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RESEARCH ARTICLE

Rapid remote volcanic ashfall impact assessment for the 2022 eruption of Hunga volcano, Tonga: a bespoke approach and lessons identified

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Abstract
When disasters occur, rapid impact assessments are required to prioritise response actions, support in-country efforts and inform the mobilisation of aid. The 15 January 2022 eruption of Hunga volcano, Tonga, and the resulting atmospheric shockwave, ashfall, underwater mass disturbance and tsunami, caused substantial impacts across the Kingdom of Tonga. Volcanic impacts on the scale observed after the eruption are rare, necessitating a reliance on international advice and assistance. The situation was complicated by the loss of Tonga's international submarine fibreoptic cable (causing a complete loss of communications for approximately 20 days) along with border closures due to the COVID-19 pandemic. A need emerged for a rapid remote volcanic impact assessment and provision of specialist advice to help inform the response of international partners. Here we present a novel methodology for conducting rapid remote volcanic ashfall impact assessments, conducted over a 10-day period following the eruption. We used three different hazard models for ashfall thickness across the main island of Tongatapu and available asset information and vulnerability functions for buildings, agriculture, electricity networks, water supply and roads, to provide initial estimates of losses due to ashfall from the 15 January eruption. For buildings, we estimated losses both as total losses and as percentages of the total replacement cost of buildings on Tongatapu. For agriculture, we made probabilistic estimates of production losses for three different crop classes. For ashfall clean-up, we estimated ranges of ashfall volumes requiring clean-up from road surfaces and roofs. For water supply, electricity networks and roads, our analysis was limited to assessing the exposure of important assets to ashfall, as we had insufficient information on system configurations to take the analysis further. Key constraints on our analysis were the limited nature of critical infrastructure asset inventories and the lack of volcanic vulnerability models for tropical regions including Pacific Island nations. Key steps towards iteratively improving rapid remote impact assessments will include developing vulnerability functions for tropical environments as well as ground-truthing estimated losses from remote approaches against in-person impact assessment campaigns.

Keywords Risk assessment · Loss assessment · Disaster risk reduction · Volcanic risk · Pacific Islands, Tonga

Introduction

Rapid post-disaster impact assessments aim to support disaster response efforts and decision-making by producing credible and timely estimates of the impact of disasters (Gunasekera et al. 2018; Merz et al. 2020; UNDRR 2019). As these assessments are often imperative to prioritise response and recovery actions, release funds to support response and recovery and mobilise aid, post-disaster impact assessment needs to be conducted in a timely manner (UNDRR 2019; World Bank 2014). As access and

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Extended author information available on the last page of the article communications may be limited in post-disaster environments, rapid impact assessments may need to be conducted remotely (UNDRR 2019; World Bank 2014).

The 15 January 2022 eruption of Hunga volcano, the Kingdom of Tonga (hereafter referred to as Tonga), and resultant volcanic ashfall, airwave, underwater mass disturbance and tsunami caused significant impacts to Tonga (Borrero et al. 2023; The World Bank 2022). This included disruption to telecommunications (via damage to the submarine telecommunications cable) that lasted approximately 20 days, with re-establishment of telecommunications to the outer islands of Tonga taking substantially longer (Borrero et al. 2023; The World Bank 2022). During the initial 10 days following the eruption (15–25 Jan 2022), when telecommunications with Tonga were limited and COVID-19 restrictions prevented overseas support on the ground, there was a need to remotely assess the potential impact of the disaster on Tonga to support emergency management and international aid efforts.

In this paper, we present a bespoke approach undertaken for the rapid, remote assessment of volcanic ashfall impacts following the 15 January 2022 eruption of Hunga volcano, Tonga. We focused on assessing potential ashfall impacts to buildings, critical infrastructure and agriculture. We also estimated clean-up requirements on Tongatapu (the main island), as these are known to be important for community well-being in the aftermath of volcanic ashfall (Deligne et al. 2022; Wilson et al. 2014, 2012).

The approach follows established volcanic impact assessment methodologies (Jenkins et al. 2014; UNDRR 2019). It relies heavily on local expertise and leveraged international research partnerships to (a) supplement and corroborate exposure data (such as critical infrastructure asset attributes, building construction types and farm type spatial distribution) and (b) critically evaluate the applicability of available ashfall vulnerability models and impact metrics to the Tongan disaster risk context. The paper also discusses the lessons, successes, challenges and opportunities learned for future rapid remote volcanic ashfall disaster impact assessments, which are particularly valuable for syn-eruption and post-eruption contexts with limited communications. We outline the methodological approach (Method section); present the results of the rapid impact assessment as conducted in the initial 10-day period (Results: Exposure, Impact and Loss Estimates section); summarise the recommendations provided to Tongan authorities, reflect on the successes and challenges of the approach adopted in this study, and finally examine the broader challenges of applying traditional volcanic impact assessment approaches in this risk context (Discussion section).

Event background

On 15 January 2022, at approximately 17:15 (0415 UTC), Hunga volcano, located ~ 65 km northwest of Tongatapu Island, produced a violent, submarine, explosive eruption that lasted approximately 1 h (Borrero et al. 2023). During this paroxysmal phase, the eruption generated a large atmospheric pressure wave and multiple tsunami (Borrero et al. 2023; Carvajal et al. 2022; Lynett et al. 2022; Omira et al. 2022). The eruption had been preceded by several weeks of volcanic unrest and minor explosive activity, with eruptive activity beginning on 20 Dec 2021 (Global Volcanism Program 2022a, 2022b, 2021). Hunga volcano, sometimes referred to as Hunga-Tonga Hunga-Ha'apai, after the two small islands that comprise the emergent parts of the volcano, is located on the northern rim of a submarine volcanic caldera (Cronin et al. 2017). The 15 January 2022 eruption has been estimated to have had a Volcanic Explosivity Index (VEI) ~ 6 (Global Volcanism Program 2022a; Poli and Shapiro 2022). The eruption plume dispersed volcanic ash across the Ha'apai, Tongatapu and 'Eua island groups resulting in ashfall deposits estimated to be 5–50 mm thick (The World Bank 2022).

Syn-eruption underwater debris flows severed submarine telecommunications cables that service Tonga (Clare et al. 2023) which disrupted telecommunications with Tonga for at least 20 days. In addition to this, and the COVID-19 pandemic management within Tonga, there was very limited access for post-event impact and needs assessments. The Government of Tonga officially requested technical assistance from international research partners to address this knowledge gap (The World Bank 2022). While the Tonga Meteorological Service and Tonga Geological Services were able to communicate important anecdotal observations to international partners by satellite phone, there was a lack of immediate detailed quantitative information on the eruption and impacts observed. This study was conceived to support Aotearoa New Zealand's (NZ) response to this information request, facilitated by the NZ Ministry of Foreign Affairs and Trade (MFAT), and serves as proof of concept for future events.

Science advice support

There is precedent for the provision of specialist volcanic science advice from Aotearoa NZ to Pacific nations. For example, expertise on volcano monitoring and impact and risk assessment was provided to the Government of Vanuatu for both the 2017–2018 eruptions of Manaro Voui volcano, Ambae.[1] (Jenkins et al. 2024) and the 2018 fissure eruption

[1] https://www.gns.cri.nz/research-projects/vanuatu-ambae-eruption/

of Ambrym volcano (Deligne et al. 2019). Aotearoa NZ also has a long-standing relationship with Tonga which includes the provision of science advice during times of disaster (Deligne et al. 2019; MFAT 2022; OECD 2023). Immediately following the 15 January 2022 eruption, global science agencies began to support information gathering, impact assessment and science advice efforts. To provide a coordinated science response to the crisis, the NZ Volcanic Science Advisory Panel was activated in the hours after the eruption[2]

Initially, there were concerns about high numbers of fatalities given the estimated scale of the eruption and tsunami, garnered from initial satellite observations and New Zealand Defence Force (NZDF) overflight imagery.[3] Secondly, there were concerns about widespread volcanic ashfall contamination and damage to food and cash crop agriculture on several Tongan islands, including Tongatapu. The analysis presented here was undertaken to address growing concerns around ashfall impacts to the built environment, and was designed to inform the prioritisation of international response actions. A final report was prepared for the New Zealand MFAT Aid Programme (New Zealand Ministry of Foreign Affairs and Trade 2023).

Overview of volcanic ash impacts

Volcanic ashfall is a spatially far-reaching volcanic eruption hazard that can cover large areas. Although ashfalls rarely endanger human life directly, threats to public health and disruption to critical infrastructure, aviation, agricultural production and the built environment can lead to substantial societal impacts, even at thicknesses of just a few millimetres (Wilson et al. 2012; Jenkins et al. 2014). Relatively small eruptions can cause widespread disruption, damage and economic loss. For example, the VEI 3 1995/1996 eruptions of Ruapehu volcano, Aotearoa New Zealand, covered over 20,000 km^2 of agricultural land with thin (< 5 mm) ashfalls, and caused significant damage and/or disruption to aviation, a hydroelectric power station, electricity transmission lines, state highways, water supply systems and alpine tourism with economic losses estimated at > NZD130 million (1996 value) (Johnston et al. 2000). Another example is the 2010 eruption of Eyjafjallajökull, which caused substantial impacts to air industry, air quality and ecosystems (e.g. Arnalds et al. 2013).

Although ashfall impacts to the built environment are generally well-characterised for countries in temperate climates (e.g. Johnston et al. 2000; Magill et al. 2013; Craig et al. 2016a, b; Hayes et al. 2019), there are knowledge and data gaps for impacts in tropical regions, particularly for the small island nations of the South Pacific (Jenkins et al. 2024). Volcanic ash vulnerability models are available for many asset types (Deligne et al. 2022; Fitzgerald et al. 2023; Wilson et al. 2014) particularly for the built environment (Blake et al. 2017; Hayes et al. 2017; Wardman et al. 2012; Wilson et al. 2017, 2014). However, the suitability of these models for the Pacific Island context, where asset configuration, construction type and materials may differ from the contexts where vulnerability models were developed, is not yet well understood. This challenge was addressed via consultation on the applicability of available vulnerability models with local experts and subject matter experts (Method section).

Methods

A bespoke rapid, remote volcanic impact assessment approach was undertaken in the first 10 days following the eruption, using pre-existing vulnerability models, and the best available hazard (ashfall thickness) and exposed asset (critical infrastructure, buildings, farms) data (Fig. 1). Impacts from volcanic ashfall were the focus of this study, while other science expert groups considered tsunami, airwave and cascading impacts (e.g. Borrero et al. 2023; Carvajal et al. 2022; Lynett et al. 2022; Omira et al. 2022; UNOSAT 2022). Volcanic ashfall impact assessments were conducted for exposed assets and sectors of high societal importance, namely, agriculture, buildings, critical infrastructure and clean-up requirements.

We followed a conventional impact assessment approach (AS/NZS 2009; UNISDR 2015) using hazard models and asset inventories to assess exposed elements, then apply vulnerability models to quantify impact (Fig. 2). Development of the hazard, exposure and vulnerability components of the impact assessment was heavily reliant on expert input (i.e. local and subject matter experts; Fig. 2) and work is underway to validate the assumptions and approach adopted here (Auapa'au et al. n.d.). We used publicly available asset data, supplemented by expert opinion and private data provided by research partners (the Asian Development Bank (ADB); Fig. 2). Each asset class and/or sector required an individualised approach to acquire or assume spatial locations and asset attributes. These approaches are detailed in the "Building exposure and loss" to "Critical infrastructure exposure" sections. We used a recent volcanic vulnerability model stocktake (Fitzgerald et al. 2023; Hayes et al. 2024) to select appropriate vulnerability models for each respective sector and/or asset class (e.g. taro vs coconut crop vulnerability). The impact metrics (e.g. loss from crop damage)

[2] The NZ Volcanic Science Advisory Panel is comprised of representatives from government agencies and university-based subject matter experts. It is chaired by NZ's National Emergency Management Agency.

[3] https://www.nzdf.mil.nz/media-centre/news/nzdf-update-on-response-to-tonga/

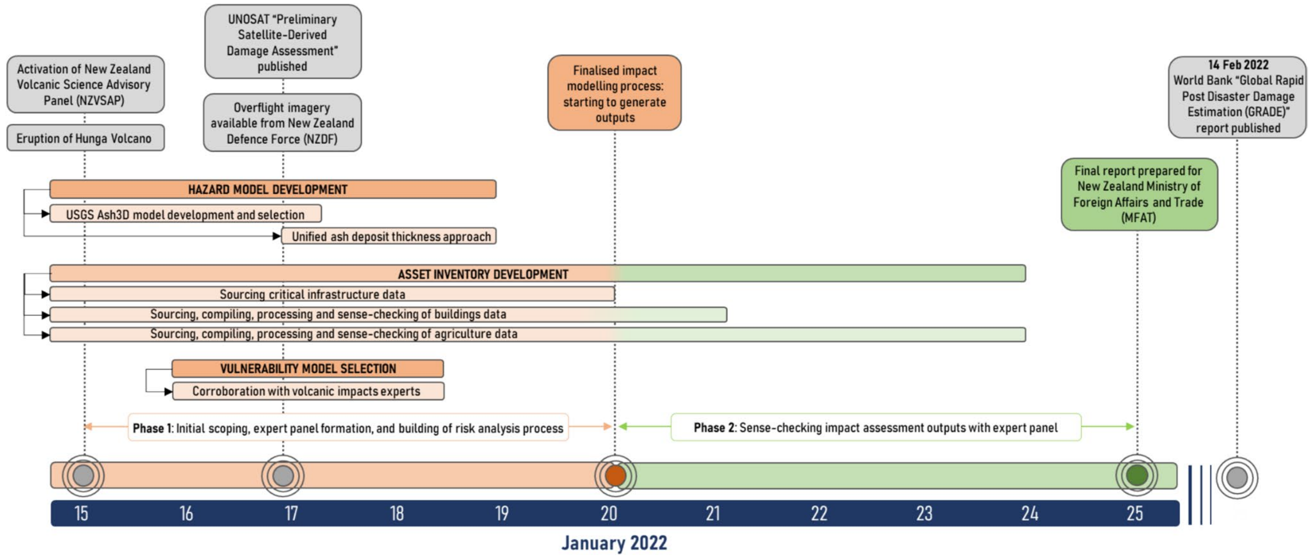

Fig. 1 Timeline of impact assessment process

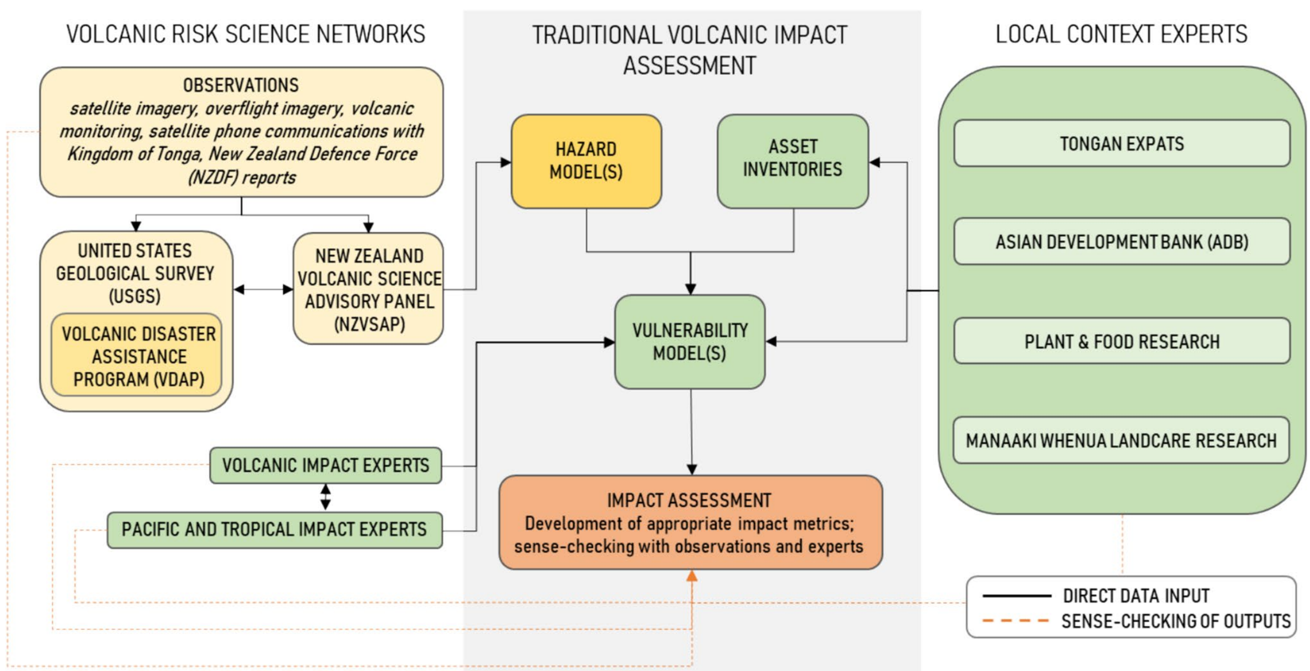

Fig. 2 Conceptual diagram of the impact assessment approach. "Volcanic Impact Experts" (left) refers to quantitative volcanic impact and risk academics and volcanic impact and risk scientists based at science agencies, such as GNS Science (Aotearoa New Zealand), the United States Geological Survey (USGS; USA) and National Institute of Water and Atmospheric Research (NIWA; Aotearoa New Zealand). "Pacific and Tropical Impact Experts" (left) refers to disaster risk experts in Pacific and Tropical settings based at academic institutions or science agencies, and/or Pacific Island expats based at all agencies

were guided by response and international aid priorities and corroborated by local and subject matter experts (Fig. 2). In the case of buildings and agriculture, the impact metric was loss in Tongan Pa'anga (TOP), the local currency; for ash clean-up, we quantified the cost in TOP.

The impact assessment fell into two distinct phases: Phase 1, initial scoping, expert panel formation and building of the impact assessment process, and Phase 2, sense-checking impact assessment outputs with the expert panel (Fig. 1). The transition between these two phases is defined by the point where impact assessment outputs began to be generated (Fig. 1). There was a high degree of uncertainty in the early stages of analysis, due to telecommunication disruption and generally poor geographical data coverage. This uncertainty was iteratively reduced throughout the analysis through expert input and empirical reports (Fig. 2).

Hazard information

Shortly after the eruption, the United States Geological Survey (USGS) Volcanic Disaster Advisory Panel (VDAP) identified the need to develop volcanic ash transport and dispersion (VATD) models to support rapid impact assessment. The USGS Volcanic Hazards Program developed early iterations of such hazard models employing the widely used Ash3D VATD model (used operationally by the USGS) ((e.g. Barker et al. 2019; Buckland et al. 2022; Mastin and Van Eaton 2020)) (Figs. 2 and 3). These hazard models were developed using eruption source parameters elicited using initial reports, photography and satellite imagery (e.g. for plume height and eruption duration estimations). The USGS generated multiple Ash3D model outputs (10 km grid resolution), varying the eruption volume, plume height, amount of umbrella spreading and the eruption duration. Based on early anecdotal observations of the ashfall deposit thickness, the New Zealand Volcanic Science Advisory Panel (NZVSAP) volcanic ash working group selected an ash deposition model most representative of early empirical reports. This model assumed a 30 km column height (with umbrella spreading), 1-h eruption duration and 0.5 km^3 dense rock equivalent (DRE) eruption volume (Fig. 3).

Early empirical reports from in-country Tongan research partners, reports from the NZDF and satellite imagery (UNOSAT 2022) suggested that outputs from the chosen USGS Ash3D model were likely at the higher end of the credible range of ashfall deposit thickness. To capture an inherent level of uncertainty in the hazard model and to provide a potentially more representative range of impact estimates, we developed two additional hazard models for use in the impact assessment. For these we applied uniform ashfall thicknesses of 20 mm and 30 mm across Tongatapu, to represent credible minimum and median (respectively) thicknesses in line with empirical reports (Fig. 1). These three hazard models (USGS Ash3D, 20 mm and 30 mm) were applied consistently in the impact assessment across all sectors, to provide a credible range of impact estimates.

Building exposure and loss

A recent building inventory for Tongatapu was provided by the ADB (The World Bank 2021). Vulnerability models for volcanic ashfall and buildings are available for a

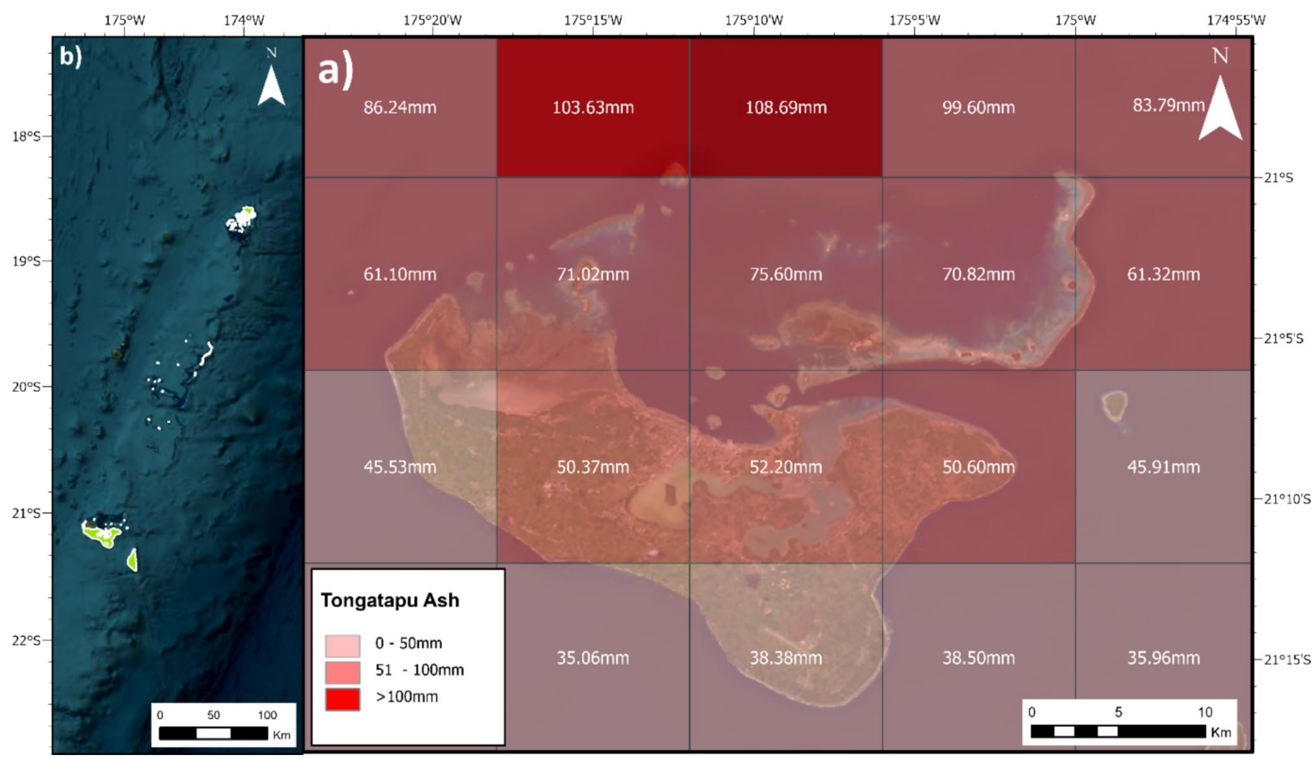

Fig. 3 Map of the Kingdom of Tonga, Tongatapu and Nukualofa, overlaid by the USGS Ash3D hazard model, 2022. The cells correspond to the resolution of the Ash3D model outputs, with the printed values showing the ash deposition thickness in the model output

range of geographical contexts (Fitzgerald et al. 2023; Hayes et al. 2024). Two of the available models use damage ratio (the loss from property damage as a fraction of the replacement cost) or percentage loss as the impact metric (Magill et al. 2006; Maqsood et al. 2014). Maqsood et al. (2014) was selected for this impact assessment, as that study compiles Asia–Pacific best practice for estimating building damage from volcanic ashfall and presents a suite of functions for a range of building typologies.

Maqsood et al. (2014) classifies building vulnerability to ash loading (kPa) by construction type, storey class and roof pitch. The ADB building inventory includes building-specific data on construction type, storeys and roof material, but not roof pitch. We therefore used construction type, primarily, to match the ADB building inventory to the Maqsood et al. (2014) vulnerability function suite (), with an assumed "medium" roof pitch across all buildings in Tongatapu. This approach was corroborated by volcanic impact experts (Fig. 2). We converted ash deposit thickness (mm) to ash loading (kPa) by assuming a deposit density of 1000 kg m^{-3}, as is commonly used in volcanological studies of eruptions of similar composition (e.g. Barker et al. 2019; Magill et al. 2015; Taddeucci et al. 2011).

Using the risk analysis software "RiskScape™ " (Paulik et al. 2022), we applied the relevant Maqsood et al. (2014) function () with the respective hazard data (USGS Ash3D, 20 mm and 30 mm) to define a damage ratio for each building in Tongatapu. The ADB building inventory included replacement value (TOP) for each building; this was multiplied by the calculated damage ratio to determine loss (TOP) for each hazard model (Buildings section) (Table 1).

Agricultural impacts

A recent agricultural inventory for Tongatapu was provided by the ADB (The World Bank 2021) (Fig. 4). Vulnerability functions for volcanic ashfall and agriculture are limited, and those that do exist (Craig et al. 2021; Wilson and Kaye 2007; Yu et al. 2014) are generally applicable to temperate, export-focused agricultural systems. Craig et al. (2021) presents a suite of volcanic ashfall vulnerability models for different farm types ($n = 13$), of which, three are applicable to Tongatapu agricultural sectors (root vegetables, leafy vegetables and fruits).

In Tongatapu, cultivated land (61% of Tongatapu land coverage) is generally comprised of horticultural farms, forests or orchards (Ministry of Agriculture Food Forestry and Fisheries (MAFFF) Tonga Statistics Department (2015)). Kitchen gardens, for subsistence farming (0.12% of cultivated land), are common at residential properties; however, we do not have the vulnerability models or exposure inventories to support impact assessment for kitchen gardens and their crops. Of the seven land use types in the ADB dataset (farm, forest, grass, nature reserve, orchard, park and scrub; Fig. 4), we assume crops are present on farms, forests and orchards. Due to disrupted telecommunications limiting access to Tongan government reports and local expertise, we assumed % land cover of the three different crop macro-types (fruit, root, leafy) of the different land use parcels, in accordance with local government reporting (Ministry of Agriculture Food Forestry and Fisheries (MAFFF) Tonga Statistics Department (2015))(Table 2). Tropical impact experts corroborated the approach and supported our mixed cropping assumptions (Fig. 2; Table 2).

Craig et al. (2021) uses Impact State (IS) as the impact metric, which provides a description of farm damages and the effects on production. We applied the Craig et al. (2021)

Table 1 Matching of Maqsood et al. (2014) building classes (vulnerability curve ID) for volcanic ash vulnerability models (wood, concrete, unreinforced masonry) to ADB building inventory construction types (World Bank Group 2021)

Vulnerability curve ID	Description	Storey class	Storeys	Roof pitch	ADB construction type
A4	Wood, light frame (≤ 5000 sqft), non-engineered	Low-rise	1–2	Medium	Steel frame; timber frame; traditional; low-level masonry wall with timber frame; multi-storey — timber frame on both levels; multi-storey — timber frame on concrete piers; open-walled structure — non wooden poll; open-walled structure — wooden poll;
A11	Concrete Frame/Reinforced Masonry, non-engineered	Low-rise	1–3	Medium	Multi-storey — concrete frame with timber frame on top; concrete moment frame; concrete frame with masonry infill; multi-storey — reinforced masonry with timber frame on top; reinforced masonry
A21	Unreinforced Masonry bearing walls, non-engineered	Low-rise	1–2	Medium	Unreinforced masonry

Fig. 4 Non-urban land use classes on Tongatapu. Data provided by the Asian Development Bank (ADB) (The World Bank 2021)

Table 2 Composite asset inventory for agriculture on Tongatapu

	Root	Fruit	Leafy	Total land use
Farm	77.7%	20.5%	1.8%	12,861 ha (61%)
	Tongan Agricultural Census, 2015, % land cover of root vegetables for cultivated land	Tongan Agricultural Census, 2015, % land cover of fruit vegetables for cultivated land	Tongan Agricultural Census, 2015, % land cover of leafy vegetables for cultivated land	
Forest	0%	50%	0%	6301 ha (30%)
	-	Local subject matter expert-corroborated the assumption that fruit is grown on forest floors	-	
Orchard	0%	100%	0%	1554 ha (7%)
	-	Local subject matter expert-corroborated the assumption that there is no mixed cropping (to maximise fruit yield)	-	
Grass	-	-	-	5 ha (< 1%)
Nature reserve	-	-	-	15 ha (< 1%)
Park	-	-	-	22 ha (< 1%)
Scrub	-	-	-	472 ha (2%)
Total cultivated land	16,496 ha	4352 ha	382 ha	21,230 ha

vulnerability functions for root, leafy and fruit agricultural crops (proportional land coverage of crop in Table 2), with the respective ash thickness models (USGS Ash3D, 20 mm and 30 mm) to define a probability of any crop, within a given land parcel, being in IS0-4 (Craig et al. 2021) (Agriculture section).

Volcanic ashfall clean-up

A key uncertainty in the early phases of the impact analysis was how substantial the clean-up effort would be and whether any resources (e.g. heavy machinery, dump trucks, disposal sites) would be needed to support the clean-up. An important parameter informing resource needs is the anticipated volume of ash requiring removal (Hayes et al. 2015). We used a clean-up model based on the approach outlined in (Hayes et al. 2019) to inform the ash removal volume estimations. Our conceptual approach assumes that the proportion of deposited ash that is removed scales with ash thickness. This is based on estimations of ash clean-up volumes from eruptions around the world (Hayes et al. 2015). The approach identifies ash thickness thresholds that are likely to initiate a more thorough cleaning process (i.e. increased proportion of the deposited ash being removed). The model achieves this by including different urban surfaces (e.g. roads, roofs, impervious surfaces, vegetation) in the calculation as thickness increases (see Fig. 5). This approach has not previously been used in a tropical setting like Tongatapu, where ash might be more readily absorbed into more porous soils and vegetation compared to the more subtropical locations it was developed for and tested with (Hayes et al. 2017; 2019). Thus, the proportion of ash that can effectively be left in situ may be higher than that experienced in subtropical climates and may have the effect of reducing removal volumes. Therefore, its application here was subject to considerable uncertainty. For this reason, we adopted a modified approach to that previously applied for buildings and agriculture, which we detail below.

The model is probabilistic and requires two inputs: (1) estimates of the minimum and maximum ash thickness, and (2) urban surface area estimations for roads, roofs and other impervious surfaces (e.g. pavement). The former was estimated using available photos and numerical model estimates available at the time of analysis, and the later used available exposure data from ADB and OpenStreetMap (OSM). OSM roads and building footprints (as a proxy for roofs) were used (downloaded on 19 January 2022 using the OSMnx Python package by (Boeing 2017). For both datasets, road lanes were assumed to be approximately 3 m in width when calculating road area. We assumed ± 10% uncertainty in the surface area of each geospatial dataset to account for potential inaccuracies (e.g. missing or additional features). We used multiple models with differing combinations of ash thickness ranges and exposure data sets to make comparisons across the different assumptions easier (Fig. 5). The ash volume was then calculated by multiplying the ash thickness (after converting it to metres) and the surface area (m^2) appropriate for that thickness threshold (Fig. 5). Monte Carlo sampling using uniform distributions was used to produce 10,000 simulations for each model. Probability of exceedance curves for the potential volume requiring removal for each model were then produced (Clean-up section). These were then presented as 10–90th

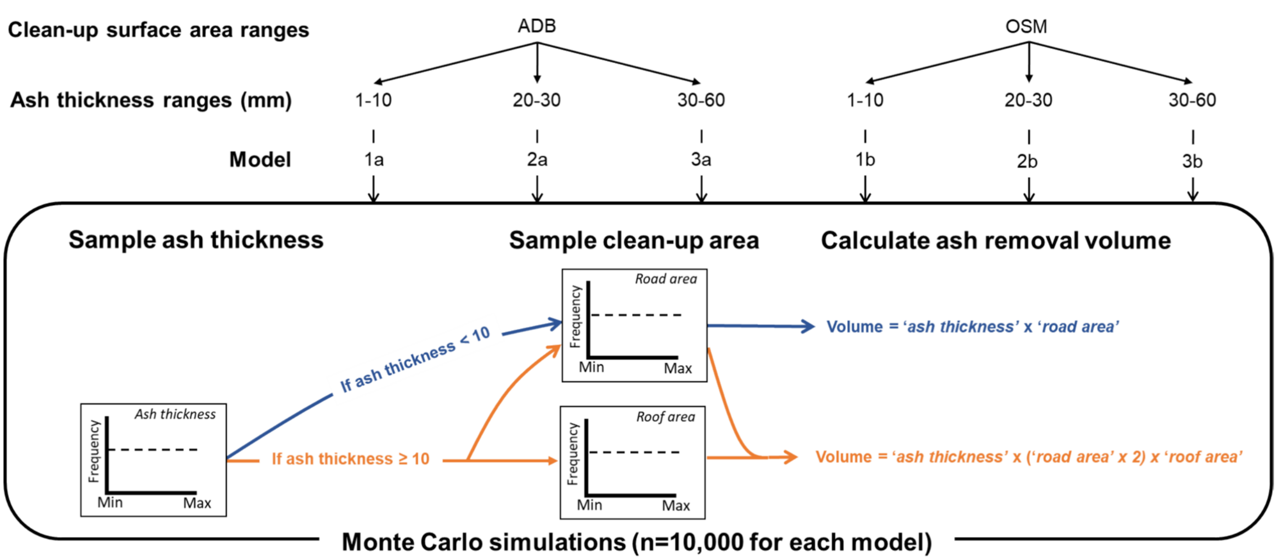

Fig. 5 Modelling framework for estimating volume of volcanic ash for removal using multiple model configurations and Monte Carlo simulations. ADB, Asian Development Bank road and building footprint datasets; OSM, OpenStreetMap road and building footprint datasets. Road area is multiplied by 2 where ash thickness ≥ 10 mm to account for additional impervious surfaces that may require clean-up such as footpaths or off-road parking lots

Table 3 Exposure assessment results for Tongatapu buildings

USGS Ash3D thickness (mm)	Building count	Sector									
		Residential	Commercial	Utilities	Industrial	Education	Public	Health	Religion	Agricultural	Other
30–39	2116	1609	96	16	16	73	134	1	48	5	118
40–49	2418	2045	69	4	3	42	34	4	72	0	145
50–59	23,040	19,159	908	100	123	576	535	51	644	4	940
60–69	599	508	15	2	1	16	18	0	14	0	25
Total	28,173	23,321	1088	122	143	707	721	56	778	9	1228

percentile ranges in official reporting to succinctly communicate the uncertainty in the estimations.[4]

Critical infrastructure exposure

A rapid ashfall exposure assessment for critical infrastructure network components was undertaken for water (tanks, pumps and other), electricity (generation and utility poles (high voltage and low voltage carrying)) and roads on Tongatapu. The inclusion of these assets and exclusion of others were driven by data availability, time constraints and desired outputs to inform rapid risk management and response decision-making (Methods section). The three hazard models (Hazard Information section) and infrastructure asset data were overlain spatially to determine the ash thickness (Ash3D model, 20 mm, 30 mm) at each network component. The results of this exposure assessment are presented in the "Critical Infrastructure Exposure" section. Impact assessment for critical infrastructure systems was not considered feasible as there was limited knowledge of the asset type and configuration during the limited timeframe for the rapid remote impact assessment and little opportunity to obtain authoritative advice from local critical infrastructure operators during the period of communications disruption.

Results: exposure, impact and loss estimates

Buildings

Results for the exposure assessment of Tongatapu buildings to ashfall are presented in Table 3. For the USGS Ash3D hazard model, there are 28,173 buildings exposed to > 30 mm ashfall and 599 exposed to > 60 mm ashfall. The modelled impact to Tongatapu buildings is presented in (Table 4), and spatial representation of building loss is shown in Fig. 6. Modelled total loss estimates range widely from ~ TOP$25,000 (~ USD$10,579) to ~ TOP$18 M (~ USD$ 7.6 M) depending on which ashfall hazard model is used (Table 4). These estimated losses do not include clean-up costs (e.g. Hayes et al. 2017), as these were not feasible to estimate due to data limitations and knowledge gaps for volcanic clean-up operations in tropical contexts, and are a small fraction of the total estimated replacement value of Tongatapu buildings (0.002 to 0.1419%; Table 4), suggesting relatively low impact to the building stock. This seemed consistent with overflight imagery (UNOSAT 2022) which did not appear to show significant structural damage in areas affected only by ash. Total building losses associated with both volcanic ashfall and tsunami have been estimated to be substantially higher at ~ TOP$83.3 M (US$33.8 M) (The World Bank 2022).

Likely impacts from ashfall could include damage to non-structural elements (e.g. gutters), contamination (internal and external) requiring clean up, and corrosion to metal roofs and fittings that may be an issue in the longer term, especially if ash deposits are not removed. Ashfall thickness across the three hazard models (~ 20–61 mm) is well below the likely roof collapse ash loading thresholds for the building/roof typologies exposed (Maqsood et al. 2014), so structural damage to buildings was unlikely. A possible exception was "post and beam" buildings (informal settlements/traditional buildings). It is important to note that the replacement values (TOP) in the ADB dataset assume that damaged buildings would follow a "build back better" approach, meaning that the costs calculated may be an overestimation of the actual replacement cost, depending on the recovery approach undertaken.

These results are regarded as highly uncertain. The vulnerability models applied (Table 1) are not well-validated

Table 4 Loss assessment results for Tongatapu buildings

Hazard model	Total loss (TOP)	% loss of total replacement value
USGS Ash3D	$18,446,471	0.1419%
30 mm uniform	$659,481	0.0051%
20 mm uniform	$26,570	0.0002%

[4] The full code to reproduce the results is available at https://github.com/josh-hayes/Tonga_ash_cleanup.

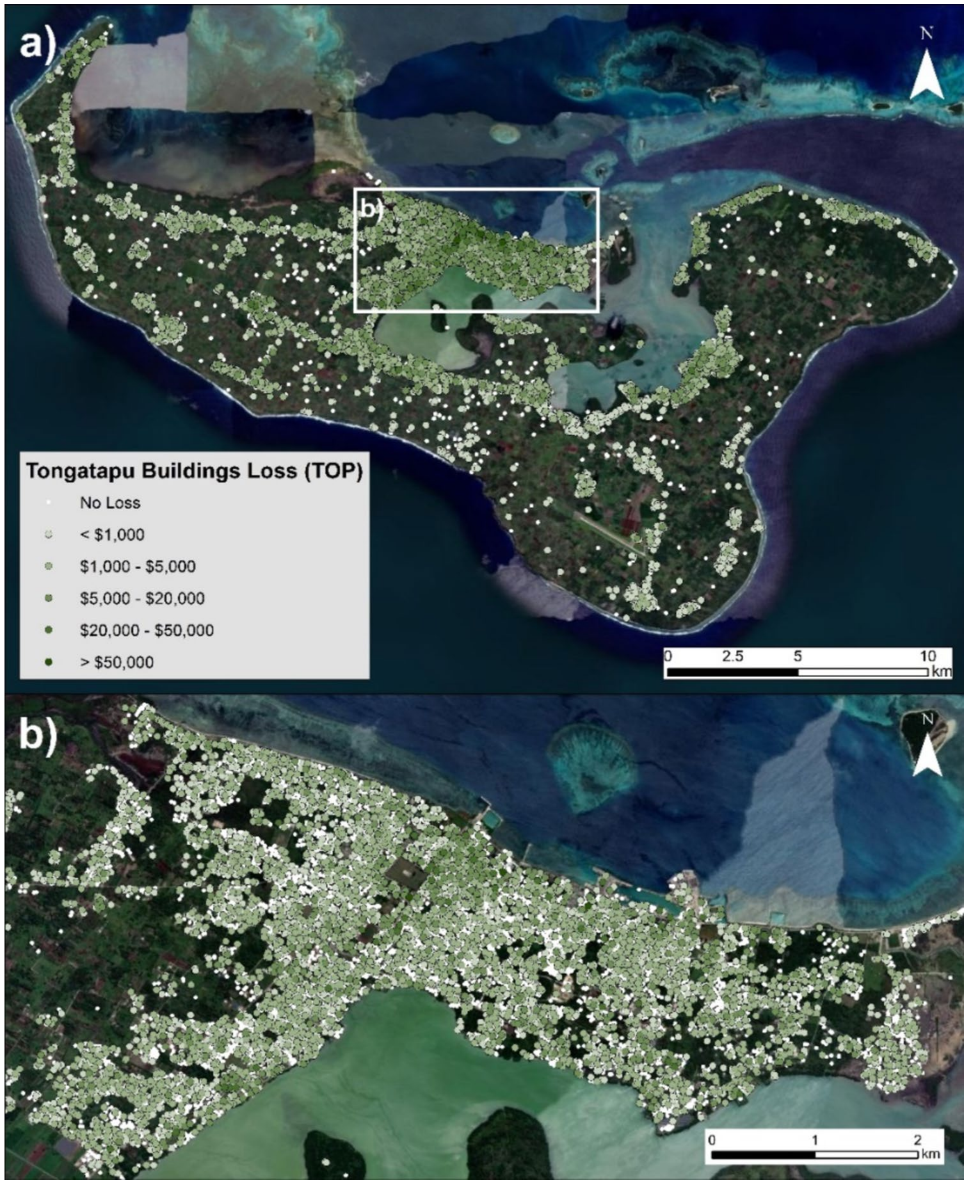

Fig. 6 Tongatapu building loss using USGS Ash3D hazard model. a The results for the island of Tongatapu and b the results for the largest and capital city of Nuku'alofa

and are particularly poor predictors for low-damage states. At larger ashfall thicknesses, where structural damage is possible, the building typologies are more important to pair with the appropriate vulnerability function, rather than the roof type. It is likely that while structural types might be comparable between the ADB and Maqsood et al. (2014) classifications, the roof types for Maqsood et al. (2014) are not always going to be the dominant type seen in Tonga (metal sheet), making these functions less suitable and reliable.

Agriculture

Results for the impact assessment for agriculture are presented as probabilities of exceeding ISs for the three different crop classes (Root, Fruit, Leafy), across the three different hazard models (Table 5). As anticipated, due to the range of ashfall thicknesses across the three hazard approaches (USGS Ash3D, 30 mm uniform, 20 mm uniform), there is a higher likelihood of reaching IS2 (up to 30% production loss) and IS3 (~ 60% production loss) when applying the USGS Ash3D hazard model (Table 5). Increasingly lower probabilities of exceeding ISs are calculated when applying the 30-mm uniform and 20-mm uniform hazard layers respectively (Table 5). Leafy vegetables are more vulnerable to ashfall, as higher probabilities for reaching higher impact states are observed across all three hazard model approaches. They were likely to be highly impacted (including the leaves of root vegetables) and may experience production losses > 60% in the short-medium term. Root vegetables and fruits were likely to see a low-medium impact, with estimated production losses between 30 and 40% in the short-medium

Table 5 Probability of reaching impact states 0–4 for three crop types (root, fruit and leafy) from Craig et al. (2021), with probabilities shown for three hazard layers (USGS Ash3D, 30 mm uniform, 20 mm uniform)

Craig et al. (2021) Impact States	Probability of exceeding impact states				
	IS0	IS1	IS2	IS3	IS4
	No disruption	Slight lower productivity, recoverable harvest	Up to 30% production loss	~60% production loss	>90% reduction in yield; >1 season to recover
USGS Ash3D (upper bound)					
Root	0.11	0.13	0.34	0.32	0.10
Fruit	0.10	0.09	0.29	0.38	0.14
Leafy	0.04	0.11	0.33	0.21	0.31
30 mm uniform thickness					
Root	0.15	0.23	0.33	0.22	0.07
Fruit	0.10	0.10	0.30	0.40	0.11
Leafy	0.04	0.11	0.35	0.20	0.30
20 mm uniform thickness (lower bound)					
Root	0.17	0.30	0.32	0.16	0.05
Fruit	0.29	0.03	0.32	0.28	0.08
Leafy	0.04	0.16	0.34	0.19	0.26

term. An important consideration is that there may be some overlap in "root" and "leafy" vegetables, as both crops can result from the same plant. Additionally, mixed cropping over a very small scale can also occur in the Pacific environment (i.e. root vegetables being grown around fruit trees), which is not considered by existing vulnerability models. This highlights an important gap in asset inventories and volcanic ashfall vulnerability for Pacific Island agriculture. Further, our impact modelling approach for agriculture was limited by the short-term outlook of available vulnerability models and impact assessment approaches for agricultural sectors. We have limited capacity to forecast long-term impacts to agricultural sectors, particularly for the Pacific Islands. These longer-term impacts may include an increase in production over successive harvests due to the inclusion of macro-nutrients and micro-nutrients from the ash, such as magnesium, calcium, sodium, sulphur, copper, iron and zinc in soils. Currently, there are no methods for quantitatively assessing these potential positive effects.

Clean-up

Ashfall clean-up modelling produced highly unconstrained volume outputs from as low as 15,000 m^3 to 640,000 for likely ash removal due to the high degree of uncertainty associated with key input parameters (e.g. ash thickness; land cover of impermeable surfaces) in the early phases of the eruption response (Table 6). The uncertainty associated with the ash hazard led to a variation of three orders of magnitude across the models. The difference between exposure datasets had only a modest influence, with the OSM dataset producing slightly lower estimates than when the ADB exposure dataset was used

Table 6 Ash volumes that may require removal on Tongatapu. Ranges are the 10th–90th percentile, 50th percentile in square brackets. Values rounded to 2 s.f. For model descriptions, see Fig. 5

Model	Ash thickness range (mm)	Exposure dataset	10–90th percentile (median) modelled volume from roads (m^3)	10–90th percentile (median) modelled volume from roofs (m^3)	10 – 90th percentile (median) total modelled volume removal range (m^3)
1a	1–10	ADB	6700–32,000 (20,000)	7500–35,000 (22,000)	21,000–100,000 (62,000)
1b	1–10	OSM	4100–20,000 (12,000)	7300–36,000 (21,000)	15,000–75,000 (45,000)
2a	20–30	ADB	74,000–111,000 (89,000)	82,000–120,000 (99,000)	230,000–330,000 (280,000)
2b	20–30	OSM	45,000–64,000 (54,000)	81,000–110,000 (97,000)	170,000–240,000 (210,000)
3a	30–60	ADB	120,000–200,000 (160,000)	130,000–230,000 (180,000)	360,000–640,000 (500,000)
3b	30–60	OSM	71,000–120,000 (97,000)	130,000–220,000 (180,000)	270,000–470,000 (370,000)

(Table 6), which was due mostly to the discrepancies in the road datasets. If we were to filter the ADB dataset to only include paved/metalled roads, clean-up volumes would be slightly less than using the OSM roads, so it is possible that the OSM dataset is missing some of the unpaved roads that the ADB dataset includes. Based on international experiences of ash clean-up, unpaved roads typically do not undergo extensive ash removal (Hayes et al. 2015; 2019). Despite the uncertainty, the modelling outputs all indicated that a considerable clean-up effort would be required on Tongatapu with a need for heavy earth-moving machinery such as diggers and trucks, which was a key question in the initial development phase of the rapid impact assessment.

Critical infrastructure exposure

The results of the volcanic ash exposure assessment of Tongatapu critical infrastructure network components are presented in Table 7. For the USGS Ash3D model, we estimated that 19,711 electricity network utility poles (4382 high voltage and 15,329 low voltage), 640 electricity generation sites, 166 water pumps, 179 water tanks and 2416 km of roads were exposed to > 30 mm of ash. Notably, we estimated that network components exposed to > 60 mm of ash include 498 electricity network utility poles (162 high voltage and 336 low voltage), 18 electricity generation sites and 44.8 km of road.

According to the 2021 Census, 92% of households on Tongatapu have access to piped, treated water (Fig. 7; Tonga Statistics Department 2021). Groundwater is pumped from a wellfield managed by the Tonga Water Board using diesel pumps. It is chlorinated and gravity-fed to households from elevated storage tanks. The only component of the fully enclosed system vulnerable to ashfall is the pumping equipment. Solar-powered pumps would require that ash be cleared from solar panels, and uncovered diesel pumps may be affected by airborne ash as well as being reliant on a supply of diesel. We were unable to take this analysis further without access to further information on the operation of pumps during and following the eruption. Further, while most households are supplied with piped water, only 7% of households use this as their main source of drinking water, with 75% of households preferring to drink water from either their own water tank or a community water tank. The extent to which ashfall contaminated water tanks and affected the potability of tank water supplies is unknown.

Based on the estimated exposure (Table 7), all electricity assets were in exceedance of electricity flashover thresholds (~ 3 mm; (Wardman et al. 2012)). However, heavy rains, which were forecast at the time of exposure assessment, would likely have negated any further impacts. Ashfall induced tree and vegetation fall on to lines was likely (causing electricity line breakages). The Popua Power Station is a diesel generation site (accounting for 50–80% of electricity generation for Tongatapu) and is a key site for Tongatapu's electricity connectivity. This station was exposed to ~ 58 mm of estimated ash for the USGS Ash3D hazard model (Table 7, Fig. 8), so any disruptive impacts to this power station would likely disrupt electricity connectivity. With two planned 5000 kW battery energy storage systems (BESS) due for commission in 2021, future disruption from similar events could be reduced. While not explicitly assessed, we also assume solar generation (Fig. 8) was disrupted from ash coverage, pending any clean-up efforts.

Given the amount of estimated ashfall that Tongatapu roads were exposed to (~ 20–61 mm, Table 7, Fig. 9), disruption was highly likely across all Tongatapu roads, particularly in areas of higher ash thickness, such as in Nuku'alofa (52 mm in USGS Ash3D model, Fig. 9). Typical disruptive mechanisms include loss of traction, impassability and visibility reduction (Blake et al. 2017). Clean-up requirements will vary depending on the ash thickness deposited and the use class of the road ((Hayes et al. 2015); see the "Volcanic Ashfall Clean-up" and "Clean-up" sections).

Table 7 Infrastructure exposure assessment results for the USGS Ash3D hazard model

USGS Ash3D ashfall thickness (mm)	Asset Count	Water Supply				Electricity						Road
		Tanks	Pumps	Other	Total	HV Poles	LV Poles	Solar	Wind	Other gen	Total	km
30–39	2886	31	22	0	53	598	1400	0	0	67	2,065	307.2
40–49	2515	34	21	0	55	462	1423	0	0	50	1935	210
50–59	20,771	114	123	64	301	3160	12,170	1	1	503	15,835	1854
60–69	628	0	0	0	0	162	336	0	0	18	516	44.8
Total	26,800	179	166	64	409	4382	15,329	1	1	638	20,351	2416

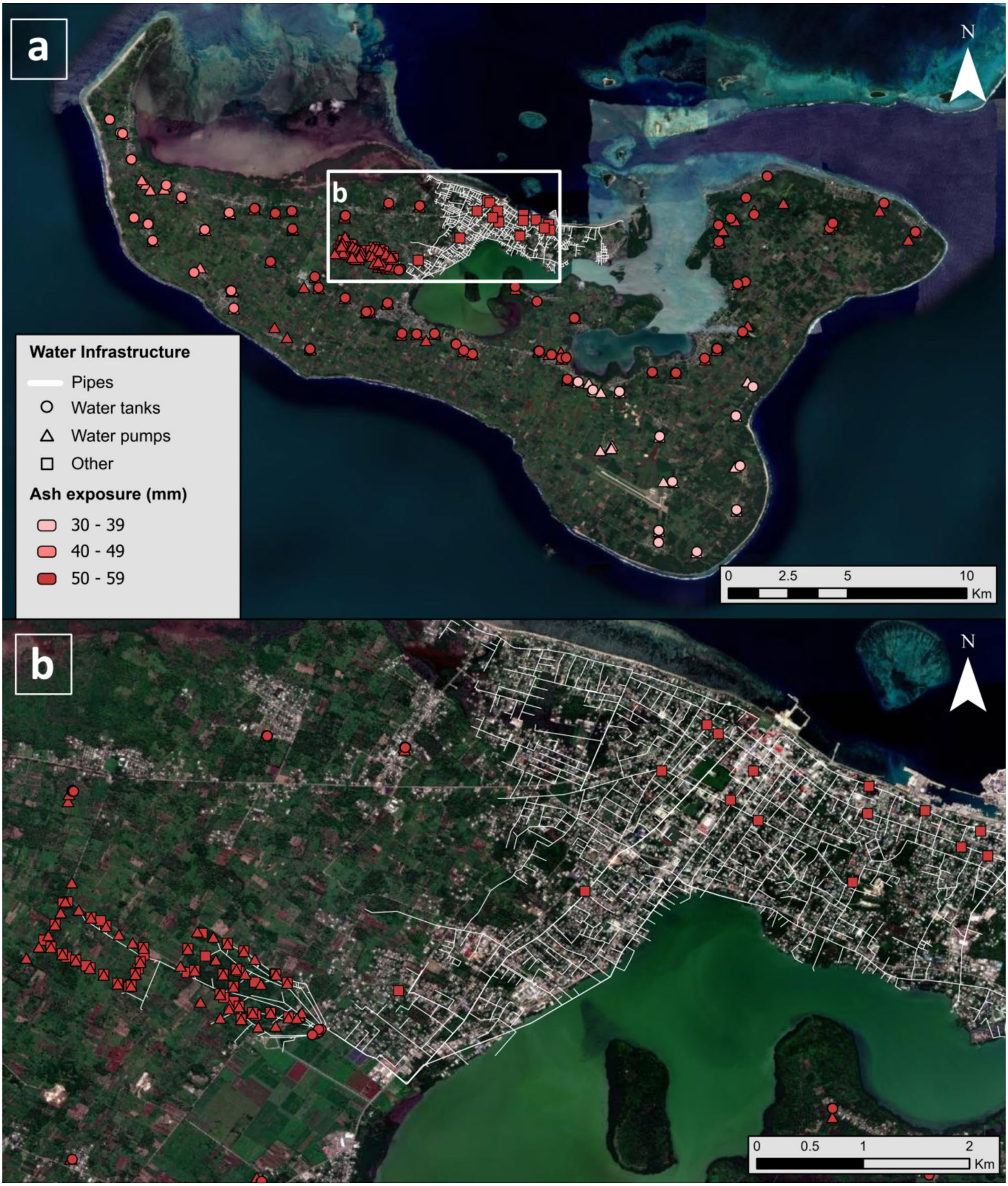

Fig. 7 Water sector exposure. Source hazard data: USGS Ash3D; 30 km column height; 1-h duration; 0.5 km3 (with umbrella), Source asset data: ADB 2021 database (The World Bank 2021). a The results for the island of Tongatapu and b the results for the largest and capital city of Nuku'alofa

Fig. 8 Electricity sector exposure. Source hazard data: USGS Ash3D; 30 km column height; 1-h duration; 0.5 km3 (with umbrella), Source asset data: ADB 2021 database (The World Bank 2021). a The results for the island of Tongatapu and b the results for the largest and capital city of Nuku'alofa

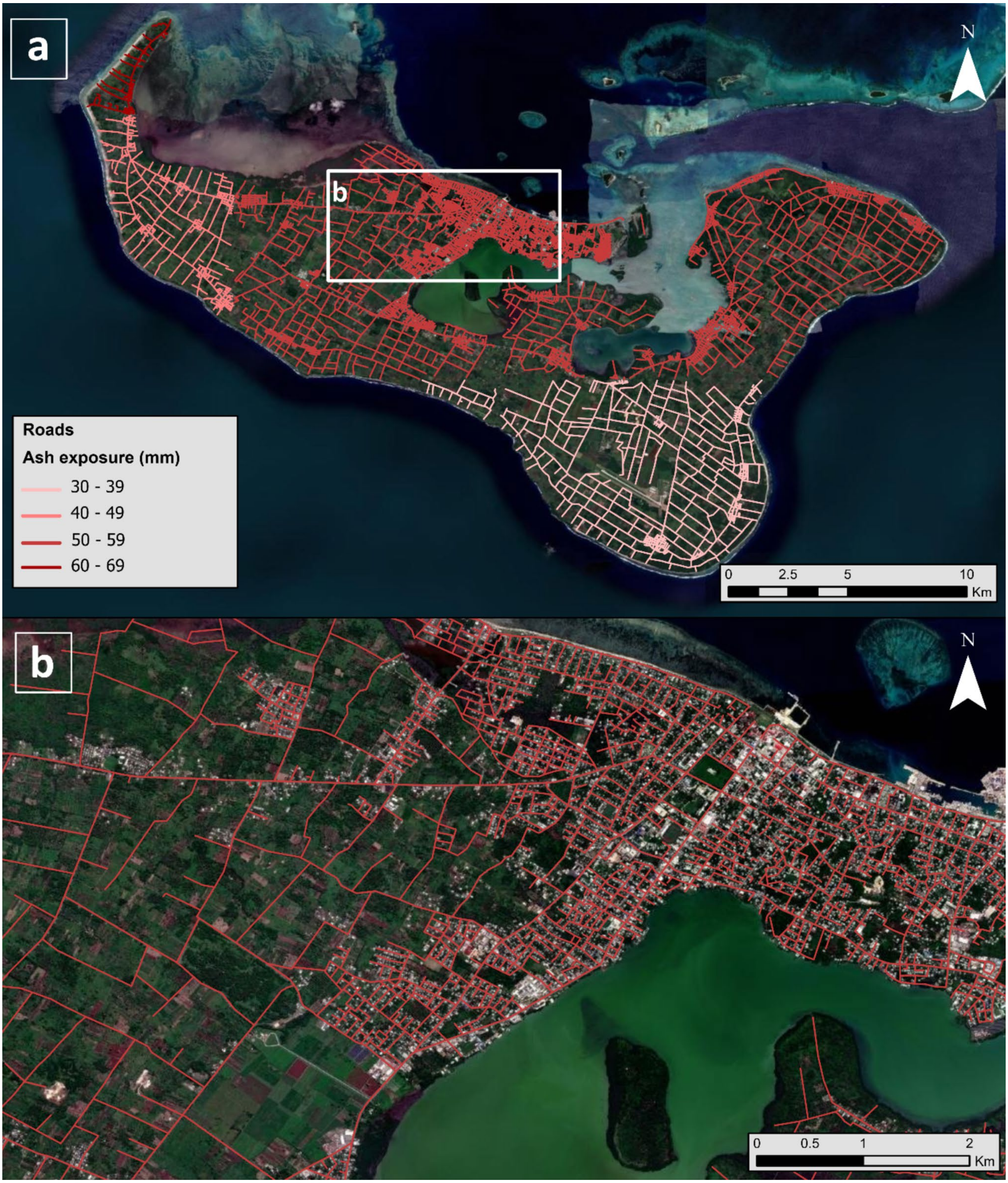

Fig. 9 Road exposure results. Source hazard data: USGS Ash3D; 30 km column height; 1-h duration; 0.5 km.3 (with umbrella), Source asset data: ADB 2021 database (The World Bank 2021)

Discussion

The aim of this study was to conduct a rapid, remote impact assessment for buildings, agriculture and infrastructure sectors to support the international aid response to the 2022 Hunga volcano eruption crisis. Over the 10-day analysis period, we achieved this aim and developed a novel methodological approach for volcanic impact assessment in this time-sensitive context. There are considerable uncertainties and limitations to the approach presented here, as would be the case for any other rapid, remote impact assessment conducted over such a short time frame. The final report, prepared for the NZ MFAT on day 10 post-eruption, was used in conjunction with other information sources to direct resources and science efforts. The information provided initial quantitative estimates of impacts and losses, and eased concerns around widespread, severe built environment impacts from volcanic ashfall during a period of great uncertainty.

A useful comparison point for this analysis is the World Bank Group Global Rapid Post Disaster Damage Estimation (GRADE) report (The World Bank 2022), released on 14 February 2022. The GRADE report is undoubtedly more comprehensive in scope, as it assessed the multi-hazard (tsunami, ashfall) impacts to the entire nation of Tonga, whereas our study focused on ashfall impacts to the built environment on the main island of Tongatapu. The GRADE report concluded that (1) the majority of economic loss (76%) was concentrated on the island of Tongatapu; (2) the impact to agriculture could be mostly attributed to volcanic ashfall (~ 80% of impact); (3) the impacts to agriculture were mostly observed for fruit, vegetables, and cash crops, and root crops would be reasonable resilient; and (4) volcanic impacts to infrastructure were minimal, and mostly attributed to the tsunami (The World Bank 2022). The GRADE report conclusions both justify the approach undertaken in this study (e.g. focus on Tongatapu impacts and volcanic impacts to agriculture) and produce impact estimates that are well aligned with those produced in this study (e.g. impacts most acutely felt for fruit, vegetable and cash crops). The GRADE report was published on 14 February 2022 (Fig. 1), approximately 1 month following the eruption, and following re-establishment of telecommunications with Tonga. One clear benefit of the approach undertaken in this study was the timeliness of the study: results were being iterated, disseminated and finalised between 5 and 10 days post-eruption (Fig. 1). The main success of this study was the development of a rapid, remote assessment process for volcanic impacts, while maintaining a high level of scientific credibility in the impact assessment inputs, process and assumptions. Science research timeframes are often unsuitable for the production of operationally relevant decision-support information such as impact assessments; however, increasingly, approaches are being developed that satisfy both science credibility drivers and decision-making requirements (e.g. Barclay et al. 2008; Hayes et al. 2020; Weir et al. 2022). This success was acutely dependent on expertise and data provided by volcanic risk subject matter experts, local context experts and international science networks (Fig. 2). The importance of building multidisciplinary and transdisciplinary teams of science, practice and policy actors to address complex disaster risk challenges is well-evidenced in the literature (Barton et al. 2020; Cash et al. 2003; Mach et al. 2020; Wyborn et al. 2017). In other contexts, where international networks and relationships between science, practice and policy are less well established, the methodology adopted here may not be practicable.

Volcanic vulnerability models are increasingly available across a broad range of societal elements (Fitzgerald et al. 2023; Hayes et al. 2024). While coverage is improving, the applicability of these models to certain geographic contexts remains challenging (Fitzgerald et al. 2023; Hayes et al. 2024). The majority of volcanic vulnerability models have been developed for temperate (and to a lesser extent, subtropical) contexts (Fitzgerald et al. 2023; Hayes et al. 2024). A notable global research need is the development of vulnerability models for tropical contexts, where elements (such as agricultural sectors or building typologies) can vary considerably. Further, existing volcanic vulnerability models are limited in their temporal reach. It is well-known that volcanic eruptions can have long-lasting impacts on elements and communities exposed (Deligne et al. 2022; Dominguez et al. 2021; Few et al. 2017; Phillips et al. 2019; Wilson et al. 2012); however, there are limited data, frameworks and tools to support longitudinal volcanic impact forecasting. This is particularly challenging for agricultural sectors, where it is well documented that production disruption and systemic impacts can emerge or persist beyond the cessation of volcanic activity (Craig et al. 2016b, 2016a; Wilson et al. 2010; Wilson and Kaye 2007). Additionally, existing volcanic vulnerability models for agricultural sectors have limited consideration of seasonality (Craig et al. 2021; Wilson and Kaye 2007). Crop and livestock production cycles introduce considerable variability in vulnerability with respect to natural hazards. Capturing this variability is essential to improving volcanic impact assessment methodologies.

The analysis focus was spatially and temporally limited. We only considered volcanic ashfall impacts to Tongatapu Island (due to spatial density of at-risk elements and data availability), immediately following the 15 January 2022 Hunga volcano eruption. This single-hazard, short-term outlook, while appropriate for the purposes of this study (to provide timely, relevant volcanic impact information), is a key limitation of the approach. This was in part due to incomplete asset inventories (i.e. limited to Tongatapu). As asset inventories for Pacific Island nations become increasingly available, the spatial scope of future rapid ashfall impact assessment will inherently broaden. The nuances of the local risk context are rarely captured in asset inventories and hence limit impact assessment capabilities. The prevalence of kitchen gardens, subsistence farming and mixed cropping in the Pacific Island context is under-represented in available asset inventories, despite being of vital importance to communities and economies. Similarly, with respect to building asset inventories, local building typologies are often projected onto building typologies in more well-researched contexts (such as temperate volcanic regions of Aotearoa New Zealand or the USA), introducing considerable uncertainty in volcanic impact forecasting. However, assumptions made regarding the building stock in Tongatapu may be reasonable, as 91% of roofs are metal and 96% of walls are wood or concrete (Tonga Statistics Department 2021) and thus relatively similar to the building stock in temperate volcanic regions.

Further, the ashfall hazard model (USGS Ash3D model) applied in this study, though very widely used in volcanological studies (Barker et al. 2019; Buckland et al. 2022; Mastin and Van Eaton 2020), introduced several limitations. We were operating in a rapid, uncertain environment with much unknown about the eruption at the time of analysis. The USGS Ash3D ash dispersion and deposition model outputs were the best available hazard data for use in the impact assessment, at the time. In the years following the eruption, many studies have elucidated the eruption source parameter (ESP) conditions during the eruption, which differ from those used for the Ash3D simulation (e.g. Carr et al. 2022; Gupta et al. 2022; Van Eaton et al. 2023). For instance, Mastin et al. (2024) discussed the relatively ash-poor characteristics of the eruption given the plume height (likely 0.1–0.2 km^3, in contrast to the value of 0.5 km^3 used for the USGS Ash3D model run for this analysis), which would results in an overestimation of ash deposition using the Ash3D model, as volume of erupted ash was assumed using the VEI (via the relationship to plume height). Though the Ash3D model was the best available data to use at the time, enhancing the credibility of rapidly-produced simulations such as these will enhance the credibility of impact estimates (e.g. through using satellite-derived estimations of the volume of erupted ash).

Volcanic eruptions are inherently multi-hazard phenomena, with only limited studies proposing vulnerability models or impact assessment frameworks that capture these complex spatio-temporal dynamics (e.g. Zuccaro et al. 2008; Hayes et al. 2020; Weir et al. 2022; Weir et al. 2024). In the case of the 2022 eruption of Hunga volcano, where a volcanogenic tsunami caused considerable impacts to exposed elements and communities, it is challenging to forecast the relative impact contribution from multi-hazards. For example, the ash clean-up modelling included in this assessment only considered the ash contribution to waste generation. However, additional waste streams such as building and vegetation debris as a result of the tsunami will also be important to consider (Hayes et al. 2021). At the time, we lacked understanding of the extent of tsunami damage and how that related to likely waste generation in order to be able to quantify it. Deligne et al. (2022) outlines four emergent areas in the characterisation of volcanic multi-hazard impacts to the built environment, including an expanded role of big Earth data, higher spatio-temporal resolution modelling and increasing transdisciplinary collaborations. These identified emergent areas could assist in addressing existing data and understanding gaps.

A key step towards iteratively improving rapid remote impact assessments is validating the results by comparing them with documented findings from in-person impact assessment visits with Tongan agencies and critical infrastructure operators. Our wider research team has conducted two such field campaigns in June and August 2023 (Auapa'au et al. n.d.) and will carry out a validation exercise in due course.

Summary

We present a novel methodology for conducting rapid, remote volcanic ashfall impact assessments. This approach has particular utility for post-eruption periods of high uncertainty and limited communications. Here we have used three different hazard models for ashfall thickness across Tongatapu and available asset information and vulnerability functions for buildings, agriculture, electricity networks, water supply and roads, to provide initial estimates of losses due to ashfall from the 15 January 2022 eruption of Hunga volcano, Tonga. For buildings, we estimated losses, both as total losses (~TOP$25,000 to ~TOP$18 M for the three hazard models) and as a percentage of the total replacement cost of buildings on Tongatapu (2×10^{-4}%–0.14% for the three hazard models). For agriculture, we made probabilistic estimates of production losses for three different crop types. The estimated probability of exceeding IS4 (>90% reduction in yield) is up to 0.10 for root vegetables, up to 0.14 for fruits and up to 0.31 for leafy vegetables (across the three hazard models). For ashfall clean-up, we estimated ranges of ashfall volumes requiring clean-up from both road surfaces and roofs (up to 270,000–470,000m^3). For water supply, electricity networks and roads, our analysis was limited to assessing the exposure of important assets to ashfall, as we had insufficient information on system configurations to take the analysis further. Key constraints to our analysis were the limited nature of critical infrastructure asset inventories and the lack of volcanic vulnerability models for Pacific islands. Key steps towards iteratively improving rapid remote impact assessments will include developing vulnerability functions for tropical environments, including Pacific islands, as well as ground-truthing estimated losses from remote approaches against in-person impact assessment campaigns.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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