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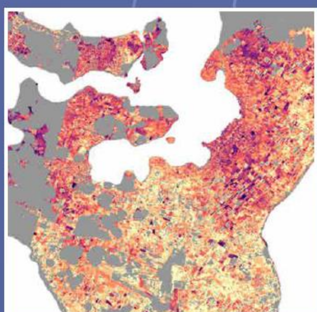
A rapid geospatial analysis of the impact of the **Hunga Tonga** volcano eruption






A rapid geospatial analysis of the impact of the Hunga Tonga volcano eruption

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Executive summary

On the 15 January 2022 the underwater Hunga Tonga–Hunga Ha'apai volcano, located in the north of Tongatapu (the main island of Tonga), erupted following several minor eruptions over the previous weeks. It was reported as the largest recorded eruption in the past 30 years. On the 14 January 2022, the Tonga Geological Services issued an alert for the Hunga Tonga–Hunga Ha'apai volcanic activity and a tsunami marine warning. The powerful eruption subsequently resulted in a tsunami in Tonga and the surrounding region, with effects reaching countries including Fiji, America Samoa and as far as Chile and Peru. With around 86 percent of Tongans engaged in agriculture, the impacts of the eruption and tsunami may have impacted all agriculture sectors, including fisheries, crops and livestock. The volcanic plume reached 30 km into the atmosphere, releasing volcanic gases and aerosols that were subsequently carried over neighboring countries, potentially impacting public health and the environment. The Government of Tonga declared a state of emergency on 16 January 2022.

Considering the limitations in obtaining information and communications and the need to provide timely information about the impacts on infrastructure, agriculture, fishery, natural resources, air pollution, a rapid geospatial evaluation of the damages following the event has been undertaken by the Food and Agriculture Organization of the United Nations (FAO). Assessments include land cover (LC) change, identification of flooded areas, ash cover, potential damage to crop due to ash cover and floods, exposure of people to ash and floods, damage to agricultural-related built-up areas, coastline area change, and air pollution. This work aims to support current and future response programmes.

This assessment began a week after the eruption using data from multiple sources and lasted approximately ten days. Satellite imagery, and spatial and statistical datasets were used as the main datasets considering the time constraints. Four key areas of interest were selected for the analysis (Tongatapu, Eua, Ha'apai and Vava'u divisions). Land cover changes, flooded areas, ash coverage, coastline changes and damage proxy maps were generated. Available baseline datasets for population and land cover for Tongatapu were compared with the results from this assessment. The results from this analysis were combined with each other and/or spatial and statistical data to assess the crop area impacted by flooding and ash cover, the population exposed to ash cover, and damage to agricultural-related built-up areas and infrastructure. Atmospheric and meteorological data was also evaluated in the form of stratospheric (sulphur dioxide) SO2 column amounts, (ultraviolet) UV aerosol index and precipitation.

According to this assessment, 1) Tongatapu was observed to incur the greatest change in land cover (72 percent), followed by the Eua (66 percent), Ha'apai (62 percent), and Vava'u (39 percent) divisions; 2) grassland (84 percent) and shrubland (75 percent) experienced the greatest changes across all regions, and cropland the least (15 percent); 3) forests, built-up areas, barren land, water bodies, mangrove and coconut changed by 63 percent, 45 percent, 20 percent, 38 percent, 65 percent, and 27 percent, respectively; 4) in terms of inundation area, Ha'apai exhibited the greatest amount of flooding (5 percent), and Eua the least (1 percent); 5) while the percent of the population exposed to flooding was similar for all divisions (1 744 [2 percent], 114 [3 percent], 143 [3], and 451 [4 percent] people for Tongatapu, Eua, Haʻapai and Vavaʻu, respectively); 6) built-up areas, barren land and mangroves were the most affected by the floods (5 percent, 14 percent, and 12 percent, respectively); 7) total damage to built-up areas was the greatest in Tongatapu (0.50 percent), all the damaged area values were similar (and low) for all regions; 8) the greatest amount of ash coverage was observed for Tongatapu, and the least for Vavaʻu, and all regions predominantly experienced no-to-medium ash coverage; 9) the greatest impact of the fallen ash to cropland was identified for Tongatapu (medium ash coverage), followed by Eua and Haʻapai (low ash coverage), while crops in Vavaʻu were generally unaffected; 10) the population of Tongatapu was the most impacted by ash coverage (80 percent, 62 180 people); and 11) Haʻapai was found to experience the greatest change in coastline, and Tongatapu the least.

The results suggest that Tongatapu was the most affected by the volcanic eruption, while Vavaʻu experienced the lowest impact. Furthermore, there was a clear surge in precipitation following the eruption. The same trend was also observed for SO2 in the stratosphere and the UV aerosol index for the four regions. The volcanic plume was observed to travel to neighbouring countries, containing elevated amounts of SO2, thus affecting the surrounding regions after the eruption.

This assessment can be further enhanced by incorporating field data into the methodological approach, to validate the results and reduce errors associated with the gaps in satellite imagery (for example due to cloud cover and limited data availability). The inclusion of field data has the potential to improve the mapping of land cover, land use, floods, ash thickness, severity of damage to agricultural infrastructure and other information. Thus far, field data have been unavailable due to the short assessment period and problems related to accessibility and communication. Future work should strengthen open access of field and remote sensing datasets as well as models (for data gap filling and predictions) in support to early warning, preparedness and emergency assessments, in particular in remote areas such as Tonga that can become difficult to access.

1. Background

Tonga, a Polynesian country located in the Pacific Ocean, is made up of close to 170 islands. It has a population of 105 697 and gross domestic product (GDP) per capita income of 4 623 USD (based on 2020 statistics) (World Bank, 2022a, 2022b). The underwater Hunga Tonga–Hunga Ha'apai volcano is located approximately 60 km to the north of Tongatapu, the main island of Tonga (Figure 1A).

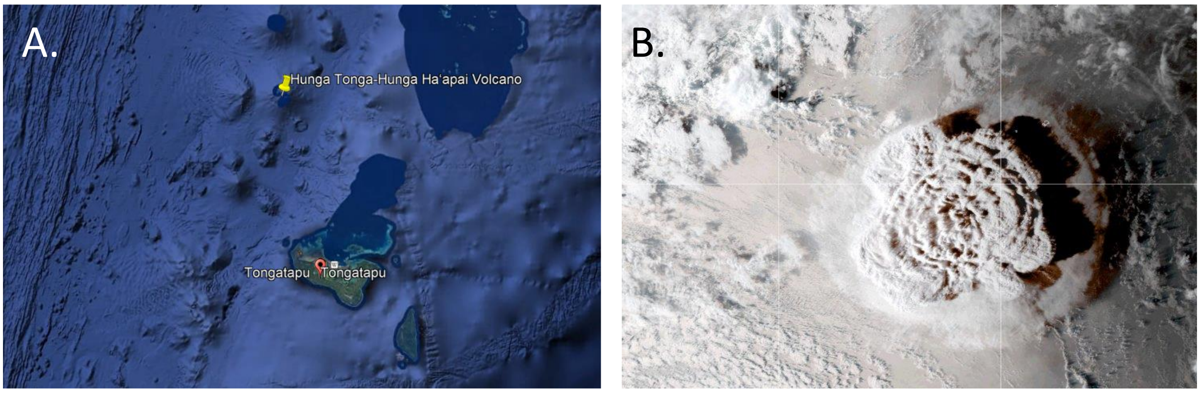

Figure 1. A. Location of Hunga Tonga–Hunga Ha'apai volcano with respect to Tongatapu, the main island of Tonga; B. the volcanic eruption on 15 January 2022 captured using the National Oceanic and Atmospheric Administration's (NOAA) Geostationary Operational Environmental Satellite 17 (GOES-17)
Source: NASA Earth Observatory. 2022. Hunga Tonga-Hunga Ha'apai Erupts.

Recent volcanic activity began in December 2021, with a strong eruption on the 13 January 2022, and an even more powerful eruption on the 15 January 2022, releasing extensive amounts of volcanic gas, aerosols and ash into the atmosphere and causing a tsunami that impacted other countries across the globe. The volcanic plume reached 500 km in diameter and travelled well into the stratosphere, above 30 km (NASA Earth Observatory, 2022). The gases and aerosols contained in the plume can potentially impact the climate, for example altering the amount of sunlight reaching the Earth's surface and inducing acid rain, which is detrimental to vegetation and soil.

The tsunami caused by the Hunga Tonga–Hunga Ha'apai volcanic eruption and the huge amounts of ash released by the volcano induced the most damage following the event. Approximately 86 percent of the population of Tonga is involved in agriculture, and thus sectors including fisheries, crops and livestock are particularly vulnerable to the subsequent impacts of the eruption (FAO, 2022). Root crops cultivated across the country are especially sensitive to the fallen ash, possibly preventing harvesting at the correct time and requiring the restoration of soil prior to the sowing of the subsequent crop.

Ash fall can also affect municipal and farm water supplies (Wilson *et al.*, 2010) as well as critical infrastructures (e.g., electricity networks and power plants) (Wilson *et al.*, 2011). The agriculture sector in coastal areas is also likely to be impacted by the inundation caused by the tsunami, and more so if combined with the fallen ash due to impacts of the crops and soil.

The effects of the volcanic eruption on the agricultural sector are likely to have an impact on the Tonga's GDP, with agriculture making up to 14 percent of the country's GDP between 2015–2016 (FAO, 2022). Thus, it is critical to assess the damage caused by the eruption in a timely manner. Remote sensing techniques offer a solution to evaluate the impacts of the event due to free data availability, and high temporal and spatial resolution. This is particularly true for such emergency situations, where rapid responses are required and on-ground data is unavailable, especially in the remote region of Tonga and the surrounding areas.

FAO is actively involved in helping communities (both at the national and global level) to enhance the preparedness, prevention and mitigation of natural disasters, such as floods (FAO, 2018). Here, FAO is providing a rapid geospatial analysis of the impact of the Tonga volcano eruption. The objective of this report is to present the methodological approach established for this rapid geospatial analysis and the results on land cover changes, flooded areas, infrastructure damage, ash coverage, coastline changes, and atmospheric and meteorological data.

2. Methodological approach

Figure 2 outlines the methodological approach used to conduct the analysis presented in this report. We make full use of the data available within the limited time required for this assessment. Future work will improve on the methodology by employing additional data and analysis steps.

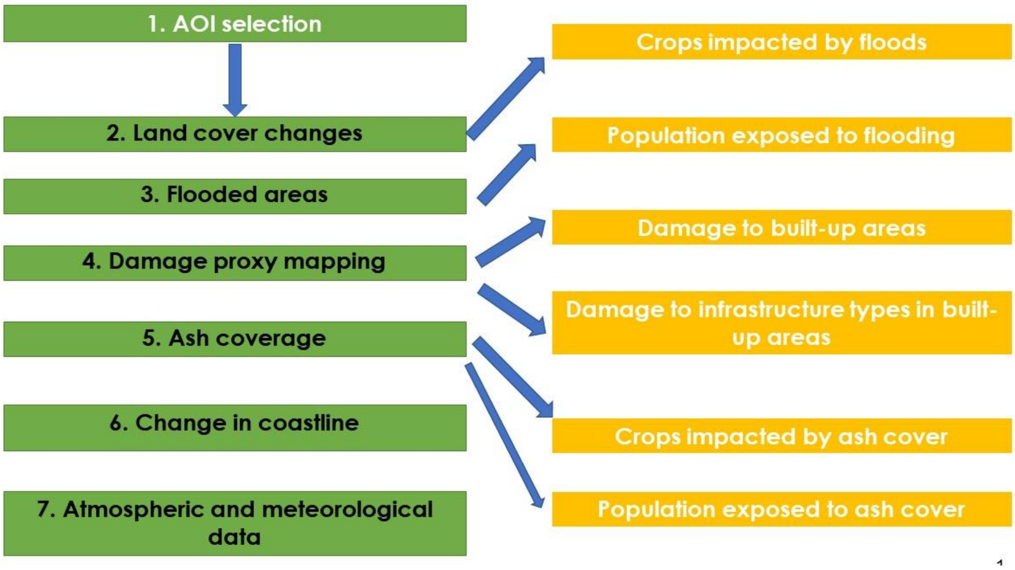

Figure 2. Outline of the methodological approach used for the rapid geospatial assessment of Hunga Tonga–Hunga Ha'apai volcano eruption

The steps used for the assessment are summarized in the following:

i. Four key areas were selected as the areas of interest (AOIs) for the analysis. Administrative boundaries from Global Administrative Areas (GADM) were used.

ii. Land cover maps were generated to assess the changes in land cover pre and post eruption based on nine classes.

iii. Flooded area was mapped based on land-water classifications from Sentinel-2 optical imagery. Flooded area was calculated for each land type using the maps created in Step 2. Population data for each AOI was also used to generate estimates of the population exposed to flooding.

iv. Damage proxy maps were created using Sentinel-1 imagery based on coherence change detection in the SEPAL platform. Maps were overlayed with built-up areas determined in Step 2 to get built-up damage. Infrastructure information was used to evaluate the damage to infrastructure across built-up areas in Tongatapu, the main island of Tonga.

v. Ash coverage was assessed using the normalized differential vegetation index (NDVI) maps derived from Sentinel-2 and Landsat imagery. The NDVI was classified to estimate the ash covered depth on vegetation, and the potentially impacted cropland due to ash cover. The ash coverage was combined with population data to determine the population exposed to ash cover.

vi. Coastline changes were calculated using land cover maps before and after the eruption based on Sentinel-2 imagery.

vii. SO2 column amounts at the lower stratosphere and the UV aerosol index were extracted from the Ozone Mapping and Profiler Suite (OMPS) imagery. Precipitation data was obtained from the Integrated Multi-satellitE Retrievals for GPM (IMERGE) estimations based on Global Precipitation Measurement (GPM) satellite observations.

2.1. Definition of the areas of interest

In order to select the AOIs, administrative boundaries from the Humanitarian Data Exchange platform (HDX), Global Administrative Areas (GADM), and Global Administrative Units Layers (GAUL) were examined for the proposed study area of Tonga. A comparison was made between the HDX, GADM, and GAUL administrative layers for Tonga. Missing areas were detected for both GAUL and HDX. They do not fully reflect the coastline and delineation of each island. Thus, the administrative boundaries from GADM were selected for this assessment as they provide more detail and up-to-date administrative information compared to HDX and GAUL.

The following four areas were selected as the AOIs for the analysis based on (GADM) (Figure 3).

- AOI1: Tongatapu division (Nuku'afola): 175° 22' 48'' W, 21° 17' 24'' S, 174° 56' 60'' W, 21° 0' 0'' S
- AOI2: Eua division: 174° 59' 24'' W, 21° 28' 48'' S, 174° 48' 36'' W, 21° 15' 36'' S
- AO13: Ha'apai division: 175° 28' 12'' W, 20° 36' 0'' S, 174° 11' 60'' W, 19° 32' 24'' S
- AOI4: Vava'u division: 174° 41' 60'' W, 18° 51' 0'' S, 173° 52' 48'' W, 18° 33' 0'' S

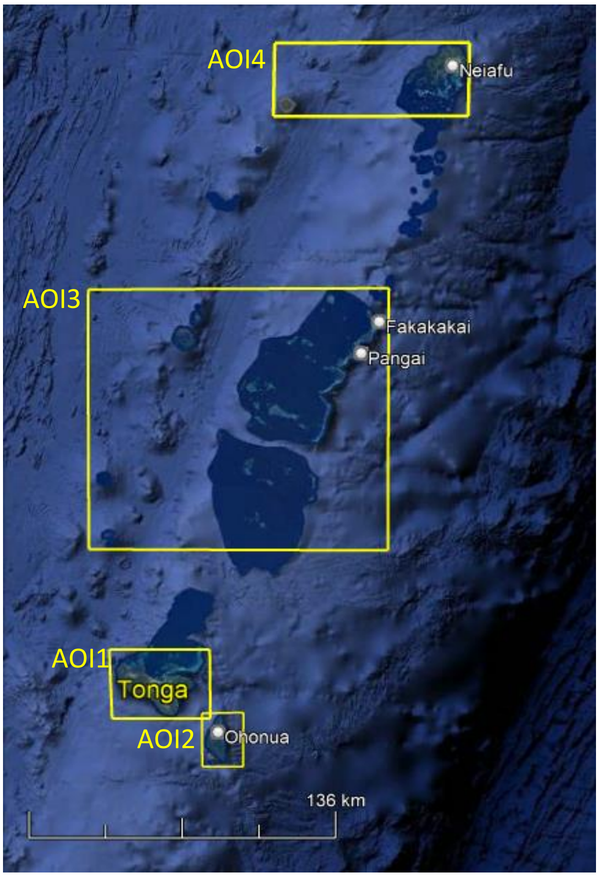

Figure 3. The four areas of interest selected for the assessments: AOI1- Tongatapu division (Nuku'afola); AOI2- Eua division; AO13- Ha'apai division; and AOI4- Vava'u division

2.2. Population data

Assessing the impact of the volcanic eruption on the population of the four AOIs requires the use of population data. Here, the 2020 population from Worldpop (Worldpop, 2020) was calculated for the subsequent analysis of population exposure to ash and flooding. The Worldpop population raster (100 x 100 m grid) results in a total population of 77 786 in Tongatapu, which is 4 percent higher compared to that of the 2016 population census from the Asian Development Bank (ADB) (ADB, 2021). Although specific population information at the town level is available only from the 2016 population census for AOI1, the Worldpop values can be used to extract population information for all AOIs. Thus, Worldpop data was selected as the data source to generate population information for all AOIs. Table 1 provides information of the number of inhabited and uninhabited islands in each AOI. Table 2 provides population statistics in each AOI according to Worldpop and the 2016 population census. Figure 4 presents the geographic distribution of population in each AOI.

Figure 5 presents the geographic distribution of population in Tongatapu according to the population census (ADB, 2021). Appendix 1 presents the 2016 and 2020 population of Tongatapu (AOI) from the population census and Worldpop, respectively.

Table 1. Number of inhabited islands for each AOI

Division	Inhabited islands	Uninhabited islands	Total islands
Tongatapu (AOI1)	16	2	18
Eua (AOI2)	2	0	2
Ha'apai (AOI3)	38	17	55
Vava'u (AOI4)	44	20	64
Total	**100**	**39**	**139**

Table 2. Population statistics in Tonga according to Worldpop for the year 2020 (and population census for Tongatapu in 2016 only)

Division	Population	Mean (people/ ha)	Maximum (people/ha)	Minimum (people/ha)
Tongatapu (AOI1)	77 786 (74 327)	2.25	19	0
Eua (AOI2)	4 478	0.39	15	0
Ha'apai (AOI3)	5 035	0.29	16	0
Vava'u (AOI4)	12 739	0.59	9	0
Total	100 038	0.03	19	0

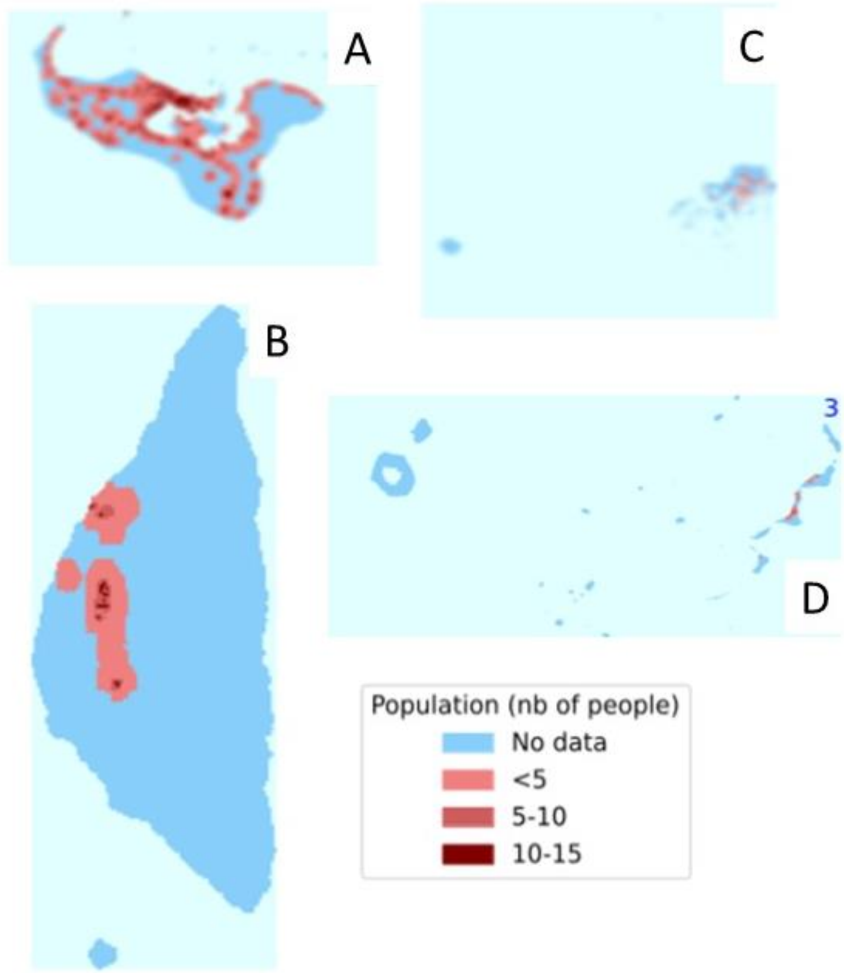

Figure 4. 100 x 100m population grid for Tonga (Worldpop, 2020) for each division (A. Tongatapu [AOI1]; B. Eua [AOI2]; C. Ha'apai [AOI3]; and D. Vava'u [AOI4])

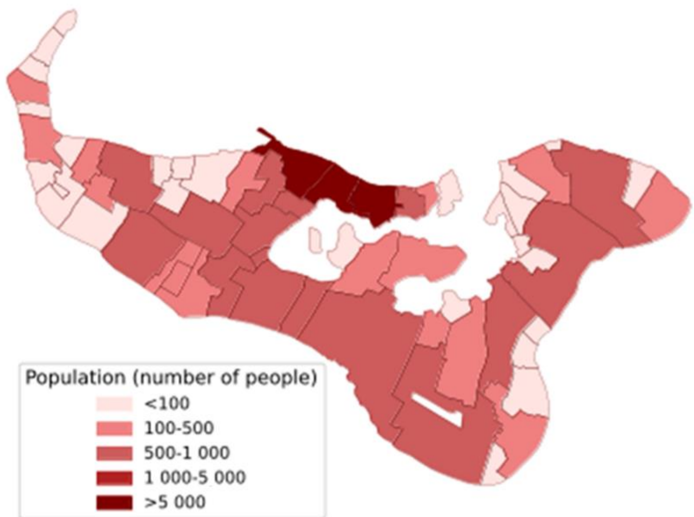

Figure 5. 2016 Population census in Tongatapu
Source: Asian Development Bank. 2021. Multi-Hazard Disaster Risk Assessment, Tongatapu. Interim Exposure Development Report. Consultants' Reports, Sydney.

2.3. Land cover assessment

Land cover data was employed to assess the impact from the volcanic eruption on land cover/land use across the four selected AOIs. Based on the available data sources, nine land cover classes were defined to produce the land cover dataset. The land cover dataset was identified to align as much as possible with the land cover classes used by the Secretariat of the Pacific Community. The land cover classes are as follows: forest; shrubland; grassland; cropland; built-up; bare land, water bodies, mangrove, and coconut. Land cover maps before and after the eruption were derived based on high resolution Sentinel-2 images (10 m). Pre and post mosaics were created using images from 1 January 2021–31 December 2021 and 14 January 2022–26 January 2022, respectively. Training data, sampled using the randomly stratified approach based on the Worldcover product for 2020, was collected from 1 800 locations (200 for each class) to classify land cover before and after the eruption. Locations of the training data collection points were allocated using the random stratified sampling method based on the Worldcover land cover map for 2020 for all the classes (except for coconut). Additional training data were collected manually using very high-resolution (VHR) imagery from Bing and Google Earth for coconut land cover class. A machine learning model, trained using 70 percent of the training data and Sentinel-2 imagery, was used to develop the land cover 2021. Using the remaining 30 percent data, the Kappa index and overall accuracy were equal to 73 percent and 76 percent, respectively. For the land cover change detection, a machine learning model, trained using the training data and Sentinel-2 imagery, was used to develop proxy land cover information. To validate the derived land cover map, it was compared with the ADB land cover map from 2018. See Section 3.1 for more details.

2.4. Flood assessment

The flood assessment was performed using optical imagery collected from the Sentinel-2 satellite. The imagery is of a high spatial (10 m) and temporal (five days) resolution. Sentinel-1 data is also high resolution (10 m) and has the advantage of not being affected by cloud cover. All images were collected and analyzed using SEPAL (FAO, 2020), a platform for the analysis and monitoring of satellite imagery. First, optical mosaics were derived before (1 January 2021–13 January 2022) and after (16 January 2022–23 January 2022) the eruption for each area of interest. The optical mosaics were then used to classify land and water pre and post eruption. There was extensive cloud and ash cover in the post event images. A mask was applied to remove the cloud and ash pixels, however the extensive coverage of these pixels led to inaccurate results. Thus, the standard SEPAL cloud-mask was used. To overcome the bottleneck with cloud cover, the Sentinel-1 data was subsequently analysed using the same steps (creation of radar mosaics pre and post event followed by land and water classification).

The impact of flooding on land cover was calculated using the land cover map detailed in Section 2.3. A flood mask was applied to the land cover maps of each AOI to determine the flooded area across each land cover type. The number of people exposed to flooding for each AOI was estimated using the Worldpop population data (Section 2.2) and the flood masks.

2.5. Damage proxy maps and damage to built-up areas

The SEPAL platform was employed to create damage proxy maps (DPMs) based on Sentinel-1 synthetic aperture radar (SAR) data, which is independent of cloud cover. The method used to estimate the damage is based on the coherence change detection (CCD) algorithm, which requires three image pairs; two prior to the event and one following the event (FAO, 2021). Figure 6 presents the workflow used to calculate the DPMs. A mask of the built-up areas (derived from the land cover maps in Section 2.3) was then applied to the DPMs to calculate the damage proxy maps for each AOI.

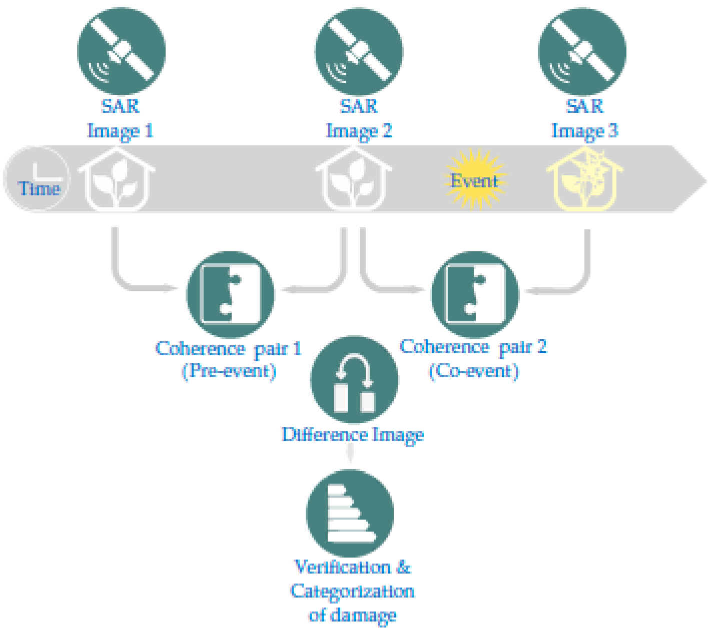

Figure 6. Workflow for the damage proxy map assessment
Source: FAO. 2021. Impact of the May conflict escalation on the agricultural area in the Gaza Strip, Rome

2.6. Assessment of infrastructure damage in built-up areas within the Tongatapu (AOI1) division

The potential damage to infrastructure in the Tongatapu division (AOI1) was estimated by selecting the following four infrastructure types based on data from ADB (2021): roads; buildings; water and power infrastructure (polylines); and water and infrastructure (points). The data (shapefiles) contains classifications of each of the infrastructure types (e.g., roads [paved, non-paved]; buildings [commercial, educational, government]; water and power infrastructure polylines [pipelines, underground lines]; and water and power infrastructure points [capacitators, transformers]). The classification of each infrastructure type was overlayed with the DPM of built-up areas derived following the eruption.

2.7. Ash coverage impact assessment

To estimate the ash covered areas following the volcanic eruption, Sentinel-2 and Landsat 8 satellite imagery from 1 October 2021–13 January 2022 and 15 January 2022–26 January 2022 were acquired, cloud masked and mosaicked. This assessment assumes that the presence of ash decreases the spectral reflectance of vegetation in the red and (near infrared) NIR regions. Therefore, reductions in NDVI values can be used as an indicator to estimate the depth of ash cover on vegetation (crops, shrubs, grass, trees etc.). Two NDVI layers were prepared pre and post eruption. Positive NDVI values (0 to 1) were classified into 10 classes. The reduction in the class value for all cloud free pixels was calculated to estimate the magnitude of ash cover depth. No change was denoted as ash free; a reduction of a single class was denoted as 1 and on so on. Hence, 1 represents the thinnest ash covered areas and 9 represents the thickest ash covered areas. Some areas were masked due to the presence of cloud. The gaps in the data were filled using the universal kriging method. Figure 7 depicts the experimental variogram model used in the kriging approach for AOI1.

The crop area potentially impacted by ash was determined using the land cover map in Section 2.3 and the ash exposure classification prepared for the four AOIs. Here, ash exposure is classified into four classes, namely, 1 (no ash), 2 (low ash exposure), 3 (medium ash exposure) and 4 (high ash exposure). The crop cover from the land cover map was extracted for each exposure class to determine the total crop area exposed to ash following the eruption. Note that it is not possible to specify crop type here due to lack of data for all AOIs.

The number of people exposed to ash cover for each AOI was estimated using the Worldpop population data (Section 2.2) and the ash exposure classification, which was reclassified into 1 (no ash), 2 (low ash exposure), 3 (medium ash exposure) and 4 (high ash exposure).

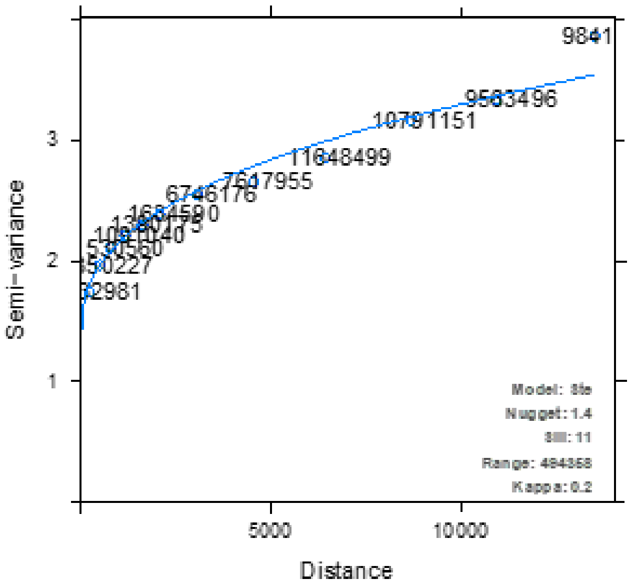

Figure 7. Experimental variogram and fitted variogram for AOI 1

2.8. Coastline area assessment

The change in coastline area was calculated using 2021 (1 January 2021–31 December 2021) and 2022 (14 January 2022–26 January 2022) land cover by classifying Sentinel-2 imagery. Selected areas were further assessed by comparing VHR Google images and Maxar open imagery pre and post event, respectively.

2.9. Precipitation and atmospheric parameters

The eruption released massive amounts of ash and caused a tsunami. The volcanic plume reached the stratosphere. Volcanoes typically emit large amounts of SO2 and aerosols, effecting both human health, the environment and atmospheric chemistry. SO2 is a greenhouse gas and sulphate aerosols can have a cooling effect on the troposphere. Here, we show the SO2 vertical column amounts in the lower stratosphere and the UV aerosol index before, during and after the eruption derived from the Ozone Mapping and Profile Suite (OMPS) Nadir Mapping (NM) SO2 Total Column 1-Orbit L2 Swath and OMPS-NPP L2 NM Aerosol Index swath orbital V2 products, respectively, at a 50 km x 50 km resolution. Average daily values were calculated for Tonga and the surrounding area between 12–20 January 2022. Elevated SO2 column amounts were observed in neighboring countries in the following days due to the eruption.

The precipitation data used here is the GPM IMERGE early run daily accumulated precipitation (combined microwave-infra-red) estimate (GPM_3IMERGDE v06) at 0.1-degree x 0.1 degree. The daily accumulated precipitation between 1–25 January 2022 was extracted and averaged for each AOI.

3. Results

3.1. Land cover

Figure 8 presents the land cover classification for each AOI, based on nine classes (forest, shrubland, grassland, cropland, built-up, bare land, water bodies, mangrove, and coconut). The estimated area of each land cover class is reported in Table 3. The forest class is observed to dominate the AOIs (62.59, 44.75, and 53.63 percent for Eua (AOI2), Ha'apai (AOI3) and Vava'u (AOI4), respectively) except for Tongatapu (AOI1), where grassland makes up the majority (34.30 percent). Cropland is determined as 12.55, 1.10, 1.81 and 2.02 percent for AOI1–4, respectively. Note that cropland exceeds built-up areas (8.19 percent) in Tongatapu (AOI1).

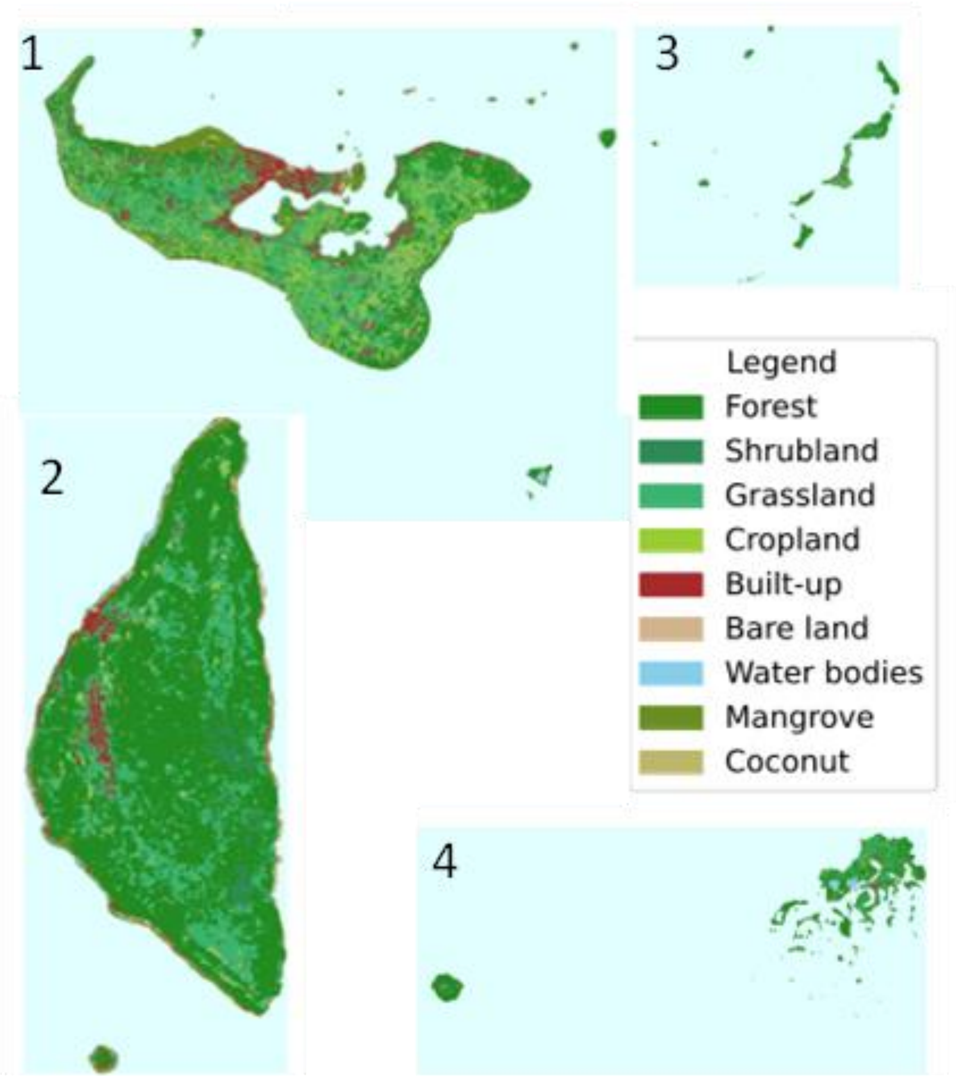

Figure 8. Land cover map of Tongatapu (1), Eua (2), Ha'apai (3) and Vava'u (4) for the year 2021

Table 3. Land cover area estimates in km² (and percentage of total area) of the four AOIs

Landcover type / Division	Forest	Shrubland	Grassland	Crop land	Built-up	Barren land	Water bodies	Mangrove	Coconut	Total
Tonga-tapu (AOI1)	70.8 (25.29)	6.37 (2.28)	96.04 (34.30)	35.15 (12.55)	22.94 (8.19)	8.02 (2.86)	1.67 (0.60)	24.47 (8.74)	14.54 (5.19)	280.00
Eua (AOI2)	58.38 (62.59)	2.86 (3.07)	20.48 (21.96)	1.03 (1.10)	2.58 (2.77)	2.23 (2.39)	1.09 (1.17)	3.38 (3.62)	1.25 (1.34)	93.28
Ha'apai (AOI3)	62.56 (44.76)	14.76 (10.56)	12.28 (8.79)	2.53 (1.81)	3.19 (2.28)	15.72 (11.25)	8.61 (6.16)	16.69 (11.94)	3.45 (2.47)	139.78
Vava'u (AOI4)	89.94 (53.63)	5.68 (3.39)	32.86 (19.59)	3.38 (2.02)	4.05 (2.41)	4.22 (2.52)	10.72 (6.39)	15.6 (9.30)	1.28 (0.76)	167.72

3.1.1. Land cover impact assessment

Figure 9 provides an example of a forest area before and after the eruption, whereby volcanic ash and/or plume are observed to cover a large part of the area. Figure 10 and Table 4 present the impact of the volcanic eruption on each land cover class based on comparisons of the pre and post event land cover maps. Tongatapu (AOI 1), the main island of Tonga, exhibits the greatest change in land cover area (72.15 percent), followed by Eua (AOI 2) (66.17 percent), Ha'apai (AOI 3) (61.81 percent) and Vava'u (AOI 4) (38.79 percent). Shrubland and grassland are determined to have experienced the greatest changes across all AOIs (74.69 percent and 83.68 percent, respectively), and cropland the least (14.56 percent).

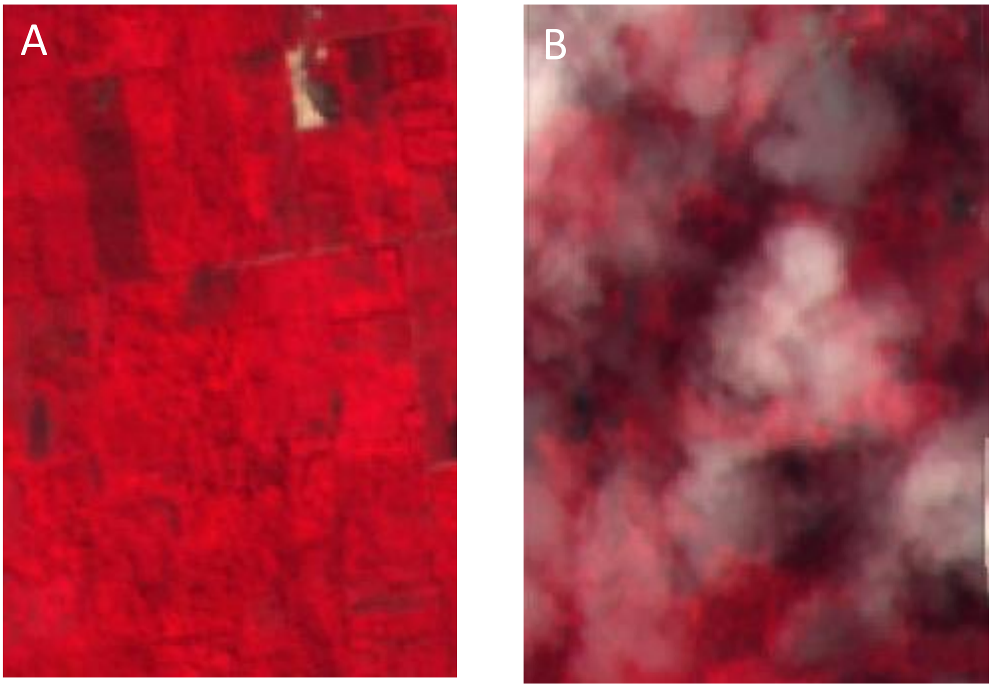

Figure 9. Comparison of forest area in Eua A. before and B. after the event based on optical Sentinel-2 imagery (colour false negative spectral values)

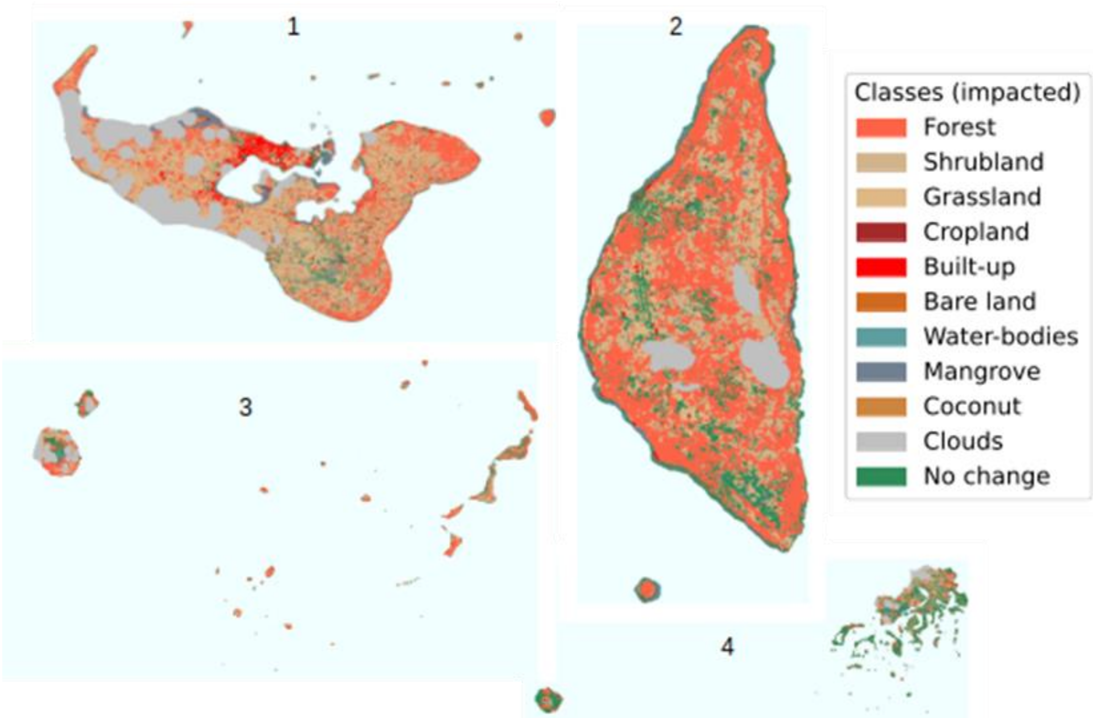

Figure 10. Post volcanic eruption land cover impact in Tongatapu (1), Eua (2), Ha'apai (3) and Vava'u (4) divisions

Table 4. Estimates of impacted land cover (km², percentage) by the volcanic eruption in Tongatapu (1), Eua (2), Ha'apai (3) and Vava'u (4) divisions

		Land cover type									
Division	Variable	Forest	Shrubland	Grassland	Cropland	Built-up	Barren land	Water bodies	Mangrove	Coconut	Total
Tongatapu (AOI1)	LC area	70.8	6.37	96.04	35.15	22.94	8.02	1.67	24.47	14.54	280
	Impacted LC	54.12	5.9	94.36	4.92	12.37	0.82	1.09	23.59	4.85	202.02
	percentage	76.44	92.62	98.25	14.00	53.92	10.22	65.27	96.40	33.36	72.15
Eua (AOI2)	LC area	58.38	2.86	20.48	1.03	2.58	2.23	1.09	3.38	1.25	93.28
	Impacted LC	45.38	1	10.53	0.12	0.63	0.47	0.61	2.9	0.08	61.72
	percentage	77.73	34.97	51.42	11.65	24.42	21.08	55.96	85.80	6.40	66.17
Ha'apai (AOI3)	LC area	62.56	14.76	12.28	2.53	3.19	15.72	8.61	16.69	3.45	139.78
	Impacted LC	50.37	10.87	11.47	0.6	0.755	3.77	2.32	5.8	0.45	86.405
	percentage	80.51	73.64	93.40	23.72	23.67	23.98	26.95	34.75	13.04	61.81
Vava'u (AOI4)	LC area	89.94	5.68	32.86	3.38	4.05	4.22	10.72	15.6	1.28	167.72
	Impacted LC	28.3	4.39	18.92	0.487	0.98	0.96	4.38	6.59	0.05	65.057
	percentage	31.47	77.29	57.58	14.41	24.20	22.75	40.86	42.24	3.91	38.79
Total	Land area	281.68	29.67	161.66	42.09	32.76	30.19	22.09	60.14	20.52	680.78
	Impacted area	178.17	22.16	135.28	6.127	14.735	6.02	8.4	38.88	5.43	415.202
	percentage	63.25	74.69	83.68	14.56	44.98	19.94	38.03	64.65	26.46	9

3.1.2. Comparison of land cover areas

The 2021 land cover map prepared in this assessment (FAO 2021) was compared with the 2018 ADB land cover area for Tongatapu (AOI1) from ADB (2021), the only AOI with recent available land cover data. The FAO 2021 map was prepared based on nine classes, Sentinel-2 imagery and a machine learning algorithm on the SEPAL platform, while the

ADB map was prepared using seven classes based on OpenStreetMap (OSM). Table 5 presents the land cover areas for Tongatapu from the two datasets.

Table 5. Total land cover area from ADB (2021) and FAO 2021 for Tongatapu (AOI1)

ADB 2018		**FAO 2021**	
Land Cover classes	Area (km²)	Land Cover classes	Area (km²)
Farm	128.61	Forest	68.49
Forest	63.01	Shrubland	6.13
Grass	0.05	Grassland	95.17
Nature Reserve	0.15	Cropland	34.91
Orchard	15.54	Built-up	21.76
Park	0.22	Bare area	3.83
Scrub	4.72	Water	0.03
		Mangrove	14.65
		Coconut	14.54
Total area	**212.30**	**Total area**	**259.05**

When comparing the results between the two land cover maps, we can observe the agreement between the two land cover datasets. For example, the class “farm” from ADB mostly corresponds the “cropland” and “grassland” from the FAO map. Similarly, “orchard trees” from ADB, mostly corresponds to "coconut” in FAO 2021. The comparison between these two land cover datasets is reported in

Table *6*. Without additional field data collection, the agreement between the two land cover datasets and area estimates can act as a validation to the quality of the land cover datasets prepared in this assessment for the four AOIs. The current FAO LC map can be improved with numerous techniques, for example semantic interoperability. However, the need to provide rapid results limits the possibility for further enhancement to the methodology.

3.2. Flood extent assessment

Sentinel-2 imagery was used to map the extent of flooding following the volcanic eruption. There was extensive cloud and ash cover in the post event images. A mask was applied to remove the cloud and ash pixels, however the extensive coverage of these pixels led to inaccurate results. Thus, the standard SEPAL cloud-mask was used. To overcome this bottleneck with cloud cover, Sentinel-1 data was subsequently used following the same steps to determine flood area maps (creation of radar mosaics pre and post event followed by land and water classification). Sentinel-1 data is of high resolution (10 m) and has the advantage of not being affected by cloud cover. Note Sentinel-1 post-event images were not available for the Tongatapu and Eua divisions (AOIs 1 and 2) until the 27 January 2022, over a week after the eruption, while for Ha'apai and Vava'u (AOIs 3 and 4), images were available on the 15, 22 and 27 January.

Table 7 compares the total flooded area determined for each AOI using Sentinel-1 and 2 images, with values for the latter based on the total cloud-free land area. The values for Ha'apai (AOI3) and Vava'u (AOI4) are similar from Sentinel-1 and -2. In contrast, there is a large gap between the flooded areas for Tongatapu (AOI1) and Eua (AOI2), which can be explained by the lack of Sentinel-1 imagery following the eruption. Thus, we can assume that the Sentinel-2 imagery can be employed to determine a first rapid estimate of the area flooded following the volcanic eruption, given problems with extensive cloud cover and lack of images following the event. Future work can incorporate hydrological modelling into the analysis for more accurate results.

Table 6. Comparison of total land cover area from ADB (2021) and FAO 2021 for Tongatapu

ADB Land Cover	Area (km^2)	FAO Land cover	Area (km^2)
Farm	128.61	Grassland + Cropland	130.08
Forest	63.01	Forest	68.49
Scrub	4.72	Shrubland	6.13
Orchard	15.54	Coconut	14.54
Total	**211.88**	**Total**	**219.25**

Table 7. Total flooded area for Tongatapu (AOI1), Eua (AOI2), Ha'apai (AOI3), and Vava'u (AOI4) determined using Sentinel-1 and 2 images

				Sentinel-1		
Division	Total land area (km²)	Total cloud-free land area (km²)	Pre-event image dates	Post-event image dates	Total area flood (km²)	Percentage total flooded (cloud free) area
Tongatapu (AOI1)	280	206	1 January 2021–13 January 2022	16 January 2022–23 January 2022	8.12	3.95
Eua (AOI2)	93	83	1 January 2021–13 January 2022	16 January 2022–23 January 2022	0.97	1.17
Ha'apai (AOI3)	140	103	1 January 2021–13 January 2022	16 January 2022–23 January 2022	5.14	5
Vava'u (AOI4)	168	131	1 January 2021–13 January 2022	16 January 2022–23 January 2022	4.31	3.29
Total	**681**	**522**			**23.55**	**13.41**
				Sentinel-2		
Tongatapu (AOI1)	280	206	1 January 2018–13 January 2021	27 January 2022	1.78	0.64
Eua (AOI2)	93	83	1 January 2018–13 January 2021	27 January 2022	1.27	1.36
Ha'apai (AOI3)	140	103	1 January 2021–13 January 2022	15 January 2022–27 January 2022	4.68	3.35
Vava'u (AOI4)	168	131	1 January 2021–13 January 2022	15 January 2022–27 January 2022	5.79	3.45
Total	**681**	**522**			**13.52**	**1.99**

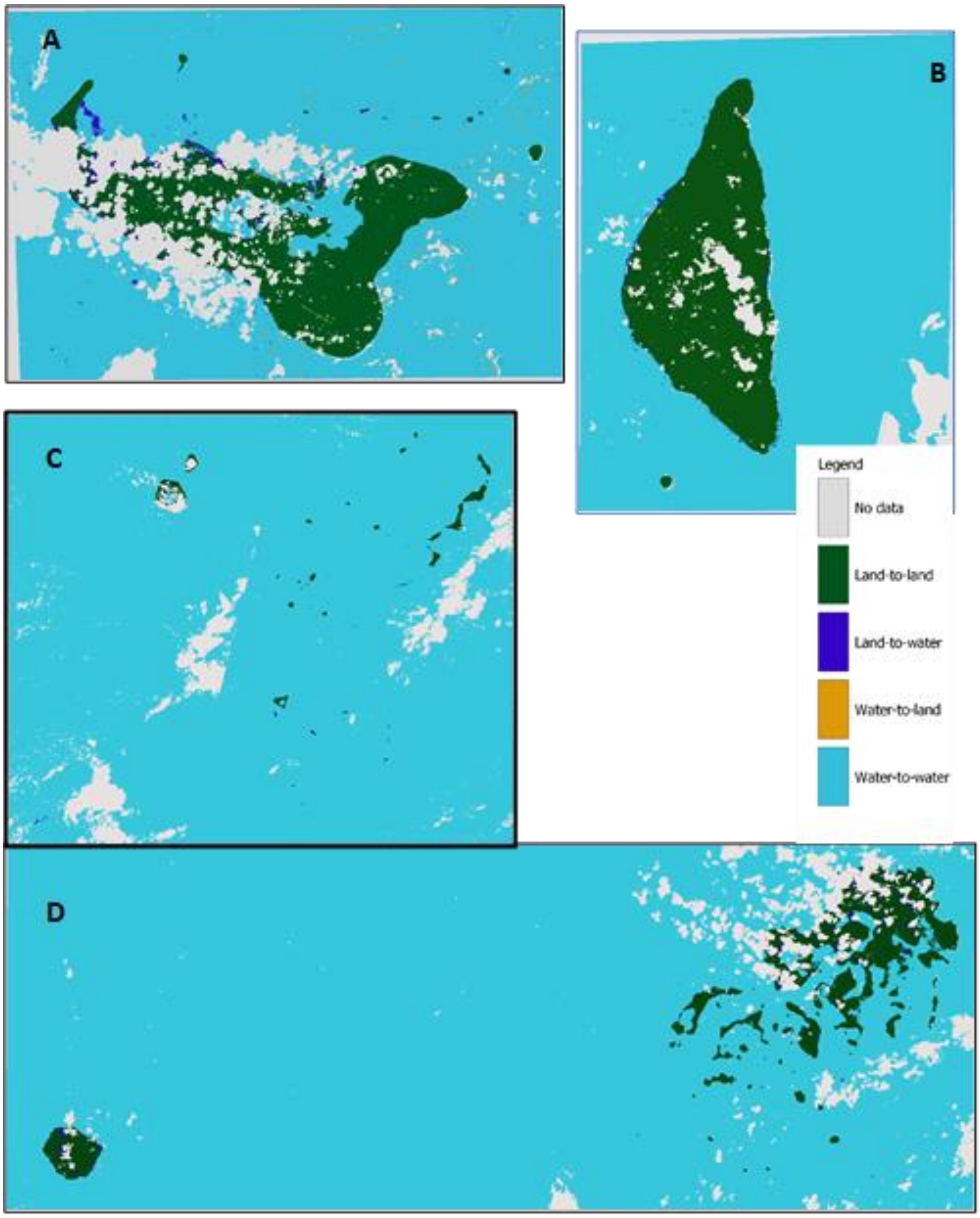

Figure 11. Classification of land and water based on Sentinel-2 imagery for each division (A. Tongatapu [AOI1]; B. Eua [AOI2]; C. Ha'apai [AOI3]; and D. Vava'u [AOI4])

3.2.1. Impact of flooding on land cover

The flooded area maps were overlayed with the 2021 land cover map prepared for this assessment to determine the flooded area across each land cover type. Table 8 reports the results, and in particular, the area of cropland exposed to flooding in each AOI, based on the total cloud-free land area. Note that it was not possible to determine the crop types exposed to flooding due to a lack of data availability. The results suggest that built-up areas, barren land, and mangroves are the most effected by the floods.

3.2.2. Population exposure to flooding

The population exposed to flooding in each AOI was estimated using the Worldpop 2020 population statistics (Worldpop, 2020) overlaid over the flooded area maps of Sentinel-2 (Table 8). The population data was classified into four classes, namely, very low, low, medium and high population density. The proportion of the population potentially exposed to flooding is approximately the same for all AOIs.

Table 8. Population exposed to flooding

Population exposed to flooding by population density (percentage of total division population)						
Division	Very low density	Low density	Medium density	High density	Total population exposed to flooding	Total division population
Tongatapu (AOI1)	561 (0.72)	334 (0.43)	442 (0.57)	418 (0.54)	1 755 (2.26)	77 786
Eua (AOI2)	39 (0.87)	55 (1.23)	20 (0.45)	0	114 (2.55)	4 478
Ha'apai (AOI3)	94 (2.10)	35 (0.78)	15 (0.33)	0	143 (2.84)	5 035
Vava'u (AOI4)	231 (1.81)	180 (1.41)	39 (0.31)	0	451 (3.54)	12 739

Source for population data: Worldpop (2020).

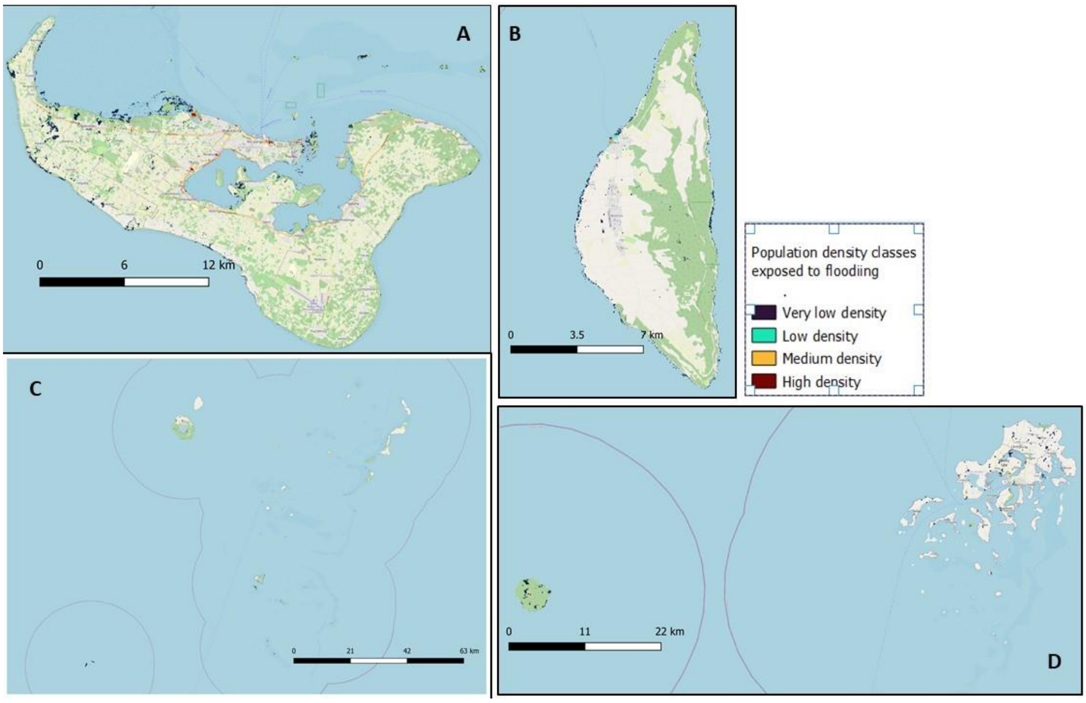

Figure 12. Population exposed to flooding (A. Tongatapu [AOI1]; B. Eua [AOI2]; C. Ha'apai [AOI3]; and D. Vava'u [AOI4])
Source for population data: Worldpop (2020).

3.3. Damage proxy mapping

Figure 13 demonstrates the damage proxy maps (DPMs) of all AOIs. Tongatapu (AOI1) experienced the greatest percentage of damages (Table 9). The built-up class from the 2021 land cover map was subsequently overlaid with the DPMs (Table 9). Again, Tongatapu (AOI1) exhibited the largest percentage in damaged built-up areas compared to the other AOIs.

Figure 13. Disaster proxy maps (DPM) of the four AOIs (1. AOI1; 2. AOI2; 3. AOI3; and 4. AOI4)

Table 9. Total damaged area for each AOI determined using the DPMs

Division	**Total land area (km²)**	**Total damaged area (km²)**	**Percentage of total damaged area**
Tongatapu (AOI1)	280	13.5	4.82
Eua (AOI2)	93.28	0.91	0.98
Ha'apai (AOI3)	139.78	1.17	0.84
Vava'u (AOI4)	167.72	0.91	0.54

Total	**680.78**	**16.49**	**2.42**

Table 10. Total damaged built-up area for each AOI determined using the DPMs

Division	Total land area (km^2)	Total damaged built-up area (km^2)	Percentage of total damaged built-up area
Tongatapu (AOI1)	280.00	1.41	0.50
Eua (AOI2)	93.28	0.18	0.19
Ha‘apai (AOI3)	139.78	0.03	0.02
Vava‘u (AOI4)	167.72	0.13	0.08
Total	**680.78**	**1.754**	**0.26**

3.4. Assessment of infrastructure damage to built-up areas

Figure 14, Figure 15, Figure 16 Figure 17 and Figure 18 present the estimated damage to ports, markets, roads, power and water infrastructure (lines), power and water infrastructure (polylines), and buildings in built-up areas in Tongatapu (AOI1). All figures are based on the DPMs for built-up areas.

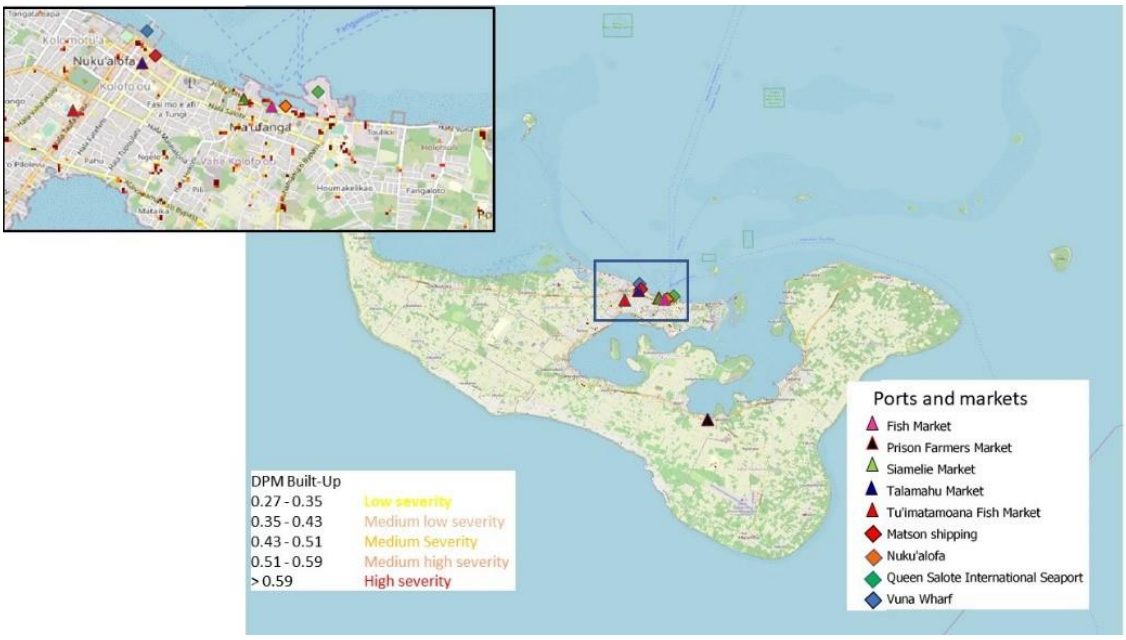

Figure 14. Location of key ports and markets in Tongatapu with respect to the damage proxy map of built-up areas (DPM Built-Up) determined following the Tonga-Hunga Ha'apai volcanic eruption

Figure 15. Potentially impacted roads in built-up areas of Tongatapu following the Tonga-Hunga Ha'apai volcanic eruption

Figure 16. Potentially impacted power and water infrastructure (lines) in built-up areas of Tongatapu following the Tonga-Hunga Ha'apai volcanic eruption

Figure 17. Potentially impacted power and water infrastructure (polylines) in built-up areas of Tongatapu following the Tonga-Hunga Haʻapai volcanic eruption

Figure 18. Potentially impacted buildings in built-up areas of Tongatapu following the Tonga-Hunga Haʻapai volcanic eruption

3.5. Ash coverage impact assessment

Table 11 reports the distribution of areas by ash cover magnitude, while Table 12 presents the percentage. Each AOI generally experienced no-to-medium ash cover (ash free, 1–5). Tongatapu (AOI1) experienced the greatest amount of ash coverage and Vava‘u (AOI4) the least.

Table 11. Distribution of areas by different ash cover magnitudes (area in km²)

AOI	Ash magnitude										Total
	Ash free	1	2	3	4	5	6	7	8	9	
AOI1: Tonga-tapu	9.18	23.60	37.49	43.39	38.48	51.71	60.88	13.17	1.85	0.25	280.00
AOI2: Eua	22.25	27.72	20.85	19.74	1.97	0.48	0.12	0.07	0.04	0	93.24
AOI3: Ha‘apai	15.51	19.30	25.31	26.83	37.54	4.16	4.01	4.72	2.39	0.69	140.47
AOI4: Vava‘u	153.72	10.57	2.06	0.73	0.30	0.14	0.06	0.02	0.01	0.00	167.61

Table 12. Percentage distribution of areas by ash cover magnitude (area in percentage)

AOI	Ash magnitude										Total
	Ash free	1	2	3	4	5	6	7	8	9	
AOI1: Tonga-tapu	3.28	8.43	13.39	15.50	13.74	18.47	21.74	4.70	0.66	0.09	100.00
AOI2: Eua	23.86	29.72	22.36	21.17	2.12	0.52	0.13	0.08	0.04	0.00	100.00
AOI3: Ha‘apai	11.04	13.74	18.02	19.10	26.72	2.96	2.86	3.36	1.70	0.49	100.00
AOI4: Vava‘u	91.71	6.31	1.23	0.44	0.18	0.09	0.03	0.01	0.00	0.00	100.00

Table 13. Summary of the distribution of ash covered area by depth classes (area in km^2)

AOI	Low (1 ,2, 3)	Medium (4, 5, 6)	High (7, 8, 9)	Total
AOI1: Tongatapu	104.48	151.07	15.27	270.82
AOI2: Eua	68.31	2.58	0.11	70.99
AOI3: Ha'apai	71.45	45.71	7.81	124.96
AOI4: Vava'u	13.36	0.50	0.03	13.89

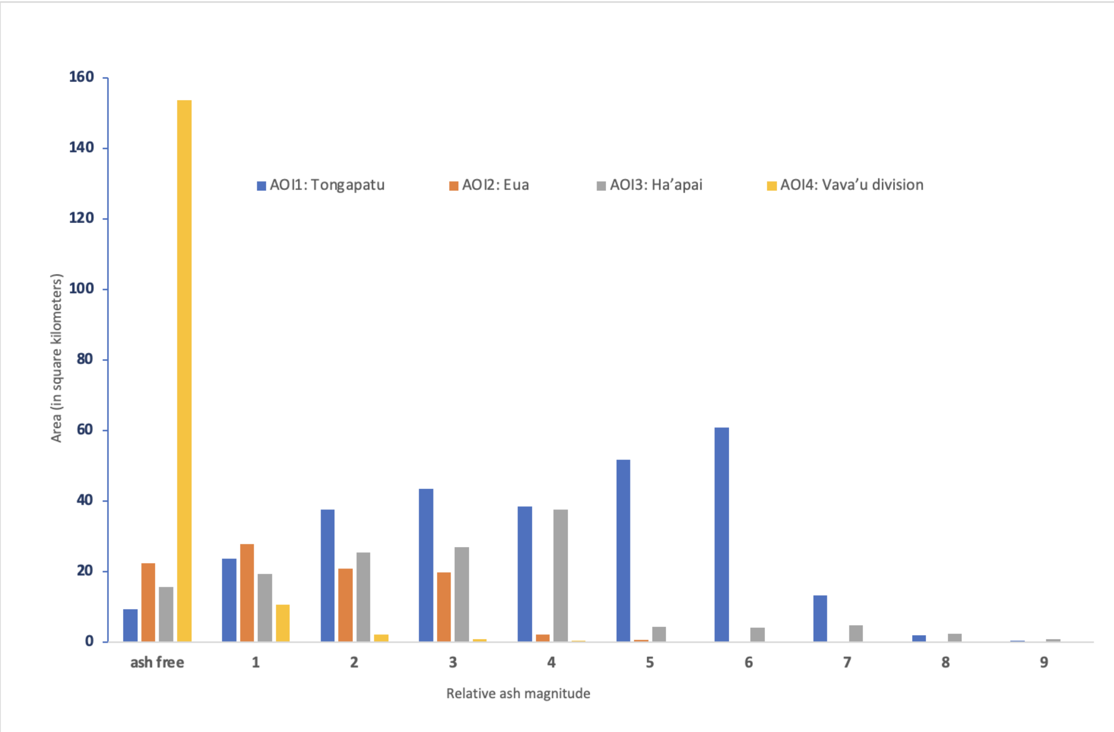

Figure 19. A representation of comparative figures of ash cover areas (km^2) in all the four AOIs (divisions)

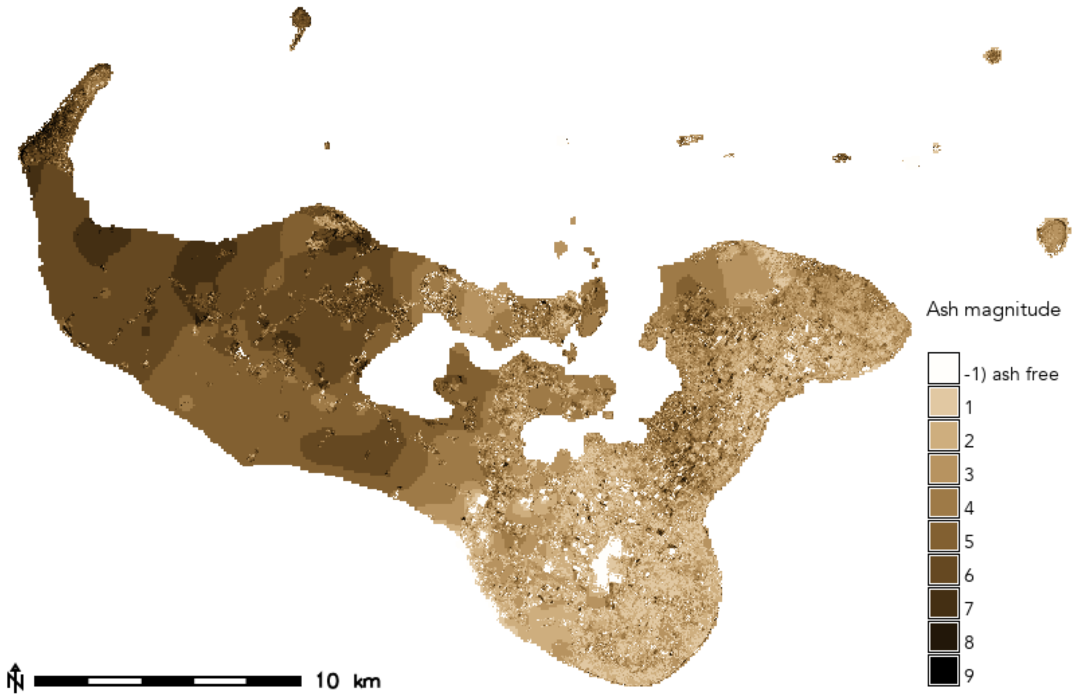

Figure 20. Ash covered areas in Tongatapu division (AOI 1)

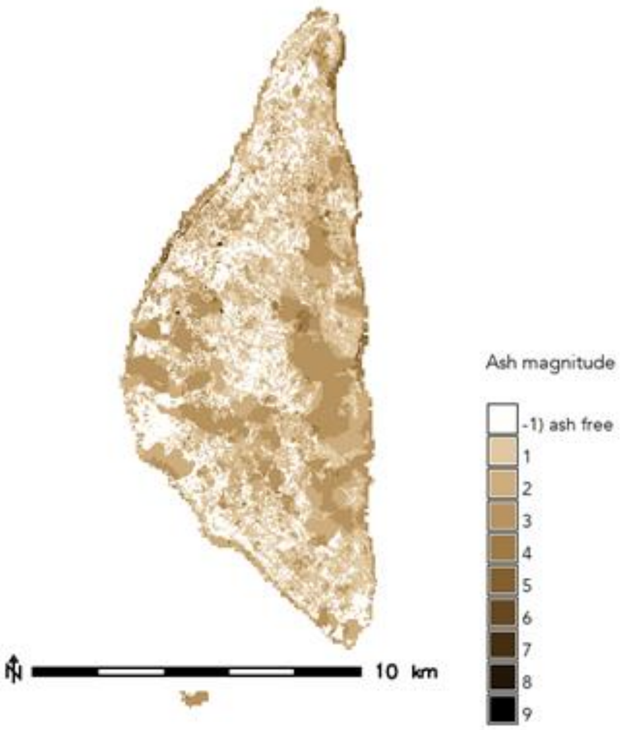

Figure 21. Ash covered areas in Eua division (AOI 2)

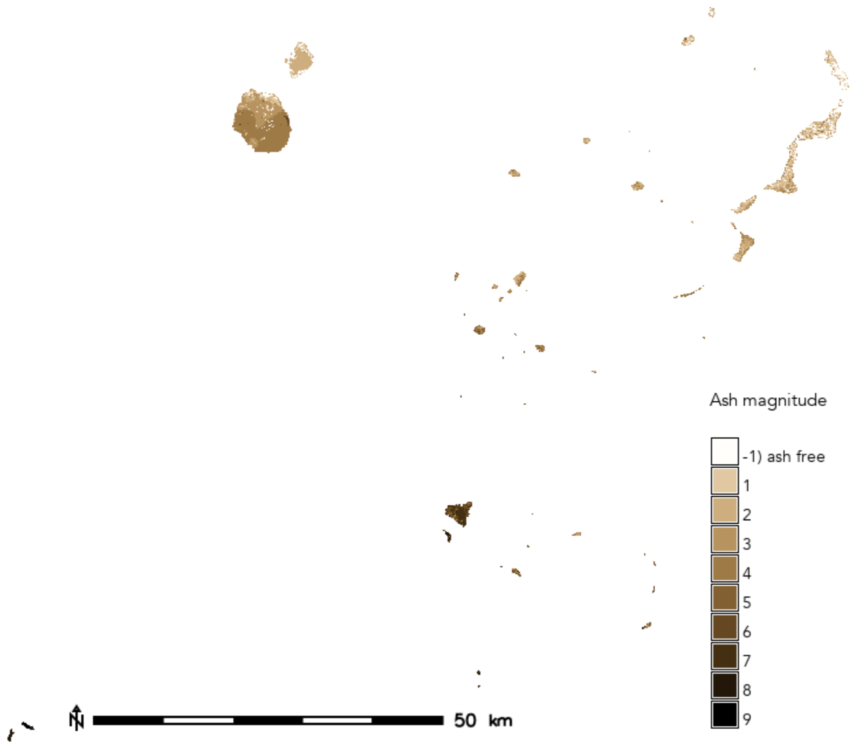

Figure 22. Ash covered areas in Ha'apai division (AOI 3)

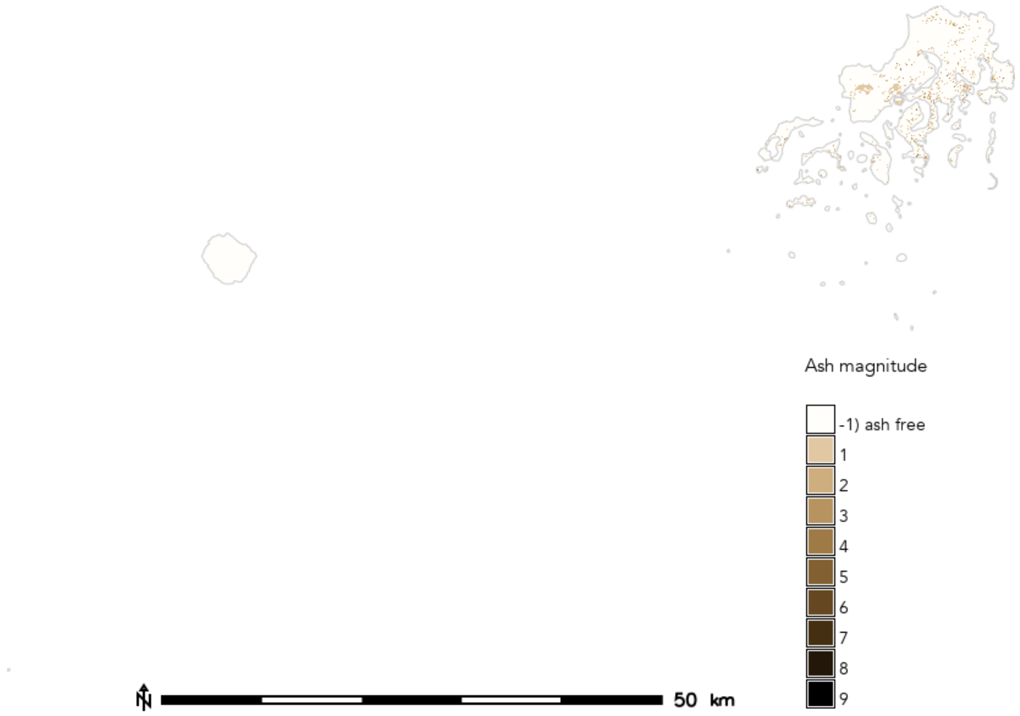

Figure 23. Ash covered areas in Vava'u division (AOI 4)

3.5.1. Assessment of crops potentially impacted by ash coverage

The ash cover magnitude was reclassified into four classes (no, low, medium and high ash coverage, Figure 24) in order to determine the crop area potentially damaged by the ash released following the volcanic eruption (Table 14). Cropland in Tongatapu (AOI1) mainly experienced medium ash exposure, while crops in Eua (AOI2) and Ha'apai (AOI3) were exposed to low ash cover, and Vava'u (AOI4) crops generally experienced no ash cover.

Table 14. Area of crop exposed to ash for each AOI in km^2 (and percentage of total AOI cropland area)

Division	No ash exposure	Low ash exposure	Medium ash exposure	High ash exposure	Total cropland area
Tongatapu (AOI1)	2.18 (6.13)	11.69 (33.26)	20.22 (57.52)	1.06 (3.03)	35.15 (100)
Eua (AOI2)	0.15 (14.15)	0.77 (74.37)	0.11 (10.27)	0.002 (0.21)	1.03 (100)
Ha'apai (AOI3)	0.97 (38.30)	1.29 (50.95)	0.11 (4.27)	0.11 (4.39)	2.53 (100)
Vava'u (AOI4)	3 (88.75)	0.31 (9.26)	0.03 (1.03)	0.00009 (<0.001)	3.38 (100)

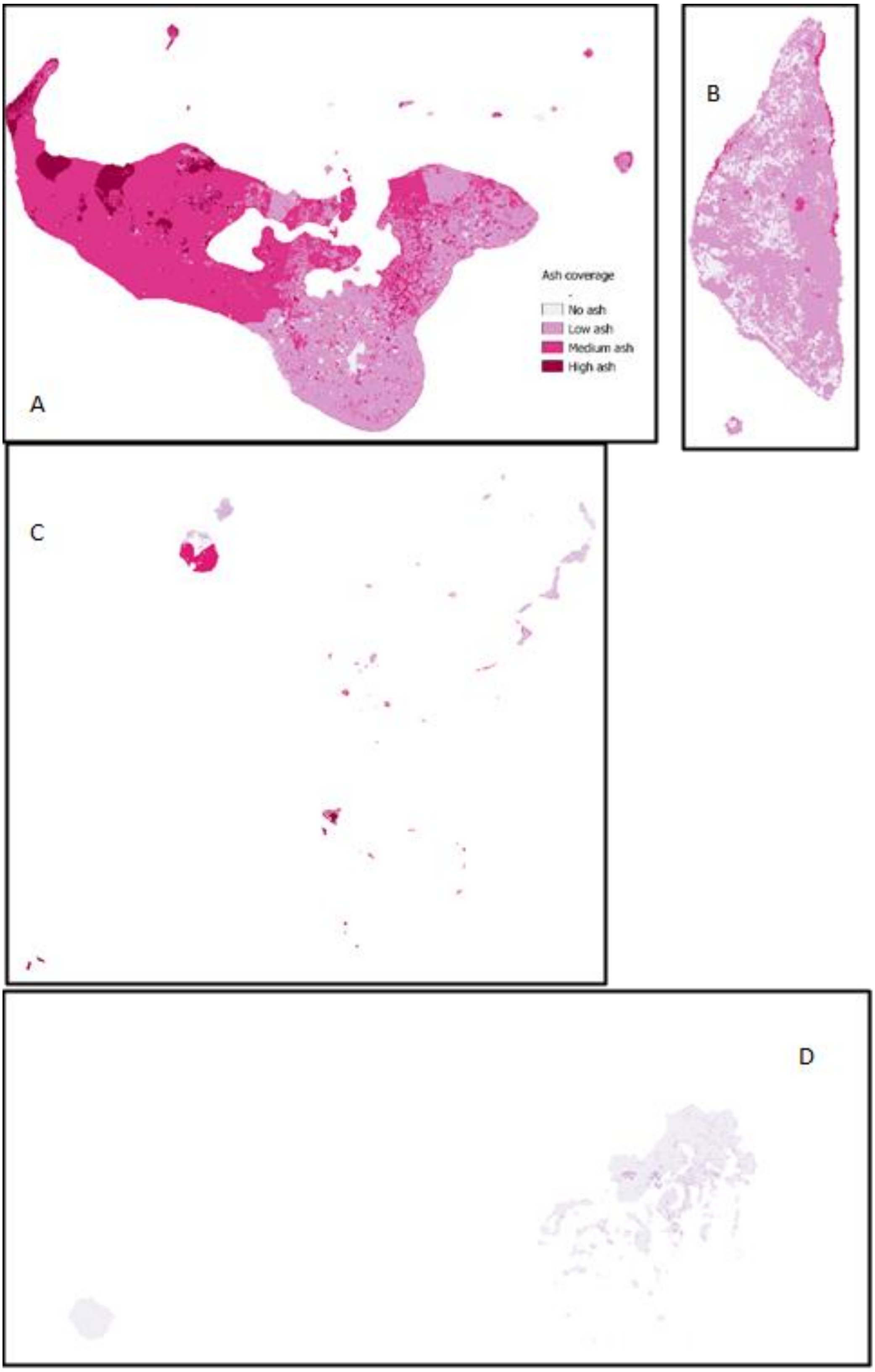

Figure 24. Exposure to ash classifications for all four AOIs (A. Tongatapu AOI1; B. Eua AOI2; C. Ha'apai AOI3; and D. Vava'u AOI4)

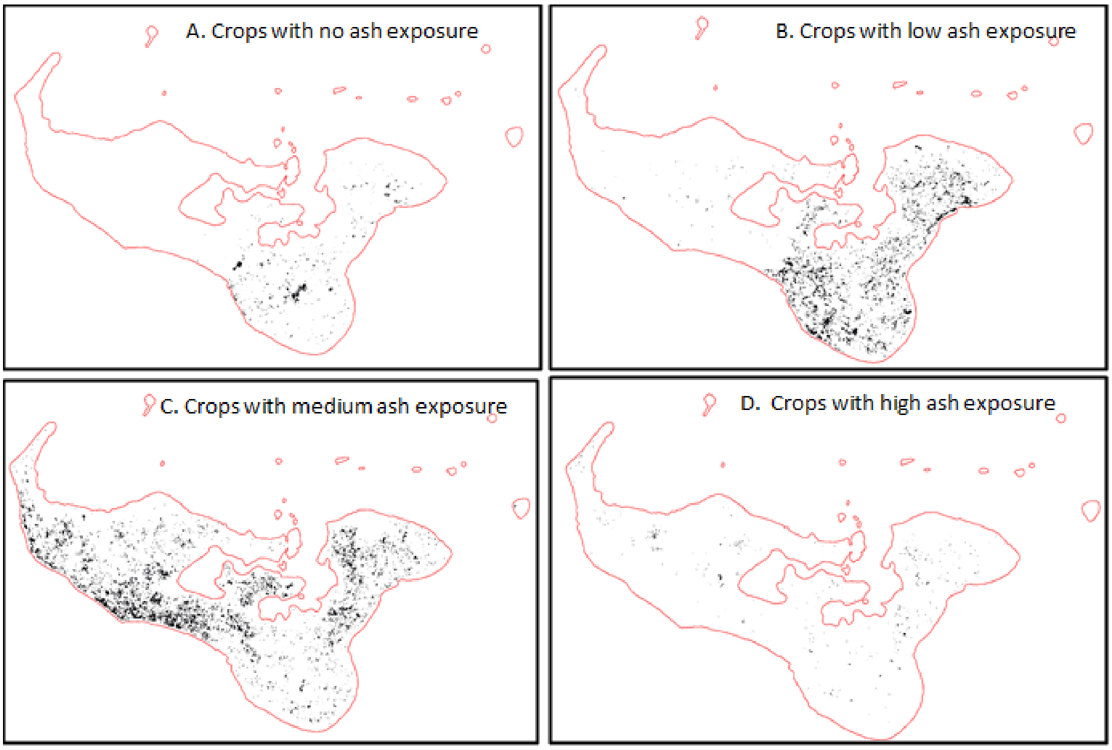

Figure 25. Distribution of crops with no, low, medium, and high ash exposure for Tongatapu (AOI1): A. crops with no ash exposure; B. crops with low ash exposure; C. crops with medium ash exposure; and D. crops with high ash exposure

3.5.2. Population exposed to ash coverage

The ash coverage classification in Figure 24 was used to determine the population exposed to difference magnitudes of ash coverage for each AOI (Table 15 and

Figure 26). The population of Tongatapu was the most impacted by ash coverage, the majority of which experienced medium ash exposure. However, for Eua and Ha'apai, most of the population were exposed to low ash coverage, while the Vava'u population generally experienced no ash coverage.

Table 15. Population exposure to no, low, medium and high ash coverage

Division	No ash exposure	Low ash exposure	Medium ash exposure	High ash exposure	Total Impacted Population	Total population	Percent-age impacted
Tonga-tapu (AOI1)	15 606	19 592	39 763	2 825	62 180	77 786	79.94
Eua (AOI2)	1 651	2 652	168	7	2 827	4 478	63.13
Ha'apai (AOI3)	2 748	1 703	508	76	2 287	5 035	45.42
Vava'u (AOI4)	11 566	1 134	39	0	1 173	12 739	9.21

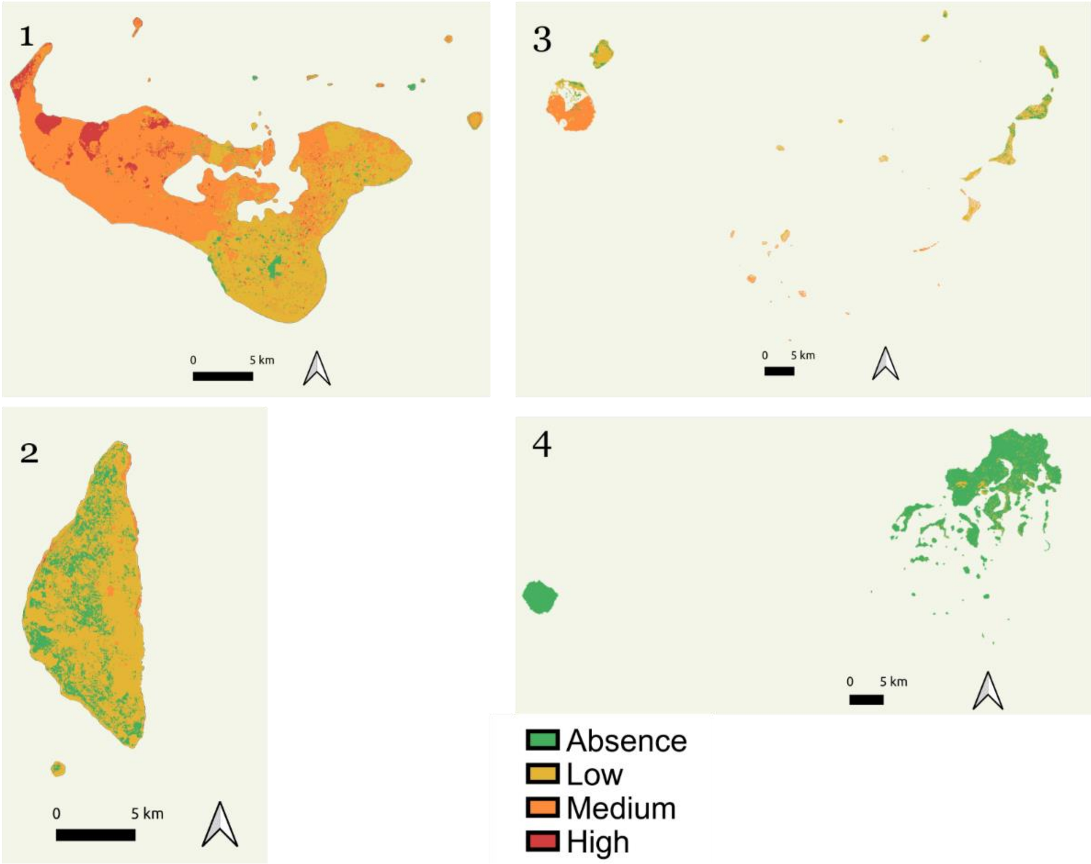

Figure 26. Spatial extent of population exposed to no, low, medium, and high ash in 1. Tongatapu (AOI1); 2. Eua (AOI2); 3. Ha'apai (AOI3); and 4. Vava'u (AOI4)

3.6. Coastline area assessment

Figure 27 and Table 16 present the results of the change in coastline assessment following the volcanic eruption. Ha'apai (AOI3) was observed to experience the greatest coastline change, and Tongatapu (AOI1) the least. However, the changes observed are limited by availability of optical imagery. Due to the use of imagery from a single date, it is possible that the changes from water to land may be related to detritus and the accumulation of materials in water.

Table 16. Change in area - km^2 (and percentage) of coastline after the volcanic eruption

Divisions	Land-to-water	Water-to-land
Tongatapu (AOI1)	0.95 (0.34%)	1.10 (0.39%)
Eua (AOI2)	0.46 (0.5%)	0.57 (0.61%)
Ha'apai (AOI3)	2.32 (1.66%)	2.31 (1.66%)
Vava'u (AOI4)	1.49 (0.89%)	4.37 (2.66%)
Total	5.23 (0.77%)	8.36 (1.23%)

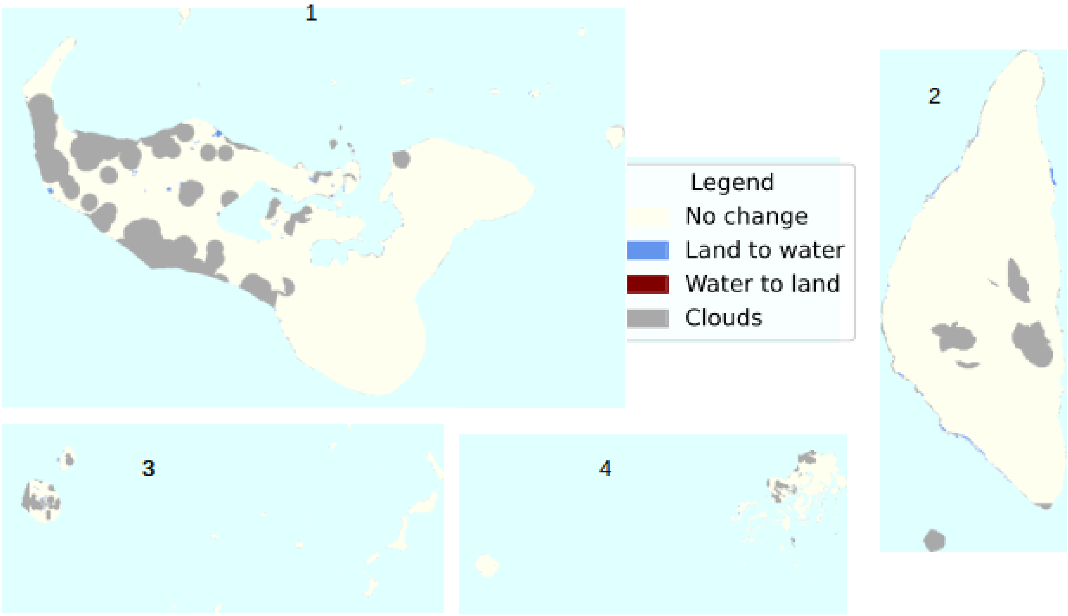

Figure 27. Change of coastline in the four divisions 1. Tongatapu (AOI1); 2. Eua (AOI2); 3. Ha'apai (AOI3); and 4. Vava'u (AOI4)

3.7. Precipitation

Figure 28 presents the daily accumulated precipitation averaged over each area of interest covering several days before and after the eruption. The peak in precipitation around the 15 January 2022 can be linked to the ash released during the eruption. The heat from ash particles typically induces water vapor in the atmosphere to condense, thus causing precipitation. Acid rain may also be produced when the SO2 emitted by the volcano interacts with water vapor and oxygen in the atmosphere.

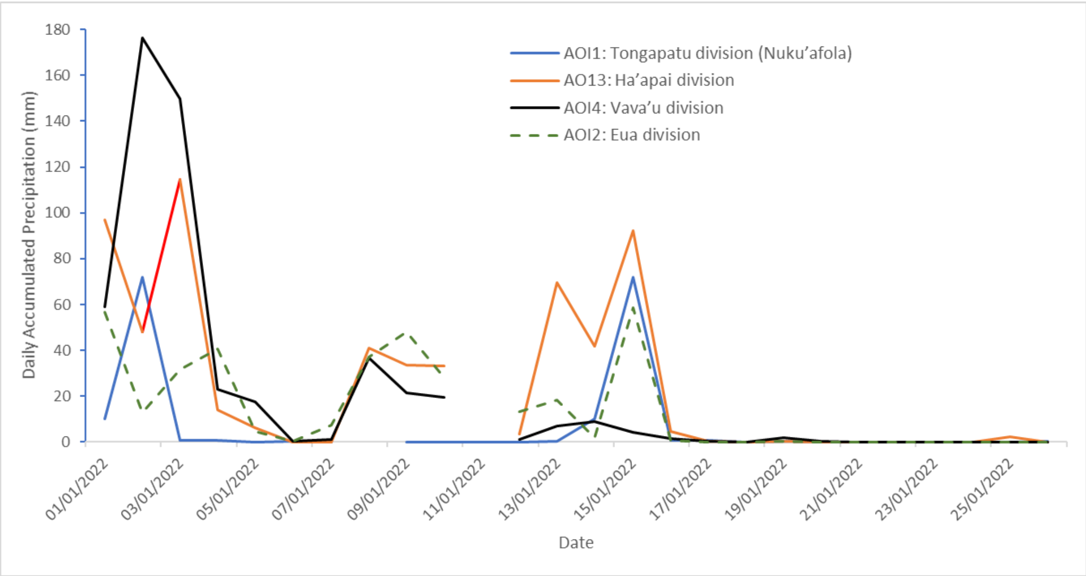

Figure 28. Daily accumulated precipitation (GPM_3IMERGDE v06) for Tongatapu (AOI1), Eua (AOI2), Ha'apai (AOI3), and Vava'u (AOI4)

3.8. Atmospheric pollution

Figure 29 presents the column amounts of SO2 in the lower stratosphere above Tonga and the surrounding region before, during and after the eruption. The UV aerosol index is also shown. A peak in both variables is evident due to the eruption, which injected a volcanic plume over 30 km high. A secondary peak is also observed for the UV index, indicating a further rise in aerosols even days after the eruption. The stratosphere is the upper layer of the atmosphere, and thus plumes reaching this layer can have an impact on the climate. Figure 30 shows the elevated column amounts of SO2 on the 16 January across Australia. This suggests transboundary effects of the volcanic plume, particularly as the SO2 amounts are observed to reach high levels on the 16 January (approx. 27 DU).

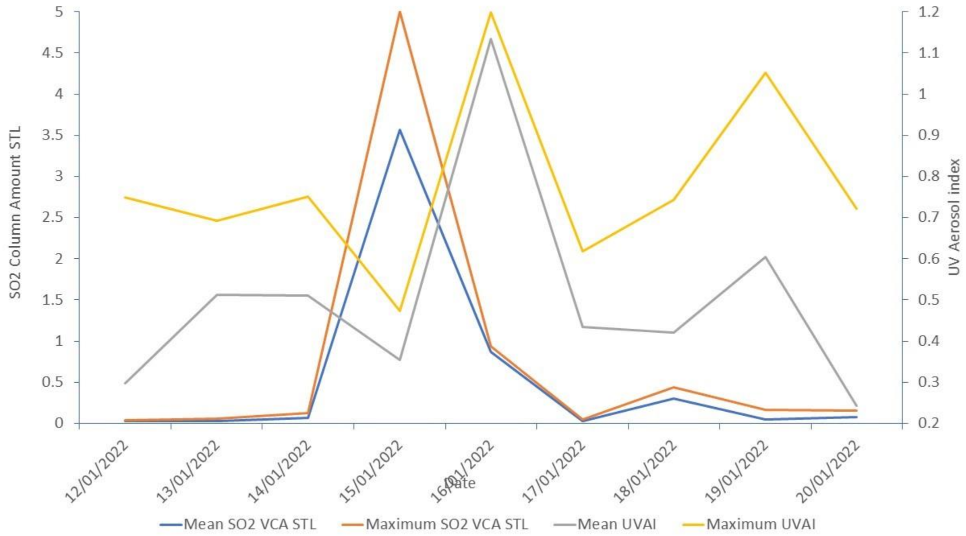

Figure 29. Daily SO2 column amounts in the lower stratosphere (STL) (DU) and the UV aerosol index before, during and after the eruption for Tonga and the surrounding area

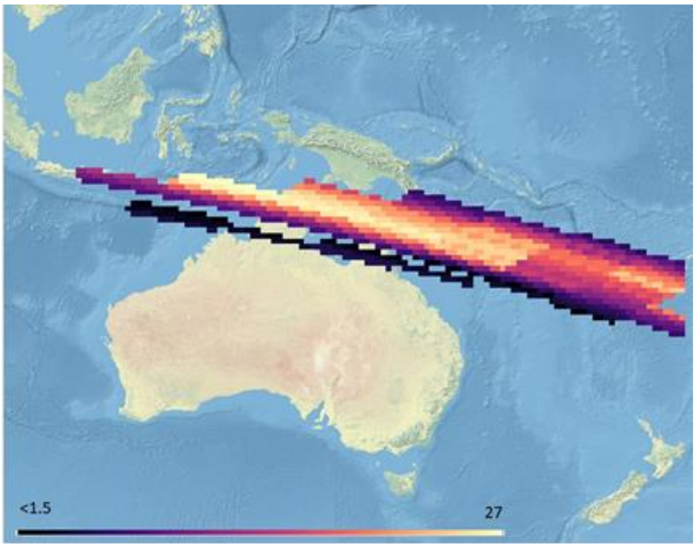

Figure 30. SO2 elevated column amounts in the lower stratosphere on the 16 January 2022

4. Recommendations

The results presented in this assessment were prepared during a 10-day time period, thus our analysis faced time and data availability constraints (in particular, the availability of high resolution optical and radar imagery). This assessment can be further enhanced with additional field information, better data quality and models. This includes the following:

- Make available field data for land cover and land use future assessments with particular attention to the ISO 19144-2 LCML standard.
- Cross-reference and triangulate the land cover results with available datasets (e.g., OSM), which was not possible here for each AOI.
- Use of a VHR digital elevation model (DEM). The flow of water from a higher to lower elevation is crucial in flood and vegetation growth assessments and can be derived from a VHR digital elevation model.
- Undertake field validation of the results, when it is timely possible and practical. Integrating satellite imagery with field data can improve the accuracy of the results, particularly due to the limitations of cloud imagery, the digital collection of training points and the satellite imagery availability for the AOIs faced in this assessment.
- Use hydrodynamic models to overcome problems with cloud cover (Sentinel-2) and limited data availability (Sentinel-1).
- Monitor the volcanic plume traverse with precipitation to determine occurrences of possible acid rain.
- Investigate the potential impact of the plume as it traversed in surrounding regions (e.g., surface temperatures, evolution of gases and aerosols).

Despite the limitations of the results, such a rapid geospatial assessment plays a key role in gaining an overview of the impact of the eruption on Tonga and the surrounding region, and in particular, its potential effect on the agricultural sector in Tonga. From our results, we can identify the most impacted areas and sectors that require attention and can thus focus on these using improved methods and indicators in future assessments, integrating additional information on ash cover, flooding and vegetation growth during the next month.

All results have been prepared in different format such as .csv, .xls, .tiff, .kmz. The latter file format can be easily used in Google Earth to navigate through the different AOIs and visualize the results.

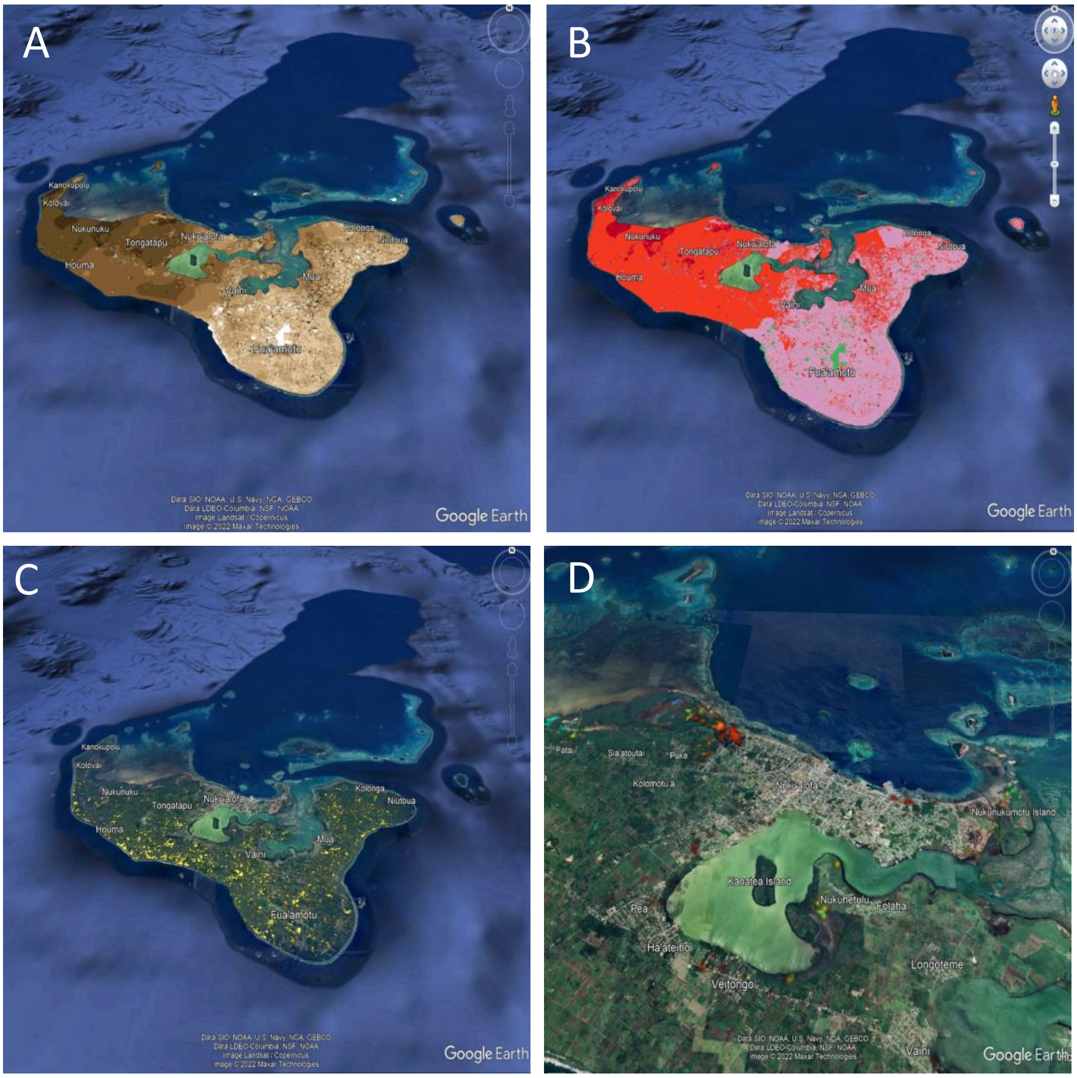

Figure 31. Visualisation of the results from this rapid geospatial impact assessment using Google Earth: A. ash cover; B. exposure of people to ash; C. exposure of crop to ash; and D. exposure of people to flood

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Appendix 1 – Population data in Tongatapu (AOI1)

2016 Census		2020 Worldpop			
Town	Population	Population	Mean	Minimum	Maximum
Kolofo'ou	8 226	3 684	8.6	3.9	12.9
Ma'ufanga	7 365	3 807	8.7	3.3	14.2
Nukumotu	53	178	0.9	0.5	2.6
Popua	1 854	1 263	5.7	2.1	13.5
Tukutonga	508	437	4.0	0.8	10.6
Kolomotu'a	7 571	4 016	6.9	1.1	16.7
Havelu	3 503	1 625	8.2	2.2	15.2
Tofoa	3 510	2 664	4.6	0.5	15.5
Hofoa	1 173	1 620	3.8	0.6	15.5
Puke	911	1 483	3.8	0.5	13.7
Sia'atoutai	460	1 246	2.2	0.4	14.7
Vaini	3 285	4 147	1.5	0.1	17.0
Malapo	652	1 028	4.1	1.0	14.9
Longoteme	603	1 040	1.4	0.3	10.0
Folaha	946	2 007	3.1	0.6	16.0
Nukuhetulu	344	569	2.2	0.5	10.1
Veitongo	1 199	887	2.2	0.3	12.9
Ha'ateiho	2 664	2 322	2.3	0.2	13.1
Pea	2 014	2 583	2.7	0.5	16.3
Tokomololo	1 288	1 210	2.1	0.2	13.9
Tatakamo-tonga	1 879	1 479	1.4	0.4	11.8

2016 Census		2020 Worldpop			
Holonga	488	794	4.2	1.5	11.8
Pelehake	797	1 901	1.9	0.4	15.1
Fua'amotu	1 639	4 831	2.0	0.2	18.8
Nakolo	411	506	2.7	0.4	12.3
Ha'asini	878	1 713	2.2	0.3	14.7
Lavenga-tonga	356	1 053	2.1	0.4	10.9
Haveluliku	182	184	1.5	0.7	4.5
Fatumu	413	628	3.3	0.7	11.7
Lapaha	1 995	2 003	1.0	0.2	17.2
Talasiu	366	331	1.7	0.3	5.6
Hoi	427	463	5.9	2.4	9.9
Nukuleka	226	497	3.1	0.7	9.9
Makaunga	389	509	2.0	0.5	9.9
Talafo'ou	362	485	1.8	0.4	9.5
Manuka	272	166	3.5	1.0	10.5
Navutoka	717	539	1.0	0.2	10.7
Kolonga	1 135	1 357	0.9	0.2	10.3
Afa	478	426	1.6	0.2	9.8
Niutoua	671	561	0.8	0.2	6.8
Nukunuku	1 989	1 078	1.3	0.4	5.8
Matahau	570	799	3.6	0.7	14.2
Matafonua	235	574	4.0	1.2	13.2
Fatai	304	588	4.4	0.7	13.9
Lakepa	360	557	2.6	0.6	12.6
Vaotu'u	488	1 132	1.8	0.2	17.4
'Utulau	622	1 484	2.8	0.2	15.7
Ha'alalo	605	681	4.2	0.8	13.7

2016 Census		2020 Worldpop			
Ha'akame	742	672	2.7	0.7	16.0
Houma	2 097	2 584	2.4	0.3	18.6
Kolovai	618	507	1.8	0.2	10.6
Te'ekiu	577	766	2.8	0.5	13.5
Masilamea	228	504	2.7	0.8	10.9
Fahefa	431	688	1.5	0.2	13.8
Ha'utu	253	151	4.1	2.0	14.8
Kala'au	152	143	0.7	0.2	2.6
Fo'ui	657	709	1.6	0.2	11.1
Ha'avakatolo	195	287	2.4	0.3	9.8
'Ahau	386	279	2.0	0.2	9.7
Kanokupolu	339	498	2.9	0.3	9.7
Ha'atafu	269	132	1.3	0.2	4.3
Total population	74 327	73 054			

Appendix 2 – Land cover legend for 2021

Table 17. Land cover classes used for land cover map presented in Figure 8 and producer accuracy for 2021 land cover map for all AOIs

Code	Class	Description	Example image	Producer accuracy
10	Forest (trees)	Dense, closed canopy formation of evergreen or semi-evergreen broadleaf vegetation with a multiple strata structure. Upper stratum of trees over 30 m tall. Understory composed of evergreen or semievergreen shrubs; herbaceous cover is discontinuous.		0.82
20	Shrubland	Natural shrubs (H=0.5 to 1.5 m), occasionally with scattered rocks and boulders.		0.68
30	Grassland	Natural herbaceous vegetation - close to very open, occasionally with sparse shrubs.		0.55
40	Cropland	Annual herbaceous crop - irrigated/rainfed.		0.98
50	Built-up	Built-up land, including populated places, industrial sites, major roads, and extraction sites.		0.95

Code	Class	Description	Example image	Producer accuracy
60	Bare Land	Bare or almost bare land with low density of natural vegetation and where no agriculture activities are present.		0.55
80	Water Bodies	Perennial freshwater, natural or artificial		0.86
95	Mangrove	Coastal forests of stilted shrubs or trees bordering the ocean or coastal estuaries, composed of one or several mangrove species.		0.82
99	Coconut	Parcels planted with coconut trees, with single or mixed fruit species and crops, associated with permanently grassed surfaces.		0.52
	Overall producer accuracy			**76%**
	Kappa			**73%**

Appendix 3 – Ash cover assessment after January 2022 using Maxar open data

Extent of ash cover is an important indicator necessary to assess the impact from the Tonga January 2022 volcanic eruption on natural resources, agriculture, and other sectors. GADM was used to delineate the administrative boundary of Tonga islands. Four AOIs were identified to represent four divisions and to prepare the results from this assessment in impacted areas. Maxar open data imageries were acquired and mosaicked[1]. These data are mainly available for AOI1. A set of six pre and post event comparisons of the cloud locations were selected to understand the impact of ash cover on the Tongatapu island. Figure 32 is the Maxar open data coverage for the January 2022 volcanic eruption in Tonga and Figure 33 presents the location of these comparisons.

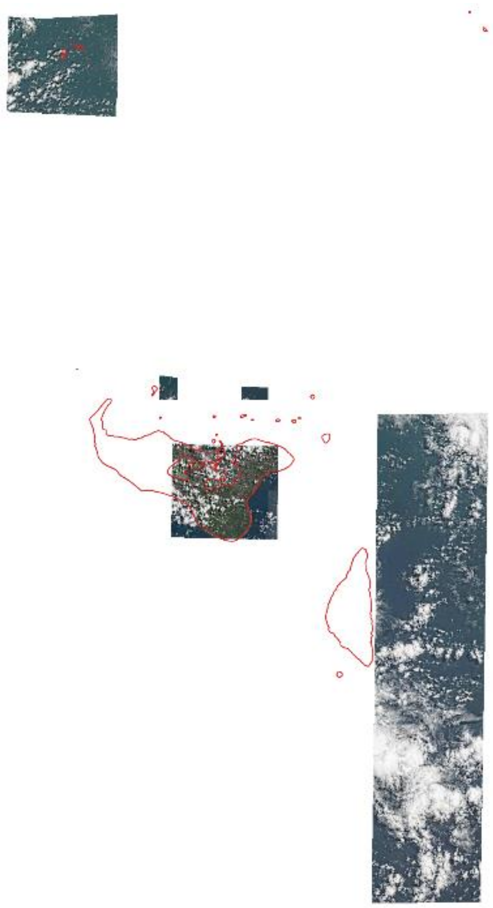
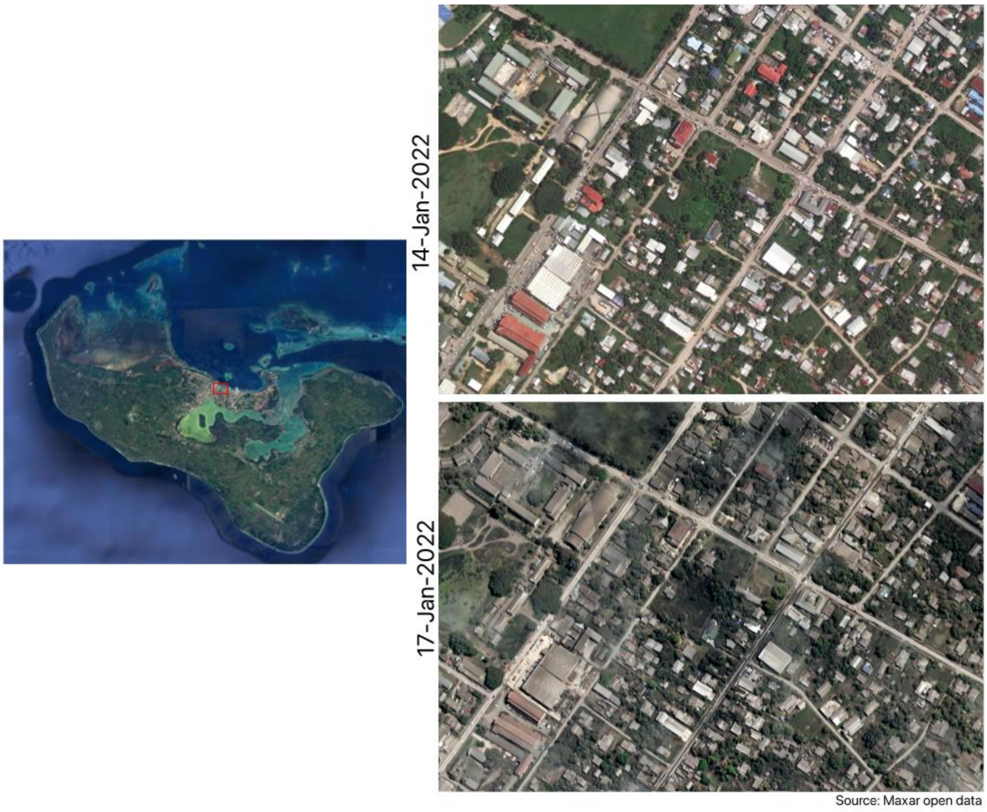
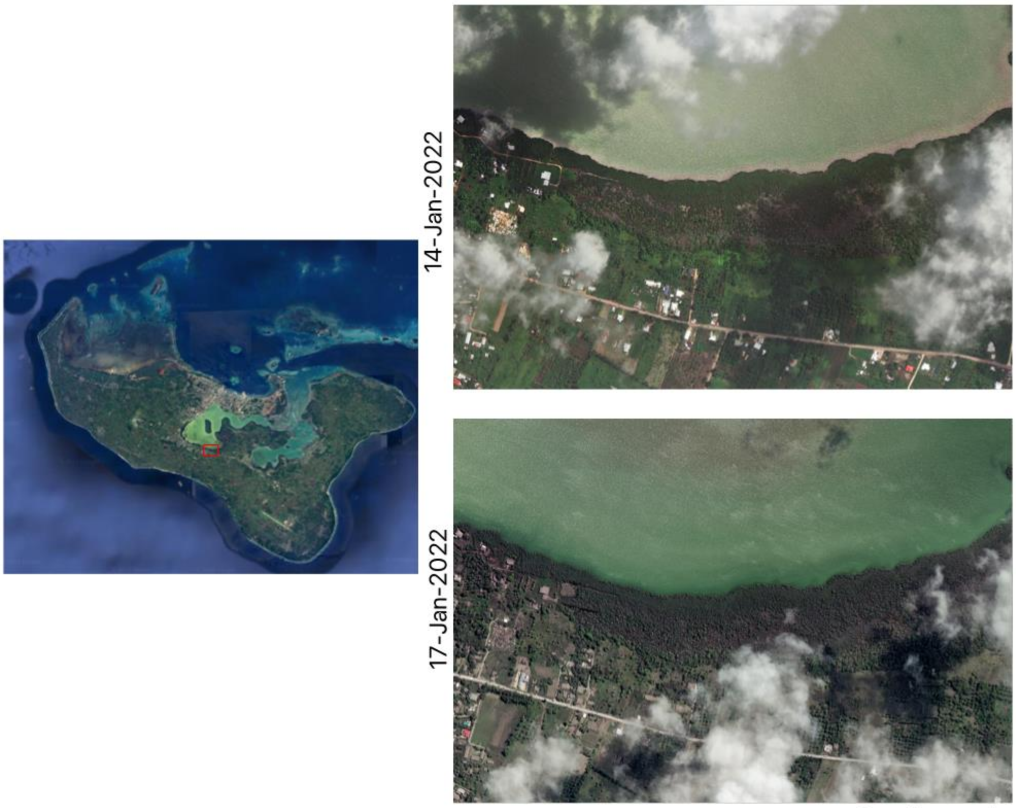


Figure 32. Maxar open data coverage for the January 2022 volcanic eruption in Tonga

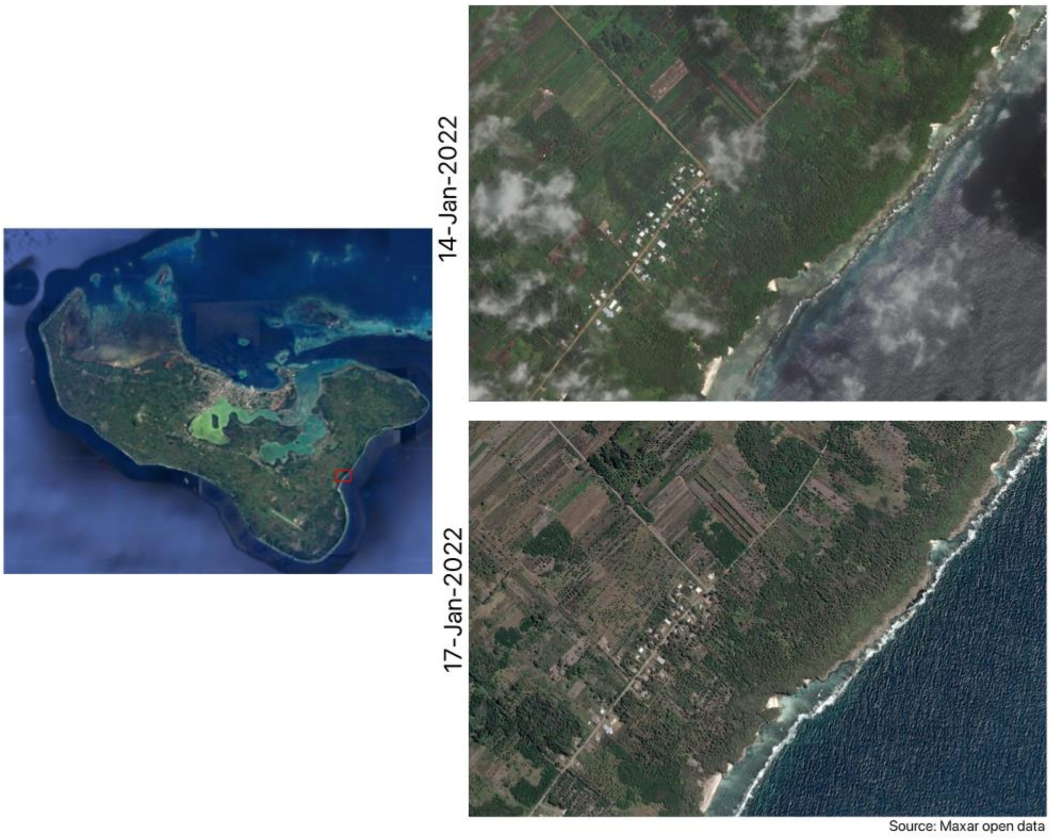
[1] https://www.maxar.com/open-data

Figure 33. Geographic locations of the sites used in the comparisons

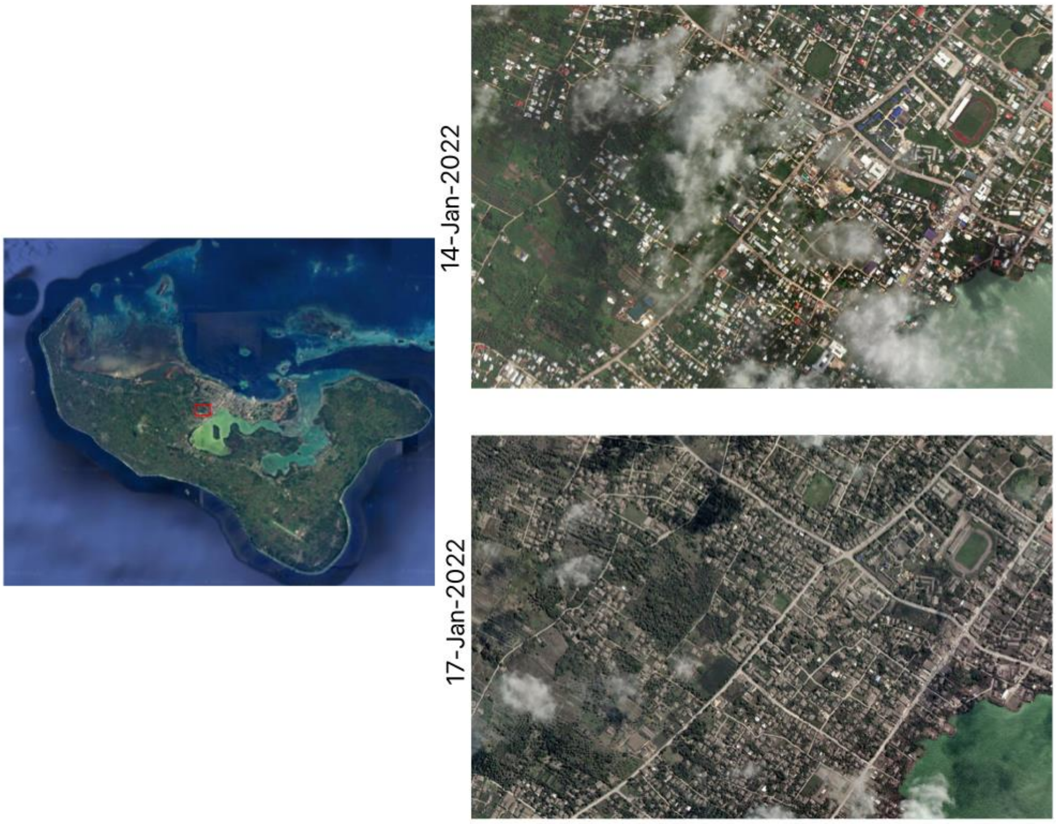




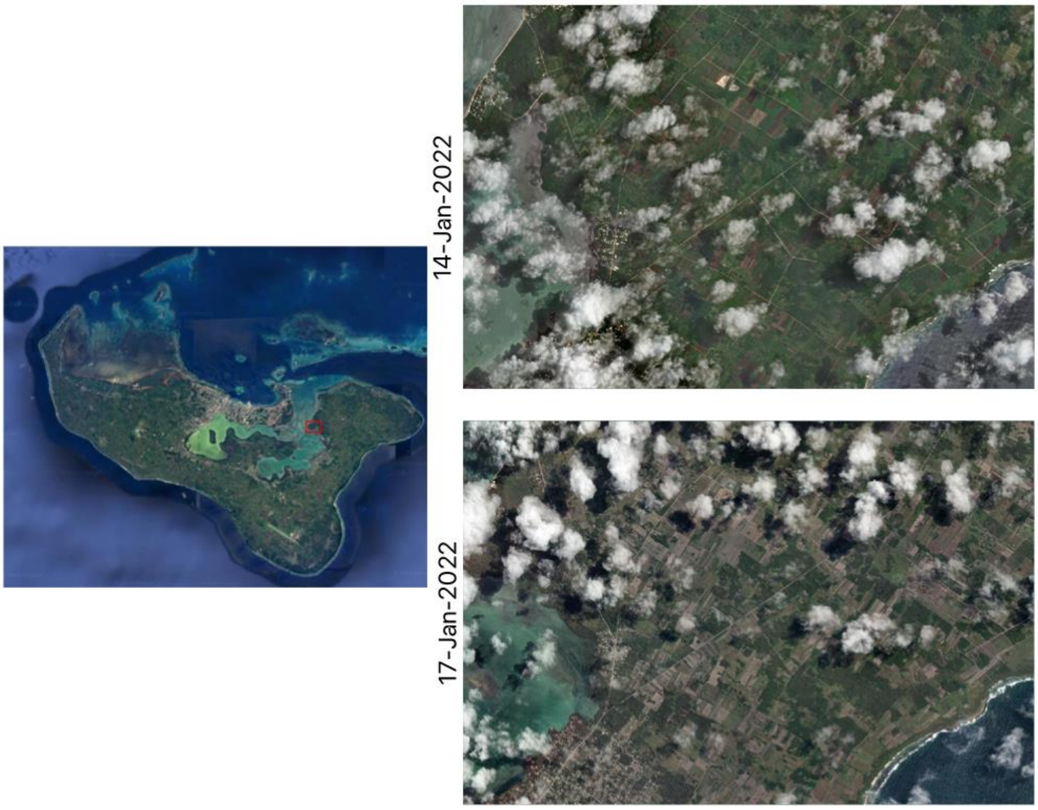
Source: Maxar open data



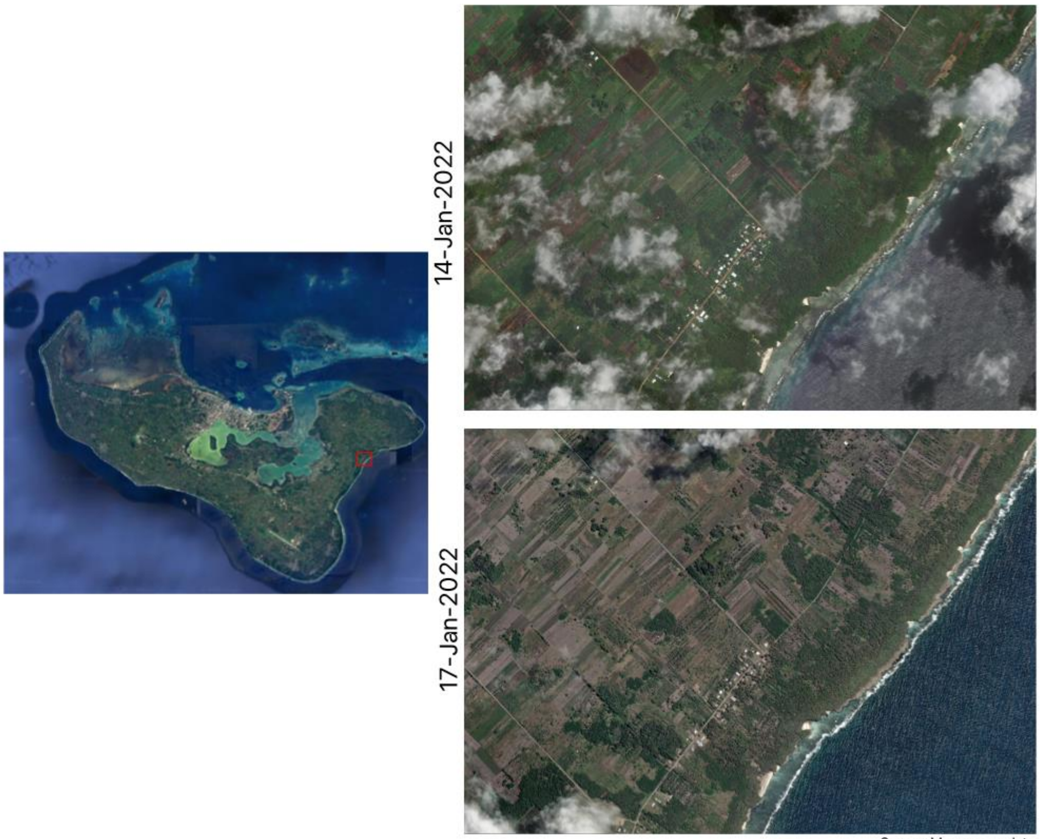
Source: Maxar open data



Source: Maxar open data



Source: Maxar open data



Source: Maxar open data

A rapid geospatial analysis of the impact of the Hunga Tonga volcano eruption

On the 15th January 2022 the underwater Hunga Tonga–Hunga Ha'apai volcano, located in the north of Tongatapu (the main island of Tonga), erupted following several minor eruptions over the previous weeks. It was reported as the largest recorded eruption in the past 30 years. On the 14th January 2022, the Tonga Geological Services issued an alert of the Hunga Tonga Hunga Ha'apai volcanic activity and issued a tsunami marine warning. The powerful eruption resulted in a tsunami in Tonga and the surrounding region, with effects reaching countries including Fiji, America Samoa and as far as Chile and Peru. A total of 84% of the population of Tonga has been reported to be affected by the tsunami and extensive ash cover, with impacts on infrastructure, agriculture, fishery, natural resources, air pollution, as well as water contamination (from ash fall and acid rain), fish poisoning (from volcanic fluid polluting the oceans). Three deaths have been confirmed in Tonga as a result of the tsunami, with approximately two dozen people injured and around 240 damaged houses. Furthermore, the volcanic plume reached above 30 km into the atmosphere, releasing volcanic gas and aerosols that were subsequently carried over neighbouring countries, potentially impacting public health and also the atmosphere.

There is a critical need to understand the impact of the volcanic eruption. Thus, the Food and Agriculture Organization of the United Nations (FAO) has performed a rapid geospatial evaluation of the damages following the event. Assessments include land cover change, identification of flooded areas, ash cover, potential damage to crop ash and floods, and damage to built-up areas. This work aims to support current and future response programmes.

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