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article in press

# Development of a suite of lava flow scenarios for probabilistic hazard assessment in the Auckland Volcanic Field, Aotearoa New Zealand

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## Abstract

The monogenetic Auckland Volcanic Field (AVF) of Tāmaki Makaurau Auckland, Aotearoa New Zealand, presents challenges for risk assessment, including the uncertainty of future vent locations, and the style and magnitude of the resulting eruptions. The range of hazards associated with AVF-style eruptions (e.g., lava, tephra, and  
20 pyroclastic density currents) make understanding the volcanic hazard critical, particularly given the risk of extensive population exposure and the presence of nationally significant infrastructure assets within Auckland. Previous studies have assessed impacts (a component of risk) deterministically from AVF eruption scenarios, moving forward a probabilistic approach is essential to quantify uncertainty and better assess risk. To facilitate probabilistic, regionally scaled risk assessment in the AVF, this study establishes a method to develop a suite of  
25 lava hazard footprints (n= 2,244) using the MOLASSES simulation tool, which represents a range of possible eruption scenarios across the AVF. Ensemble mapping of the lava hazard footprint suite visualises a higher relative frequency of lava inundation in central-western areas of the AVF and lower frequency in the Southern AVF. Despite the known limitations of this suite of lava hazard footprints, the outputs of this study can support future application to conditionally probabilistic loss assessment in AVF, previously not possible with the inclusion of lava  
30 hazards.

## Introduction

Monogenetic volcanic fields are often characterised by overlapping hazards and high spatio-temporal uncertainties associated with both known and unknown volcanic centres. Consisting of individual volcanic vents that typically form a new vent during each eruptive period (Le Corvec et al., 2013), these conditions raise significant concerns for disaster risk management, particularly when in proximity to large populations and economic centres, e.g. Sierra Chichinautzin Volcanic Field (SCVF) in Mexico City (Torres et al., 2022), Campania Region in Italy (Alberico et al., 2011; Lirer et al., 2010) and the Auckland Volcanic Field (AVF) in New Zealand (Hopkins et al., 2021). Quantifying these uncertainties requires creating models that accommodate a sufficiently wide range of hazard behaviours with estimable likelihoods (Ang et al., 2020), a crucial step towards advancing monogenetic hazard research (Marrero et al., 2019) and understanding the risks posed to populations.

Risk is defined as a function of hazard, exposure, vulnerability, and capacity (United Nations Office for Disaster Risk Reduction, 2017). Within the risk framework, hazard quantification is crucial. By incorporating detailed (multi) hazard estimations—including magnitude, extent, and frequency—researchers can assess the potential exposure and vulnerability of communities and infrastructure, thereby informing disaster risk management (DRM) strategies (United Nations Office for Disaster Risk Reduction, 2023).

Hazard and risk assessments have been a preoccupation of volcanology for decades. Understanding the volcano's hazard intensity, eruptive style, possible phase changes and eruption frequency is a challenge researchers face across the full spectrum of volcanic types. The hazard and risk assessment has largely focussed on stratovolcano eruptions (Marrero et al., 2019), although more recently monogenetic field eruptions have become a key area of investigation. The challenge of spatial uncertainty is exacerbated in monogenetic volcanic fields due to the sheer scale of volcanically active areas (Deligne et al., 2017; El Difrawy et al., 2013; Hopkins et al., 2021; Kenedi, 2012). This complexity affects the estimation of hazard coverage, the understanding of risks, and, furthermore, limits decision-makers ability to implement DRM strategies (Ang et al., 2020; McDonald et al., 2017).

Examples of such strategies often focus on reducing the exposure of populations and/or assets through land-use management, such as local council zoning near Mount Taranaki, New Zealand (Becker et al., 2010), or the relocation of populations in high-risk zones. In some cases, efforts focus on mitigating the hazard through lava flow diversion barriers, which have been both implemented and modelled on Mount Etna, Italy (Scifoni et al., 2010), and, more recently, utilised in Iceland's 2021 Geldingardalir eruption (Sigtryggisdóttir et al, 2025). However, such engineered interventions are generally impractical in monogenetic volcanic fields. In these environments, risk reduction instead relies on preparedness for emergency response and post-event recovery (Harris, 2014). All of

these strategies require robust hazard identification and modelling; consequently, monogenetic hazard assessment has become a significant area of international research interest (Idaho National Laboratory (INL), 2024). This has produced studies such as probabilistic assessments with numerical modelling at Harrat Al Madinah, Saudi Arabia, which refined probable areas of future eruptions (El Difrawy et al., 2013) and hazard scenario development for the Chichinautzin Monogenetic Volcanic Field near Mexico City, where exposure and vulnerability analyses were undertaken across varying eruptive intensities (Torres et al., 2022).

Tāmaki Makaurau (Auckland), the most populous city of Aotearoa (New Zealand), sits on the geologically young and active Auckland Volcanic Field (AVF; see Section 1.1). Auckland has significant exposure to volcanic hazards, with a population of approximately 1.6 million people and economic contribution of a third of the country's Gross Domestic Product (Hayes et al., 2018; Kereszturi et al., 2014b). The field encompasses nationally significant assets, including Auckland International Airport and Ports of Auckland, which are critical to the flow of people and goods into, out of, and across New Zealand. The potential direct and indirect impacts on societal and economic systems from a volcanic eruption in Auckland are immense, extending beyond the AVF's geographic boundary (Deligne et al., 2017; DPMC, 2011). Understanding the potential impact of AVF eruptions is, therefore, of great importance for disaster risk reduction.

Recent developments have shifted from deterministic approaches, where single-vent/single-scenario eruptions are assessed, to developing a representative range of potential hazard footprints within a volcanic field. For the AVF, Hayes et al. (2020) developed eight multi-hazard eruption scenarios (referred to as the DEVORA eruption scenarios) as part of the DEVORA (Determining Volcanic Risk in Auckland) research programme, which explore a spectrum of credible eruption phenomena and impacts. The outputs of the simulations have been a crucial step in AVF DRM and have supported a number of supplementary investigations, including Ang et al. (2020), which used environmental data to estimate relative spatio-probabilities for the Hayes et al. (2020) eruption scenarios across the field. Together, these advances in AVF hazard assessment provide a template for moving beyond deterministic modelling towards dynamic, field-wide approaches that account for uncertainties and move AVF research closer to comprehensive probabilistic hazard and risk assessments.

Basaltic lava flows are a key hazard within the AVF (see Section 1.1), occurring in more than half of past eruptions (Kereszturi et al., 2014b) and are a main hazard of the Hayes et al. (2020) eruption scenarios (see Figure 1). Lava behaviour varies widely according to its morphotype—'a'ā, pāhoehoe, or blocky—each influenced by geochemical properties (MacDonald, 1953) and further by effusion rate and terrain (Kilburn, 2015). Erupted at

extreme temperatures of 1050–1200 °C and with viscosities several orders of magnitude higher than that of water (Kilburn, 2015), lava poses a major threat to infrastructure through ignition, bulldozing and burial. Typically, lava flow impact assessments adopt a binary assumption: any structure within the flow path is considered totally destroyed (Jenkins et al., 2017; Kereszturi et al., 2012; Tsang et al., 2020). Hayes et al. (2020) developed hand-drawn lava hazard footprints for the scenarios with a lava component, B, C, D, F, H, see Figure 1, but the application of these flows is limited, as the same effusions would manifest differently at other vent locations (Ang et al., 2020), given the location-specific topography, bathymetry, surface structures, etc. To further advance hazard and risk assessment for the AVF, a suite of numerically modelled vent location and eruption-style-specific lava-hazard footprints is necessary to better inform DRM.

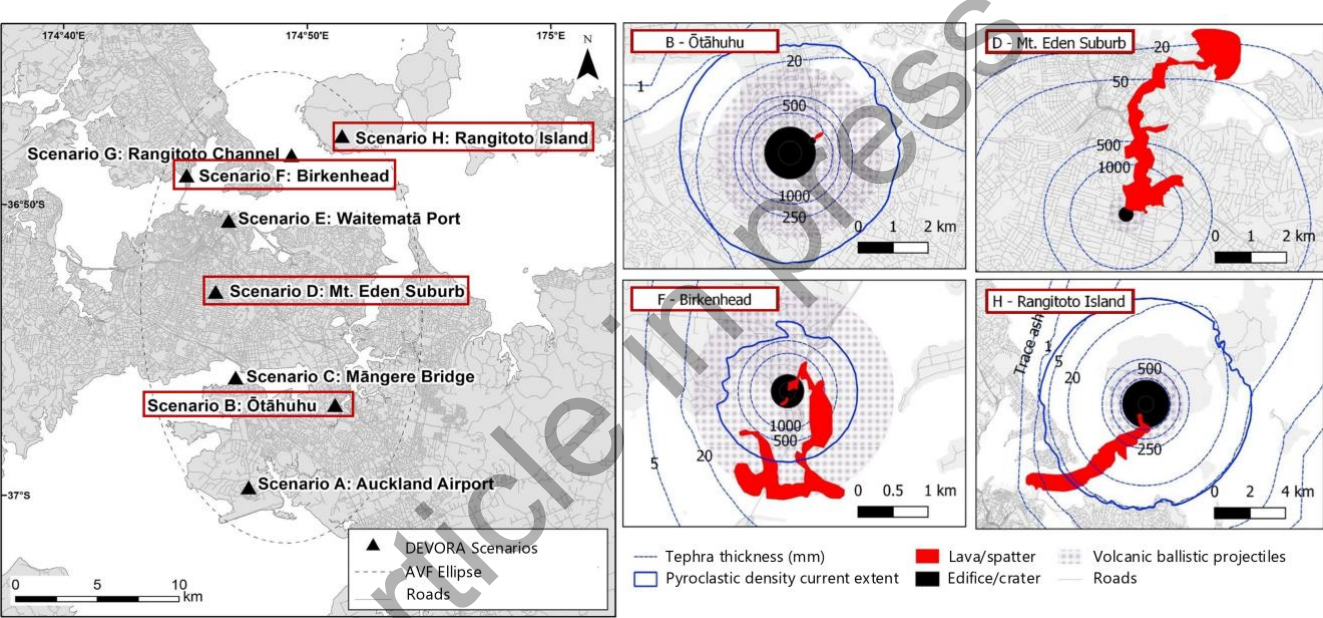


Figure 1 – Overview of the DEVORA eruption scenarios within the Auckland Volcanic Field (AVF), adapted from Hayes et al. (2020). Scenario labels highlighted with red boxes indicate the eruptive events containing a lava component. The detailed panels display the corresponding multi-hazard footprints for Scenarios B, D, F, and H, including lava and spatter extents.

This study develops an applied framework for assessing lava flow hazard for monogenetic volcanic fields, using the AVF as a case study. Section 1.1, explores the specific challenges of the AVF, while Section 1.2 discusses the complexities of lava hazard assessment. Section 2 outlines our modelling approach, simulating a range of eruptive volumes (through scenarios) across grids of probable vent locations, outputting a suite of hazard footprints. The suite is weighted according to scenario-specific probabilities producing an ensemble map. Section 3 presents the

results, followed by a discussion of their implications in Section 4. Finally, we provide recommendations for advancing lava flow modelling in the AVF and other monogenetic volcanic fields.

## 1.1 Characteristics of the Auckland Volcanic Field

115 The AVF is a monogenetic intraplate basaltic field, with magma forming at an estimated depth of ~70-90 km in the mantle (Hopkins et al., 2021). Since the AVF inception, ~190,000 years before present day, approximately 53 eruptions have occurred within the boundaries of the ~360 km<sup>2</sup> field (Deligne et al., 2017; Hopkins et al., 2021). Across these eruptions the AVF has displayed the typical characteristics of a monogenetic volcanic field, where each volcanic centre has one eruptive episode. However, the AVF presents a possible exception in the case of  
120 Rangitoto, which may represent either a long-lived eruptive centre (Linnell et al., 2016) or two separate, but geographically similar eruptions that occurred by chance (Leonard et al., 2017).

The relatively young nature of the AVF, combined with the rapid and recent urbanisation of Auckland across the 360 km<sup>2</sup> extent of the field, has created a significant risk from potential future eruptions. This has driven comprehensive multidisciplinary investigations (see Hopkins et al., 2021 for a partial review), producing an  
125 unusually detailed and precise record of volcanism—compared to other volcanic fields—that documents eruptive vent locations and styles (Kereszturi et al., 2013; Kereszturi et al., 2014b). Also identified, have been elevated likelihoods of future vent locations (i.e. volcanic eruptions) along SW–NE, or SSW–NNE, alignments (Von and Németh, 2009), possible elliptical boundary (Spörli and Eastwood, 1997), and temporal clustering of eruptions (Hopkins et al., 2021), as exemplified by the Mono-Lake excursion cluster of at least five eruptions (Cassidy and  
130 Locke, 2010; Leonard et al., 2017). The detailed characterisation has been applied to probabilistically forecast future vent locations, timing (Bebbington and Cronin, 2011; Bebbington, 2013), and magnitudes (Bebbington, 2015). These findings have supported insights into emergency and disaster management through deterministic eruptive scenarios i.e., Exercise Rūaumako and the DEVORA Scenarios (Hopkins et al., 2021).

Eruption styles and magnitudes in the AVF vary, producing diverse hazards associated with two primary  
135 eruption types: phreatomagmatic and magmatic (Hayes et al., 2018; Hopkins et al., 2021; Kereszturi et al., 2014b). These eruption types can occur in isolation or consecutively. Phreatomagmatic eruptions are explosive, driven by interactions between magma and groundwater/surface water. The volatility is dependent on water availability at the vent and surrounding locations (Houghton et al., 1999; Kereszturi et al., 2014b). The resulting hazards include explosions and pyroclastic density currents, producing geographic features like the development of maar craters,  
140 tuff rings and cones. Magmatic eruptions (which can follow an initial phreatomagmatic phase) are dominated by

lava flows (predominantly of the ‘a’ā morphotype) and developing scoria cones (Hopkins et al., 2021; Kereszturi et al., 2014a). Both styles are capable of producing additional hazards such as tephra, ballistics, and gas emissions (Hayes et al., 2018).

## 1.2 Modelling Lava Hazard in Volcanic Fields

145 Numerical modelling of lava-flow hazard has become increasingly important for capturing the variability of  
inundation footprints under different eruptive and topographic conditions. A wide range of deterministic models  
can be used to reproduce footprints with varying degrees of detail; thus, model selection requires a balance of  
physical accuracy, applicability to the volcanic area and the availability of input parameters. For instance, complex  
"physics-based" models like MAGFLOW (Cappello et al., 2015) simulate flow dynamics through parameters such  
150 as specific heat ( $c_v$ ), emissivity ( $\epsilon$ ), water content ( $H_2O$  wt.%) and density ( $\rho$ ). While these models can navigate  
flat topographies (e.g., Capello et al., 2022), acquiring these detailed rheological and thermal values is often  
unfeasible prior to or during emplacement in monogenetic eruptions (INL, 2024). In contrast, topographically  
driven models like DOWNFLOW (Favalli et al., 2005) offers a simpler modelling experience but often struggle to  
accurately simulate lava flows in low-sloping topography, as they do not conserve mass (INL, 2024). Other  
155 approaches approximate lava flow inundation using more empirical information. For example, MOLASSES  
(MODular LAVA Simulation Software for Earth Sciences; Gallant et al., 2018) adapted from the LavaPL algorithm  
by Connor et al. (2012), uses parameter inputs such as total volume, residual thickness and pulse volume. These  
represent the total eruptive volume, the approximate modal thickness and lava viscosity (Gallant et al., 2018;  
Kubaneck et al., 2015). Models that conserve mass are controlled by a set eruptive volume and better represent  
160 lower-sloped terrain, as lava is passed through neighbouring cells propagating by gravitational influence until the  
total volume has been processed through the simulated vent (Harris, 2013).

MOLASSES represents the most suitable lava flow model for application within the AVF, as it has been  
benchmarked against real flows (Kubaneck et al., 2015), proven to simulate a range of morphotypes (INL, 2024),  
applied to a distributed volcanic field (El Difrawy et al., 2013; INL, 2024) and requires simplistic parameters that  
165 can be derived from previous AVF works (Hayes et al., 2018; Kereszturi et al., 2012; Tsang, 2020). Given these  
considerations, and its alignment with the DEVORA hazard model criteria: open-source code, low processing costs,  
possible high spatial resolutions and ease of adaptability, it is the obvious choice for this study.

## Methodology

Our methodological approach for regional-scale lava flow modelling involved identifying vent locations of interest (i.e., vents with a probability of occurrence greater than zero) from Ang et al. (2020) to model the scenarios from Hayes et al. (2018). Using MOLASSES, lava flow simulations were conducted across the AVF in batches by scenario. To accommodate the varying eruption scales and computational demands of the scenarios, simulations were run at different vent grid resolutions. The resulting suite of simulated lava flow footprints was subsequently weighted by their respective scenario grid resolution and paired with the spatio-probability at each vent location. This approach enabled the creation of an ensemble map that visualises lava hazard distribution across the AVF, representing a key step towards probabilistic hazard analysis.

The process of lava flow model generation with MOLASSES (Gallant et al., 2018) includes data collection, model generation using Connor, Richardson & Connor (2020) multi-vent version, output conversion, and hazard output iteration (see Figure 2).

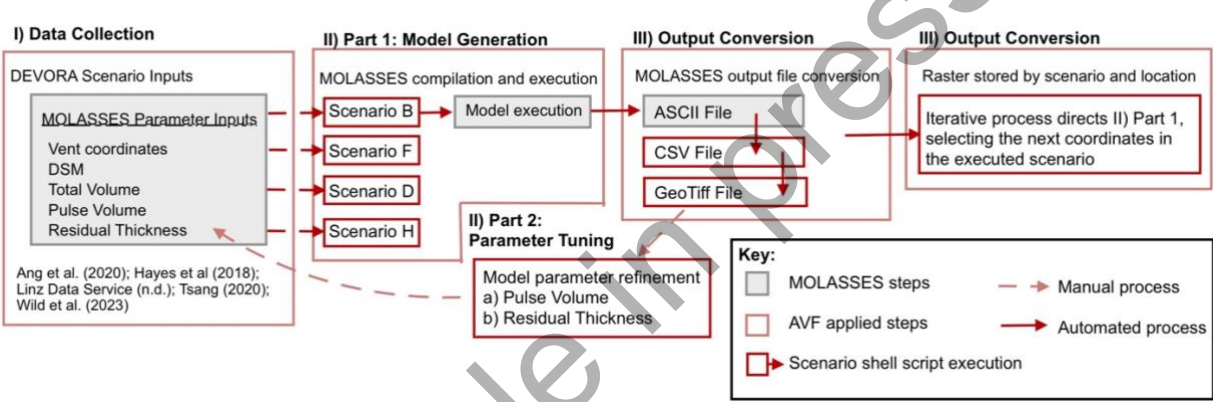


**Figure 2: Methodological framework of the application and adaptation of the MOLASSES lava flow simulator to the AVF region, utilising shell script for automation.**

In Step I, Data Collection, the required inputs are collected and adapted for the AVF context (Section 2.1). Next, Step II, model generation includes the compilation and execution of each scenario, and a parameter tuning exercise to explore the variations and implications of modelling assumptions (Sections 2.2 & 2.3). Once informed by the parameter tuning, Step III produces the final models and iterates across the AVF using file type conversions to get rasterised outputs, which through Step IV are saved by scenario and location (Section 2.4). These rasterised outputs can be used for deterministic and semi-probabilistic assessments.

## 190 2.1 Model inputs

MOLASSES is a cellular automata lava flow model that “erupts” lava from a set vent location and simulates topographically controlled flows by redistributing lava between neighbouring grid cells. The inputs for MOLASSES include: a DEM (Digital Elevation Model) or DSM (Digital Surface Model); Volcanic vent location (Northings and Eastings); Lava residual or modal thickness (m); Lava flow volume (m<sup>3</sup>); and Lava flow pulse volume (m<sup>3</sup>). Accounting for topography (or surface features) captured by the DEM (or DSM), the residual thickness input determines the minimum lava depth each cell must reach before initiating distribution of excess lava. This parameter maintains the modal thickness for the simulated lava flow, and represents lava viscosity (INL, 2024; Kubanek et al. 2015). The pulse volume input represents a proportion of the total volume that is “erupted” at intervals throughout the simulation. The total volume is the maximum amount of lava that can be simulated, controlling when the model terminates.

This study utilises defined parameters from the relevant Hayes et al. (2018) scenarios, of which, five of the eight scenarios (B, C, D, F and H) have a lava flow component in their eruptive sequences (see Figure 1) and are the focus of this study.

### *Digital Surface Model*

This study opted for a 1 m Digital Surface Model (DSM) (from LINZ Data Service, 2020a; 2020b) rather than the Digital Elevation Model (DEM) referenced in MOLASSES by recommendation from the work of Tsang et al. (2020). The DSM uses the first return from aerial LiDAR surveys (taken between 2016-2018), which includes all natural and man-made topographic features and infrastructure, allowing simulated lava flows to interact with the features of the highly modified urban landscape of Auckland. No cleaning of the DSM was conducted i.e. removal of trees or small/combustible buildings; consequently, the model perceives features that lava would easily ignite, overcome, or pass under, i.e., bridges as barriers, causing the lava thickness to accumulate and build until it overcomes the barrier’s height. The model simulates at a high resolution of 1 m, which introduces limitations and computational limitations (see Section 4.5). The DSMs were then split into five separate tiles in ArcGIS Pro to optimise processing.

### 215 *Vent locations*

The “tight” boundary—a reduced area encompassing the past eruptive vents across the AVF, as defined by Runge et al. (2015) and hereafter referred to as the Ellipse—serves as the analysis extent. This approach aligns with current

AVF research and encompasses the area considered to have equal likelihood for future eruptions. A 0.5 km<sup>2</sup> grid of vent point locations across the field (Wild et al., 2023) is used for the smaller lava flow scenarios (Scenarios B and F; Figure 3), providing high spatial density coverage. For the larger lava flow events (>59,000,000 m<sup>3</sup>; Scenarios C, D, and H), the grid coverage was coarsened to 3 km<sup>2</sup> vent spacing (Figure 3) to balance the computational load with high-resolution output, particularly considering the large total volume of these scenarios and the intentions of this research (see Section 4.6). The significant spatial overlap that is expected between neighbouring vents at 0.5 km<sup>2</sup> resolution makes modelling at that grid resolution redundant. The limitations of this assumption are discussed in Section 4.5.

Pairing vent grids with Ang et al. (2020) scenario spatio-probabilities, Figure 3 highlights vent locations with high (blue) and low (yellow) probability of each scenario's occurrence on the condition of an eruption. Importantly, the spatial probabilities do not represent the likelihood of an eruption at the vent location itself, nor are they involved within the modelling process (see Section 4.6 for future work). The results of Ang et al. (2020) were used to inform the selection of vents to be modelled, based on their occurrence exceeding 0.00001. Additionally, Scenario C was excluded from modelling, despite possessing a lava component; all vent locations with a probability of occurrence are located on the coast/offshore. Given the high-water availability, these vents would likely to undergo phreatomagmatic eruptions; uncertainties between magmatic and phreatomagmatic eruptive styles are beyond the scope of this study and of MOLASSES (see Section 4.5 for further discussion). For the same reason, all coastal/offshore vent locations for Scenario B, F, D and H were removed from the model.

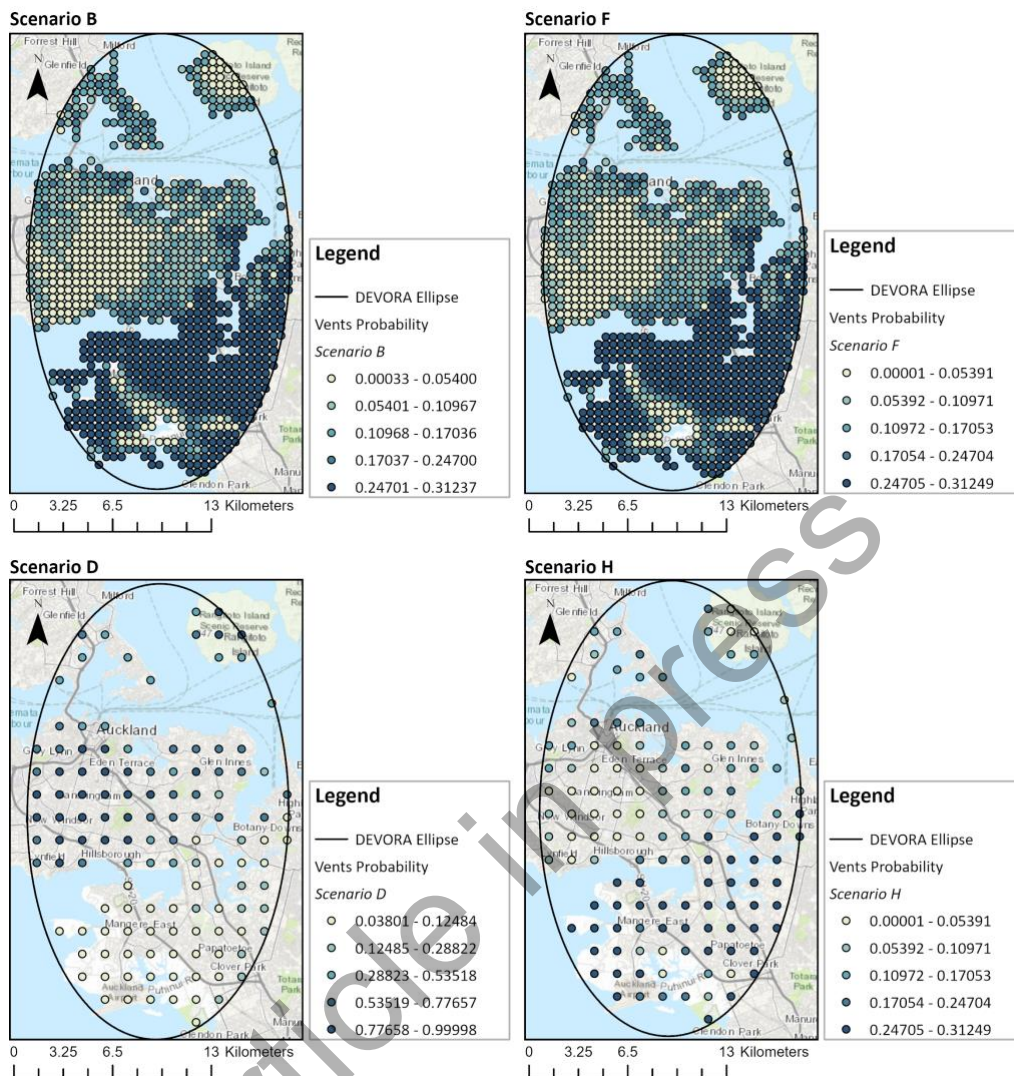


**Figure 3 – Auckland Volcanic Field (AVF) input vents for MOLASSES lava modelling, explored by the Hayes et al. (2018) scenarios. The ellipse developed by Runge et al. (2015) is the refined area for our modelling, of Scenario B & F at a 0.5 km<sup>2</sup> vent grid (Wild et al., 2023) and Scenario D & H at 3 km<sup>2</sup> vent grid with their relative probability (conditional on an eruption) noted from low (yellow) to higher (dark blue) (Ang et al., 2020).**

### *Total volume, residual thickness, pulse volume*

Total lava volume is the primary determinant for the variation in lava footprint scale. The scenario-specific total volume for MOLASSES is given in Table 1. The remaining parameter inputs, residual thickness and pulse volume, were unspecified within the Hayes et al (2020) DEVORA eruption scenarios. Looking at past lava flow thicknesses measured across the AVF, Kereszturi et al. (2012) estimates an average of 12.6 m (excluding the Rangitoto lava

flows). Alternatively, Tsang et al. (2020) specified values for residual thickness (17.5 m) and for pulse volume (10 m<sup>3</sup>, 100 m<sup>3</sup> and 1000 m<sup>3</sup>), although these values are commensurately very small (approximately 0.01% of total volume) when modelling AVF lava flows with MOLASSES. To determine the most appropriate inputs for our analysis, we analysed the influence of Kereszturi et al. (2012) and Tsang et al. (2020) in our parameter tuning exercise (detailed in Section 2.2).

## 2.2 Parameter Tuning

After the initial successful simulations of the MOLASSES model (run on an Intel vPRO i7 processor, 32GB RAM), parameter tuning was conducted to evaluate the influence of the two parameters not specified in the DEVORA scenarios – residual thickness and pulse volume. This allowed examination of their effects on the inundation area, the model's ability to capture infrastructure interactions, and the computational time required. While this exercise does not directly assess the accuracy of MOLASSES or our parameter selection to accurately replicate AVF lava flows (see Section 4.5 for limitations), the exercise serves to evaluate the model's ability to pass a visual check of flow behaviour.

Scenario B was selected for this analysis, representing the smallest lava flow and hence the quickest, and most sensitive to inundation area, serving as a proxy for the behaviour of the larger scenarios. To inform our parameter selection, the simulations were performed within a commercial area with a large complex of buildings, to maximise spatial interactions with infrastructure and analyse its influence on flow behaviour.

To best represent AVF lava flows, the residual thickness values trialled were both from previous AVF studies: an estimate of 10 m from previously emplaced lava flows (Kereszturi et al., 2012; Deligne et al., 2017), and 17.5 m, used in AVF-based MOLASSES modelling by Tsang et al. (2020). Pulse volumes were evaluated using values of 10 m<sup>3</sup>, 100 m<sup>3</sup>, and 1000 m<sup>3</sup>, reflecting ranges also used by Tsang et al. (2020). These tests provided insight into how these parameters influence the model's outputs and informed the selection of optimal input values for subsequent simulations.

## 2.3 Expanding from one location to all

The multi-vent branch of MOLASSES supports probabilistic simulation of lava flows from multi-vent inputs defined in the configuration file, where the model randomly selects a vent at simulation execution. We altered this function to achieve full coverage across the AVF Ellipse at the 0.5 km<sup>2</sup> and 3 km<sup>2</sup> vent grid (Figure 3) by creating linking shell scripts and accompanying Python scripts that developed an iterative process for modelling each

275 Scenario. Scenario H was not completed to the 3 km<sup>2</sup> grid resolution, due to the computational demand of the chosen parameters (see Section 4.5).

Configuration files were adapted for each scenario and geographic area, and the compiled code was similarly structured to allow multiple scenarios to be run concurrently. Upon execution, the model accesses a vent coordinate list, selects the first vent and updates the configuration file to reflect the active source location. After each simulation, the output is converted to CSV and GeoTIFF formats with scenario and coordinates attached for clarity and sorting. Although direct use of MOLASSES ASCII outputs was possible, conversion to CSV and GeoTIFF enabled parameter analysis and ensured compatibility with future applications. The workflow then advances to the next vent location and begins a new simulation. As a final step, files were named and sorted into vent IDs, rather than in coordinates, aligning with Wild et al. (2023) and enabling integration into wider AVF/DEVORA analyses (see Section 2.4).

## 2.4 Ensemble lava hazard

To provide insights into areas where lava pools and spreads across the Scenario range (for B, F and D), an ensemble map was created to visually represent lava inundation based on the paired vent and scenario-relative probability across the scenario suite. By multiplying each hazard footprint with the corresponding scenario spatio-probability at the vent (Ang et al., 2020) with the constant value of the vent grid, 1/1625 (B & F) and 1/124 (D), into every pixel intersected by the polygon. Notably, Scenario H was excluded from the analysis as the complete grid resolution was not (Figure 3; see Section 3.2). The result produced a single-band GeoTIFF, one per simulation, where the cell values represent the conditional probability that a vent–scenario pair produces lava at that location. Finally, we produced the map by summing these stacked GeoTIFFs. This involved computing the union spatial extent of the stack snapping it to a 10 m grid (to reduce computational resources), warping each raster onto the reference grid and accumulating it into a running NumPy array. The final output is a single GeoTIFF in which each cell contains the conditional, relative probability of being inundated by lava from any simulated vent and scenario (given an eruption).

## 300 Results

The results of the MOLASSES simulations include the area inundated, average inundation depth and the computational time elapsed. The area and depth statistics informs the lava hazard estimates, while the latter provides information important to subsequent experimental design.

3.1 Parameter Tuning

305 The parameter tuning results included statistical analysis of the outputs to determine the best parameters for the AVF-wide analysis. Table 2 summarises the results for a residual thickness of 10 m vs. 17.5 m, with the main difference being in the area inundated and the average inundation depth. Only slight changes were found for time elapsed. In altering pulse volume from 10 m<sup>3</sup> to 100 m<sup>3</sup> and then to 1000 m<sup>3</sup>, a trend of decreasing elapsed time and area inundated occurred, but the average inundation depth increased.

310 Spatial outputs (Figure 4) illustrate the impact of parameter changes on lava distribution for the same vent location. As shown in Table 2, the difference in area inundated is as expected, with smaller areas (c. 43% less) for 17.5 m residual thickness. Meanwhile, the differences generated by different pulse volumes are much more evident; higher pulse volumes (1000 m<sup>3</sup>) were less responsive to localised features such as buildings near the vent, while lower pulse volume (10 m<sup>3</sup>) produced highly sensitive lava flows that closely followed topography and interacted

315 with nearby structures.

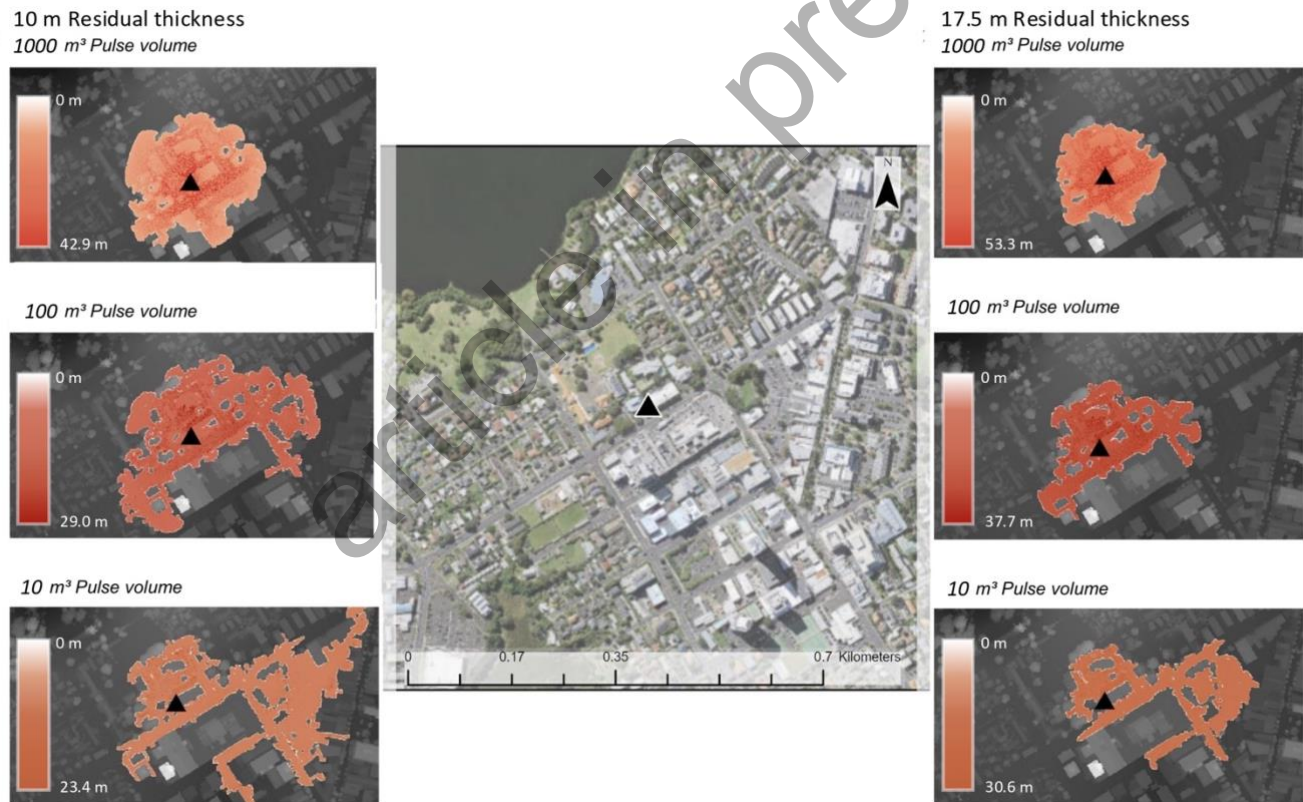


**Figure 4 – Parameter tuning results for Scenario B, detailing the spatial impact from altering residual thickness and pulse volume on the same vent location.**

The average inundation depth was strongly influenced by both the residual thickness and pulse volume values. At lower pulse volumes, the average inundation depth for both residual thickness values closely matched the residual thickness itself (Table 2). However, at the higher pulse volume (1000 m<sup>3</sup>), the average inundation depths exceeded the residual thickness values, indicating an excess of localised lava accumulation and limited redistribution occurred.

Although our parameter tuning explored residual thicknesses of both 10 m and 17.5 m, 10 m was selected as an appropriate value for all subsequent scenarios due to its alignment with AVF field measurements of average lava flow thickness. The pulse volume for modelling subsequent scenarios was chosen to balance spatial accuracy and computational efficiency: 100 m<sup>3</sup> was used for Scenario B to avoid the near-vent build-up (see Figure 4), while 1000 m<sup>3</sup> was adopted for the larger scenarios to optimise runtime and under the assumption that the effect of near-vent build-up would diminish at greater spatial scales.

## 3.2 Scenario output analysis

Informed by the parameter tuning, simulations were generated across the Auckland Volcanic Field (AVF), producing 2,244 lava hazard footprints ( $n = 1,064, 1,054, 122,$  and  $4$  for Scenarios B, F, D, and H, respectively), representing probable land-based vent locations at 0.5 km or 3 km coverage for each scenario (excluding Scenario H, see Section 3.2.4). For each scenario, selected “representative” simulations are summarised in tables, followed by spatial visualisations of the corresponding lava flows and the ranges of relative probability of the scenario (conditional on eruption) is indicated at each vent location, see Figures 5-8.

### 3.2.1 Scenario B

Scenario B represents a modelled lava flow with a total volume of 450,970 m<sup>3</sup>. Across the 1,064-vent suite, simulation times remained consistently under one minute. The spatial outputs in Figure 5 detail three representative simulations, which produce consistent footprint statistics: inundation areas ranged narrowly from 0.043 to 0.045 km<sup>2</sup>, and average inundation depths between 9.9 and 10.3 m. Figure 5 shows flow behaviour constrained by the unedited DSM, where features like trees, buildings and overpasses create barriers that route the lava flow around the features until accumulation overtops their height. In Figure 5(i), lava pools into the crater of a prior AVF eruptive vent producing a maximum inundation depth of 39 m and thinning over down-sloping terrain. Panel (ii) highlights the influence of infrastructure, with State Highway infrastructure channelling flows and an overpass acting as a barrier, causing the accumulation to a depth of 25 m. Figure 5(iii) illustrates the impact of small

residential buildings on the lava flow, reaching a height of 19 m, and the lateral spread that occurs when flows encounter the water.

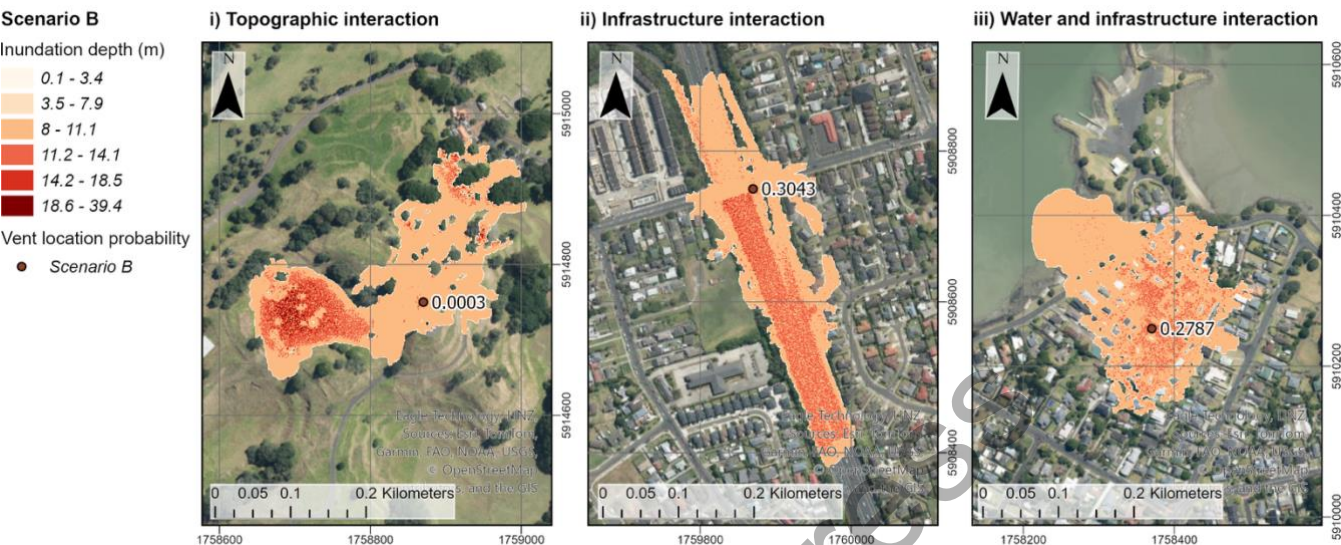


**Figure 5 - Example simulated lava flows from the Scenario B suite, representing a low-volume eruption totalling 0.45 million m<sup>3</sup>. The colour gradient shows lava inundation depth (m) from the simulated source vent location (red dot), which is given with its relative probability of occurrence. (i) Topographic interaction: Lava accumulates within localised topographic depressions; in contrast, large trees act as obstructions creating pockets of no lava. (ii) Infrastructure interaction: Man-made corridors channelise lava, while the overpass suppresses flow progression northward. (iii) Water and infrastructure interaction: Individual buildings notably obstruct lava flow, while to the north-west, lava begins to spread in a thin layer over the water.**

### 3.2.2 Scenario F

Scenario F represents an eruptive volume of 8.65 million m<sup>3</sup>. Across the 1,054 vent simulations, run times averaged approximately 20 minutes each. Figure 6 illustrates three representative flows, which produced inundation areas ranging from 0.794 to 0.819 km<sup>2</sup> and average depths between 10.78 and 10.88 m. In topographic depressions (Figure 4(i)), large-scaled pooling results in flows reaching a maximum inundation depths of 80 m. Along linear road features, see Figure 4(ii), flows channelise flows and build inundation depth as it is constrained reaching a maximum depth of 46 m. Panel (iii) demonstrates a large area of lobe/radial spreading as lava encounters water, and pockets absent from lava due to infrastructure height unable to be overcome.

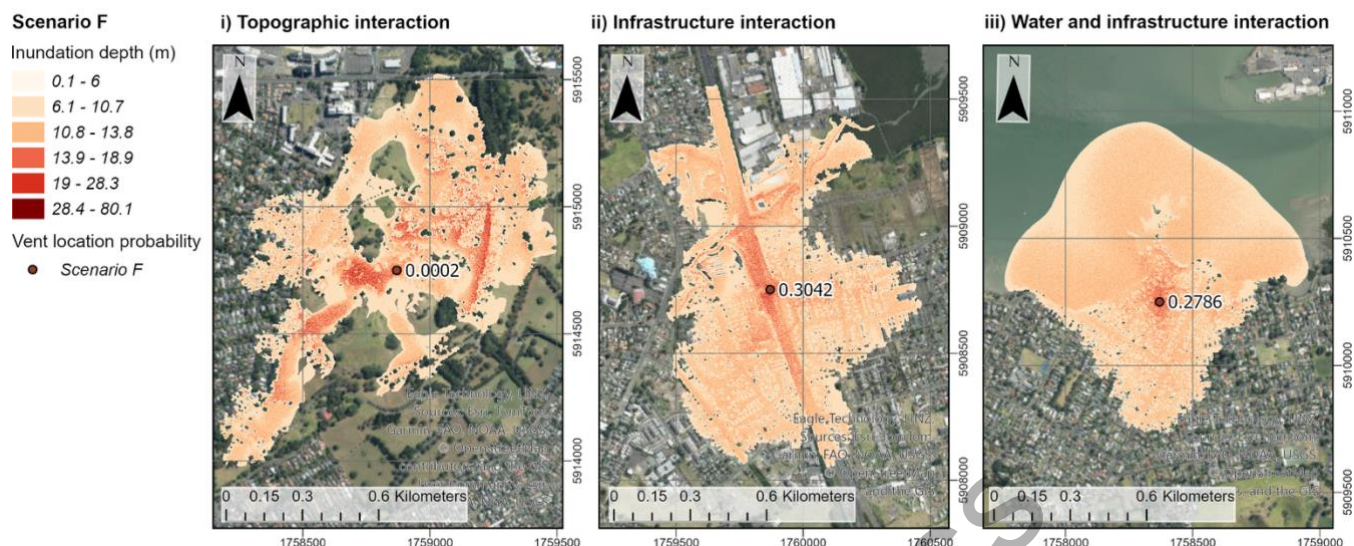


**Figure 6 - Example simulated lava flow simulations for the Scenario F suite, representing a total eruption volume of 8.65 million m<sup>3</sup>. The colour gradient shows lava inundation depth (m) from the simulated source vent location (red dot), which is given with its relative probability of occurrence. (i) Topographic interaction: Large-scale pooling occurs within topographic depressions, and flows channelise down steepest slopes. (ii) Infrastructure interaction: Road features heavily concentrate flow accumulation. (iii) Water and infrastructure interaction: The water body provides an unhindered surface supporting radial spread and comparatively thin lava depths.**

### 3.2.3 Scenario D

Scenario D represents a large total eruptive volume of 59.87 million m<sup>3</sup>, requiring greater computational resources and processing time, approximately 1000 minutes per simulation. Consequently, the spatial coverage was scaled back to 122 simulated vents. Figure 7 shows two representative simulated flows, with ~ 5.7 km<sup>2</sup> inundation area and an average inundation depth of ~ 10.5 m. Due to the size of Scenario D, some simulations, particularly those near the DSM edges, exceeded the boundary, producing a “FLOW IS OFF THE MAP” warning on completion.

Panel (i) shows lava erupted at the airport spreads outwards in a lobe pattern. Figure 7(ii) highlights a hilly residential suburb with steep coastal topography where lava channelises into confined, down-slope valleys before reaching the water, spreading laterally.

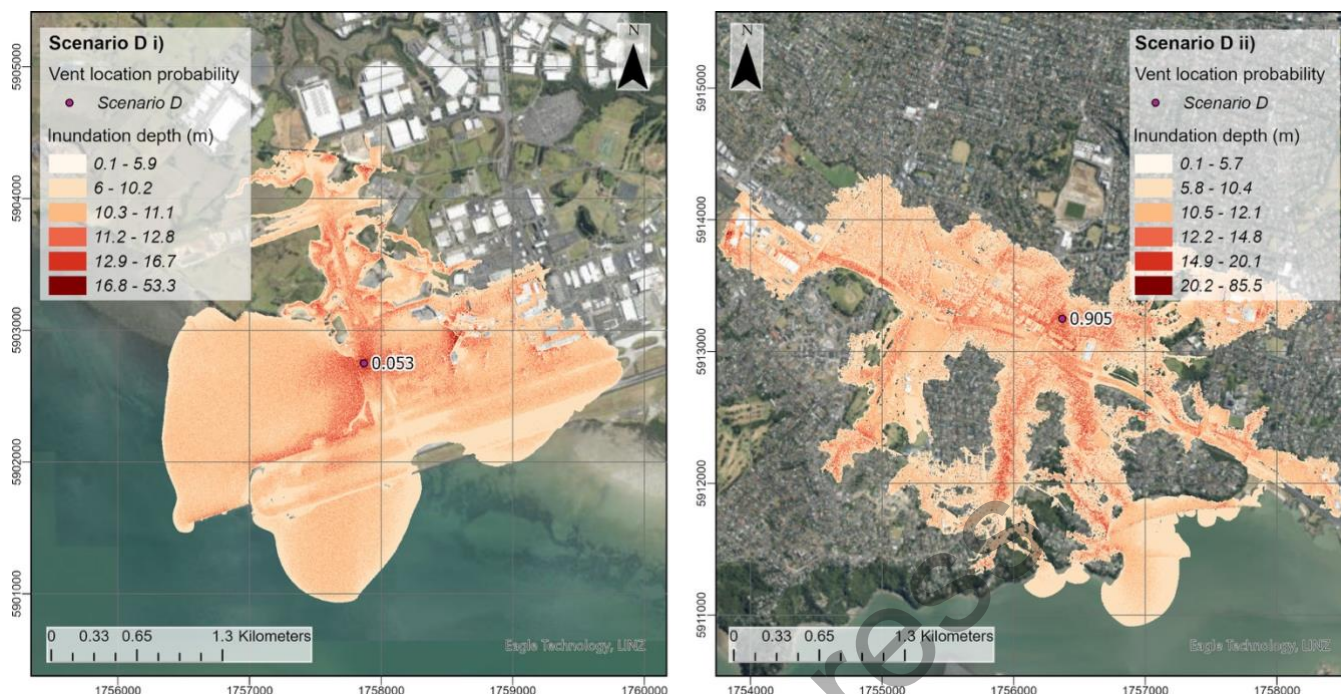
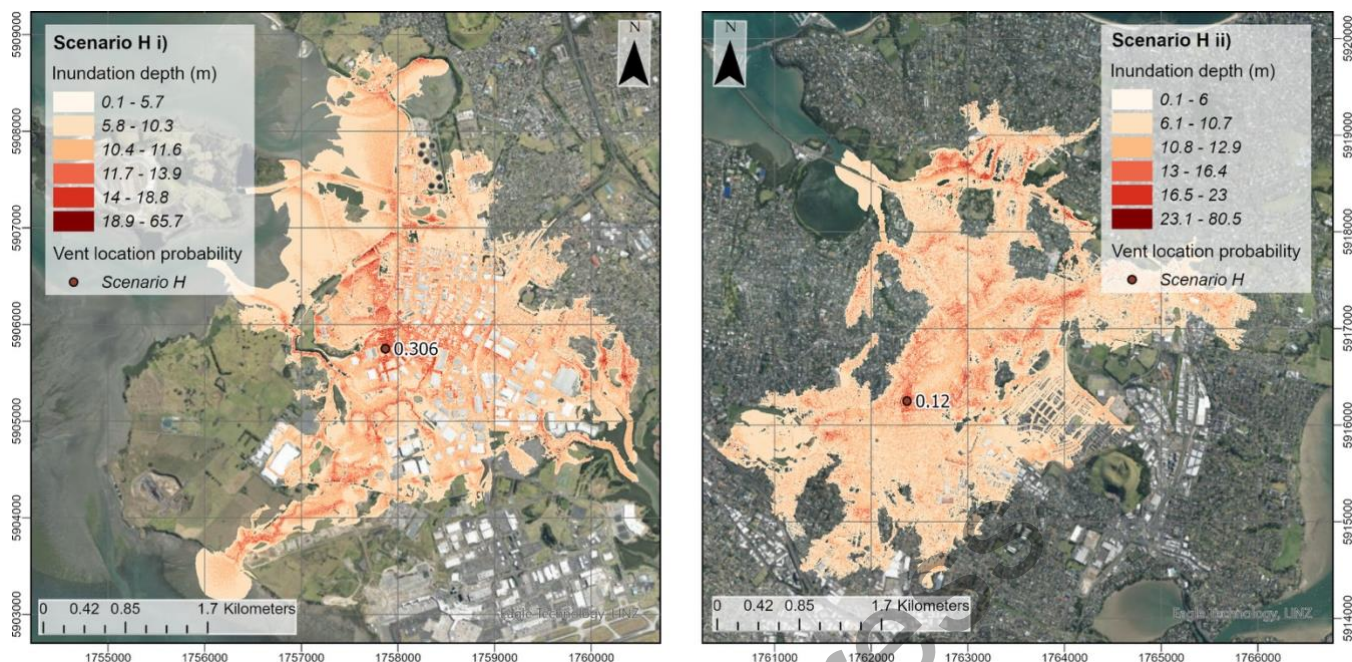


**Figure 7 - Example lava flows from the Scenario D suite demonstrating the influence topography and built infrastructure types. Simulated using MOLASSES at a 1 m DSM (includes all first returns). Inundation depth (m) is represented by a colour gradient from light orange to dark red, with the simulated source vent location and its relative probability of occurrence indicated by a red dot. (i) Flat topography and infrastructure i.e. airport runway support spread of lava. (ii) Steep coastal topography concentrates lava into valleys, overcoming residential housing.**

### 3.2.4 Scenario H

Scenario H, the largest lava scenario simulated, has a total volume of 100 million m<sup>3</sup> which demanded extensive computation time, up to 4828 minutes per simulation. Four representative simulations of the northern, eastern, western and southern Ellipse were modelled. Figure 8 illustrates two simulations, with the inundation area of 9.45 km<sup>2</sup> for (i), 9.65 km<sup>2</sup> for (ii) and an average depth of ~10.5 m in both. Large industrial buildings control flows, creating “islands” absent from lava in panel (i). Similarly, Figure 8(ii) shows existing volcanic cones or localised hills creating “islands” as lava is unable to surmount their heights. Across Figure 8, flows channelise along local stream tributaries, road infrastructure and pools where topographic depressions are encountered. The maximum inundation depth reached is 80 m in panel (ii) and 65 m in panel (i).



400 **Figure 8 - Example lava flows from the Scenario H suite, simulated using MOLASSES at a 1 m DSM (includes all first returns). Inundation depth (m) is represented by a colour gradient from light orange to dark red, with the simulated source vent location and its relative probability of occurrence indicated by a red dot. (i) Large industrial buildings influence lava flow direction and depth. (ii) Topography controls areas of lava pooling and diversion.**

### 3.3 Weighted lava footprint ensemble

405 Figure 9 serves as a visualisation of the conditional (on an eruption) relative (Scenarios B, D & F) probability of inundation across the Ellipse. The left panel displays the ensemble distribution of lava flow hazard footprints from Scenarios B, F, and D ( $n = 1064, 1054$ , and  $122$ , respectively), weighted by vent occurrence and spatio-probability. Paired with the hillshade of the Ellipse supports the analysis of the topographic influence at scale.

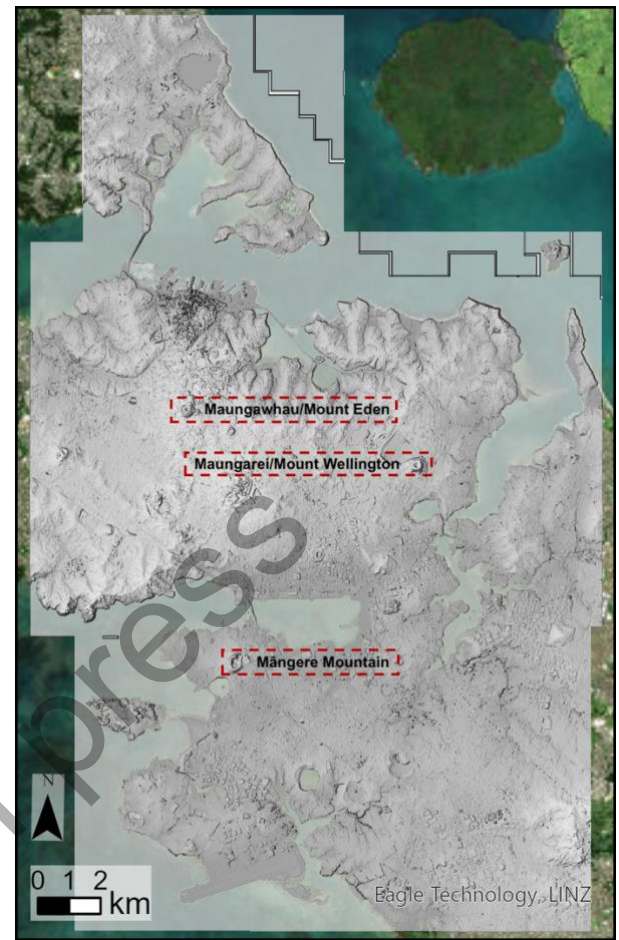
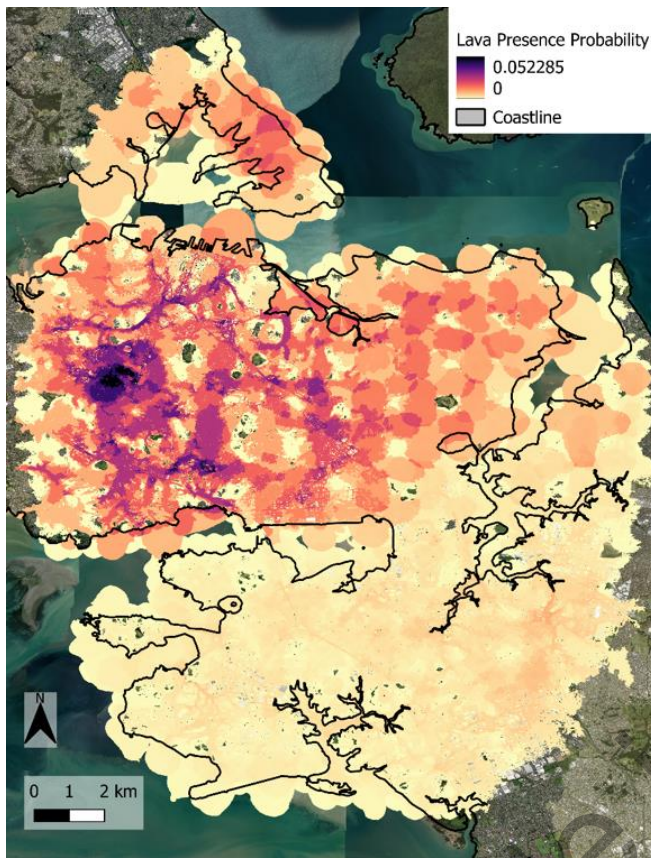


Figure 9 – DEVORA Scenarios B, D & F relative probability of lava presence (conditional on eruption) explored within the Auckland Volcanic Field (AVF) Ellipse, with comparison of the controls of topography for spread. Panel (i) Ensemble of Scenarios B, D & F, weighted by the probability of occurrence and modelled vent grid resolution. Panel (ii) AVF Ellipse with a hillshade for visual analysis of topographic controls.

A pronounced hotspot lava presence probability ( $\sim 0.05$ ) is visible in the western AVF Ellipse. In contrast, the southern extent shows consistently lower probabilities, indicating a reduced probability of inundation under the weighted scenario set. Overall, areas of elevated probability broadly correspond with the Scenario D spatio-probability distribution shown in Figure 3, whereas lower-probability areas more closely reflect the smaller inundation extents of Scenarios B and F.

Additional elevated probabilities occur across parts of the central AVF and within the eastern area, where broader lobate inundation patterns emerge. In contrast, several areas of consistently low or absent inundation remain visible within the ellipse; these features are not related to low spatio-probabilities but rather correspond to

significant elevated volcanic centres such as Maungawhau / Mount Eden, Maungarei / Mount Wellington, and Māngere Mountain, as highlighted in the hillshade in Figure 9 (ii). Linear features with increased lava presence are notable throughout the map, representing road corridors and low-lying highways that easily channelise lava.

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## Discussion

### 4.1 Parameter tuning

The parameter tuning exercise demonstrated that the two parameters not specified in the DEVORA scenarios, residual thickness and pulse volume, both strongly control simulated lava flow behaviour. Residual thickness  
430 influenced the scale of the inundation area and with the resulting average inundation depth. Between the two values tested (10 m and 17.5 m), lower residual thickness enabled earlier redistribution of excess lava (with redistribution commencing at 10 m rather than 17.5 m), therefore, represents mobile, lower-viscosity flows. Higher residual thickness values corresponded to less mobile, more viscous lava. This study based our residual thickness selection  
435 of 10 m on its alignment with AVF averages (Deligne et al., 2017; Kereszturi et al., 2012), but there is an opportunity to examine lava morphotype and distinguish representative 'a'ā (more viscous) and pāhoehoe (less viscous) residual thickness values to further refine the model's applicability to the AVF. Furthermore, while out of scope for this study, defining both parameters to closely replicate the emplaced AVF lava flows that inspired the  
Hayes et al. (2020) scenarios would significantly improve the useability of the outputs (see Section 4.6).

Pulse volume primarily affected elapsed time and average inundation depth. Between the tested values, a trade-  
440 off emerges between the spatial response to surface features and computational efficiency. Smaller pulse volumes produced more topographically constrained flows, with pathways strongly influenced by local elevation and nearby structures (Figure 4). Larger pulse volumes are expected to overcome features close to the vent (Connor et al., 2012), a phenomenon evident in Figure 4.

The average inundation depth proved a key diagnostic for selecting an appropriate pulse volume across scenario  
445 scales. In testing the smallest scenario (B), the 1000 m<sup>3</sup> pulse volume produced average depths exceeding the residual thickness by just over 2 m, reflecting the build-up of lava near the vent due to short simulation times and limited end-phase redistribution associated, a phenomenon expected to diminish with larger scenarios.

## 4.2 Basic model behaviours

Following our parameter selection, it is important to consider whether simulated inundation patterns reflect plausible lava flow behaviour. Across all scenarios, lava flows channelise in confined terrain, thicken in depressions, and spread over plateaus or waterbodies (Figures 5-8). The recurrence of these behaviours throughout the simulated lava flows highlights the topographic control within the model.

This influence is further identified in larger scenarios, such as D, where flows over flat topography and waterbodies develop a lobate footprint (Figure 7). This pattern emerges from MOLASSES model's rule of Moore neighbourhood distribution, where excess lava ( $<10$  m residual thickness) at the parent cell is distributed outwards, whereas cells in the orthogonal direction (N, E, S, W) receive more from the parent than the diagonal cells (NE, SE, SW, NW) (see Section 4.5). Pulse volume (and its interaction with the fine DSM resolution; see Section 4.5) plays a key role in shaping inundation patterns, particularly in flat terrains (INL, 2024), whereas in the relatively hilly AVF, inundation areas are less sensitive to this parameter.

Infrastructure interaction is a key aspect of hazard modelling in the AVF. While the original MOLASSES model used a DEM, employing a DSM was necessary to capture Auckland's dense built environment (Tsang et al., 2020). Without further data cleaning, however, the model interpreted man-made features as impassable barriers. Small-scale structures, vegetation, and easily ignitable buildings are unlikely to impede lava flows in reality, as they may be surmounted, demolished, or destroyed by lava flow. Modelled bridges and highway overpasses may artificially obstruct movement by requiring lava accumulation before overtopping, rather than allowing passage beneath. The repercussions of this effect were partially mitigated by the chosen residual thickness of 10 m, which allows features below this threshold to be inundated. Future applications would benefit from DSM refinement to remove susceptible structures and from the use of a coarser resolution (e.g., 5 m or 10 m).

## 4.3 Scenario spatial impact

The DEVORA eruption scenarios tested in this study demonstrate the potential scale of lava hazard in an AVF eruption. The variability in hazard footprints across the different scenarios primarily reflects differences in total volume, where scenarios with smaller total volumes, such as Scenario B, produced relatively small inundation areas of  $0.045 \text{ km}^2$ , whereas larger total volumes, such as Scenario H, produced significantly larger hazard footprints, extending up to  $9.8 \text{ km}^2$  (Figures 5-8). With increasing total volume across the scenarios, the potential maximum inundation depth also increased, enabling a greater accumulation in local depressions.

Within each scenario, the area inundated and the average inundation depth remained within a consistent range, despite the changing local topography producing the visual differences (refer to Figures 5-8). The lava hazard footprints presented in this study and in Tsang et al. (2020) differ from the hand-drawn elongated flows presented by Hayes et al. (2020) in their DEVORA scenarios (Figure 1). As noted by Tsang et al (2020), while there are key differences, such as the qualitative nature of lava flows in the DEVORA study and intermittent effusion, a similar elongated flow geometry could be encouraged (depending on the local topographic control) by imposition of a scoria cone at the vent, a lower residual thickness and pulse volume (despite the values used presently were already low; see Section 4.5).

#### 4.4 Weighted lava hazard ensemble

The pattern of conditional lava hazard probabilities in Figure 9 is dominated by Scenario D. This influence is in part due to its larger flow volume than Scenarios B and F, but also due to the high probability of an eruption in the central or northern part of the field occurring as Scenario D rather than B or F (Figure 3), which have higher probability in the southern part of the field. In the latter case, the lack of controlling topography results in a uniform hazard distribution from the superposition of many approximately circular flows, whereas the larger Scenario D in the central part has flows strongly controlled by the local topography, resulting in the spatial pattern seen in Figure 9.

For this study, Scenario H was computationally intensive, so only 4 simulations were conducted to explore the spatial extent of the hazard, hence it was excluded from the ensemble map. With the inclusion of Scenario H, we would expect the lava hazard in the southern part of the field to increase, reflecting the similar spatio-probability pattern as Scenarios B and F, but a considerably larger volume. Our ensemble map not only shows clear hotspots of lava inundation but also highlights how sensitive probabilistic hazard outputs are to scenario inclusion and weighting assumptions, even when using a uniform distribution for vent locations. This result reinforces the importance of considering a range of scenarios when evaluating volcanic hazard across the AVF and elsewhere.

#### 4.5 Limitations

The limitations of the MOLASSES model in simulating AVF lava flows stem from both its capabilities and chosen input parameters.

Creating a true representation of lava flow dynamics/sequence is a limitation of the MOLASSES model, key factors such as lava composition, and temperature are not direct parameter inputs. Importantly, there is no practical

505 way to forecast (as opposed to hindcast) the vast number of such parameters, and the MOLASSES model accounts for these complexities with a small set of proxy parameters that have been shown to effectively reproduce observed inundations (INL, 2024). Additionally, the different lava eruption styles and phase changes are out of the capabilities of the model, which has direct implications on this study, with past eruptive events within the AVF indicating a phase change i.e., phreatomagmatic to magmatic (Ang et al., 2020; Kereszturi et al., 2014a).  
510 Consideration of eruption phases would significantly alter the temporal distribution of pulse volume and residual thickness, and therefore the spatial extent of the hazard.

Our simulation of MOLASSES operates under the assumption of a purely magmatic eruption that occurs at a continuous pulse volume, therefore excluding submerged vents (all Scenario C and additional B and F vents located coastal/offshore) to avoid the inherent lack of understanding in subaqueous flow behaviour and different (lower)  
515 risk profile to the suite of footprints presented. Nevertheless, as a tool for probabilistic hazard assessment, the computational efficiency and small number of easily quantified input parameters make MOLASSES a promising choice (Dietterich et al., 2017; INL, 2024).

The chosen input parameter values led to trade-offs that increased computational demand. This is largely related  
520 to the use of a 1 m resolution DSM, which inherently made the model simulations extremely computationally intensive. While fine resolutions are important for hazard modelling, coarsening to a scale greater than 1 m would not only be sufficient for the large-scale footprints produced but would better represent lava dynamics (avoiding a ‘freezing’ effect at a 1 m scale). For example, Kubanek et al. (2015) advocate for a resolution finer than the 15 m used in their study, whereas Kereszturi et al. (2012) and Torres et al. (2022) considered 10 m and 5 m resolutions,  
525 respectively, to be adequate.

Specifically, this adjustment could have enabled the following:

- 1) More intensive vent density coverage across scenarios, as the refinement of vent density for larger scenarios was limited by prioritising DSM resolution over vent coverage due to computational constraints.
- 2) Avoided issues arising from the full Ellipse DSM being too large to process, which required dividing it  
530 into sections and caused some vents near DSM edges to generate errors (“FLOW IS OFF THE MAP”) when the edge was encountered.
- 3) Cleaning the DSM to remove buildings less than the residual thickness height, easily ignitable and other surface features falsely registered by the model as topographic barriers.

Other limitations relate to the absence of simulated cones. Hayes et al. (2018) discuss the effects of cone development on lava flow direction, where lava flows often exit from the side of a cinder cone rather than the central vent (*Cinder Cone*, 2023) with the remaining edifice preventing flow in that direction. The simulated lava flows in this paper, therefore, originate from a flatter topography than would realistically occur. However, given the scale of the synthesised lava models in this study (n 2,244) and their application to an AVF-wide probabilistic multi-hazard assessment, the absence of cones is unlikely to substantially affect results.

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Importantly, this paper utilises the defined scenarios of Hayes et al. (2020), which encompass a range of possible eruption styles and volumes, though they do not cover the full spectrum of possibilities (Ang et al., 2020; Hayes et al., 2020; Kereszturi et al., 2014a). Our analysis further restricts these to consider only the subaerial lava hazard. The scenarios and generated lava hazard footprints provide insight into AVF eruptions and lava hazard, potentially aiding disaster risk management and planning, but should not be considered exact predictions, as lava flow volumes may not fully represent the complete range of potential events.

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#### 4.6 Future work

Future work should focus on using a coarser and a more representative DSM resolution, such as the values used by Kereszturi et al. (2012) and Torres et al. (2022). This alteration would enable faster modelling times and the potential to expand the coverage of Scenario D to a 0.5 km<sup>2</sup> grid and complete Scenario H to a full coverage at 3 km<sup>2</sup> or 0.5 km<sup>2</sup>.

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Through further parameter tuning exercises, defining residual thickness and pulse volume that best replicate the emplaced lava flow that inspired each scenario (B, F, D & H) would enable greater confidence in the hazard outputs, and integration into probabilistic hazard modelling. Additionally, defining the probability of each vent location experiencing an eruption would enable the analyses to move beyond the “uniform” eruptive condition applied in this study and in Ang et al. (2020), where each vent has an equal probability of occurrence. With this inclusion, our weighted hazard ensemble could be reweighted to reflect the spatial likelihood of an eruption at each point location (Bebbington and Cronin, 2011; Bebbington, 2013; Bebbington, 2015).

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Additional testing should explore how the model preforms on flat topography. The lobate pattern shown in Figure 9 indicates how the model spreads over relatively flatter elevations but does not necessarily accurately display lava flow behaviour. For the intended application of the weighted ensemble, the “lobe” pattern was sufficient to still highlight the high and low probabilities of lava presence at the regional-scale. Given this

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limitation, we recommend exercising caution when using individual footprints from flatter topographic areas for deterministic analysis.

These alterations would build on the advancements of this study and provide more representative estimates of conditional lava hazard for volcanic impact and risk assessment (including conditionally probabilistic impact and risk assessment) of the AVF, crucial for informing DRM strategies.

## Conclusions

The monogenetic Auckland Volcanic Field (AVF) presents a complex challenge for conducting risk assessments, which are required to inform disaster risk management strategies. To address spatial uncertainty, this research advances lava hazard assessment of the AVF by developing a framework for volcanic field lava hazard assessment applied to the AVF.

Using the MOLASSES model, we provide a suite of deterministic lava hazard footprints for Scenarios B, F, D and H (1,065, 1,054, 122 & 4 respectively) and a weighted ensemble map for the AVF. The lava footprints and the ensemble map (Section 3) can support disaster risk management strategies, including for infrastructure resilience, community preparedness, and multi-hazard risk assessments. The methodology (Section 2) is also applicable to other AVF volcanic hazards, such as surges, and other monogenetic or volcanically complex regions with spatio-temporal uncertainty. The synthesised lava hazard footprints are primed for deterministic and conditionally probabilistic impact and risk assessments for the AVF.

## Tables

**Table 1 - Total volume parameter inputs for the modelled scenarios**

| Scenario | <i>Total volume (m<sup>3</sup>)</i> | <i>Source</i>                                 |
|----------|-------------------------------------|-----------------------------------------------|
| <b>B</b> | 450,970                             | Kereszturi et al. (2013), Tsang et al. (2020) |
| <b>D</b> | 59,871,290                          | Kereszturi et al. (2013), Tsang et al. (2020) |
| <b>F</b> | 8,647,290                           | Kereszturi et al. (2013), Tsang et al. (2020) |
| <b>H</b> | 100,000,000                         | Hayes et al. (2018)                           |

**Table 2 – Parameter Tuning exercise for Scenario B at Takapuna Commercial Centre, accounting for variation in residual thickness and pulse volume.**

| Scenario B                |                     | 450,970 m <sup>3</sup> |                                 |                     |
|---------------------------|---------------------|------------------------|---------------------------------|---------------------|
| <u>Input:</u>             |                     | <u>Results:</u>        |                                 |                     |
| <i>Residual thickness</i> | <i>Pulse volume</i> | <i>Area inundated</i>  | <i>Average inundation depth</i> | <i>Time elapsed</i> |
| 10 m                      | 10 m <sup>3</sup>   | 0.047 km <sup>2</sup>  | 9.50 m                          | 2.9 minutes         |
| 10 m                      | 100 m <sup>3</sup>  | 0.045 km <sup>2</sup>  | 9.95 m                          | 0.5 minutes         |
| 10 m                      | 1000 m <sup>3</sup> | 0.037 km <sup>2</sup>  | 12.32 m                         | 0.13 minutes        |
| 17.5 m                    | 10 m <sup>3</sup>   | 0.027 km <sup>2</sup>  | 16.59 m                         | 2.3 minutes         |
| 17.5 m                    | 100 m <sup>3</sup>  | 0.026 km <sup>2</sup>  | 17.13 m                         | 0.31 minutes        |
| 17.5 m                    | 1000 m <sup>3</sup> | 0.022 km <sup>2</sup>  | 20.05 m                         | 0.10 minutes        |

### Author contributions

590 BM modified MOLASSES code, developed automation, analysed simulation results and wrote the manuscript. JW assisted in method development, developed the hazard ensemble map, reviewed and edited the manuscript. HC, MB, CM, JH, JL, RF contributed to initial method development, method validation and reviewed and edited the manuscript. AW and TW contributed to initial method development, method validation and manuscript review. AT contributed to method development and analysis.

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### Data availability

605 An adapted MOLASSES model setup applied to the AVF is available at [https://github.com/bethanymillar/MOLASSES\\_AVF](https://github.com/bethanymillar/MOLASSES_AVF) for further development. Lava flow hazard footprints for all Scenarios are also available as GeoTIFFs on reasonable request.

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