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RESEARCH ARTICLE

Numerical Simulation of Pyroclastic Flow of Karangetang Volcano Based on 2015 Eruption Activity

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Abstract

On May 7-9, 2015 the eruptive activity of Mount Karangetang released pyroclastic flows towards the Batuawang River for 3.6 km and hit Kora kora village which is located south of the Main Crater. This pyroclastic flow originated from lava flows during the effusive eruption period. MODIS satellite image hotspot data shows the lava flow extrusion rate and total volume at the peak began to increase since April 2015 and continued to show an increase until December 2015, with the estimated volume and lava extrusion rate on April 22, 2015 reaching 4.16x106 m^3 and 0.53 m^3/s, respectively, and on December 9, 2015 the volume reached 1.67x107 m^3 with a lava extrusion rate of 1.97 m^3/s. The results of field checks show that this pyroclastic flow is dominated by block and ash, and by using numerical simulations show the deflection of pyroclastic flow in accordance with the flow field of the Batuawang river, and the splash of pyroclastic flow towards Kora kora village in addition to the location adjacent to the river flow and also controlled by the narrowing of the river channel due to the accumulation of material in the flow field. A total of 8 numerical simulation cases have been carried out, and in our opinion with an input volume of 500 $x10^3$ m^3 and a flow material friction of 0.5 is a case that corresponds to a flow event that reaches a distance of 3.6 km from the Main Crater. Taking into account the current activity conditions we used the same parameters to estimate the area that could be affected by pyroclastic flows in the future. Numerical simulation show that the pyroclastic flow traveled 5 km in a south-southwest direction from the top of the main crater.

Keywords: Numerical simulation, Pyroclastic flow, Lava Avalanche, Karangetang volcano

1. Introduction

Karangetang volcano is one of the active volcanic islands in Indonesia, located in North Sulawesi, precisely in Siau Island (Figure 1), with a distance of about 157 km from Manado City. The highest peak is at an altitude 1797 meters above sea level (Global Volcanism Program et al., 2013). At its peak, there are two active craters namely Kawah Utama (Main Crater) in the South, and Kawah Dua (North Crater) which is further North, with structure at the peak is a normal fault and a relatively west-east direction, with basalt andesitic lava dome (Budianto et al., 2000).

Karangetang volcano is an stratovolcano with magmatic eruption type that produces dominant eruptions in the form of lava flows (Kusumadinata et al., 1979) and Pratomo (2006) classify Karangetang volcano as a volcano with a type of lava flow (Sangeangapi type), with a tendency for effusive eruption types and the origin of the magma composition is uniform which forms in Island Arc (Kusnadi et al., 2020).

In the 348 years period from 1675 to 2023 the eruption scale of Karangetang Volcano ranged from 3 to 1, and according to (Kriswati and Alfianti, 2019) rest intervals range of months to 113 years, with the dominant eruption center was in the Main Crater.

Eruption period from 1675 to 1961 was a period of explosive eruptions with an eruption scale of 2 with the eruption center from the Main Crater, and during 1962 to 2023 period the character of the eruption was in the form of magmatic eruptions (explosive) followed by flowing lava (efusive) (Pusat Vulkanologi dan Mitigasi Bencana Geologi, 2014) ("Global Volcanism Program | Report on Karangetang (Indonesia) — January 2023," n.d.).

Several recorded pyrolcastic flow events indicate that the mechanism of pyroclastic flow originates from an avalanche at the end of lava flow. Eruptive events accompanied by pyroclastic flows were recorded for the first time during the 1967 eruption from the Kawah Utama (Table 1).

On 7-9 May 2015 the eruption of Karangetang volcano released pyroclastic flows which predominantly flowed towards Batuawang River as far as a maximum of 3.6 km to the South and caused damage to residential areas in Ds Kora kora and many as 465 people were displaced (Patria et al., 2015) (BNPB, 2015).

As a form of mitigation in the aspect of volcanic disaster, it is important to know the type and zoning of a disaster from a volcanic eruption activity and numerical simulation is an effort in preparing for a volcanic eruption to determine the zoning affected by pyroclastic flows.

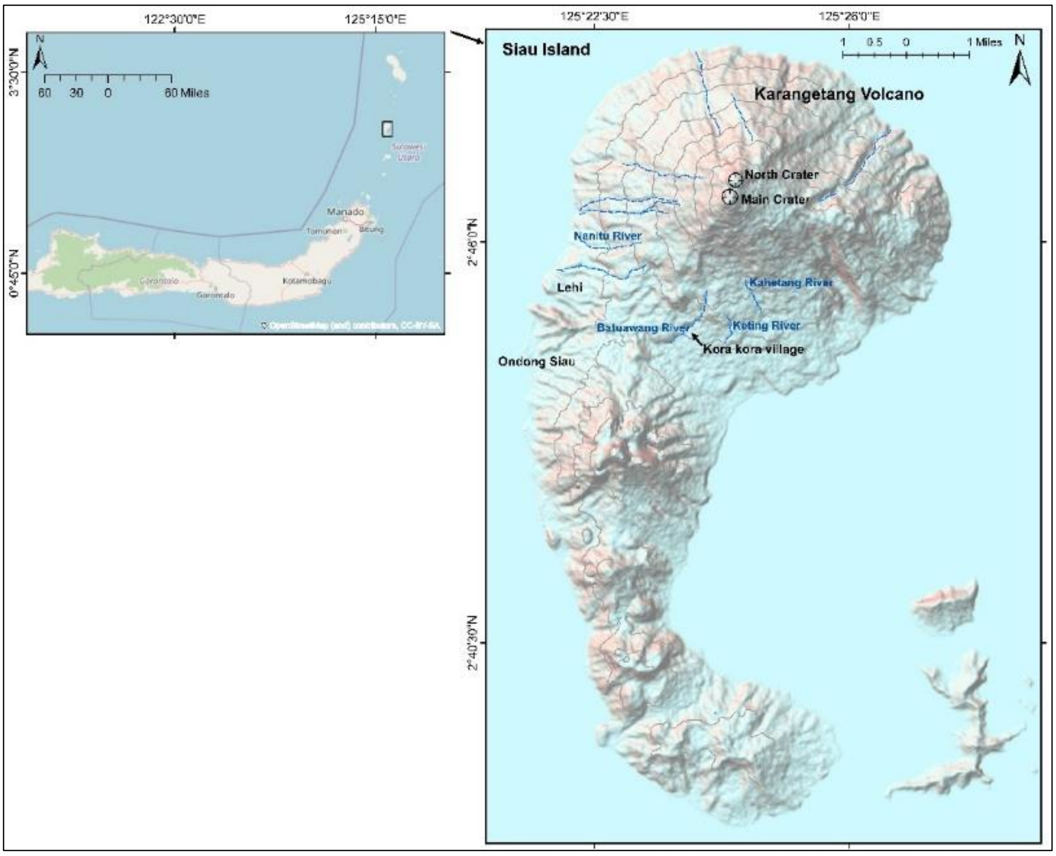

Fig 1. Location of Karangetang volcano in Siau Island, North Sulawesi

Tabel 1. Karangetang volcano pyroclastic flow events since 1967

Date	VEI	Pyroclastic flow
29/11/1967	2	incandescent lava and followed by pyroclastic flows originating from the avalanches.
23/10/1976	2	avalanche of incandescent lava which produced pyroclastic flows
5/9/1984	2	Lava flow avalanche formed pyroclastic flows into River Beting, Batuawang and River Beha.
31/12/1985	2	Pyroclastic flows into River Keting
6/2/1987	2	Burst of incandescent lava material accompanied by pyroclastic flows as far as 1500 meters.
25/10/1988	2	Explosive eruptions were followed by incandescent lava spewing, then followed by avalanches and formed pyroclastic flows.
8/8/1989	2	Lava avalanche and generate pyroclastic flows into River Beha.
Mei 1992	2	Pyroclastic flow towards River Beha Timur, 6 people deaths, 1 burn.
Juni 1997	1	Pyroclastic flow hit Ds Dame. 3 people died.
20/03/1998	1	Pyroclastic flow towards KKeting Riveras far as 1000 m.
25/06/2001	2	Pyroclastic flow from Kawah Utama. 1 person injured by surge.
15/04/ 2003	2	Pyroclastic flow towards River Batang as far as 2250 m.
16/02/2005	2	Pyroclastic flow towards River Nanitu as far as 3400 m.
27/09/2010	3	Explosive eruption with lava avalanche and generate pyroclastic flow towards Batuawang River
18/03/2011	2	Pyroclastic flow towards River Pangi and River Nanitu.
*7/05/2015	2	Pyroclastic flow towards Batuawang River in south, with 3,6 km distance and hit Kora kora village.

Source: (Kusumadinata et al., 1979) (Pusat Vulkanologi dan Mitigasi Bencana Geologi, 2014) ("Global Volcanism Program | Report on Karangetang (Indonesia) — February 2017," n.d.)

The pyroclastic flow event on 7 May 2015 reached a maximum distance of 3600 m towards Batuawang River, with seismic amplitude reaching greater than 52 mm (overscale). The ramp distance decreased about 2200-3000 m on 8-9 May 2915, with maximum seismic amplitude of 52 mm, the direction still dominates towards Batuawang River (Table 2).

To find out the application of this numerical simulation in pyroclastic flows, we tried to carry out a numerical simulation of the Karangetang Volcano eruption activity in the period May 2015.

In carrying out numerical simulations it is important and necessary to pay attention to and understand the systematics in the simulation procedure, as well as the parameters and conditions/factors that influence controlling the behavior of a flow, so that it can be used as a guide for disaster mitigation (H Itoh et al., 2000), and then by using these parameters conditions/factors, we estimated the possibility of pyroclastic flows that could occur in the future taking into account the Karangetang Volcano activity at this time. This, so that it can be estimated the affected area and the length of time a pyroclastic flow reaches a certain settlement. We will also discuss several conditions/factors that influence the simulation. results. This will certainly assist in the planning and implementation of disaster mitigation for the Karangetang volcanic eruption in the future.

As information on the volume of pyroclastic flow events in May 2015, we use calculated hotspot data, and with rock friction and particle diameter data based on model (Yamashita and Miyamoto, 1993), and to estimate the potential for future pyroclastic flows, we used visual data of the lava dome in 2019.

Table 2. Chronology event of Karangetang Pyroclastic Flow at 7-9 May 2015

Date	Time	Visual		Seismicity		Remarks
		Direction	Distance (m)	Duration (s)	Amplitudo (mm)	
7 May 2015	15.52	South	3000	240	52 (overscale)	Pyroclastic flow towards Batuawang River. Evacuation people in Ds Kora2 in south of Kawah Utama.
	16.24	South	3000	330	52 (overscale)	Pyroclastic Flow towards Batuawang River
	16.55	South	3600	1830	52 (overscale)	Pyroclastic Flow towards Batuawang River
	17.32	South	3600	105	25-50	Pyroclastic Flow towards Batuawang River
	17.34	South	3000	150	25-50	Pyroclastic Flow towards Batuawang River
	17.39	South	3000	170	15-50	Pyroclastic Flow towards Batuawang River
	17.44	South	3000	180	30-52	Pyroclastic Flow towards Batuawang River
	17.57	South	2500	60	25-50	Pyroclastic Flow towards Batuawang River
	18.01	South	3000	170	30-50	Pyroclastic Flow towards Batuawang River
	18.07-24.00	South	2200	145	52	Lava avalanche towards Batuawang River and Keting River. Sesmograf records 16 pyroclastic flows. Volcanic ash fell on south-southeast in Tatahedeng, Dame, Karalung and Kanang.
8 May 2015	00.00-06.00	-	-	115	52	Karangetang volcano covered in fog. Seismograph recorded 7 pyroclastic flow.
	06.00-12.00	South	3000	75-260	40-52	Ash plume 200 m height from Main Crater (Kawah Utama). Lava avalanche 2200 m to Batuawang River, 2000 m to Kahetang River and Keting River. 5 pyroclastic flow recored in seismograph.
	12.00-18.00	South	3000	-	-	3 pyroclastic flows towards Batuawang River recorded in Seismograph.
	18.00-24.00	South	3000	-	-	5 pyroclastic flows towards Batuawang River recorded in Seismograph
9 May 2015	00.00-12.00	South	3000	-	-	12 pyroclastic flows towards Batuawang River recorded in Seismograph. Ash fall in Beong, Kanawong, Lehi, Mini, Kinaliu, Hung and Kiawang.
	12.33	South	2500	180	25-52	Pyroclastic Flow towards Batuawang River
	12.38	South	2500	110	25-52	Pyroclastic Flow towards Batuawang River
	12.41	South	2500	180	13-52	Pyroclastic Flow towards Batuawang River
	12.43	South	2500	200	22-52	Pyroclastic Flow towards Batuawang River
	12.47	South	3000	120	30-52	Pyroclastic Flow towards Batuawang River
	12.53	South	3000	120	20-52	Pyroclastic Flow towards Batuawang River
	12.58	South	3000	200	20-52	Pyroclastic Flow towards Batuawang River
	13.01	South	2500	65	20-45	Pyroclastic Flow towards Batuawang River
	13.05	South	2500	70	15-49	Pyroclastic Flow towards Batuawang River
	14.50	South	3000	115	25-45	Pyroclastic Flow towards Batuawang River
	14.53	South	3000	350	35-52	Pyroclastic Flow towards Batuawang River
	15.01	South	3000	115	30-52	Pyroclastic Flow towards Batuawang River
	15.07	South	3000	70	15-30	Pyroclastic Flow towards Batuawang River
	15.13	South	3000	130	30-45	Pyroclastic Flow towards Batuawang River
	15.20	South	3000	140	30-52	Pyroclastic Flow towards Batuawang River
	15.30	South	3000	140	30-52	Pyroclastic Flow towards Batuawang River
	15.33	South	3000	130	28-52	Pyroclastic Flow towards Batuawang River
	15.38	South	3000	140	20-50	Pyroclastic Flow towards Batuawang River
	15.40	South	3000	110	22-50	Pyroclastic Flow towards Batuawang River
	15.42	South	3000	185	30-52	Pyroclastic Flow towards Batuawang River
	15.46	South	3000	170	30-52	Pyroclastic Flow towards Batuawang River

Source: (Patria et al., 2015)

2. Method

2.1 Lava volume estimation in May 2015

According to (Kriswati and Alfianti, 2019) volume and extrusion rate of lava in Karangetang volcano in 2000 until 2019 show an increase in 2018-2019, and in 2015 period volume lava reached 1.6 x 10^7 with discharge rate 0.58 m^3/s. To obtain an estimate of the volume lava released during the May 2015 eruption periode, we calculated the volume of lava cummulativ and the extrusion rate for the period Januray 2015 until December 2015 using hotspot data obtained from MODIS satellite imagery using band 21 and band 23. The data was then processed using the MODVOLC algorithm to obtain volume estimates during the May 2015 pyroclastic flow event. The algorithm used is the Modvolc method to detect heat anomalies in MODIS satellite in MODIS satellite images in near real time using infrared data with low spatial resolution (1km/pixel).

Hot spots will be detected if they have an NTI (Normalized Temperature Index) value greater than 0.8. Hotspot data can be used to estimate the temperature and volume flux associated with volcanic activity (Wright et al., 2004).

According to (Oppenheimer et al., 1993) to determine the area of hot lava flow with the surrounding area, it can be done by assuming that one hot spot pixel that has a temperature T_h is in a cooler temperature T_b . The combination of these two temperatures will produce T_{in} or integrated temperature.

$$L(T_{in}\lambda) = pL(T_{\square}\lambda) + (1-p)L(T_b\lambda)$$

Where L is the Plank function on a black body/black background, λ and p refers to wavelength.

To determine the flux volume using the method developed by Harris and Ripepe (2007). Flux volume E is the ratio of total heat capacity, post-extrusion cooling and heat of crystallization.

$$E: \frac{Q_{tot}}{\rho(c_p \Delta T + L\mu)}$$

Q_{tot} : Total radiation heat flux and convection heat flux

$Q_{rad} = A\sigma\varepsilon T_{\square}^{4}$ dan $Q_{conv} = h_c(T_h - T_{air})$

$\sigma = 5.67x10^{8}$W m^{-2} K^{-4}

ε =rock emissivity.

2.2 **Numerical Simulation Model of Pyroclastic Flow**

Pyroclastic flow is a turbulent mass and gas with high pressure and low particle concentration that can occur through the mecanism of eruption column collapse, direct ash flow from summit, and also direct flow from the crater without an accompanying vertical eruption column (Fisher, 1979), this mass and gas flow according to their density relative to the surrounding fluid and due to earth gravity (Branney and Kokelaar, 2002), and by using numerical simulations for pyroclastic flows we can improve the analysis of potential volcanic disasters and minimize damage, especially in residential areas (Baxter et al., 1998).

In this paper we use the numerical model developed by (Yamashita and Miyamoto, 1993) with basic development derived from the equations made by (Kanatani, 1984). This numerical model has been used to simulate several volcanic pyroclastic flows events in Indonesia including Merapi eruption in November 1994 (H. Itoh et al., 2000), pyroclastic flows events in Semeru on December 2002 (Shimomura et al., 2019a), pyroclastic flows events historical of Merapi (Rukmini et al., 2019), and Merapi eruptions on November 2010 (Shimomura et al., 2019b).

Pyroclastic flows are divided into 2 layers parts. The basal layer has characteristics in the form of mass gravity flow of material from coarse grains, then the upper layer contains finer materials (as clouds), which is influenced by turbulent air generated by high-speed movement of the lower layers.

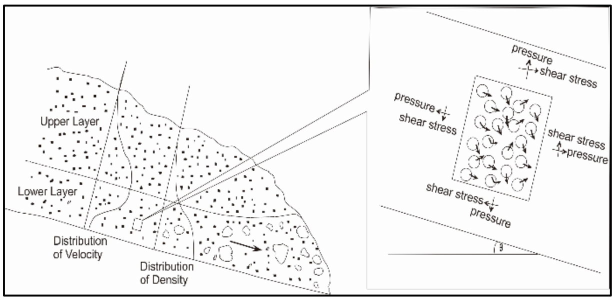

Fig 2. Schematic of pyroclastic flow model by (Yamashita and Miyamoto, 1993).

Basal part of the flow, material particles will collide with each other, resulting in pressure and shear stress. The pressure and shear stress are described by the equation developed by Kanatani (1984) as:

$$P = \frac{1}{200}\frac{c}{1-\left(\frac{c}{c^*}\right)^{\frac{1}{3}}}T_e\sigma D^2\left(\frac{\partial u}{\partial z}\right)^2 \ldots\ldots\ldots .1$$

$$\tau = \frac{3}{200\sqrt{10}}\frac{c^{\frac{3}{4}}}{1-(c/c^*)^{\frac{1}{3}}}T\mu\sigma D^2\left|\frac{\partial u}{\partial z}\right|\left[\frac{\partial u}{\partial z}\right] \ldots\ldots .2$$

$$c = \left(\frac{\sqrt{10}}{3}\frac{i_e}{\mu}\right), i_e = \frac{\tau}{P} \ldots\ldots .3$$

With P is the flow pressure and τ is the flow shear stress. $\frac{\partial u}{\partial z}$ velocity gradient, z axis perpendicular to the plane of flow. T_e is flow constant, i_e flow potential energy, σ particle density, D particle diameter, μ friction coefficient material, c^* particle concentration volume, c particle concentration.

Numerical Equation for Mass flow:

(Flow mass conversation)

$$\frac{\partial\square}{\partial t} + \frac{\partial\bar{u}\square}{\partial x} + \frac{\partial\bar{v}\square}{\partial y} = 0 \qquad (4)$$

(Particle mass conversation)

$$\frac{\partial c\square}{\partial t} + C_x\frac{\partial z}{\partial t} + \frac{\partial c\bar{u}\square}{\partial x} + \frac{\partial c\bar{v}\square}{\partial y} = 0 \qquad (5)$$

(Flow momentum conversation)

$$\frac{\partial\bar{u}\square}{\partial t} + \beta\frac{\partial\bar{u}\bar{u}\square}{\partial x} + \beta\frac{\partial\bar{v}\bar{u}\square}{\partial y} = -g\square\frac{\partial(\square + z)}{\partial y} - \frac{F}{\rho}\bar{u}\sqrt{\bar{u}^2 + \bar{v}^2} \qquad (6)$$

$$\frac{\partial\bar{v}\square}{\partial t} + \beta\frac{\partial\bar{u}\bar{u}\square}{\partial x} + \beta\frac{\partial\bar{v}\bar{v}\square}{\partial y} = -g\square\frac{\partial(\square + z)}{\partial y} - \frac{F}{\rho}\bar{u}\sqrt{\bar{u}^2 + \bar{v}^2} \qquad (7)$$

(Friction coefficient)

$$F = \frac{3}{32\sqrt{10}}.\frac{c^{\frac{3}{4}}}{1-\left(\frac{c}{c_x}\right)^{\frac{1}{3}}}Te\sigma\left(\frac{D}{\square}\right)^2 \qquad (8)$$

$$c = \left(\frac{\sqrt{10}}{3}.\frac{i_e}{u}\right)^3 \qquad (9)$$

With equation 1 is an equation for calculating mass flow which is the development of a form model to describe material movement in the 2D shallow flow model. Equation 2 is an equation for calculating the concentration of flow mass particle. Equation 3, 4 and 5 are equations for calculating the mass momentum of the flow, with h is the thickness, $\bar{v}\square$ and $\bar{u}h$ is the discharge flux at the x and y positions, c is the particle concentration, F is the friction coefficient, $\bar{v}$ and $\bar{u}$ is the average velocity at x and y positions, and D is the particle diameter.

Sedimentation process of pyroclastic flow particles is described in equations 6-9. The deposition of flow particle mass occurs gradually, with h is the thickness of the flow mass and $\bar{u}$ are the average velocity of the flow in the x direction and $\bar{v}$ are the average velocity of the flow in the y direction, respectively, and z is the base elevation of the flow field. Then, β is the momentum correction constant. The sedimentation mechanism of the pyroclastic flow mass is explained through equations 8 and 9. The sedimentation process occurs when the potential energy of the particle mass flow decreases. The decreasing energy gradient quickly reduces the mass concentration of particles, so that the flow cannot retain the particles which then causes the sedimentation process. This also means that the friction coefficient constant μ is a factor that determines the extent of the mass flow and the area affected.

2.3 Parameters and boundary conditions

Some questions that need to be answered in pyroclastic flow disaster mitigation efforts are from which side of the peak, or lava dome, or the end of the lava flow that allows pyroclastic flows to occur, in which direction the flow will flow, how much volume will flow, and when it will occur. These questions can be answered by continuous monitoring efforts, and numerical simulation can be a tool to answer where the flow will occur, in which direction, and how much volume and affected areas.

Numerical simulations are run with input parameters in the form of topographic data, volume, discharge rate, time duration, coefficient of friction, flow direction and width of the groove opening. The topographic data that we use in this simulation is Aster GDEM2 data with a resolution of 30 m which we then increase the resolution to 15 m with the aim that the simulation is more accurate, and represents the topography before 2015 eruption (Figure 3).

Discharge rate is a function of volume and time ratio, and based on Table 2, the seismic data shows that pyroclastic flows event occurred during 7-9 May 2015 with the flow time ranges from 60-1830 seconds, in this simulation we used 5 minutes for input with the total time required for the flow to completely stop is 120 minutes .

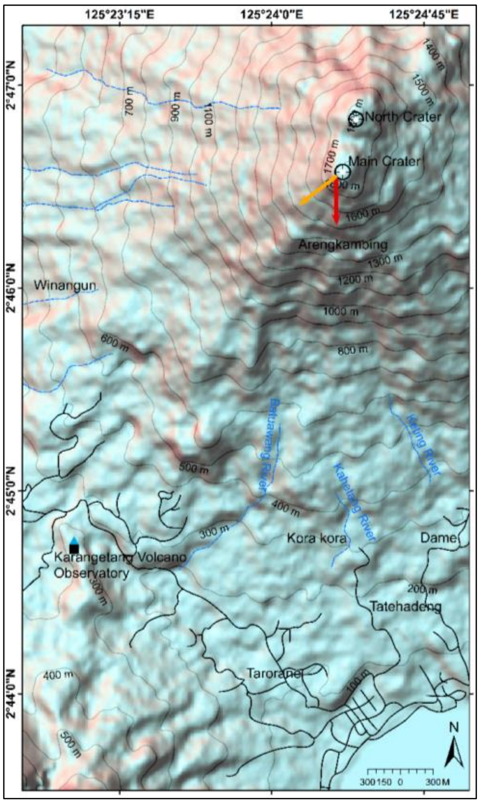

Fig 3. Topography of the Southern part of Karangetang volcano, inflow point and flow direction for 2015 pyroclastic flow simulation (red arrow), and potentially future pyroclastic flow (orange arrow).

As volume input data, we used the heat anomaly data at the surface, and considering the chronology of pyroclastic flow events that occurred more than once (Table 2), that the lava dome did not collapse all at once, we conducted the 2015 pyroclastic flow as 8 cases and particle diameter 30 cm, with an estimated coefficient of friction of 0.5 and 0.7, gradient inflow point 45 with particle density of 2.6 g/cm^3 (Table 4).

3. Results

3.1 Chronology of the eruption in May 2015

The activity level of Karangetang Volcano was raised from Standby (Waspada) to Alert (Siaga) on September 3, 2013 until the end of April 2015. Visually during January-April 2015, incandescent lava flows from the Main Crater towards the river located southeast of the peak which flows towards the south, namely Batuawang River, Keting River, Kahetang River, and Beha Timur River. The distance of the lava avalanched reached 2200 m. According to Patria et al (2015) by visual observation, the activity of Karangetang Volcano in the period April 30-May 18, 2015 was generally in the form of incandescent lava flows from the tip of the lava tongue (Figure 4), and sometimes accompanied by the occurrence of pyroclastic flow heading south towards the Batuawang River path. On April 29-April 30, 2015 incandescent lava flows from the Main Crater towards Batuawang River, Kahetang River, and Keting River as far as 450-2000 m. On 1-4 May 2015, incandescent lava flows to Batuawang River for 1000 - 2200 m, to Kahetang River for 1000 - 2000 m, and to Keting River for 1000 - 2000 m. This activity continued until May 6, 2015 with a distance of 2200 m to Batuawang River, and as far as 1000-2000 to Kahetang River and Keting River, on May 7, 2015 the evacuated population reached 465 people (Patria et al., 2015) ("Global Volcanism Program | Karangetang," n.d.) (BNPB, n.d.).

According to Patria et al (2015) on May 7, 2015, observed pyroclastic flow to Batuawang River as far as ± 3,600 m. Pyroclastic material buried the sabo dam in Kora-Kora village and the direction of the pyroclastic flow turned towards residential areas, so that one house was destroyed and three houses were covered with thick ash. The results of checking the situation on the southern slope, precisely in Batuawang River and Kora kora villages in 2016 and 2019 (Figure 5), confirm this.

1 May 2015, 08:02 PM

2 May 2015, 08:09 PM

3 May 2015, 08:37 PM

4 May 2015, 07:42 PM

Fig 4. Incandescent lava on May 1-4, 2015. Photographed from Karangetang Volcano Observatory. Photos taken by Cahya Patria during crisis in May 2015.

As shown in Figure 5, pyroclastic flow deposits in the form of boulders and fine-sized ash particles reached Kora kora village, roads and residential areas within 200 meters of the Batuawang river were hit and severely damaged (Location 1) and (Location 3). Pyroclastic deposits reached the sabo dam (Location 2), and at (Location 4) there was a deflection of pyroclastic flow, some of the pyroclastic flow came out of the river channel, and flowed to (Location 3) and (Location 1). Since 2016, the Batuawang river channel and pyroclastic flow deposits on the riverbanks have become the location of sandstone mining activities (Location 3). And the excavation starts around (Location 4) and continues towards the sabo dam (Location 2). Main flow of Batuawang River shows in (Locations 2,5,6, and 7), and (Location 7) shows the limit of lava flow in 2019 period that has reached the upper reaches of Batuawang River.

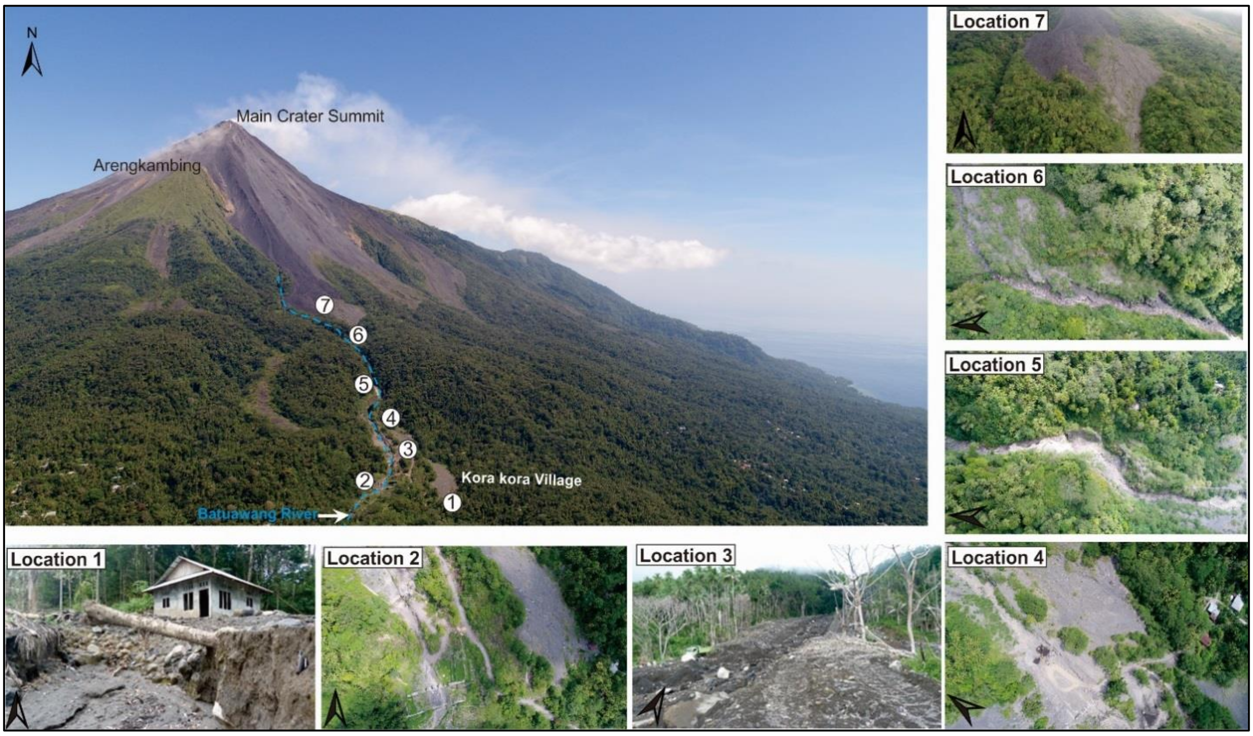

Fig 5. Situation of Kora kora village and Batuawang River south of the Main Crater of Karangetang Volcano. Location 1 and 3 in 2016, while the main image and locations 2, and Location 4-7 were taken using a drone in 2019. Photos taken by Willi in May 2016 and October 2019

3.2 Lava volume estimation in May 2015

Strong thermal anomalies were detected from January 12 to February 1, 2015. This heat anomaly was then detected to reappear on April 24 to June 11, 2015 ("Global Volcanism Program | Karangetang," n.d.). In the early period of 2015 the rate of lava ejection of Karangetang Volcano decreased, and reached its lowest point in April 2015, with an estimated volume on May 15, 2015 reaching 3.18 x 10^6 m^3, (Table 3). The trend of lava discharge rate (Figure 6) and volume (Figure 7) increased from May 2015 to December 2015, and this is in line with the analysis of Kriswati and Alfianti (2019) that the rate of lava extrusion in the 2000-2019 period tends to increase due to lava glide activity, especially in the 2011 and 2015 eruption periods, with eruptive activity issued dominant lava flows from the Main Crater, towards the west-southwest (Santoso et al., 2022).

Tabel 3. Total volume and rate of lava ejection of Karangetang Volcano during January-December 2015

Date	Total Volume(m3)	Discharge Rate (m3/s)
20/01/2015	2.07E+06	1.30
01/02/2015	8.13E+03	0.77
22/04/2015	9.33E+05	0.66
15/05/2015	3.18E+06	1.31
07/06/2015	2.23E+05	0.28
14/07/2015	3.16E+05	0.17
20/08/2015	2.25E+06	1.24
17/09/2015	3.43E+06	1.41
15/10/2015	8.82E+05	0.34
10/11/2015	1.49E+03	0.14
09/12/2015	4.23E+04	0.03

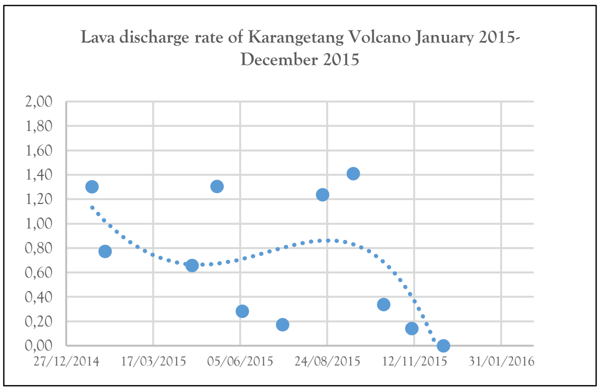

Fig 6. Lava discharge rate Januari-Desember 2015

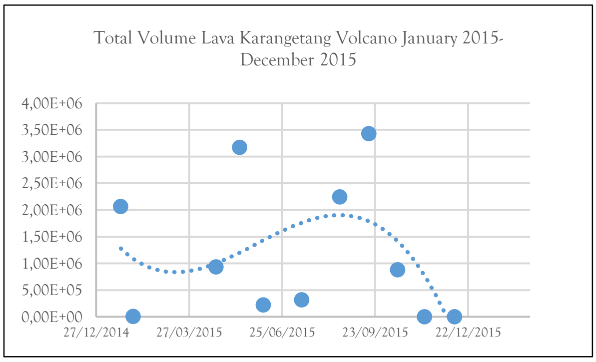

Fig 7. Total volume lava Januari-Desember

3.3 Simulation 2015 pyroclastic flow

The Karangetang Volcano pyroclastic flow event on May 7-9, 2015 dominantly flowed towards River Batuawang, and a small part flowed towards Kahetang River and Keting River(Table 2). Based on the volume of thermal anomaly data (Table 3) and the chronology of pyroclastic flow events (Table 2) with the absence of official reports on the total volume of pyroclastic flow events, we made 8 cases with variations in volume and parameters and different boundary conditions, with the direction of flow to the south (Table 4).

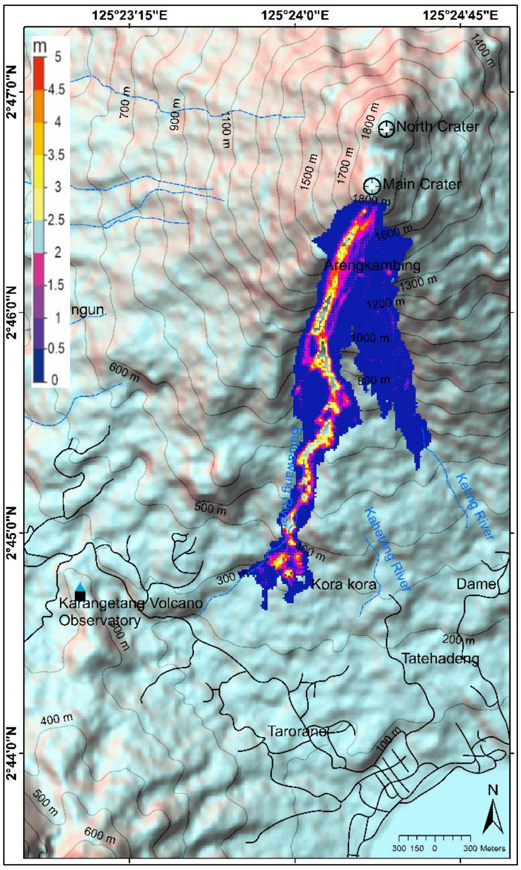

Fig 8 (a). Case 1 with 500 x 10^3 m^3 and μ 0.5

From the simulation results (Figure 8), all cases show that the flow direction flows towards River Batuawang, and a small portion of pyroclastics flows towards Kahetang River. Case 1 (Vol 500 x 10^3 m^3 , μ 0.5) reached a distance of 3.68 km and reached Kora kora Ds. Case 2 (Vol 500 x 10^3 m^3, μ 0.7) reached a distance of 3.35 km. Case 3 (Vol 1000 x 10^3 m^3, μ 0.5) reach distance reached 3.88 km. Case 4 (Vol 1000 x 10^3 m^3, μ 0.7) range distance reached 3.72 km. From the simulation results (Figure 8), all cases show that the flow direction flows towards River Batuawang, and a small portion of pyroclastics flows towards Kahetang River. Case 1 (Vol 500 x 10^3 m^3 , μ 0.5) reached a distance of 3.68 km and reached Kora kora villages. Case 2 (Vol 500 x 10^3 m^3, μ 0.7) reached a distance of 3.35 km. Case 3 (Vol 1000 x 10^3 m^3, μ 0.5) reach distance reached 3.88 km. Case 4 (Vol 1000 x 10^3 m^3, μ 0.7) range distance reached 3.72 km. Case 5 (Vol 1500 x 10^3 m^3, μ 0.5) reached a distance of 4.61 km reaching Tatehadeng, and at an altitude of 300-400 meters some pyroclastic flows flowed southwestward for 983 meters. Case 6 (Vol 1500 x 10^3 m^3, μ 0.7) a range of 4.49 km reached Tatehadeng, and at an altitude of 300-400 meters some pyroclastic flows flowed southwest for 521 meters. Case 7 (Vol 2000 x 10^3 m^3, μ 0.5) reach distance 4.83 km reached Tatehadeng, 2.2 km towards the Kahetang River and at an altitude of 300-400 meters, some pyroclastic flows flowed southwestward for 1031 meters. Case 8 (Vol 1500 x 10^3 m^3, μ 0.5) reach distance 4.80 km reached Tatehadeng, 2.2 km towards the Kahetang River and an altitude of 300-400 meters, some pyroclastic flows flowed southwestward for 651 meters.

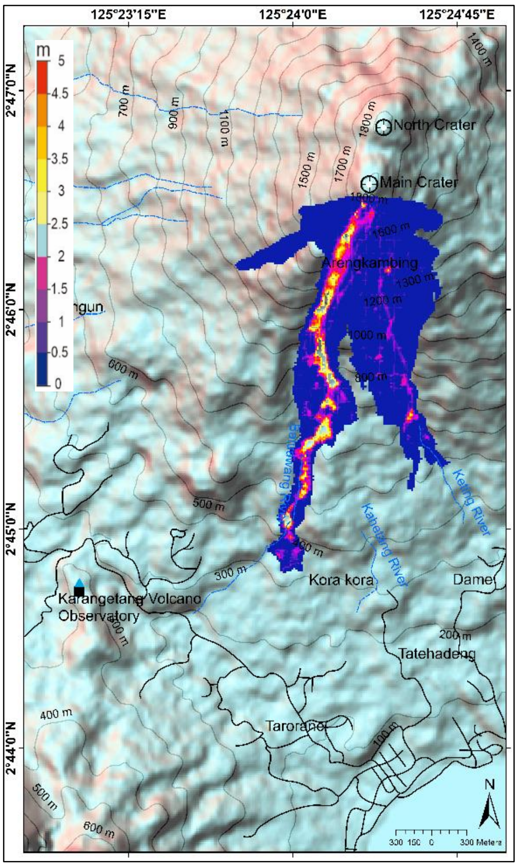

Fig 8 (b). Case 2 with 500 x 10^3 m^3 and μ 0.7

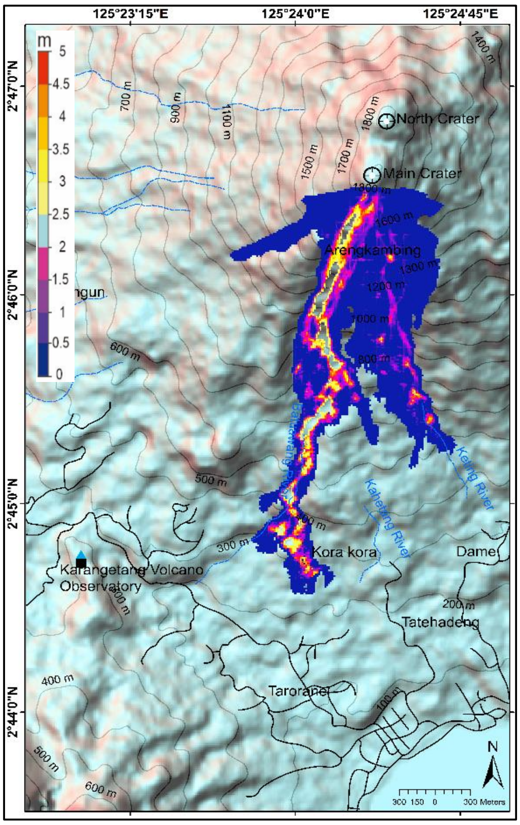

Fig 8 (c). Case 3 with 1000 x 10^3 m^3 and μ 0.5

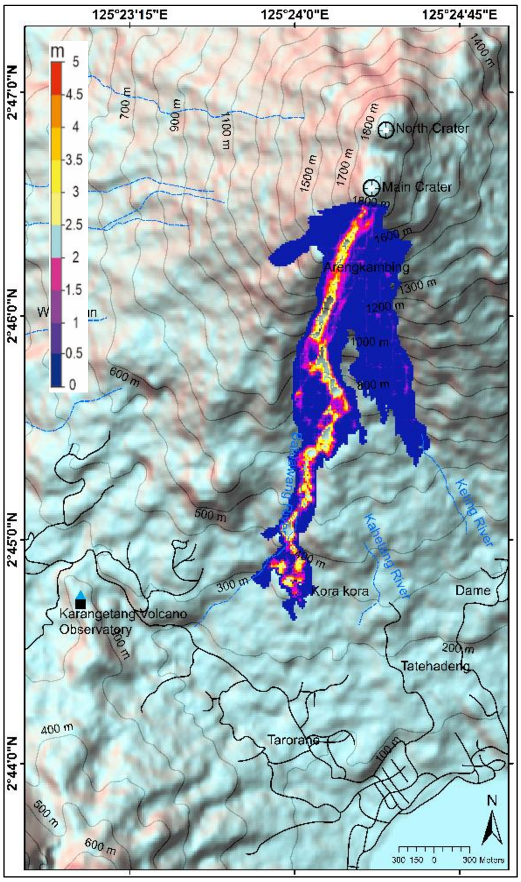

Fig 8 (d). Case 4 1000 x 10^3 m^3 with μ 0.7

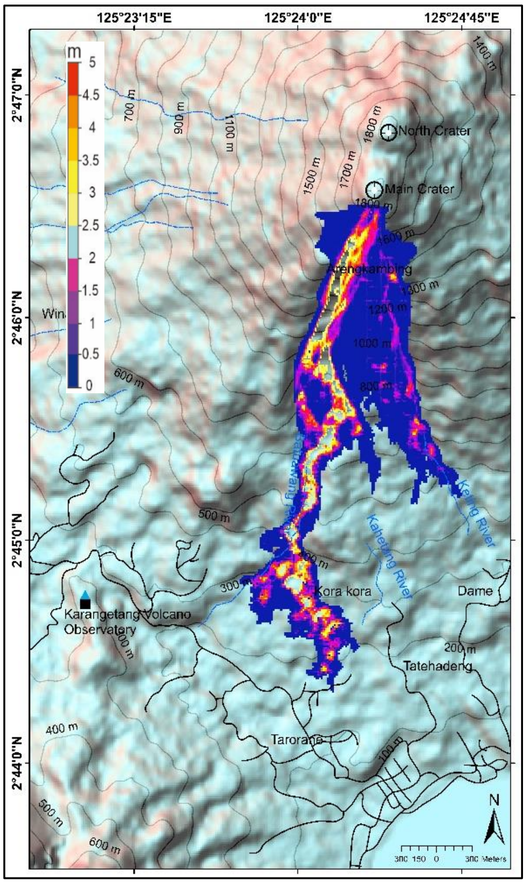

Fig 8 (f). Case 6 1500 x 10^3 m^3 with μ 0.7

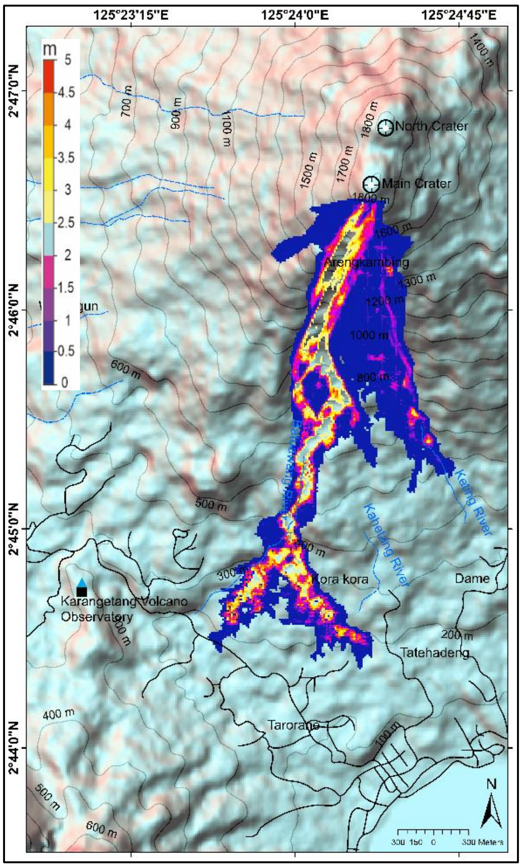

Fig 8 (e). Case 5 1500 x 10^3 m^3 with μ 0.5

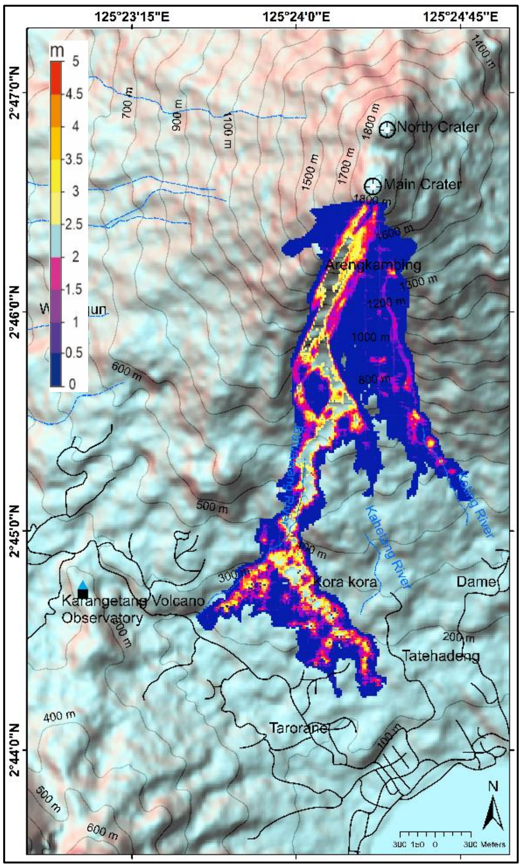

Fig 8 (g). Case 7 2000 x 10^3 m^3 with μ 0.5

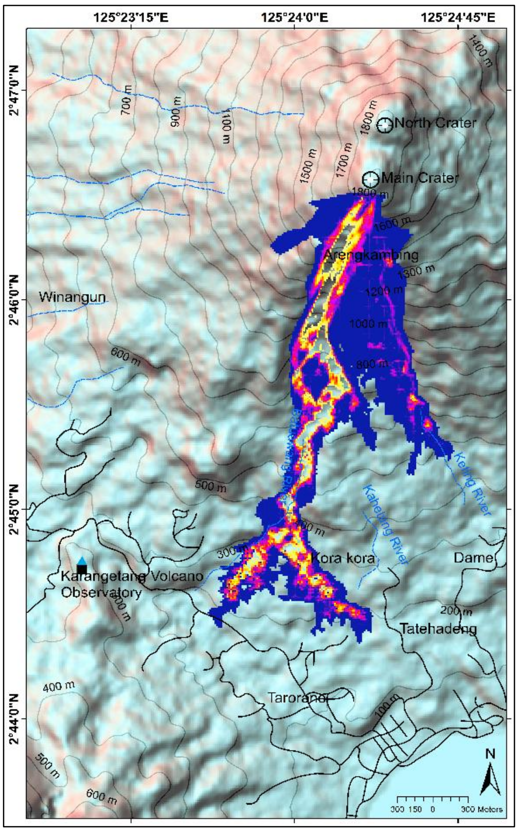

Fig 8 (h). Case 8 2000 x 10^3 m^3 with μ 0.7

3.4 Assessment for Potential future Pyroclastic flow along westsouth slope

After the May 2015 pyroclastic flow event, Karangetang Volcano activity tended not to stop. June-December 2015 period lava flows and some pyroclastic flow events still occurred towards River Batuawang, and a small part of the pyrocalstic flow towards Kahetang River and Keting River. In the period of January 2016 activity tended to decline, dominated by plume smoke from the Main Crater, a silent fire point was observed at the top of the Kawah Utama February-March 2016, and on March 16, 2016 PVMBG lowered the status from Siaga to Waspada. On May 10, 2017 a gas-and-steam plume apparently containing ash rose to an altitude of 3.6 km and drifted over 35 km SE, and on October 10, 2017 sulfuric smoke rose 200 m from the Main Crater and several tremors have occurred. Explosive eruption accompanied by an ash plume as high as 600 m from the Kawah Utama, which was accompanied by incandescent flames from the Main Crater on February 2, 2018.

Fig 9. Visual of the summit of G.Karangetang showing gusts from both craters at the summit of approximately 200 m. Photographed by Willi from Hiung Village. December 7, 2019.

After ± 2 years of rest, in November 2018 G. Karangetang erupted again characterized by the occurrence of a Strombolian eruption as high as 500 meters above the North Crater (Crater Two) and the occurrence of incandescent lava to the Sumpihi river (west of the North crater), volcanic activity increased, so on December 20, 2018 at 18:00 ;WITA the activity level became Level III (Alert). Increased activity continued into 2019, lava flows from the North Crater flowed towards Batubulan and reached the sea in February 2019. Throughout the 2019-2023 period CVGHM reported increased visual activity and seismicity. Smoke plumes emerged from both craters, the main crater and the North Crater (Figure 9). The period 2019 to 2023 was dominated by the formation of lava domes in the Main Crater (Figure 10), lava flows, and lava avalanches in 2019 (Figure 11), and 2023 (Figure 12).

Fig 10. Visual of Lava Dome on Karangetang Peak, precisely on the Main Crater Peak in the South. Photographed by Willi from Karangetang Volcano Observatory, December 3, 2019.

Fig 11. Effusive eruption in the form of strombolian (25m high flames) followed by lava flows towards southwestern slopes. Photo taken by Richard Korompis in December 2019 from Karangetang Volcano Observatory.

Fig 12. Lava avalances to southwest and south in Juni 2023. Photo by David Adriansyah in June 2023 from Karangetang Volcano Observatory.

3.4.1 Hazard assesment along westsouth slope

Based on recent activity, we estimated the potential pyroclastic flows that will occur later will flow to the southwest, and simulated pyroclastic flows to determine the range and area of land that is likely to be affected later.

Table 5. Input parameters for potentially area on southwest slope

Case	Spatial Resolution (m)	Volume ($x10^3$ m^3)	Friction factor (μ)	Discharge Rate (m^3/s)	Maximum Particle Diameter (cm)	Direction	Duration (minute)	Gradient inflow point
1	15	500	0.5	1600	30	Southwest	5	45
2	15	1000	0.5	3300	30	Southwest	5	45

Considering the simulation results in (Figure 8), we used the same parameters and boundary conditions to simulate the collapse of the lava dome from the main crater to the Southwest. The parameters and boundary conditions can be seen in Table 5. Simulations were conducted with 2 different cases to see the relationship between volume variation, friction coefficient, and impact area distance. According to the current condition, the activity of Mount Karangetang dominantly emits lava from the Main Crater, in the south. The simulation results can be seen in Figure 13 (a) and Figure 13 (b).

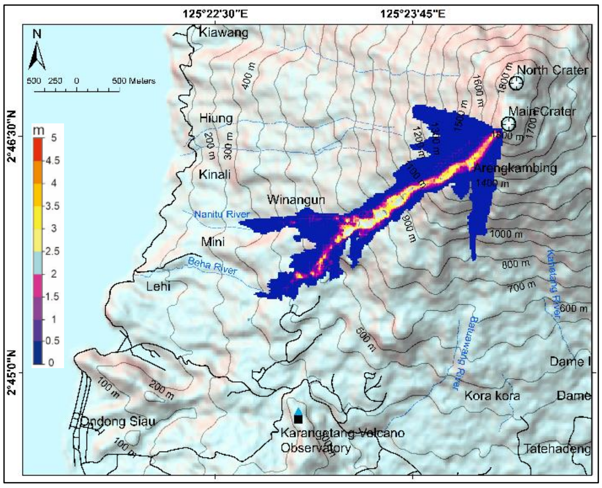

Fig 13 (a). Case 1 with 500 x 10^3 m^3 and μ 0.5

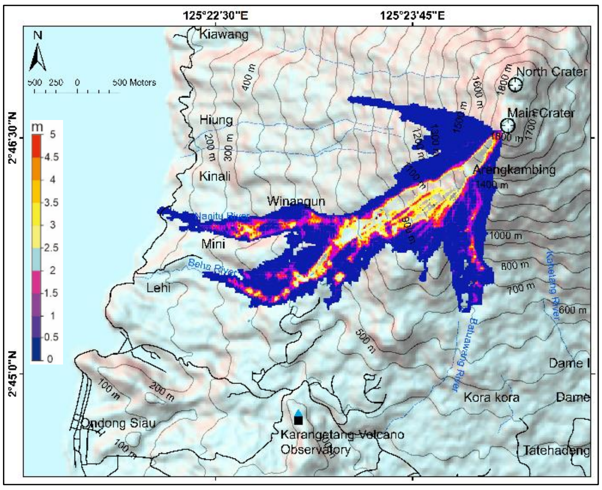

Fig 13 (b). Case 2 with 1000 x 10^3 m^3 and μ 0.5

Case 1 (Vol 500 x 103 m3, µ 0.5) pyroclastic flow flowed southwest, and divided into two flow directions at an altitude of 700 m. The direction of the flow was toward the Beha River for 3.43 km, and toward the Nanitu River for 3.04 km. Towards the Beha River it flows for 3.43 km, and towards the Nanitu River for 3.04 km. Case 2 (Vol 1000 x 103 m3, µ 0.5) pyroclastic flows flowed southwest, to Nanitu River for 4.18 km, to Beha River for 4.47 km, and a small part of the pyroclastic flows flowed south, to Batuawang River for 2.18 km.

5. Discussion

According to Kriswati and Alfianti, (2019) MODIS satellite imagery can be the primary data in monitoring the rate of lava extrusion, but has several weaknesses, including the possibility of not recording data due to weather and conditions at the top of the volcano, as shown in Table 3 shows data in March 2015 was not recorded. This condition can be caused by rainy weather, or the peak is covered with fog, and also smoke emissions from the peak. Santoso et al. (2022) stated that conditions at the peak due to fog, and thin clouds can cause bias, and this can be overcome by using high-resolution satellite imagery.

Fig 14. White gas-and-steam plumes emanating from two craters at Karangetang at 0630 on 16 November 2018. Courtesy of MAGMA Indonesia via Øystein Lund Andersen in ("Global Volcanism Program | Report on Karangetang (Indonesia) — May 2019," n.d.)

Fig 15. Lava flow from the North Crater flowing northwest to the sea and causing a cut-off road to Batubulan Village. Photographed by Willi using drone in October 2019.

Based on MODIS satellite image data, the volcanism period of Karangetang Volcano shows an increase in lava extrusion rate and volume throughout 2015, with its activity centered on the Main Crater in the South. This volcanic activity began from June 2014 to March 2016 in the form of intermittent ash puffs, lava flows, lava avalanched, and continuous thermal anomalies from a slowly growing lava dome south of the highest peak in Main Crater (“Global Volcanism Program | Report on Karangetang (Indonesia) — May 2018,” n.d.).

Volcanism activity of Karangetang Volcano in the period before 2018 was generally centered on the Main Crater. The North Crater began to show activity on November 16, 2018 with white gas and steam coming out of two craters in Karangetang at 06:30 on November 16, 2018. (Figure 14).

The activity of the North Crater continues to release lava flows to the northwest, towards Batubulan Village and continues to the sea and causes the main route to Batubulan Village to be cut off in Februari 2019 (Figure 15). Meanwhile, in the period 2018 to 2019, the Main Crater also emitted lava flows to the west and it is estimated that the lava flow is 1 km from the nearest village, namely Hiung Village (Figure 16).

When compared to the numerical simulation of pyroclastic flows in Figure 8, with lava flows originating from the tip of the lava flow tongue, if at the end of the lava flow there is a lava avalanched that produces pyroclastic flows, and even with a volume of less than 500 x 10^3 m^3 , it is likely that the resulting pyroclastic flows will reach Hiung Village and continue towards the sea.

Fig 16. Lava flow from the Main Crater towards the west, precisely to Hiung Village. Photographed by Willi using drone in October 2019.

The pyroclastic flow on May 7-9, 2015 flowed towards the Batuawang River, and the results of our numerical simulations for the pyroclastic flow event (Figure 8) on the May 7-9, 2015 eruption event show agreement with those reported by Patria et al (2015). The pyroclastic flow from the Main Crater flowed south, along the wall of Arengkambing, then at an altitude of 1000 meters, this pyroclastic flow experienced a bend in the wall of Arengkambing, for approximately 200 meters, and at an altitude of 800 meters, the pyroclastic flow then returned to flow south until it reached Kora kora Village. The pyroclastic flow began to enter the upper reaches of Batuawang River at 800 meters (Figure 5 Location 7).

Our numerical simulation results show, before reaching Kora kora Village, at an altitude of 400 meters, the pyroclastic flow is deflected, part of the pyroclastic flow continues to flow on the Batuawang River path and reaches the sabo dam (Figure 5 Location 2), and part of it is deflected towards Kora kora Village, (Figure 8 a-h) and (Figure 5 Location 4, Location 3, and Location 1). This then hit Kora kora Village, except in (Figure 8 b) with a volume of 500 x 103 m^3 and μ 0.7 pyroclastic material turned towards Kora kora Village, but did not hit Kora kora Village. his is due to the deposition process controlled by the increasing value of the coefficient of friction (μ), and this is in accordance with equation 9, with constant flow energy, the particle concentration will decrease as the μ value increases, then causing the sedimentation process.

The deflection event of the pyroclastic flow direction when entering the Batuawang River as mentioned in session 3.1, caused the flow direction to flow towards Kora kora Village, the pyroclastic flow then hit the plantation area and highway and caused damage to residential areas in Kora kora Village. From the results of our numerical simulations, this can be controlled by the flow volume, friction coefficient, flow field, and rapid deposition process, as well as the accuracy of the DEM topography used. We estimate based on the numerical simulation results that to explain the pyroclastic flow event on May 7, 2015 at 4:55 pm as described in Session 1 Table 2 is consistent with the results shown in Figure 8 a, with a volume of 500 x 10^3 m^3 and μ 0.5. In Figure 8 a, the pyroclastic flow is divided into two paths towards Kora kora Village and part of the flow continues to flow on the Batuawang River path, as well as the results in Figure 8 c,d,e,f,g, and h, deflection of pyroclastic flow direction occurs at 400 m altitude. This is in accordance with equations 6-9 which explain the process of material deposition controlled by volume and energy gradients, the topographic shape of the flow field, and the coefficient of friction. Deflection of pyroclastic flow direction occurs when the volume and gradient increase, and along with the acceleration of deposition in the topographic plane controlled by the value of the coefficient of friction, causing the river channel to narrow rapidly so that pyroclastic flows seek areas that tend to be lower, in this case then causing the direction of pyroclastic flow in the May 7, 2015 pyroclastic event (Table 2) to flow towards Kora kora Village.

Topographic changes at the summit strongly influence the direction of pyroclastic flows. These topographic changes can be controlled by the rate of lava extrusion at the summit which then causes morphological changes. The rate of lava extrusion at the top of the crater can change the shape of the morphology, which can then affect changes in the pattern of pyroclastic flow direction. In addition, changes in the collapse point can also cause changes in the direction of pyroclastic flows as happened in the 1993 Unzen Volcano eruption (Yamasato, 1997). The dynamics of the process during an eruption also affect the pyroclastic flow pattern, especially river paths that are directly connected to the summit, crater openings and lava domes (Ratdomopurbo et al., 2013). The rate of lava extrusion of Karangetang Volcano since 2015 until now, indicates that there are several possibilities for pyroclastic flows that can come from the collapse of the lava dome at the summit and also from the tip of the tongue of the lava flow, as described in Session 3.4. According to Santoso et al., (2022), the most recent lava distribution in the summit area is on the south and west sides of the Main Crater, and the west side of the North Crater. With reference to the parameters and boundary conditions of numerical simulations in Sessions 3.3 and 3.4, for the south side of the Main Crater, if pyroclastic flows occur from the center of the Main Crater to the south, and if there is a change in the point of collapse of the lava dome, then the expansion of pyroclastic flows can reach the upper reaches of the Keting River and Kahetang River to the villages of Tatehadeng and Dame (Figure 1). On the western flank of the Main Crater, changes in the collapse point of the kava dome at the summit can produce pyroclastic flows towards Hiung and Kiawang villages (Figure 13). And on the western side of the North Crater, the extension of pyroclastic flows can reach the villages of Kiawang, Niambangeng, and Nameng.

6. Conclution

The eruption of Karangetang Volcano on May 7-9, 2015, which produced pyroclastic flows and hit Kora kora Village, which is 3.6 km from the Main Crater, occurred due to the deflection of the pyroclastic flow direction in the Batuawang river channel. This deflection of pyroclastic flow direction can be explained well using numerical simulations that we have done. The results of numerical simulations show that the rapid deposition that occurs in the Batuawang River channel causes a narrowing of the flow field, so that the pyroclastic flow turns towards Kora kora Village which is only 200 meters from the Batuawang River flow. The results of field checks show that the pyroclastic flow material is block and ash flow.

Based on recent activity, there are several possibilities for pyroclastic flows to the South of the Main Crater, and West of the Main Crater and North Crater. The worst-case scenario is that if the flow does not originate from the lava dome at the summit, but from the tip of the lava tongue, then with a relatively lower volume than the estimated volume we present in this paper, the pyroclastic flow may hit the nearest settlement from the tip of the lava tongue.

From the results of this numerical simulation experiment, we can also conclude that numerical simulation can help to explain changes in pyroclastic flow behavior, and can also help to predict possible areas that could be affected by pyroclastic flows in the future.

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References

Baxter, P.J., Neri, A., Todesco, M., 1998. Physical Modelling and Human Survival in Pyroclastic Flows. Natural Hazards 17, 163–176. https://doi.org/10.1023/A:1008031004183

BNPB, I., n.d. Gunung Karangetang Meletus, 465 Warga Sitaro Mengungsi [WWW Document]. BNPB. URL https://bnpb.go.id/berita/gunung-karangetang-meletus-465-warga-sitaro-mengungsi (accessed 10.5.23).

Branney, M.J., Kokelaar, P., 2002. Pyroclastic Density Currents and the sedimentation of Ignimbrites, Journal of Chemical Information and Modeling. https://doi.org/10.1017/CBO9781107415324.004

Budianto, A., Kartadinata, M.N., Kusdaryanto, 2000. Geological Map of Karangetang Volcano, North Sulawesi.

Fisher, R.V., 1979. Models for pyroclastic surges and pyroclastic flows. Journal of Volcanology and Geothermal Research 6, 305–318. https://doi.org/10.1016/0377-0273(79)90008-8

Global Volcanism Program, Smithsonian Institution, Venzke, E., 2013. Volcanoes of the World, v.4.3.4.

Global Volcanism Program | Karangetang [WWW Document], n.d. . Smithsonian Institution | Global Volcanism Program. URL https://volcano.si.edu/volcano.cfm?vn=267020 (accessed 10.5.23a).

Global Volcanism Program | Karangetang [WWW Document], n.d. . Smithsonian Institution | Global Volcanism Program. URL https://volcano.si.edu/volcano.cfm?vn=267020 (accessed 8.5.23b).

Global Volcanism Program | Report on Karangetang (Indonesia) — January 2023 [WWW Document], n.d. URL https://volcano.si.edu/ShowReport.cfm?doi=10.5479/si.GVP.BGVN202301-267020 (accessed 10.5.23).

Global Volcanism Program | Report on Karangetang (Indonesia) — May 2018 [WWW Document], n.d. URL https://volcano.si.edu/ShowReport.cfm?doi=10.5479/si.GVP.BGVN201805-267020 (accessed 11.9.23).

Global Volcanism Program | Report on Karangetang (Indonesia) — May 2019 [WWW Document], n.d. URL https://volcano.si.edu/ShowReport.cfm?doi=10.5479/si.GVP.BGVN201905-267020 (accessed 11.10.23).

Harris, A.J.L., Ripepe, M., 2007. Regional earthquake as a trigger for enhanced volcanic activity: Evidence from MODIS thermal data. Geophys. Res. Lett. 34, L02304. https://doi.org/10.1029/2006GL028251

Itoh, H, Takahama, J., Takahashi, M., Miyamoto, K., 2000. Hazard estimation of the possible pyroclastic flow disasters using numerical simulation related to the 1994 activity at Merapi Volcano. Journal of Volcanology and Geothermal Research 100, 503–516. https://doi.org/10.1016/S0377-0273(00)00153-0

Itoh, H., Takahama, J., Takahashi, M., Miyamoto, K., 2000. Hazard estimation of the possible pyroclastic flow disasters using numerical simulation related to the 1994 activity at Merapi Volcano. Journal of Volcanology and Geothermal Research. https://doi.org/10.1016/S0377-0273(00)00153-0

Kanatani, K.I., 1984. Flow of granular materials on an inclined plane.

Kriswati, E., Alfianti, H., 2019. Estimasi Volume Lava G. Karangetang Dan G. Anak Krakatau Berdasarkan Metode Penginderaan Jauh. Bulletin of Volcanology and Geological Hazard 13.

Kusnadi, I., Wahyudi, Y., Ardiansyah, D., Banggur, W., 2020. Kajian Geokimia lava Gunung Karangetang. PROSIDING KOLOKIUM KAJIAN KEGUNUNGAPIAN 2019 1, 25–33.

Kusumadinata, K., Hadian, R., Hamidi, S., Reksowirogo, L.D., 1979. Data dasar gunungapi Indonesia.

Oppenheimer, C., Francis, P.W., Rothery, D.A., Carlton, R.W.T., Glaze, L.S., 1993. Infrared image analysis of volcanic thermal features: Láscar Volcano, Chile, 1984-1992. J. Geophys. Res. 98, 4269–4286. https://doi.org/10.1029/92JB02134

Patria, C., Basuki, A., Tamaka, H., Kuswarno, 2015. Laporan Tanggap Darurat Karangetang Mei 2015.doc.

Pratomo, I., 2006. Klasifikasi gunung api aktif Indonesia, studi kasus dari beberapa letusan gunung api dalam sejarah. Indonesian Journal on Geoscience 1, 209–227.

Pusat Vulkanologi dan Mitigasi Bencana Geologi, 2014. Sejarah Erupsi Gunung Karangetang [WWW Document]. URL https://vsi.esdm.go.id/index.php/gunungapi/data-dasar-gunungapi/490-g-karangetang?start=1 (accessed 4.22.23).

Rukmini, N.A., Sulistiyani, Shimomura, M., 2019. Numerical Simulation of Historical Pyroclastic Flows of Merapi (1994, 2001, and 2006 Eruptions). Journal of Disaster Research 14, 90–104. https://doi.org/10.20965/jdr.2019.p0090

Santoso, I., Ismanto, R.D., Chusnayah, F., Tjahjaningsih, A., Suwarsono, Vetrita, Y., 2022. Lava flow mapping Karangetang Volcano during 2019 eruption using Sentinel-2 Images and Random Forest model. IOP

Conf. Ser.: Earth Environ. Sci. 1109, 012063. https://doi.org/10.1088/1755-1315/1109/1/012063
Shimomura, M., Banggur, W.F.S., Loeqman, A., 2019a. Numerical Simulation of Pyroclastic Flow at Mt. Semeru in 2002. Journal of Disaster Research 14, 116–125. https://doi.org/10.20965/jdr.2019.p0116
Shimomura, M., Putra, R., Rukmini, N.A., Sulistiyani, 2019b. Numerical Simulation of Mt. Merapi Pyroclastic Flow in 2010. Journal of Disaster Research 14, 105–115. https://doi.org/10.20965/jdr.2019.p0105
Wright, R., Flynn, L.P., Garbeil, H., Harris, A.J.L., Pilger, E., 2004. MODVOLC: near-real-time thermal monitoring of global volcanism. Journal of Volcanology and Geothermal Research 135, 29–49. https://doi.org/10.1016/j.jvolgeores.2003.12.008
Yamashita, S., Miyamoto, K., 1993. Model of pyroclastic flow and its numerical simulation.