Supplementary Material A – Probabilistic Tephra Fall Modelling Approach

A disruption scoring framework for critical infrastructure exposed to multiple hazard sources: tephra fall on Japan's electricity network

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Tephra fall footprints for the 62 study volcanoes on mainland Japan were generated by conducting probabilistic tephra fall hazard modelling for Fujisan using TephraProb (Bonadonna et al., 2005; Biass et al., 2016), then spatially repositioning the simulated footprints for Fujisan to each volcano. We modelled tephra fall distribution across a 1 x 1 km resolution grid (UTM Zone 54N) for areas extending 1,000 km from Fujisan, with 1,000 eruptions simulated per Volcanic Explosivity Index class (VEI ≤ 3, 4, 5, 6 and 7; Newhall and Self, 1982). Through spatial repositioning, we obtained a total of 310,000 tephra fall distributions across the 62 volcanoes (1,000 footprints x 5 VEI class x 62 volcanoes).

Probabilistic tephra fall distributions were produced using Eruption Range Scenarios (ERS) in TephraProb which stochastically samples both eruption source parameters and wind conditions (Biass et al., 2016). TephraProb is based on the Tephra2 model, which uses the analytical solution to the advection-diffusion equation to calculate tephra mass accumulation. We refer the reader to Bonadonna et al. (2005) and Connor & Connor (2006) for an in-depth overview of the Tephra2 model, and to Biass et al. (2016) for a complete description of the TephraProb Matlab package.

All eruptions were modelled using the sub-Plinian / Plinian eruptive style. We used studies of eruptions in Japan to inform eruption source parameters (ESPs) where available; otherwise, analogue eruptions were used. When published parameter estimates exhibited substantial variability, we selected a broad range to reflect this uncertainty. The rationale for the characterisation of each ESP used in the tephra fall hazard modelling and a summary of the input parameters to TephraProb is provided below (Table S1).

Plume height

In the absence of more specific data and to cover a range of potential scenarios, we used the plume height ranges provided by Newhall and Self (1982) for each VEI class to inform plume heights. For VEI ≤ 3, we adopted the minimum plume height for VEI 2 eruptions as the minimum bound (1 km) and the maximum height for VEI 3 as the maximum bound (15 km). Newhall and Self (1982) do not provide maximum bounds for VEI 5+ eruptions. Therefore, to constrain the maximum bounds, we used the Large Magnitude Explosive Volcanic Eruptions (LaMEVE) database (Crosweller et al., 2012) and selected the central value of the maximum column heights for VEI 5, 6, and 7 eruptions in Japan to use as maximum plume heights. Plume heights were sampled within TephraProb using a logarithmic distribution, so that smaller plume heighted were more likely to be sampled than larger plume heights. Plume heights were not modified based on their interaction with wind (e.g. wind-bent plumes; Woodhouse et al., 2013).

Erupted mass

The erupted mass was calculated using the empirical relationship by Mastin et al. (2009), shown in the equation below. The minimum and maximum erupted volume for each VEI class was calculated from the corresponding minimum and maximum plume heights H (km). We assumed a dense rock equivalent (DRE) density of 2500 kg/m^3 to convert from erupted volume (km^3 DRE) to erupted mass (kg).

$$Volume\ (km^3\ DRE) = 10^{\left(\frac{(H-25.9)}{6.63}\right)}$$

Total grain-size distribution and particle density

It is difficult to constrain the total grain-size distribution (TGSD) as it is dependent on the collection of well-preserved field data. Therefore, we used analogue eruptions and studies to define our TGSD characterisation. To constrain the median diameter (Med, ϕ), we used the following:

- VEI ≤ 3 – Posterior mean Med (ϕ) from the White et al. (2017) inversion of 2011 Shinmoedake eruption at Kirishimayama, using isomass and grain size. We used the 95% confidence interval as the minimum and maximum bounds.
- VEI 4 – Parameters used by Biass et al. (2017) in their modelling of a VEI 4 eruption at Sakurajima volcano.
- VEI 5 to 7 –Tsuji et al. (2017) used a Med (ϕ) of 1.5 following analysis of tephra deposits from Kuju volcano in their modelling of a VEI 5 eruption. We adopted this value as the maximum Med (ϕ). We used the Med (ϕ) of 3 that Magill et al. (2015) found as being representative of the Hoei eruption at Fujisan as a minimum Med (ϕ).

Minimum and maximum grain sizes of 7 and -7 phi were selected as deliberately wide bounding but credible for those VEI classes where the above published sources did not provide both minimum and maximum bounds.

Lithic and pumice density

Lithic and pumice density was specified as 2500 kg/m^3 and 1000 kg/m^3, respectively, as these are commonly adopted values.

Empirically derived Tephra2 parameters

The Tephra2 deposition model requires a diffusion coefficient and fall time threshold to be specified to characterise the atmospheric spread and deposition of small and large particles. Usually, these values are obtained by conducting inversion modelling on field data (Connor and Connor, 2006). However, as we are limited by available field data that we can use for this purpose, we relied on published values already determined from similar eruptions:

- VEI ≤ 3 – Values used in Mannen et al. (2020) for modelling the 2011 Shinmoedake eruption at Kirishimayama volcano
- VEI 4 – Values used in Biass et al. (2017) for modelling a VEI 4 eruption at Sakurajima volcano.
- VEI 5 to 7 – Values used in Takarada (2017) for modelling a VEI 5 eruption at Fujisan volcano.

Table S1: Summary of TephraProb input parameters for tephra fall modelling

Input parameters	**Range**	**VEI ≤ 3**	**VEI 4**	**VEI 5**	**VEI 6**	**VEI 7**
Grid		1 x 1 km resolution grid within 1,000 km of Fujisan				
Wind		ECMWF ERA5 wind data (2015-2024; 6-hour interval)				
Volcano		Fujisan				
Vent Easting		293573				
Vent Northing		3915447				
Vent Zone (UTM)		54N				
Vent Height (m)		3776				
Plume Height (km above vent)	Min	1	10	25	30	37
	Max	15	25	30	37	43
Erupted Mass (x 10^{10} kg)	Min	0.044	1	180	1000	12000
	Max	5.7	180	1000	12000	95000

Grain Size (ϕ)	Min	7				
	Max	-7				
Median Diameter (ϕ)	Min	-0.7	-2.5	1.5	1.5	1.5
	Max	0.2	-1	3	3	3
Standard Deviation (ϕ)	Min	2	1.8	2	2	2
	Max	3	2.5	3	3	3
Eddy Constant		0.04				
Diffusion Coefficient		500	2500	1000	1000	1000
Fall Time Threshold		3600	4000	3600	3600	3600
Lithic Density (kg/m^3)		2500				
Pumice Density (kg/m^3)		1000				
Column Steps		50				
Part Steps		50				
Alpha		1				
Beta		1				

The tephra fall footprints for Fujisan were reprojected from UTM 54N (EPSG: 32654) to an equal area projection (World Mollweide - ESRI: 54009) before spatially repositioning to other volcanoes. To reposition the footprint, we aligned the grid cell containing Fujisan with the grid cell containing the target volcano. Grid cells that are offshore and those containing less than 0.1 kg/m^3 of tephra were removed.

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