SPATIAL ANALYSIS OF VOLCANIC ASH DISTRIBUTION DUE TO VOLCANIC ERUPTION IN JAVA ISLAND

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ABSTRACT:

Indonesia is located on the Ring of Fire with the most geologically active than any other countries, which makes it vulnerable due to the massive earthquakes and volcanic eruptions. Java Island has the most active volcano with high risks such as human risk and infrastructure from volcanic ash because of volcanic eruptions. The availability of the map of potential volcanic hazards is important to help mitigate the risk caused by volcanic eruptions. However, to the best of the author's knowledge, the distribution of volcanic ash has never been assessed in detail in the disaster-prone hazard map published by the Centre for Volcanology and Geological Hazard Mitigation (CVGHM), Indonesia. This research reported the potential distribution of volcanic ash due to volcanic eruptions in the future in Java island. Following the principles of Probabilistic Hazard Assessment and TephraProb software, the modeling of volcanic ash potential was performed using various parameters such as historical data, eruption source parameter, total grain-size distribution, tephra2 parameter, and the wind speed around the volcanoes as an input. The map shows the distribution of volcanic ash based on the volcanic ash accumulation (kg/m2) and the volcanic ash hazard map is classified into three classes. There are 19 models of volcanic ash distribution with various probabilities of exceedance based on 19 A-type volcanoes on Java Island. This volcano's distribution of volcanic ash tends to the southwest as the wind speed and direction.

1. INTRODUCTION

Indonesia is one of the countries located in the Pacific Ring of Fire, which is the most geologically active region in the world. In addition, Indonesia is also located between three tectonic plates, namely the Eurasian, Indo-Australian, and Pacific plates. The configuration of these three plates makes Indonesia a country prone to geological disasters such as earthquakes, tsunamis, landslides, and volcanic eruptions. This is also supported by the fact that Indonesia has 127 active volcanoes, which is the largest number of volcanoes and causes the most casualties in the world (ESDM, 2021). However, the large number of volcanoes makes Indonesia dominate the world's geothermal energy sources by 40% (Masum & Akbar, 2019). This will certainly benefit Indonesia in terms of abundant renewable energy resources with a note if managed properly.

Active volcanoes in Indonesia are spread across several islands in the Pacific Ring of Fire, namely Sumatra, Java, Bali, and islands in eastern Indonesia. Among these islands, Java is one of the islands with the highest number of active volcanoes in Indonesia. On Java Island, there are 34 active volcanoes. With the existence of these volcanoes, it will certainly provide an advantage for Java Island in the form of abundant geothermal energy sources compared to other regions.

On the other hand, the volcano will produce materials identified as volcanic hazards when it erupts, such as lava, lava flows, pyroclastic fallout, volcanic ash, toxic gases, and so on. These materials have local and global adverse impacts (Malawani et al., 2021). Locally, the adverse impacts of volcanic materials include disruption of the drainage system due to material sedimentation, damage to the post-eruption volcanic structure, contamination of water bodies, and course directly related to the damage to buildings (residential, public facilities, and critical facilities) and the increase in the number of casualties; while the global adverse impacts include climate disruption due to volcanic ash and other materials that spread in the atmosphere (Malawani et al., 2021). However, volcanic ash is the most diffuse material, often occurring and disturbing surrounding objects because it spreads quickly and widely even in small thickness fractions (Blong et al., 2017). In addition to disrupting airline flights, agriculture, and the health of residents, volcanic ash can damage buildings in its path if they receive a very large ash load (Blong et al., 2017).

1.1 Study Area

Java Island is one of the islands that has the largest number of active volcanoes in Indonesia. On Java Island, there are 34 active volcanoes with details of 19 type A volcanoes (historical records of eruptions since 1600), 10 type B volcanoes (historical records of eruptions before 1600), and 5 type C volcanoes (no historical records of eruptions) (ESDM, 2021). In this research, type A volcanoes are used for hazard modeling because they have a complete historical record as a basis for modeling. The following is the distribution of type A volcanoes on the island of Java, totaling 19 mountains (shown in Figure 1).

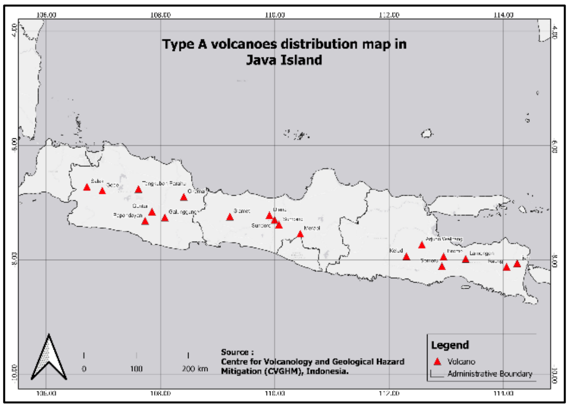

Figure 1 Type A Volcanoes Distribution Map in Java Island

Based on the map, there are 7 volcanoes in West Java Province (Salak, Gede, Tangkuban Parahu, Guntur, Papandayan, Galunggung, and Ciremai), 5 volcanoes in Central Java Province and Yogyakarta Special Region (Slamet, Dieng, Sundoro, Sumbing, and Merapi), and 7 volcanoes in East Java Province (Arjuno Welirang, Kelud, Semeru, Bromo, Lamongan, Raung, and Ijen). In Indonesia (especially on Sumatra Island and Java Island), the formation of volcanoes occurs due to the collision of the Indian Ocean crust with the Asian continental crust (CVGHM, 2015).

1.2 Purpose of The Study

Java Island is an area prone to volcanic eruptions with volcanic ash. To reduce casualties due to the disaster, it is necessary to do modeling related to the potential distribution of volcanic ash when a volcanic eruption occurs on Java Island so that mitigation efforts can be maximized. The purposes of this study are :

- Create a map of volcanic ash distribution due to type A volcanic eruptions on Java Island.
- Create a classified hazard map of volcanic ash distribution.

2. MATERIALS AND METHODS

2.1 Datasets Used

The data used in this study primarily consists of five main data, namely:

- Grid File, which consists of a region of interest coordinate, vent easting & northing, vent zone, mean elevation in UTM (Universal Transverse Mercator),
- Eruption Source Parameter (ESP), which consists of eruption volume, plume height, and eruption duration for each volcano derived from Volcanic Explosivity Index (VEI) data in the Global Volcanism Program – Smithsonian Institution
- Total Grain-Size Distribution (TGSD) and Advection-Diffusion Parameter for each volcano derived from Mt. Gede parameter (in paper).
- Wind speed over the volcano's vent with a spatial resolution of 2.5 degrees derived from NOAA NCEP/NCAR Reanalysis 1.
- SRTM (Shuttle Radar Topographic Mission) Digital Elevation Model for calculating mean elevation in Grid File with a spatial resolution of 90 meters derived from USGS.

2.2 Methods

This research includes five main stages. The first stage is determining the Region Of Interest (ROI) grid area for each volcano, the second stage is determining the eruption source parameters and volcanic ash characteristics, the third stage is determining the wind speed at each volcano, the fourth stage is modeling the distribution of volcanic ash probabilistically, and the fifth stage is classifying the danger of volcanic ash distribution into several classes. In the first stage, the method used to create a map of the potential distribution of volcanic ash due to volcanic eruptions on Java Island is Probabilistic Hazard Assessment (Biass et al., 2016).

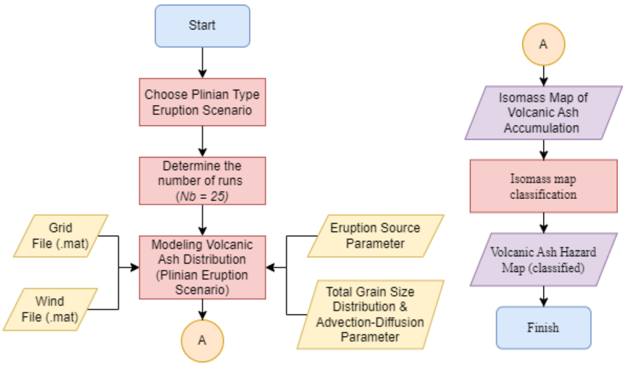

Figure 2 The Framework of Volcanic Ash Modeling

2.3 VEI Data Extraction for ESP

The Volcanic Explosivity Index (VEI) is agreed as a relative measure of explosive eruptions developed by Newhall and Self (Lockwood & Hazlett, 2010). The greater the VEI value, the greater the strength of the eruption. The VEI value is related to the volume of the eruption, the height of the ash column during the eruption, and the duration of the eruption (Lockwood & Hazlett, 2010). This table shows the correlation between VEI and Eruption Source Parameter.

VEI	***Eruption Volume (m3)***		***Plume Height (m)***	
	Min	***Max***	***Min***	***Max***
0	0	10000	0	100
1	10000	1000000	100	1000
2	1000000	10000000	1000	5000
3	1.00E+07	1.00E+08	3000	15000
4	1.00E+08	1.00E+09	10000	25000
5	1.00E+09	1.00E+10	20000	35000
6	1.00E+10	1.00E+11	30000	40000
7	1.00E+11	1.00E+12	40000	50000
8	1.00E+12	1.00E+14	50000	100000

Table 1 VEI index along with eruption volume and plume height (NPS, 2022)

In the historical database of Indonesian volcanic eruptions, esp data is not well recorded, there is only VEI data, while modeling the distribution of volcanic ash requires more detailed esp data. Therefore, the table above is used to convert VEI data into ESP data. Based on the historical occurrence of GVP, the mountains in Java Island have a maximum VEI from 1 to 5, resulting in the parameters for each VEI listed in appendix A.

2.4 TGSD and Advection Diffusion Parameter

The characteristics of volcanic ash consisting of TGSD and Advection-Diffusion parameters are assumed to be the same as the characteristic values on Mt. Gede because only these parameters are available and published in full. This parameter is also used for 18 other volcanoes.

TGSD		**Advection-Diffusion**	
Phi	-7 – 7 ϕ	Eddy Constant	0.04
Median Phi	1 – 3 ϕ	Diffusion Coefficient	4900 m^2/s
Standard Deviation Phi	1 – 3 ϕ	Fall Time Threshold	5000 s
Aggregation	30% - 70%	Lithic Density	2300 kg/m^3
Diameter	5 ϕ	Pumice Density	935 kg/m^3
		Column Steps	100
		Particle Steps	20
		Alpha	1
		Beta	1

Table 2 TGSD and Diffuse Advection Parameters of Mount Gede (Tennant et al., 2021)

2.5 Volcanic Ash Modeling

After collecting data on the ROI grid, eruption source parameters, volcanic ash characteristics, and wind speed, the next step is to model the distribution of volcanic ash probabilistically using TephraProb software. In this software, the volcanic ash distribution model is represented in the form of a Probabilistic Isomass Map, which is the distribution of volcanic ash based on ash accumulation in kg/m^2. The principle used in TephraProb to model the distribution of volcanic ash is the Tephra2 model. The Tephra2 model uses the advection-diffusion equation to calculate the accumulation of tephra at locations around the volcano based on a predefined set of eruption conditions. The advection-diffusion equation used produces an output of volcanic ash mass accumulation at each land surface coordinate. The equation is as follows (Connor & Connor, 2011):

$$M(x,y) = \sum_{i=1}^{H} \sum_{j=\Phi_{\min}}^{\Phi_{\max}} M_{i,j}^{0} f_{i,j}(x,y) \quad (1)$$

Description :

- $M(x,y)$: ash accumulation (kg/m^2)
- $M^0_{i,j}$: eruption mass
- $f_{i,j}(x,y)$: mass conservation mass
- H : plume height (m)
- ϕ : phi (volcanic ash size in phi units)

The calculation of the probability value of the resulting model is listed in the following formula (Biass et al., 2016):

$$P_M(x,y) = \frac{\sum_{i=1}^{N_R} n_i}{N_R} \quad (2)$$

Description :

- P_M = Probability of Volcanic Ash Accumulation (%)
- N_R = number of runs

$$n_i = \begin{cases} 1 & if\ Mi(x,y) \geq threshold \mid eruption \\ 0 & \text{otherwise} \end{cases}$$

Based on this formula, the probability of the volcanic ash mass accumulation model is determined based on the similarity of the models created and the number of models created.

2.6 Hazard Classification

The volcanic ash distribution hazard map was created based on the Isomass Map (probabilistic volcanic ash distribution model) that had been previously created by classifying it into three hazard classes, namely hazard class 1, class 2, and class 3. In addition to affecting human health in the respiratory system and aviation traffic, volcanic ash also affects the damage to the infrastructure it passes through, especially on the roof. Therefore, the division of hazard classes of volcanic ash distribution is adjusted to the roof live load regulated in SNI 1727 - 2013 concerning Minimum Loads for the Design of Buildings and Other Structures (National Standards Agency, 2013) and SNI 1727 - 2020 concerning Minimum Design Loads and related Criteria for Buildings and Other Structures (National Standards Agency, 2020), with the hazard level limit based on the roof construction of buildings in 1983 - 2013 and the roof construction of buildings above 2013.

Class	Accumulation Interval (kg/m^2)	Description
1	0 – 20	Does not cause damage to the roof of the building
2	20 – 100	Causes damage to building roofs for building roof construction 1983 - 2013
3	> 100	Causes damage to building roofs for roof construction of buildings above 2013

Table 3 Volcanic ash distribution hazard class

3. RESULT AND DISCUSSION

3.1 Probabilistic Isomass Maps

In this study, the isomass map created has a 90% probability. The following is the Isomass Map for all type A volcanoes on the island of Java with 90% probability.

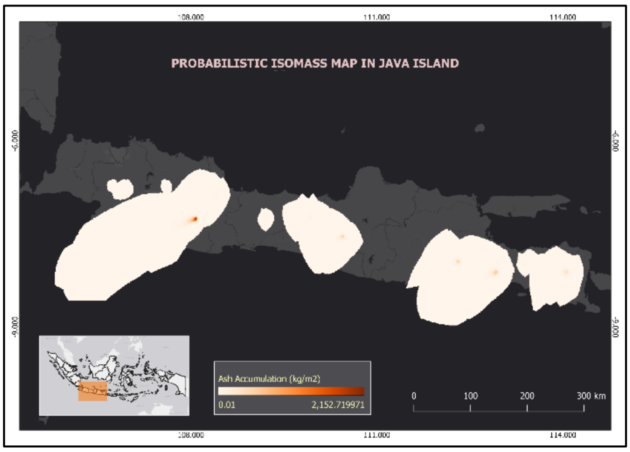

Figure 3 Probabilistic Isomass Map in Java Island

Based on Figure 3, each type A volcano in Java Island has different accumulation and distribution of volcanic ash. This depends on the maximum VEI for each volcano, the higher the VEI value, the greater the volcanic ash accumulation because the plume height and eruption volume are also large according to table 1. There are some volcanic ash accumulations from one volcano that are covered by another volcano due to the difference in maximum VEI values. The resulting volcanic ash accumulation is in the range of 0.01 kg/m^2 to 2152.719 kg/m^2.

3.2 Volcanic Ash Hazard Map

The hazard model used is the Isomass Map with 90% probability. After the classification of hazards for all Isomass Maps of type A volcanoes on Java Island, there are hazards of volcanic ash distribution of volcanoes that are fully classified and some are partially classified. The following is a classified hazard map for all type A volcanoes on Java Island.

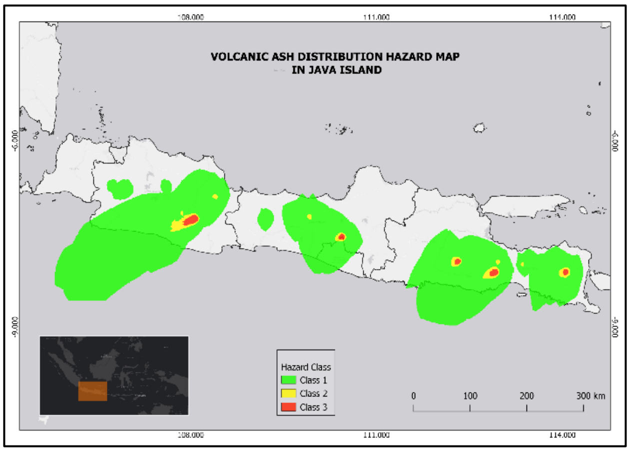

Figure 4 Volcanic Ash Distribution Hazard Map in Java Island

Based on the figure 4, the majority of the volcanic ash distribution models produced have a low hazard level (class 3) compared to the other 2 classes. The farther the building is from the volcano's vent, the lower the hazard impact.

3.3 Hazard Area Calculation

The calculation of volcanic ash distribution area is done for each hazard class of each volcano.

VEI	Hazard Area (km^2)		
	Class 1	Class 2	Class 3
Salak	420.954	0	0
Gede	1049.681	0	0
Tangkuban Parahu	456.432	0	0
Guntur	421.297	27.954	0
Papandayan	1095.507	23.965	0
Sumbing	84.046	0	0
Galunggung	31600.493	529.843	375.274
Ciremai	8237.093	58.926	0
Slamet	876.848	0	0
Dieng	5578.210	58.025	0
Sundoro	487.244	0	0
Merapi	9683.682	162.112	90.063
Kelud	7776.759	184.058	83.024
Arjuno Welirang	1029.089	0	0
Bromo	2362.247	39.986	0
Semeru	18443.338	294.938	155.957
Lamongan	1289.772	31.973	0
Raung	8074.326	206.613	85.843
Ijen	371.446	0	0

Table 4 Hazard Class Area for Each Mountain

Based on table 4, the area of the resulting hazard class varies greatly depending on the number of hazard classes generated and the accumulation of ash produced based on the VEI level. Mount Galunggung has the largest hazard area compared to other volcanoes, both from class 1, 2, and 3. This is because Mount Galunggung has the highest VEI level which is the largest compared to other mountains. Meanwhile, Mt. Sumbing has the smallest hazard area compared to other volcanoes, which only has 1 class. This is because Mt. Sumbing only has the highest VEI of 1, so the height of the ash column and the volume of eruption produced are not too large.

3.4 Suitability Analysis

The analysis of the suitability of the results was carried out by comparing the classified hazard map from the Tephra2 modeling with the disaster-prone area map from the Center for Volcanology and Geological Hazard Mitigation (CVGHM). The volcano disaster prone area map is a map showing the level of vulnerability that has the potential to cause a disaster in an area in the event of a volcanic eruption (CVGHM, 2016). This map is prepared based on geological data, volcanology, distribution of settlements and infrastructure; which contains information about the type of volcano hazard, disaster-prone areas, directions/routes for self-rescue, and evacuation sites (CVGHM, 2016).

In this case, a volcano CVGHM map with the same number of classes as the model result map was selected, namely for Mount Galunggung. The following is a map of Mt. Galunggung's disaster prone area map which is the result of digitizing the original map at a scale of 1 : 200,000 which is shown in Figure 5.

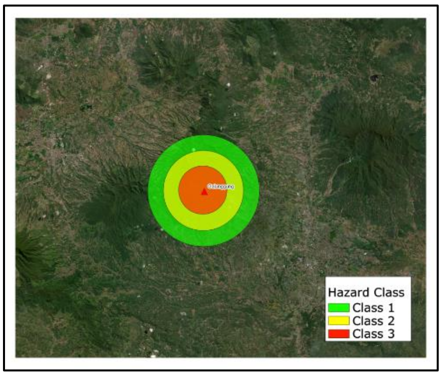

Figure 5 Disaster prone area map of Mt. Galunggung (recreated from CVGHM, 2016)

In addition, a map of the modeling results that has been classified to a scale of 1: 200.000. This was done to facilitate the suitability analysis, especially to visually see the area.

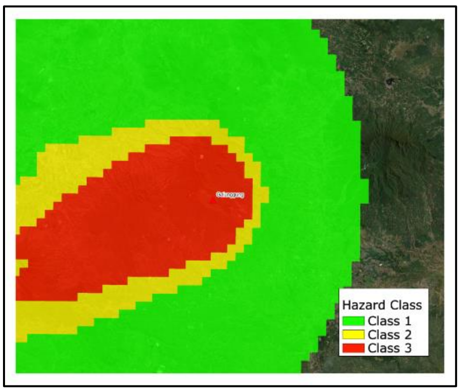

Figure 6 Hazard Map of Mt. Galunggung Volcanic Ash Distribution (Tephra2 Model)

When the two maps are compared, visually the hazard area of the model map is more than that of the CVGHM map. If the model map is scaled up, the volcanic ash coverage reaches the sea with a tendency of the ash distribution direction to the southwest. In addition to the visual comparison analysis, comparisons were also made for other parameters such as the number of classes, year of production, hazard area, and hazard impact, which are listed in table 5 below:

Parameter		CVGHM Map	Tephra2 Map
Number of classes		3	3
Year of Production		2016	2023
Hazard Area	Class 1	75.3982 km^2	31600.4932 km^2
	Class 2	50.2654 km^2	529.8426 km^2
	Class 3	28.2743 km^2	375.2739 km^2
Hazard Impact	Class 1	Struck by ejected material with a maximum diameter of 10 mm	Does not cause damage to the roof of the building
	Class 2	Struck by a stone with a maximum diameter of 64 mm	Causes damage to building roofs for building roof construction 1983 - 2013
	Class 3	Struck by a rock > 64 mm in diameter	Causes damage to building roofs for roof construction of buildings above 2013

Table 5 Comparison between CVGHM Map and Tephra2 Map

In the CVGHM Map, the hazard impact of each class depends on the size of the material ejected from the volcano, while the modeled map is based on the burden of volcanic ash accumulation on roof damage. For the hazard area, the hazard area of the modeled map is larger than that of the CVGHM Map for both classes 1, 2, and 3. From the differences in these parameters, it can be concluded that the modeled hazard map of Mt. Galunggung is not in accordance with CVGHM Map in terms of map-making methods, hazard area, and hazard impact.

4. CONCLUSION

The resulting volcanic ash distribution map is a Probabilistic Isomass Map that represents the accumulation of volcanic ash in kg/m2 with a total of 19 maps of 90% probability in the eruption strength range from VEI 1 to 5; however, these maps have not been validated with a certain accuracy assessment method (validity percentage). Volcanic ash hazard maps have been created based on the Probabilistic Isomass Map with a 90% probability classified into three classes based on the Indonesian National Standard on building loading, resulting in 19 hazard maps. However, these maps have not been validated with a certain accuracy assessment method (validity percentage), and only visually analyzed for the number of hazard classes, year of map making, hazard class area, and damage impact for each hazard class of volcanic ash distribution with the Disaster Prone Area Map from CVGHM.

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REFERENCES

Biass, S., Bonadonna, C., Connor, L., & Connor, C. (2016). *TephraProb*: a *MATLAB* package for probabilistic hazard assessments of tephra fallout. Applied Volcanology.

Blong, R. J., Grasso, P., Jenkins, S. F., Magill, C. R., Wilson, T. M., McMullan, K., & Kandlbauer, J. (2017). *Estimating building vulnerability to volcanic ash fall for insurance and other purposes*. *Applied Volcanology*, *6*(2).

Connor, L., & Connor, C. (2011). *Tephra2 Users Manual*.

CVGHM. (2015). *Gunungapi*.

CVGHM. (2016). *Peta Kawasan Rawan Bencana Gunung Api Galunggung, Jawa Barat*.

ESDM. (2021, September 20). Tipe Gunung Api di Indonesia (A, B, dan C). https://magma.esdm.go.id/v1/edukasi/tipegunung-api-di-indonesia-a-b-dan-c

Lockwood, J. P., & Hazlett, R. W. (2010). *Volcanoes : Global Perspectives*. Wiley-Blackwell.

Malawani, M. N., Lavigne, F., Gomez, C., Mutaqin, B. W., & Hadmoko, D. S. (2021). *Review of Local and Global Impacts of Volcanic Eruptions and Disaster Management Practices: The Indonesian Example*. *Geoscience*, *11*(109).

Masum, M., & Akbar, M. A. (2019). *The Pacific Ring of Fire is Working as a Home Country of Geotermal Resources in the World . Earth and Environmental Science*.

National Standards Agency. (2013). *SNI 1727 – 2013 - Beban Minimum untuk Perancanagan Bangunan Gedung dan Struktur Lain*.

National Standards Agency. (2020). *SNI 1727 – 2020 - Beban Desain Minimum dan Kriteria terkait untuk Bangunan Gedung dan Struktur Lain*.

NPS. (2022). *Volcanic Explosivity Index (VEI)*. https://www.nps.gov/subjects/volcanoes/volcanic-explosivity-index.htm

APPENDIX

VEI Maksimum	1	2	3	4	5
Minimum Eruption Volume (m^3)	10000	1000000	10000000	100000000	1000000000
Maximum Eruption Volume (m^3)	1000000	10000000	100000000	1000000000	10000000000
Minimum Plume Height – from vent (m)	100	1000	3000	10000	20000
Maximum Plume Height – from vent (m)	1000	5000	15000	25000	35000
Minimum Eruption Mass (kg)	9350000	935000000	9350000.000	93500000000	935000000000
Maximum Eruption Mass (kg)	935000000	9350000000	93500000000	935000000000	9350000000000
Minimum Duration (hour)	1	2	3	4	5
Maximum Duration (hour)	2	3	4	5	6

Appendix A. Eruption Source Parameter in VEI 1 - 5