015 to present, has 13 spectral band multispectral instruments with the spatial resolution of Visible and NIR at 10 meters, red edge, and SWIR at 20 meters, and atmospheric bands at 60 meters. We used the data from satellite band Short Wave Infrared (SWIR), Near Infrared (NIR), and Green, which are bands 12, 8, and 3 on Sentinel-2. Representation of the SWIR, NIR, and Green shows the high location of thermal activity in the color red.

Planet Scope Images is a high-resolution satellite that can capture more than 346 million km$^2$ of land surface/day that provides data in multispectral mode, operated by Planet Labs [12]. Planet Scope satellites have Sun-Synchronous orbits and International Space Station (ISS) orbits with four visible bands (Red, Green, Blue, Near-Infrared (NIR)), 3 meters spatial resolution, 12-bit radiometric resolution, and have a temporal resolution of 1 day [13]. With these characteristics, Planet Scope images have the advantage of monitoring the change and evolution of the earth. Images of Anak Krakatau from January 01, 2018 to January 12, 2019 were analyzed to observe events such as lava flow, morphology, and changes in the Anak Krakatau island landscape.

2.2.2. Morphological changes. Anak Krakatau erupted on December 22, 2018, destroyed part of the southwest slope of the volcano into the sea. This wing collapse occurs at 13:56 (UTC), 115 seconds after high frequency seismic (2-8 Hz) is recorded by the seismic station and produces volcanogenic tsunamis with waves propagated in all directions [1]. To observed the changes in the morphology of Anak Krakatau, this study used data recording by drones (UAV) type of Alap-PA2 06D from BPPT (Agency for Assessment and Application of Technology). The mapping was carried out by the Nir Awak Aircraft Technical Team (PUNA) on April 29 to May 3, 2019 with a mapping distance of 75 km and a flying altitude of 2,000 ft. Data in georeferencing as such its position correctly matches the control points and is extracted, so that altitude information can be used as DEM (Digital Elevation Model) data. The georeferencing procedure is carried out on ArcMap using the "Georeferencing" tool. This stage is carried out to obtain information about the topography after the volcano's body parts were destroyed.

DEMNAS is DEM data which is the form from several data sources including IFSAR data (5 m resolution), TERRASAR-X (5 m resolution), and ALOS PALSAR (11.25 m resolution), by adding stereo-plotting Masspoint data. DEMNAS produced by the Geospatial Information Agency (BIG) which has a spatial resolution of 8.25 m using the EGM2008 datum, can be downloaded at (http://tides.big.go.id/DEMNAS/DEMNAS.php). The format downloaded is GeoTIFF (TIF). The DEMNAS region with the size (15°x 15°) downloaded in this study is DEMNAS_1109-44. DEMNAS is used to get topographic information before the body parts of the volcano are destroyed.

2.3. Field observation and sample collection
The biggest impact after the eruption occurred on December 22, 2018, was in Anak Krakatau and Panjang Island. Sampling was conducted twice at Anak Krakatau and Panjang Island on February 23, 2019, and March 14, 2019. Observations and sampling spread from the east, south, west, and north of Anak Krakatau. Eruption material was observed in Anak Krakatau, morphological forms, elevations, and erosion forms. Due to the hazardous field conditions with lots of loose material, sampling is done as easily as possible, covering transects from the lowest to the highest accessible elevation.

3. Results and discussion

3.1. Lava flows
Anak Krakatau is located at the latitude of 6° 6’ 7.2” S and longitude 105° 25’ 22.8” E is an active volcano with eruptions (explosive and effusive) in Indonesia. Mount Anak Krakatau was built from alternating layers of 18 lava flows and 18 pyroclastic deposits beginning in 1927 that had been made
with a geological map [8]. Figure 2 shows information about lava flows that occurred in 1972-2018. The image is based on an earlier geological map from 1972-2017 [8]. Figure 2b visualizes the lava flow recorded by Sentinel-2 with bands 12, 8, and 3 on 12 July 2018 (Sentinel-2 images freely available on Google Earth Engine and the Copernicus Open Access Hub taken by the portal EO browser). The red color shows lava flow and high thermal activity in the southern Anak Krakatau. Thermal activity on 12 July 2018 in Anak Krakatau was detected by using MODIS data of Fire Information for Resorce Management System (FIRMS) method. The high thermal activity in Anak Krakatau was 104.2°C (Figure 2c) recorded on July 15, 2018, identified as lava flow. Lava flow mapping is done by precisely tracing the flow limits that are visible in Google Earth Pro data. Lava flow formed on area of 12.29 ha. The lava flow towards the south side, reached the coastline and clearly identify in Google Earth Pro data.

The rapid eruption makes coastline changes very significant every month (Figure 3). July 2018 Krakatau island has an area of 278.25 ha. September 2018 Anak Krakatau island increases by an area of 285.55 ha, an increase in lava flow to the Southwest-South. The biggest island change occurred in October 2018 with an area of 288.24 ha, which leads to the Southwest, between South to Southwest, and South. November 2018 area of 290.64 ha, has increased in the same direction in October 2018. And before the destruction and collapse of the body of the volcano into the sea, the last area of Anak Krakatau island is 288.
3.2. Morphological changes

It showed in Figure 4 how active and fast growth of the Anak Krakatau and destroyed the Southwest side. Observing extracted the Planet Scope Images data of December 30, 2018 the total area of 287 ha and the position of the crater of Mount Anak Krakatau was on the seabed. The shape of the volcano looks like it returned to its 1950 shape [14]. The surface of the Anak Krakatau in the Southwest that was destroyed, re-emerged above the sea surface. This area is close to the crater position of Anak Krakatau data on January 7, 2019 (Figure 4) the area of the volcano is 309 ha. The activity of this volcano on January 12, 2019, remains high because the crater at Anak Krakatau is getting wider and it is predicted that there will still be a small eruption with an area of 300 ha. Yellow lines in Figure 4 shows the destroyed area, which was previously the area where lava is added. In general, previously the growth of Anak Krakatau is an average of 4 meters per year [15].

The deposition of lava flows and all products produced during the last phase of volcanic activity. The morphological surface of Anak Krakatau (Figure 5). The first trigger for the collapse of this sector was an increase in lithostatic loading on the Southwest side. Estimates of destroyed volumes from the Anak Krakatau body obtained on two digital elevation models (DEM) show an estimated volume loss of 0.76 x 10^8 m^3. [1] have also estimated the volume of volcanic material lost at around 1.02 x 10^8 m^3. we ensured that the collapse of the sector reduces the height of Anak Krakatau island 258 to 126 m above sea level. The previous vegetation layer had a height of about 5 meters, now cover by layers of volcanic ash, lapilli, scoria, and large rocks. Vegetative area was found in the Northeast to Southeast with an area of 55 ha disappeared. The surface area of Anak Krakatau island increased after the eruption from 288 to 309 ha.
Figure 4. The evolution of Anak Krakatau island before, after, and formation of the crater hole.

The surface topography in the North-West direction to the Southeast increased (Figure 5c). The island has increased the length of around 119 m with a height of 30 m and has decreased to the latest coastline from Anak Krakatau Island. The northwest region lost part of by the volcano's destruction. The shape of the surface topography from of its the Southwest to the Northeast showed that the entire body of Southwest Anak Krakatau destroyed and now is below the sea surface (Figure 5d). The length of the coastline is longer in the northeast, about 233 m with a height of 7 m after the eruption. The volume of newly deposited material formed from the eruption and destruction of Anak Krakatau Island in this study was estimated at $0.14 \times 10^8 \text{m}^3$.

Figure 5. Morphological changes by sector collapse, material deposition, and subsequent erosion. (a) before eruption (b) and (c) Before and after comparison of the morphology deduced from DEMNAS data (before, gray lines dotted) and drone UAV (after, dark brown shading) revealing profound topographic changes, material lost, and deposition of new materials. Erosion was carving gullies on the volcano flanks by early January 2018, (d) 3D DEMNAS overlaid with data Google Earth Pro 2018 before eruption, (e) 3D UAV DEM model overlaid with data Google Earth Pro 2019 after the eruption.
Lapilli material, scoria, large stones, and volcanic ash layers are observed in Anak Krakatau Island. It showed that the material released by Anak Krakatau was layered with different sizes of each layer (Figure 6). These materials form bumps or mounds of various sizes. The height of the mounds maximum of 5 m. These mounds were roughly circular shape and extend from high to lowest areas.

The wall of the mound in the upper layers of depth 0 to 50 cm was dominated by loose material measuring 2 to 64 mm (lapilli) (Figure 6a). Depths of 50-80 cm, many rock blocks and bombs were found > 64 mm in size. Located on the Southside, which is 500 m from the new crater of Anak Krakatau. The materials from the walls of the Anak Krakatau layer are small size (2 to 64 mm). They are loose material located on the East Anak Krakatau. The location of Figure 6b was 1000 meters from the Anak Krakatau crater. The fine material flew further than the large size which usually falls on the slopes or the foot of the volcano [16]. The mound is very loose so it was easily eroded by water.

![Figure 6. The types of volcanic material coming out of the Anak Krakatau eruption. (a) found many lapilli materials, blocks and bombs erupted from Anak Krakatau, (b) Dominated by lapilli material.](image)

The erosion process began with the release of particle-material volcanic deposits by rain power [17]. From December 22, 2018 to January 8, 2019, there were 8 rainy days of rainfall, with a total rainfall of 134 mm (Table 2). The formation of drainage channels is seen using TerraSar-X data recorded on January 8, 2019. These observations showed that the formation of trench erosion occurred within a few days to a week after the eruption. Formation of drainage channels due to high rainfall which results in the runoff of surface water after the eruption. A large amount of rainfall showed the river network from the highest peak to the coast of the volcano.

In the first rainfall event, after the eruption stops, the rill networks and gutter features were formed (Figure 7). The number of rill networks and sewer features is formed around 35, which are located in the Northwest, North, Northeast, East, Southeast, and South directions. Simultaneous erosion changed the shape of the Anak Krakatau land which had a depth ranging from 0.5 to 5 meters. The maximum length of this network is around 851 meters leading to the North East and the minimum length of about 380 meters leads east from the Anak Krakatau crater. The width of the river flow formed between 0.5 meters to 13 meters.

Networks of rill and gully features formed by rainwater are abundant on the surface of the Anak Krakatau. There are about 214 erosion features comprise of rill and channel. These erosion networks
were formed after heavy and prolonged rainfall immediately after the eruption. The length of rill and channel erosion ranges from 150 to 841 m. In Figure 7c showed the surveyor team through the ditch erosion path with the body position tilted. The width of the erosion was estimated to be around 30 to 100 cm. This type of hydrogeomorphic post-eruption process was also reported to occur after the eruption of Mt. Pinatubo in the Philippines in 1991 [18], Cordón Caulle in Argentina in 2011 [19].

### Table 2. Daily rainfall at Pesawaran Climatology Station.

| Date | Dec-2018 | Jan-2019 | Feb-2019 | Mar-2019 |
|------|----------|----------|----------|----------|
| 1    | 27.5     | 19.6     | 11.5     |          |
| 2    | 7.5      |          |          |          |
| 3    |          |          |          |          |
| 4    | 1        | 4        |          |          |
| 5    | 6.5      | 1.8      | 36       |          |
| 6    | 1        | 8.5      | 2        |          |
| 7    | 16.7     |          |          |          |
| 8    | 22.5     | 2        |          |          |
| 9    | 1.5      | 3.5      | 0.5      |          |
| 10   | 7        | 150      | 9.5      |          |
| 11   | 2        | 2        |          |          |
| 12   | 4        | 14.5     | 35       |          |
| 13   | 42       | 34.5     | 1.5      |          |
| 14   | 46.5     | 30       | 0        |          |
| 15   | 1.5      |          | 29       |          |
| 16   |          |          | 1.5      |          |
| 17   | 3        | 9        | 50.5     |          |
| 18   |          |          |          |          |
| 19   | 2        | 4        | 7.5      | 0.6      |
| 20   | 0.7      | 27.5     | 0.5      |          |
| 21   |          |          | 1.8      |          |
| 22   | 53       |          | 64       |          |
| 23   | 5        | 2.2      | 18       | 1        |
| 24   | 3        | 2        | 1.5      | 19.5     |
| 25   | 2.7      |          | 47.5     |          |
| 26   | 9.7      | 27       |          | 3.5      |
| 27   |          | 8        |          | 60.5     |
| 28   |          |          | 47.8     | 33       |
| 29   | 3.5      |          |          | 3.5      |
| 30   | 60.5     |          |          |          |
| 31   |          |          |          | 19.5     |
| **Total** | 126.7 | 355.4 | 484.9 | 222.1 |
Figure 7. (a) Geomorphology of Anak Krakatau volcanic island showing the formation of erosion rills that are yellow and red is gullies. Erosion is seen using Google Earth Pro imagery January 01, 2019, (b) erosion observed during the first survey in February 2019, (c) erosion observed during the second survey in March 2019

4. Conclusions
The height of Anak Krakatau was reduced from 258 to 126 m and, about 76 x 106 m$^3$ of materials were eroded to the sea. The eruption caused Anak Krakatau to be covered by unconsolidated volcanic materials. About 214 of rills features are formed after heavy and prolonged rainfall (dimension of 380 to 851 m and 30 to 100 cm) and 35 of the gully features (length from 150 to 841 m and width from 0.5 to 13 m) run from the highest peak to the coastline.

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