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# A new volcanic multi-hazard impact model for water supply systems: Application at Taranaki Mounga, Aotearoa New Zealand

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## ABSTRACT

Water supply systems provide an essential service for society and are highly vulnerable to damage and disruption during volcanic eruptions. Impacts sustained by water supply systems during volcanic eruptions have resulted in prolonged and repeated supply outages. Previous approaches to assessing volcanic impacts to water supply systems have been relatively simplistic, based on hazard intensity thresholds, and only considering direct damage. There is a need for water supply risk assessment approaches informed by vulnerability models that consider the pivotal role of system design and indirect impacts; such as supply and demand fluctuations, personnel shortages, and disruptions to interdependent infrastructure networks. We present a whole-of-system volcanic vulnerability model and impact assessment framework for water supply systems that can be used to estimate system-wide impacts during future volcanic eruptions. This model is developed in collaboration with volcanic risk researchers and water supply engineers in Aotearoa New Zealand and applied to a case study in the Taranaki region for a long-duration and multi-hazard eruption scenario from the active stratovolcano Taranaki Mounga. The model provides an assessment of the functionality of water supply systems affected directly and indirectly by the scenario eruption, interdependent critical infrastructure services, and associated emergency management actions (e.g., evacuations). This scenario, and its modelled impacts, allows practitioners to explore potential mitigation and emergency response options. This framework can be applied in other volcanic contexts to assess impacts on water supplies from future eruptions, highlight key systemic vulnerabilities, and provide a basis for the prioritisation and implementation of risk management strategies.

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## 1. Introduction

Water supply systems (WSS) are complex critical infrastructure systems that are of fundamental importance to human health and underpin the development and sustainability of communities, industry, and economic development [1,2]. Volcanic eruptions can produce multiple, long-duration, complex hazards that can disrupt the supply of potable water to customers, causing significant societal impacts and economic losses [3–9]. WSS include the following components: water sources, such as streams, lakes, reservoirs or groundwater aquifers; water extraction systems, such as intakes and abstraction pumps; pipe networks to transport water from extraction to treatment; water treatment plants (WTPs), such as ultraviolet purification, sand or membrane filters and chemical

**Table 1**
Observed impacts to WSS componentry from volcanic processes.

| Impact | Eruption (year) | Location | Notes | References |
|---|---|---|---|---|
| Lahars can damage or destroy water intakes on rivers or streams | Cordón Caulle (2011) | Villa la Angostura, Argentina | Very thick ashfalls (~170 mm) caused lahars which severely damaged water intakes in stream-fed systems. The systems were eventually abandoned. | ; [11] |
| | La Soufrière (2021) | Systems in north of St Vincent | Lahars damaged river intake structures across the northern part of St Vincent. | [3]. |
| Pumice and ash can clog surface water intakes | Cordón Caulle (2011) | Bariloche, Argentina | Thick pumice rafts clogged water intakes on Lago Nahuel Huapi. | [11] |
| | Ruapehu (1945) | Taumaranui, New Zealand | Suspended ash blocked filters at water intakes on the Whanganui River and slowed pumping. | [12] |
| Ash suspended in surface water sources increases turbidity | Te Maari (2012) | Rangipo, New Zealand | Suspended ash from the Te Maari eruption triggered the 20 NTU[1] threshold for the automatic shutdown of the intake for the Rangipo Prison water supply. This largely protected the plant from damage. | [13] |
| | Cordón Caulle (2011) | Bariloche, Argentina ( Fig. 2A) | Suspended ash from the Cordon Caulle eruption raised turbidity to 26 NTU[1] in Lago Nahuel Huapi which caused major problems for Bariloche's main WTP as it was not designed for this level of turbidity and had no initial coag-floc treatment step thus additional suspended material penetrated into the treatment train. | [11] |
| | Chaitén (2008) | Esquel, Argentina | It was necessary to increase chlorine dosing to compensate for increased turbidity in intake water. | [14] |
| Suspended ash can damage pump impellers and motors | Cordón Caulle (2011) | Bariloche & Villa la Angostura, Argentina | Suspended ash ingress into lake intakes caused accelerated wear to pump impellers and motors in these systems where water is pumped uphill to treatment plants rather than being gravity-fed. | [11] |
| Ashfall into surface waters can increase dissolved constituents | Te Maari (2012) | Rangipo, New Zealand | Marked but transient increases in dissolved constituents (notably aluminium, cobalt, copper, iron and manganese) were recorded in streams receiving ashfall from the Te Maari eruption. | [15] |
| | Chaitén (2008) | Esquel, Argentina | Residents of Esquel noticed unusual metallic tastes in their water, due to elevated iron and aluminium from ashfall into the open canal conveying water to the WTP. Levels remained well below drinking-water guideline levels. | [14] |
| Ash can enter and block open-air sand filters and clarifiers through intake and by direct fallout | La Soufrière (2021) | Systems in north of St Vincent (St Vincent and the Grenadines) (Fig. 2B) | Sand filters were heavily contaminated by ashfall and had to be dug out manually. | [16] |
| | Cordon Caulle (2011) | San Martin de los Andes, Argentina (Fig. 2C) | Approximately 20 mm fine ash fell entered the open-air slow sand filters, where it acted as a cement and blocked the pores in the filter media. A greatly increased level of maintenance was required. | Stewart (pers. Comm.) |
| | Guagua Pichincha (1999) | Quito, Ecuador | Sand filters required cleaning every 1–6 h compared to every 8–10 h during normal operation. | [17] |
| Ashfall can cause power outages which will affect electrical pumping | Hunga (2022) | Nuku'alofa, Tonga | Nuku'alofa's reticulated water supply was largely resilient to ashfall as it is based on a groundwater wellfield and is fully enclosed between source and consumer. However, ash-induced power outages interfered with electrical pumping, reducing water production. | Auapaau et al., *in review* |
| Ashfalls generate an increased water demand | All | | Water demand invariably increases following ashfall as residents use water to clean up. Water consumption needs to be proactively managed to avoid depleting treated water supplies, particularly when water production is slowed or stopped. | All above plus Stewart et al. [4]; Wilson et al. [8] |

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[1] Nephelometric Turbidity Unit.

disinfection; storage reservoirs; and distribution systems [10].

The nature and severity of impacts on water supplies from volcanic eruptions is primarily determined by WSS design rather than hazard intensity (such as ashfall thickness). For example, the June 2011 eruption of Cordon Caulle volcano, Chile, deposited approximately 50 mm ashfall on the city of Bariloche and the town of Ingeniero Jacobacci, both in Argentina. Bariloche's WSS has an intake on Lago Nahuel Huapi, and ash entered the WSS both through the lake intake, where it caused extensive damage to pumping equipment, and by fallout into unenclosed sand filters, which blocked filters. Water production was maintained, but a great deal of additional maintenance was required. Ingeniero Jacobacci's WSS is based on a network of groundwater wells, and the system is fully enclosed from source to consumer. There were no impacts on the WSS itself but managing water demand, particularly for damping down resuspended ash deposits, was a challenge in the months after the eruption ([11], Table 1).

Volcanic eruption impacts can include physical damage to assets, impacts to water sources, increased demand during clean-up operations, and disruptions to supply chains and interdependent infrastructure sectors ([3–5,11,18,19]). Due to the diversity of WSS and their potential impact mechanisms, water supply impacts need to be considered on a site-specific basis. Impact assessments need to include a holistic understanding of a WSS' vulnerabilities and interdependencies to allow disaster risk reduction (DRR) principles, which aim to reduce hazard impacts through policy and strategies, to be applied [20,21]. Volcanic impact assessments inform DRR strategies by demonstrating the potential hazard impacts on society, informing mitigation strategies, and effectively quantifying and communicating potential risk to communities and decision-makers [20–22]. Vulnerability models evaluate the relative susceptibility of the elements at risk to hazard impacts and are a vital component of hazard impact assessments [20,23].

This study seeks to improve volcanic impact assessments for water supplies by proposing a framework that can be customised to include localised information on WSS design, thereby improving the understanding of impacts to inform targeted mitigation actions. Previous volcanic vulnerability models for WSS have followed a relatively simplistic approach, using hazard thresholds such as ashfall thickness or lahar velocity to determine water supply impact states based on historical eruption data [6,24,25]. These models also focus on direct impacts to generic WSS and do not consider the indirect impacts (e.g. electricity outages) or the resilience of diverse water supply typologies to certain impacts (e.g. groundwater systems, systems with contingencies) ([11,7]). Further, this approach to assessing vulnerability does not allow for the evolution of vulnerability during repeated volcanic activity, as potentially overlapping restoration times for impacts or mitigation measures are not considered. Due to the diverse range of WSS designs it is difficult to create robust generic vulnerability models; therefore, where possible, site-specific vulnerability models created using comprehensive local inventory surveys should be favoured [24]. Recognizing the need for a system-based approach, some studies have used 'demand classes' or 'loss-of-services/functionality scores' that are refined through engagement with key stakeholders in water supply and critical infrastructure systems [26–28]. Such impact metrics that define WSS functionality and service are more useful for risk management and contingency planning than previous damage thresholds [29,30]. However, there is a need for water supply vulnerability models that capture diverse system designs and indirect hazard impacts that can be used to assess impacts for multi-hazard, long-duration volcanic eruptions.

To address these issues, we introduce a volcanic impact assessment framework for water supplies that incorporates distinctive system design characteristics when estimating vulnerability and likely impacts. System characteristics considered include water source characteristics, backup electricity supply for emergency generation, filtration methods, intake condition, and damage to buildings and componentry. To achieve this, we developed a whole-of-system volcanic vulnerability model for WSS using relevant case studies from historical eruptions [3–6,11,15,31–33]. This approach has been widely used for other critical infrastructure and economic sectors [7,34,35–37]. We then apply our new vulnerability model and impact assessment framework to a case study from the Taranaki region of Aotearoa New Zealand (A-NZ). This study also partners with local water supply and emergency management agencies, recognizing that effective scientific contributions to DRR are founded on collaboration between scientists and practitioners to produce useful and credible research outcomes for the local risk context [38–40].

## 2. Volcanic impacts on water supplies

### 2.1. Direct impacts on water supplies

WSS encompass water sources, water extraction systems (e.g. intake, abstraction pump), pipe networks, WTPs, storage reservoirs, and distribution systems ([10]; Fig. 1). Volcanic hazards can disrupt WSS components through direct impacts on key assets and supporting infrastructure such as electricity networks ([4–6]; Wilson et al., 2010). Ashfall (tephra <2 mm diameter) is the principal concern as the most frequent and widespread volcanic hazard. However, lahars, pyroclastic density currents (PDCs), lava flows, and other volcanic mass movement events can also have immediate and long-term impacts following an eruption through the addition of large amounts of volcanic material to WSS [3,33,41]; . Impacts to WSS from these volcanic hazards are less well documented than those from ashfall, but can cause severe damage and disruption to WSS, particularly for stream-fed systems. Observed direct impacts to WSS from volcanic processes are summarised in Table 1.

### 2.2. Indirect impacts on water supplies

Volcanic eruptions indirectly impact WSS by increasing water demand and causing concurrent disruptions to interdependent infrastructure systems [37,42,43,44]. Surges in water demand due to clean-up operations may coincide with plants having to decrease production due to the impacts to treatment systems and water sources [5,34,11]. Operating control systems and pumps require a continuous power supply from electrical networks [5,45], and may not have sufficient generator access or capacity and fuel supply to

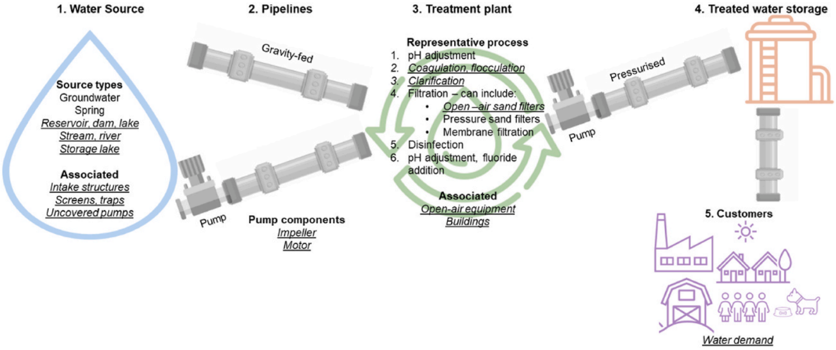

**Fig. 1.** Schematic diagram of water supply networks illustrating WSS components (**bold text**), points of vulnerability (***underlined and italicised***) and factors increasing resilience (not underlined or italicised). Figure credit: N.Deligne and C.Stewart.

rely on back-up systems. Additionally, some WSS are reliant on telecommunication networks for the remote operation of assets. Electricity and telecommunications networks can be disrupted during volcanic eruptions due to physical damage to assets, interference to radio transmission, increased network demand, and outages to interdependent infrastructure sectors [37,43]. Most water treatment processes are also dependent on surface transportation to supply consumables such as fuel and treatment chemicals and to allow staff access. Surface transportation closures are common during volcanic eruptions due to decreased visibility, compromised skid resistance, and damage to sections of road, rail, and bridges [31,35,44]. Indirect impacts are rarely included in vulnerability models and impact assessment frameworks for WSS despite an increasing need from stakeholders and end-users for a whole-of-system approach to assessing impact [46].

### 2.3. *WSS vulnerability to volcanic impacts*

System design is a key influence on vulnerability of WSS to volcanic processes. This design is largely constrained by local topography and hydrology which influence the availability of water sources ([5,6,11]; Wilson et al., 2013). Previous volcanic impacts to WSS demonstrate the significance of water source type and extraction method, treatment process, reticulation method, system contingencies, and supply management in determining systemic vulnerability and impact (Fig. 2 [4,5,7]).

Some of the most commonly present and highly vulnerable components of WSS are intake structures on rivers and streams,

**Fig. 2.** Direct impacts from volcanic ashfall to water supply. A: Ash inundation in settling ponds in a stream-fed water treatment system in Argentina following the 2011–2012 Puyehue-Cordón Caulle eruption (*Photo Credit: Carol Stewart*). B: Thick ash deposits surround the Richmond River near water intakes, St Vincent during the 2021 eruption of La Soufrière (*Photo credit: UWI Seismic Research Centre*). C: ~50 mm ashfall at Bariloche WTP following the 2011–2012 Puyehue-Cordón Caulle eruption (*Photo credit: Departamento Provincial de Agua, Bariloche*).

pumping equipment, and open-air sand filters (Table 1 [3,11,34]). Intakes located on rivers and streams are exposed to large amounts of volcanic material from ashfall and lahar, which can cause damage and blockages to intake structures and allow contaminated water into the WSS. In contrast, groundwater-fed systems are relatively resilient to the direct impacts of ashfall, apart from possible effects on unenclosed well head pumps due to airborne ash and/or electricity outages [33]. Similarly, in addition to their dependence on electricity supply, abstraction pumps and associated equipment can also be damaged by volcanic material if not maintained in an enclosed environment [11]. As turbidity levels increase due to the addition of volcanic material WTPs become less effective at treating water [4]. Open-air sand filters are particularly vulnerable to ashfall impacts and can rapidly become overwhelmed with material and ineffective at treatment during an eruption. Impacts and service disruptions can be minimised when automatic turbidity shutdown systems on intakes, gravity-fed pipelines and/or enclosed treatment systems are installed on reservoir or lake sources (Wilson et al., 2013; [7]). WSS with contingencies such as onsite backup power generators and diesel storage, chemical treatment and spare parts stockpiles, treated water storage, and coordinated planning for a volcanic eruption will be more resilient [13].

Water supply operators and decision-makers can also build systemic resilience through effective asset management during volcanic eruptions and by implementing long-term risk treatments. These risk treatment measures include increasing water storage in the system to allow for WSS shutdowns for clean-up and maintenance without disrupting supply, and increasing the capacity of back-up power generators for pumps [5,7,11,19,13]; [null]; [34]. Response actions such as the closing of intake structures, covering of open-air sand filters and electrical equipment, the establishment of an increased maintenance and treatment schedule, and effective public communication on water-saving measures can greatly reduce the risk of sustained water supply outages [5,34]. Water supply managers with previous experience dealing with volcanic eruptions are much more likely to effectively respond to the crisis [5,11,13].

## 3. Case study area

Taranaki Mounga,[1] located on the west coast of Te Ika-a-Māui the North Island of Aotearoa New Zealand, is a basaltic-andesite stratovolcano [47–58]. Historic eruptions, most recently in AD 1790, have produced widespread ashfall, lahars, pyroclastic density currents, ballistics, lava flows and landslides [48,50,52–55,58–60]. The volcano is estimated to have a 33–42 % probability of an eruption within the next 50 years, demonstrating the need for timely risk identification, analysis and treatment for exposed communities and assets [49,51]. The Taranaki region is home to 117 561 people and has the second-highest Gross Domestic Product (GDP) per capita in Aotearoa New Zealand [61]. The region is a significant producer in the agriculture and energy industries, and houses nationally important critical infrastructure [7,36,62,63]. Population centres and critical infrastructure networks circumnavigate the volcanic ring plain in Taranaki which, in the event of an eruption and during volcanic unrest, will face considerable disruption (Fig. 3). This would impact national supply chains, and potentially cause a decline in future investment and business certainty in the region [64,65].

A key vulnerability for the Taranaki region is the use of surface water originating from Taranaki Mounga for 12 out of the 18 major public water supply schemes across the region. The sophistication and criticality of WSS in Taranaki vary considerably, with their level of development influenced by the size of the population and industries they serve. Previous research has highlighted the high exposure and vulnerability of Taranaki surface water-fed and agricultural supplies to volcanic hazards, however, a systemic regional water supply approach to risk identification and management is needed to inform resilience-building strategies [7,66,67]. Weir et al. [68] quantified the systemic vulnerability of water supplies in Taranaki and likely impacts during several multi-hazard eruption scenarios using co-developed dependency models and existing impact quantification schemes [6,25]. However, this analysis did not incorporate specific design elements such as water extraction, treatment methods and damage restoration.

DRR at the regional level in Aotearoa New Zealand is facilitated by civil defence and emergency management (CDEM) groups who develop plans and strategies to manage disaster risk within their region and respond to adverse events [69–71]. In the Taranaki, this role is delegated to the Taranaki CDEM group (known as Taranaki Emergency Management Office; TEMO) who are responsible for planning and responding to volcanic activity in the region. Municipal water services (water supply, wastewater, and stormwater) are provided by the three district councils in the region; New Plymouth District Council (NPDC), Stratford District Council (SDC), and South Taranaki District Council (STDC), who operate and maintain various water assets such as WTPs (Fig. 3). These councils who oversee the provision of potable water work closely with TEMO, risk scientists, and other organisations to create and implement water supply resilience strategies for volcanic eruptions [72].

Water supply schemes in Taranaki that have a surface water source are fed by rivers and streams flowing from the mounga (Table 2). Many of the region's water supplies have a limited 2–3 days of treated water storage which under an eruption scenario can be depleted quickly due to high demand for clean-up activities and water production disruption [14]. Additionally, several water supply schemes use a conventional treatment methods with unenclosed filtration, clarification and disinfection equipment. Due to the topography of the region, many water supplies utilise gravity for distribution, however, aerial pipelines attached to bridges traverse rivers susceptible to lahars and represent a potential breakage point in the network [41]. A summary of the key components (intake, WTP, water storage and generator availability) are presented in Table 2.

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[1] The term *Mounga* is a Māori word and is used here as the local term for mountain, mount or peak. It is a local variation of the more commonly used *Maunga*.

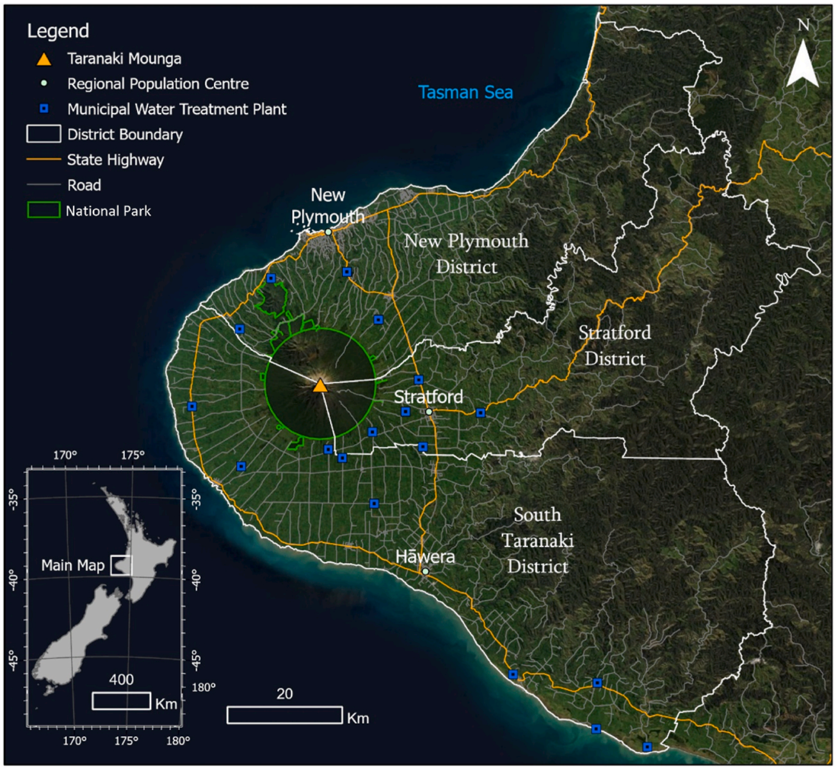

**Fig. 3.** Taranaki Region, Aotearoa New Zealand, including Taranaki Mounga, regional municipalities, and water supplies.

## 4. Methodology

This study develops a new whole-of-system, regional water supply volcanic vulnerability model and impact assessment framework that can be applied during multi-hazard, long-duration eruption scenarios. This model incorporates and quantifies the long-term systemic impacts of volcanic eruptions on water supplies, centralises system design in impact quantification, and can be applied to a diverse range of WSS reflecting the highly localised nature of water supply components. The developed vulnerability model was applied to the Taranaki region, Aotearoa New Zealand using a credible long-duration multi-hazard eruption scenario to illustrate its application across a range of WSS. This includes the influence of management decisions, wider emergency management actions such as evacuations, and critical infrastructure interdependencies.

An iterative engagement process was conducted with water utility managers, local councils (NPDC, SDC, STDC) and the regional emergency management authority (Taranaki CDEM) to co-develop the key objectives and scope of this study, validate and refine the main outputs, and discuss the implications of this research for regional water supplies in Taranaki. This engagement was conducted through regular semi-structured meetings with water supply engineers from NPDC and at a workshop with local councils in New Plymouth which was facilitated by the Taranaki CDEM group (Fig. 4). This process could be applied to other volcanic settings to allow for the incorporation of local WSS design, vulnerabilities and restoration times to be incorporated.

### 4.1. Water supply vulnerability model

#### 4.1.1. Fault tree analysis

Fault tree analysis (FTA) was used to determine the associated probability of system failure using Boolean logic and decision rules [,73]. A fault tree consisting of leaf nodes, branches, and decision gates, forming a visual network of potential routes for WSS failure was developed [74,75]. The selection of leaf nodes in the tree (Fig. 5) was informed by an extensive review of historical volcanic impact events on WSS [3–6,11,19,15,31–33,41,45,13,76–78]. The proposed fault tree depicts a typical surface water system but can be altered to display systems with other typologies by simply removing or adding branches. The fault tree was developed and refined with input from the key stakeholders of this study at arranged meetings and a water supply resilience workshop in New Plymouth in December 2021 (Fig. 4).

#### 4.1.2. Quantifying systemic impact

Impact states (IS) describe the loss of functionality to a system or asset due to a hazard using an incremental scale [79]. This study developed a four-tiered IS classification to capture water supply functionality due to volcanic hazard damage and disruption (Table 3),

**Table 2**
Summary of municipal WSS in Taranaki.

| Scheme name | Operator | Population served (ESR, 2019) | Capacity ($m^3$/day) | Intake | WTP | Storage (days) | Generator on site |
|---|---|---|---|---|---|---|---|
| Ōkato | NPDC | 530 | 1000 | Infiltration gallery in the Mangatete Stream | Enclosed filtration and disinfection | 2 | Yes |
| Ōakura | | 1625 | 3715 | Groundwater pumped from bore | Enclosed disinfection | 2 | No |
| Inglewood | | 3983 | 3800 | Infiltration gallery in the Ngatoro Stream | Enclosed clarification, filtration, and disinfection | 2 | No |
| New Plymouth | | 59 072 | 70 000 | Waiwhakaiho River water transfer tunnel, through submerged stepper screens in Lake Mangamahoe | Enclosed pre-treatment ($CO_2$, lime), unenclosed clarification and filtration, disinfection tank below ground | 2 | Yes |
| Stratford | SDC | 6773 | 8000 | Weirs in Patea River (main) and Konini Stream (auxiliary) | Enclosed settlement, filtration and disinfection | 2–3 | Yes |
| Midhurst | | 200 | 600 | Pumped from Te Popo Stream | Enclosed pre-treatment, unenclosed clarification and filtration | 10 | No |
| Toko rural | | 55 | 80 | Groundwater pumped from bore | Treatment in a small shed | 2 | No |
| Eltham | STDC | 1980 | 4700 | *Typical central and western STDC water supply systems:* River/stream intakes (Hāwera, Waimate West, and Inaha interconnected with each other) | Unenclosed clarification, filtration, and disinfection | 2–3 | No |
| Inaha | | 495 | 4500 | | | | |
| Hāwera | | 9710 | 13 000 | | | | |
| Waimate West | | 2880 | 15 000 | | | | |
| Pope | | *No info* | *No info* | | | | |
| Rahotu | | 115 | 150 | | | | |
| Ōpunake | | 1370 | 1600 | | | | |
| Patea | | 1150 | 1100 | *Typical southern STDC water supply systems:* Groundwater pumped from bore | Treatment in a small shed | 2 | No |
| Waverley | | 950 | 900 | | | | |
| Waverley Beach | | 40 | 50 | | | | |
| Waiinu Beach | | 100 | 340 | | | | |

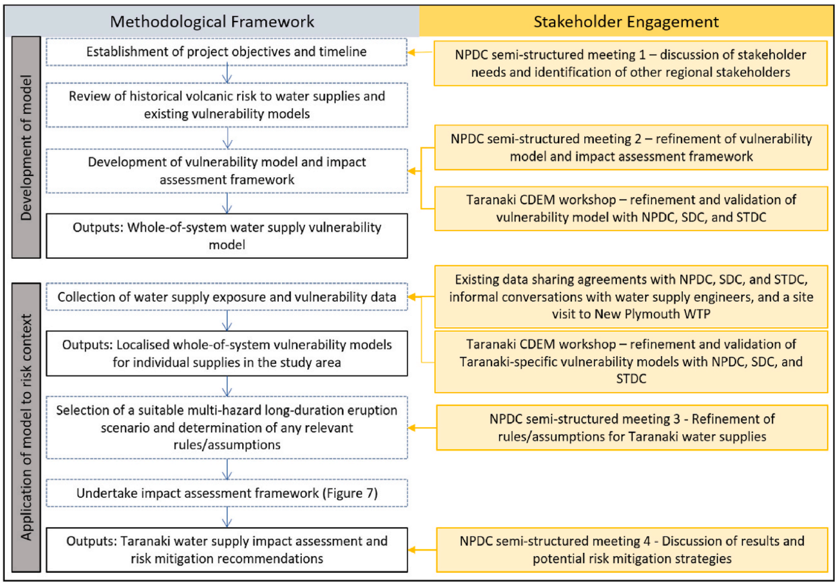

**Fig. 4.** The methodological framework and stakeholder engagement method used to develop the vulnerability model and apply it to the Taranaki region, Aotearoa New Zealand.

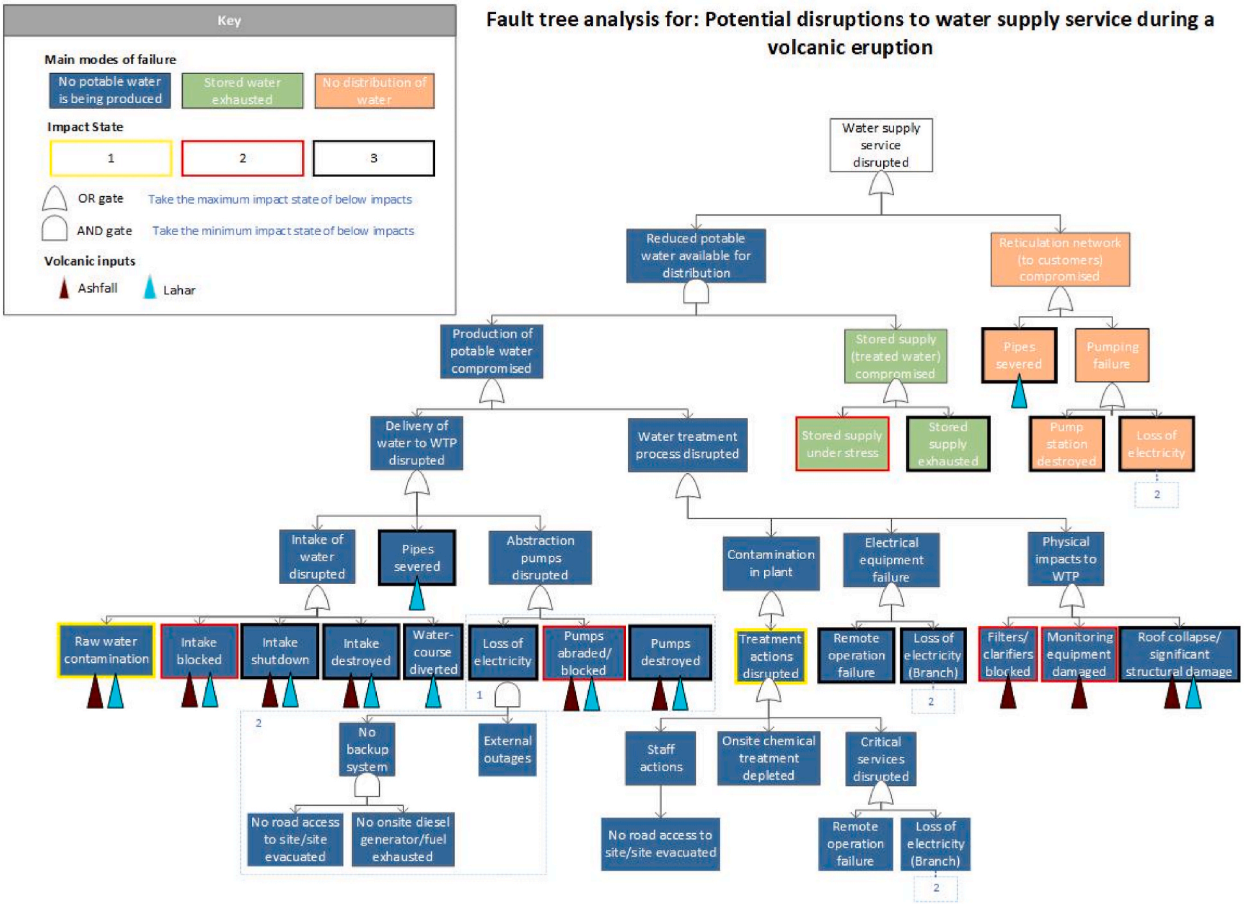

**Fig. 5.** Generic water supply fault tree developed for the whole-of-system vulnerability model in this study.

**Table 3**
The impact classification for water supplies used in this study.

| Impact State (IS) | Description |
|---|---|
| 0 | **Security in quality and quantity of water**. Supply is fully operational. There may be an increase in water usage that needs to be managed. |
| 1 | **Water quality is compromised**. Water is not microbiologically safe and boil water notices are needed. |
| 2 | **Water quantity (and potentially quality) is compromised**. Supply is under considerable stress but may be able to provide some service to customers under strict water usage restrictions. |
| 3 | **No water available.** Supply is under extreme stress, and it is unlikely that it will be able to provide service to customers. Alternative supply is needed. |

using the four demand classes defined in Buxton et al. [26]. These were then adjusted and informed during the engagement process (Fig. 4) and then combined with the fault tree to quantify water supply impact due to damage and disruption.

Each leaf node in the fault tree is associated with an IS and restoration time for each asset class (intakes, pipes, pumps, and WTP; Table 2). Assumptions were informed by existing vulnerability models for asset typologies [27,43,80,6,24,25] and documented impacts from historical eruptions [11,3,5,15,13]. These were used to inform hazard thresholds and rules that determine whether an asset is receiving an impact that meets the condition to trigger a leaf node (Table 4). IS and restoration times at leaf nodes are translated up the fault tree to determine the overall IS for a scheme and the estimated restoration time (in days), with multiple impacts occurring simultaneously to individual assets. Logic gates determine the effect of leaf nodes and asset impact on the overall WSS IS at the top of the tree. The OR gates in the tree take the maximum impact state from impacts occurring below in the structure, while the AND gate takes the minimum impact state. For example, a water supply with pipes severed (pipes IS3) and a stored supply under stress (stored supply IS2) will result in an overall IS of 2 for the WSS due to an AND gate at the interface of these two leaf node branches, however, the severed pipe requires 30 days of restoration time for which it will remain in IS2. If the water supply is to run out of stored supply during this time the ‘stored supply exhausted’ leaf node will be triggered, and the IS of the whole system will become 3.

## *4.2. Application to the Taranaki Region, aotearoa New Zealand*

### *4.2.1. Exposure dataset*

To apply the vulnerability model, a detailed exposure dataset is required. This needs to include the location of key assets within the study area, their key vulnerabilities to volcanic hazards, and how they are interconnected.

The main physical water supply assets identified in Taranaki were intakes, abstraction pumps, pipes, WTP, pump stations, and storage reservoirs (Table 2; Fig. 6). Physical asset data was sourced from the three authorities of municipal water provision in Taranaki: NPDC, SDC, and STDC. Data from the Institute of Environmental Science and Research (ESR) was also used to identify other water assets [81]. Spatial locations for regional intakes, pipes, and WTPs were able to be accessed through publicly available data portals maintained by the local councils. The location of pump stations and abstraction pumps was derived from publicly available council documents. Surface water catchments for water supplies were also delineated. Water catchments upstream of intake structures were generated using the River Environment Classification (REC) database [82].

### *4.2.2. Eruption scenario*

Weir et al. [57] developed nine eruption scenarios for Taranaki Mounga that vary in eruption magnitude and are categorised into small, medium, and large sub-suites. The volcanic hazards included in the framework are ballistics, lava flows, ashfall, pyroclastic density currents (PDCs), and lahars. Here, the large eruption scenario ‘L1’ was selected for this impact assessment as it represents a worst-case scenario for WSS and can be applied over many months to assess cumulative impacts and the long-term operation of assets. Due to the natural protection of the Te Papakura o Taranaki national park boundary, ash and lahars were deemed to be the only hazards relevant to WSS from the scenario as these are all located outside of the park boundaries [66]. The 182-day eruption scenario is characterised by highly explosive Plinian-style eruptions interspersed with small venting eruptions and periods of quiescence. The eruptions result in heavy ashfall predominately to the northeast of the vent and extensive lahars in several river catchments (Fig. 6). Hazard (ashfall and lahar) and indirect impact (electricity, power, and road outages) spatial data were utilised from Ref. [57]. For this scenario, we assumed that telecommunication outages occurred simultaneously with electricity outages [43]. We also assumed that during the scenario, water supply operators were not allowed to enter evacuation zones due to staff and contractor safety considerations [28].

### *4.2.3. Impact assessment framework*

An impact assessment for Taranaki WSS in an L1 eruption scenario was undertaken (Fig. 7). Individual fault trees were created for each WSS and captured the systemic impacts to each supply from ashfall and lahars. The rules outlined in Table 4 were coded in python and applied to determine which systemic impacts occurred during the scenario. Direct impacts were modelled using the RiskScape software. This is a flexible modelling engine for multi-hazard risk analysis [83], where spatial hazard intensity and exposure data were combined with the python functions to automate the determination of direct impacts for each day of the L1 scenario. Indirect impacts were determined using the Geographic Information System (GIS) software ArcGIS by analysing the spatial footprint of daily sector outages in relation to assets. Direct and indirect impacts to each WSS were then combined to determine the overall daily IS. These analysis tools were used for modelling efficiency but are not essential to run the model.

**Table 4**
Rules, assumptions, and restoration times used for each root cause/impact in the fault tree, estimated by water supply engineers and supported by case study observations.

| Asset class | Impact | Component IS | Estimated restoration time | Assumption/Rule for asset typology | References |
|---|---|---|---|---|---|
| Intakes | Intake blocked | 2 | 3 days | Light-moderate ashfall (2–10 mm) at the intake or in the catchment, or small lahars in the catchment will block river/stream intake structures. Heavier ashfall (10–100 mm) or significant lahars are required to block submerged lake intakes. | [11,24] |
| | Raw water contamination | 1 | 7 days for ashfall, 14 days for lahar | Light-moderate ashfall (2–10 mm) at the intake or in the catchment will cause short-medium term contamination issues (turbidity) for river/stream supplies. Lahars will cause medium-long term contamination issues for all surface water supplies. | [15,13]. |
| | Intake shutdown | 3 | Linked to contamination | Water supply managers will opt to shut down intake structures during periods of high turbidity to protect downstream assets. | |
| | Intake destroyed | 3 | 30 days | Heavy ashfall (>100 mm) or lahar at any surface water intake. | ([3,24,6] |
| | Watercourse diverted | 3 | 30 days | Repeated and widespread lahars/landsliding/sector collapse in the catchment. | [3] |
| Pipes | Pipes severed | 3 | 30 days | Lahar will sever above-ground pipes due to high lateral loads. | [27,80]. |
| Pumps | Loss of electricity - pumps | 3 | Linked to road/electricity outage duration. | Systems without onsite diesel generators and road access to supply fuel/generators/spare parts will lose electricity during external outages. | [11,6] |
| | Abstraction pumps abraded/blocked | 2 | 3 days | Light-moderate ashfall (2–10 mm) at the intake or in the catchment, or small lahars in the catchment will abrade abstraction pumps in river/stream intake structures. Heavier ashfall (10–100 mm) or lahars are required to block submerged lake pumps. | |
| | Abstraction pumps destroyed | 3 | 30 days | Heavy ashfall (>100 mm) or lahars at the intake will destroy surface water pumps. Lahars will destroy groundwater pumps. | [3] |
| | Pump station destroyed | 3 | 14 days | High ash load (>200 mm ashfall) or lahar at pump station. | [24] |
| WTP | Treatment actions disrupted | 1 | Linked to road/electricity/ telecommunications outage duration | Contamination issues may occur for supplies reliant on manual treatment, a small supply of chemical treatment, or remote systems during disruptions to the telecommunication and electricity networks. | |
| | Loss of electricity - WTP | 3 | Linked to road/electricity outage duration. | Systems without onsite diesel generators and road access to supply fuel/generators/spare parts will lose electricity during external outages. | [11,6] |
| | Remote operation failure | 3 | Linked to road/electricity/ telecommunications outage duration | Disruptions to the telecommunications network occur simultaneously with electricity disruptions. Supplies reliant on remote operation will be unable to operate electrical equipment. | |
| | Filters/clarifiers blocked | 2 | 7 days | Moderate ashfall (>20 mm) contaminating and blocking open-air filters/clarifiers. | [11] |
| | Monitoring equipment damaged | 2 | 7 days | Moderate ashfall (>20 mm) to exposed equipment. | [3]. |
| | Roof collapse/ significant structural damage | 3 | 365 days | High ash load (>200 mm ashfall or lahar at WTP building site. | |
| | Stored supply under stress | 2 | 7 days for ashfall or linked to WTP reduced operating capacity duration | Significantly increased demand for clean-up of ashfall over customer catchment. This will stress the stored supply, particularly when the WTP is operating under reduced capacity. | [46]. |
| | Stored supply exhausted | 3 | Linked to WTP production | When the WTP is producing no new water and the stored supply volume has been emptied. Water storage facilities will need 1–2 days following restoration of water production to fill reservoirs again. | [5]. |

## 5. Volcanic impact assessment results for water supply systems in taranaki

Ashfall and lahars from an L1 eruptive scenario are likely to severely impact water supply assets across the Taranaki Region leading to widespread water supply outages (Fig. 8). Fig. 9 displays the modelled impact state at each water supply scheme during the L1 scenario.

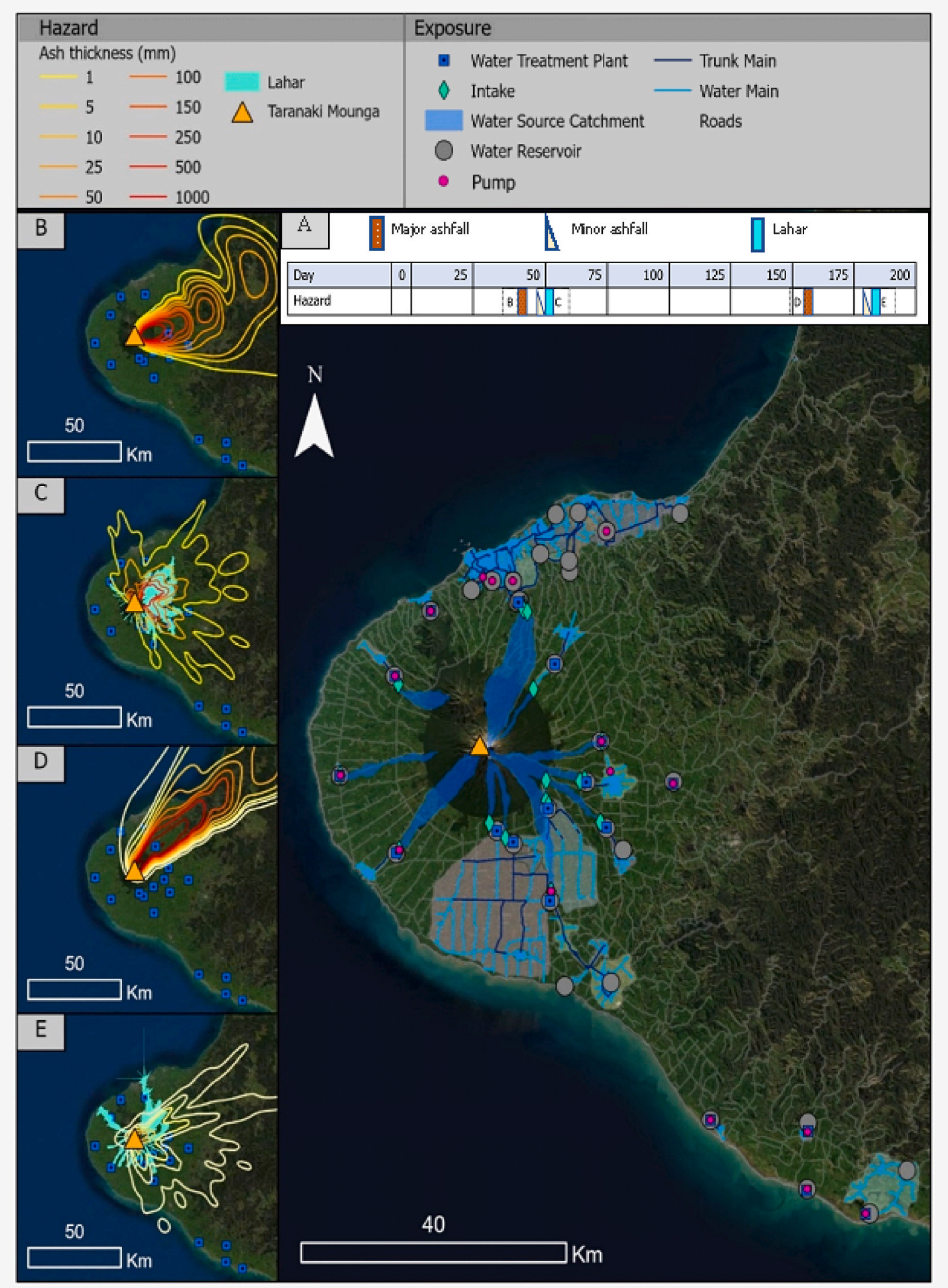

Fig. 6. The location of key water supply assets in the Taranaki region and the Taranaki Mounga eruption scenario used in this study. A: The eruption scenario timeline with hazard events labelled at certain stages in the scenario. B: Hazard occurrence on day 40 in the scenario. C: Hazard occurrence on day 49 and 50 in the scenario. D: Hazard occurrence on day 154 in the scenario. E: Hazard occurrence on day 181 and 182 in the scenario.

Heavy ashfall (>400 mm) is deposited to the east of the volcano on day 40 in the L1 eruption scenario [57], blanketing several WSS. Intakes along streams and rivers in the affected area are likely to be either blocked, shutdown, or destroyed forcing some supplies to rely on stored water to supply customers following this eruption [3,7,34,13]. WTP also receive thick ashfall deposits with ash loading at two sites exceeding 2 kPa, which likely results in roof collapse [46]. Widespread electricity outages also occur and result in pumping

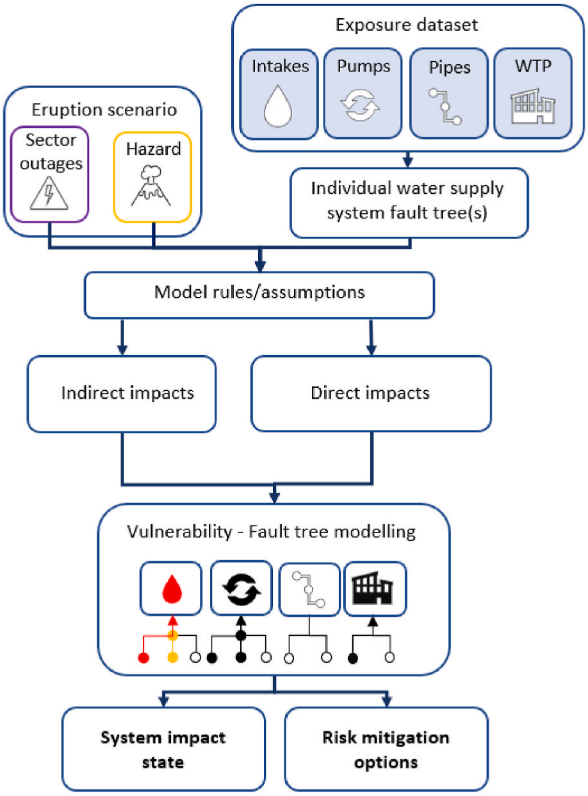

**Fig. 7.** The impact assessment framework and process used to assess systemic water supply impacts in Taranaki during the L1 eruption scenario.

failure and electrical equipment failure at sites without backup power generation (Figs. 8 and 9). Recovery from the impacts of this phase of the eruption is complicated by a minor eruption and further ashfall (<100 mm) on day 49. By this time some water supply schemes have exhausted their treated water stores. On day 50, rainfall triggers lahars that are likely to severely damage intakes, pumps, pipes, and WTP resulting in widespread loss of water supply (Figs. 8 and 9, [3,33,41]). Pre-emptive evacuations on day 30 decrease the number of people directly affected by outages during this phase of the event, however, by the end of day 50 approximately 5355 people are without water. A further 12871 people have been evacuated from highly exposed areas which will likely increase the stress on surrounding water supply schemes where these evacuees have been moved to (Fig. 9). From day 50 to day 153, there is no explosive activity which likely allows some WSS to restore service, however, due to considerable damage sustained many will continue to be out of service while restoration work is under way. A major explosive phase on day 154 likely disrupts this restoration work and triggers turbidity-related intake shutdowns for some water supply schemes [4,13]. This also triggers further evacuations, resulting in pressure on schemes where evacuees have been housed. Highly destructive lahars on day 182 are likely to destroy intake structures, sections of exposed pipelines, and assets near river channels [41]. The largest water supply scheme in the region, by volume and number of people serviced (New Plymouth), is likely to be under considerable stress during this time due to extensive intake and pipeline damage and high water usage for clean-up operations. Inglewood, Midhurst, Stratford and Eltham water schemes all experience modelled outages of greater than 140 days (Fig. 9).

## 6. Discussion

The application of the impact assessment framework to water supplies in Taranaki illustrates the vulnerability of WSS and the intensity and distribution of potential impacts during a large-scale eruption from Taranaki Mounga. The total restoration of regional water supply assets will likely take years following a large eruptive event like the scenario used in this study, and would lead to dramatic changes in the provision of drinking water in Taranaki becoming essential to provide current levels of service. Multiple schemes across the region are likely to be significantly impacted, with difficulties re-establishing secure water intake systems from water sources draining the mounga likely.

Understanding supply challenges and the likely magnitude of timeframes associated is vital when planning for both response and recovery. Current CDEM guidance recommends that households store water for a minimum of 72 h (9 L per person) [84,85]. Our model results demonstrate that households following current guidelines for emergency water storage will likely not have enough stored water to last through outages caused by large sustained volcanic eruptions. This will mean providing alternate sources of potable water to thousands of people across the region for many weeks, with nearly 17 000 people being supplied by schemes that will have outages of

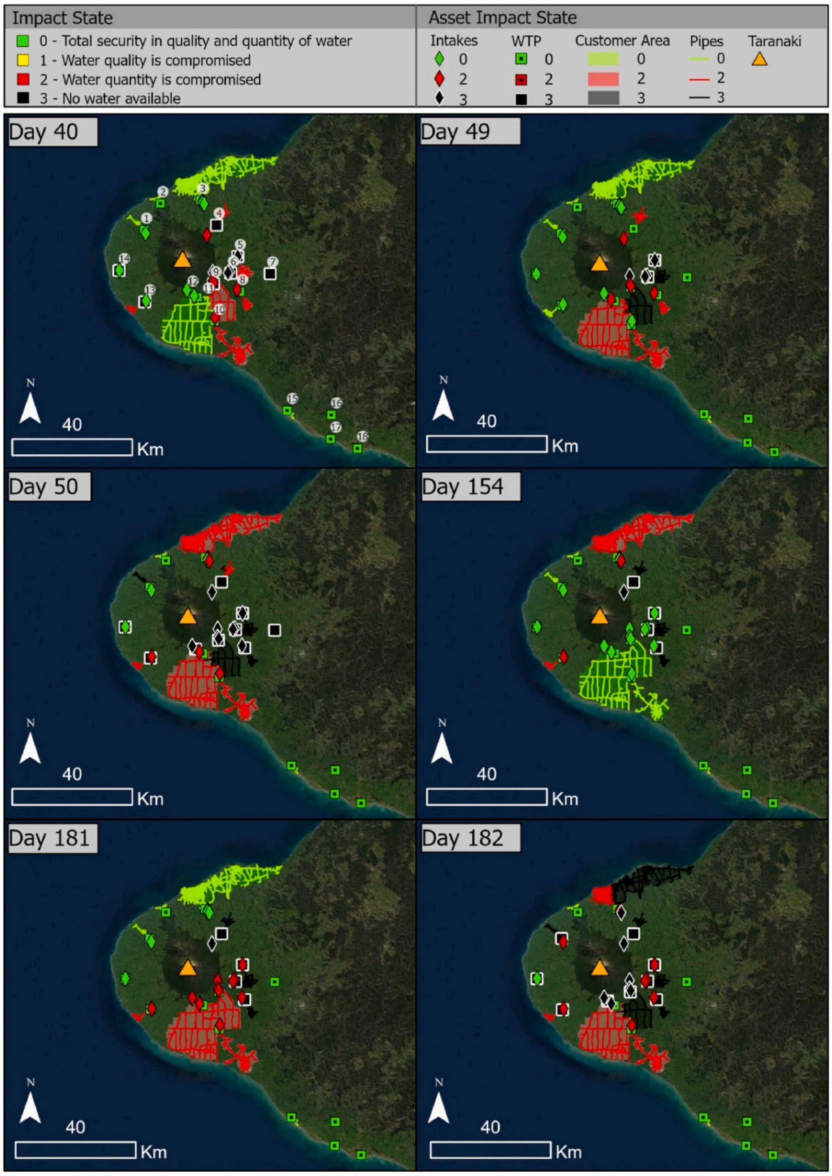

**Fig. 8.** Modelled IS for WSS components in Taranaki at various timestamps during the L1 eruption scenario. Numbered sites on the Day 40 map relate to the WSS numbered in Fig. 9.

over ~25 days. This will create a significant logistical challenge for emergency management authorities, in addition to efforts to coordinate the reestablishment of WSS and other interdependent infrastructure.

Volcanic impact modelling for WSS provides an opportunity to plan for these significant outages and identify vulnerable areas that may benefit from the application of targeted risk management strategies. These may include the installation of additional boreholes in areas where groundwater supplies are feasible, the covering of componentry (such as open-air sand filters or clarifiers), increasing treated water storage, backup power generation, more resilient water intake structures, and ensuring that emergency plans are in place which give operators clear instructions to attempt to mitigate impacts [34]. Government authorities responsible municipal water provision in Taranaki are actively considering measures, such as these, to increase WSS resilience; however, resourcing this work is challenging.

Whilst this modelling approach requires a large amount of input data (both hazard scenario information and spatially defined asset specifications), it provides a structured approach for the development of a FTA process that allows for WSS impact assessments to be undertaken in diverse volcanic settings. This methodology could be applied globally once adjusted for local WSS components and specific volcanic hazards. In areas where less data on hazard and WSS assets are available, the FTA used here should be simplified to consider only a single eruptive phase of an eruption or only one volcanic hazard. An additional simplification could be to only consider

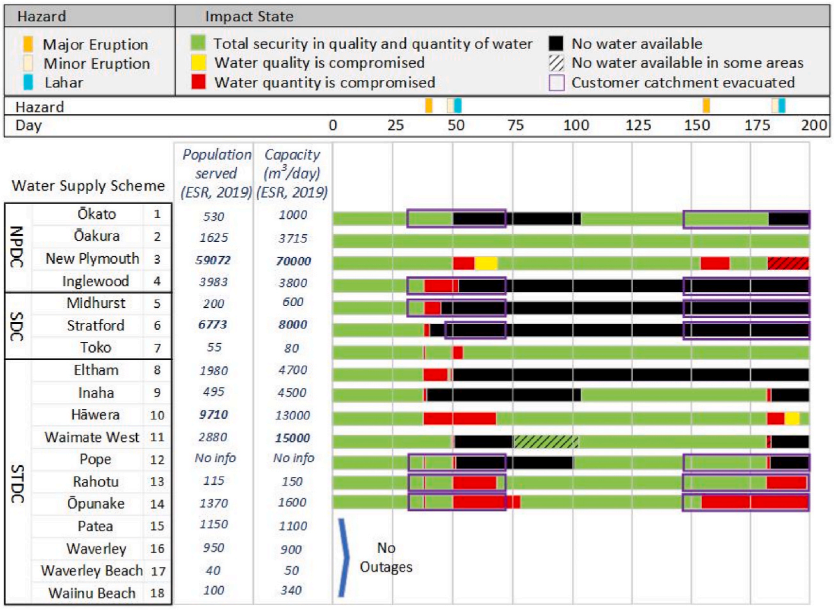

**Fig. 9.** A timeline of estimated water supply scheme IS during the L1 eruption scenario for the Taranaki region.

the direct impacts to WSS, rather than including interdependent infrastructure. An accurate inventory of WSS assets and typologies, however, is essential to any impact modelling.

### 6.1. Limitations and future research

The proposed methodology assesses impacts and outage times to WSS impacted by a given volcanic scenario, however it does not provide any information on the likelihood of these impacts occurring. Enumerating the probabilities of each type of WSS failure would generate numerical vulnerability data, such as a vulnerability index or vulnerability score (e.g. Ref. [7,67]). However, this can only be applied to one WSS at a time and would require probabilistic hazard data and individual fragility functions for different water supply asset typologies.

The FTA work presented only includes volcanic hazards relevant to the Taranaki context. Other volcanic hazards, such as pyroclastic flows and lava flows, are also not currently included in the FTA. These less far-reaching hazards are not relevant to WSS in the Taranaki Region due to the Te Papakura o Taranaki national park acting as a buffer zone between many proximal volcanic hazards and populated areas [50]. In other volcanic risk contexts, water supplies may be exposed to these hazards; thus, it is recommended that robust empirical evidence is used to undertake specific FTA development for other volcanic hazards as needed.

The modelled direct impacts on Taranaki water supplies during the L1 eruption scenario [57] demonstrate the potential effects of a future large-scale eruption of Taranaki Mounga. As we selected a large magnitude end-member or 'worst-case' eruptive scenario for Taranaki WSS, this does not capture potential impacts to WSS during smaller events which have a greater likelihood of occurrence [50]. Future research could apply our model at lower eruption intensities to identify key vulnerabilities that may be more frequently tested. Further, direct hazard impacts during the scenario were informed by impacts from historic and observed eruption events with similar hazard intensities to the L1 eruption scenario and WSS comparable to Taranaki water supply schemes [3,5,6,11,19,45,13]. Although appropriate for this impact assessment, there is large uncertainty associated with the application of empirical impact observations due to the inherent differences in hazard characteristics between two different volcanic sources and the diversity of WSS. For example, ash deposit composition directly relates to factors that determine impact intensities, such as ash settling rates and ash loading, and varies considerably between volcanic sources [4,46]. Additionally, the hazard thresholds used in this study were developed using impact datasets from mainly municipal urban WSS and may not accurately capture impacts to small-scale rural systems.

Lahar impacts were largely determined based on assumptions guided by expert elicitation. Due to limited empirical evidence of lahar impacts to WSS, the variation in physical impacts to WSS components with different lahar magnitudes and characteristics is not well understood. It was assumed that any asset in the flow path of a lahar would be severely damaged during the eruption scenario and require replacement. However, the destructive potential of lahars is dependent on several geological and hydrological parameters such as the volume, density, and velocity of the lahar flow. It is likely that small, diluted lahar flows are less likely to damage water supply assets. Therefore, this assessment may overestimate lahar impacts from smaller eruption scenarios. The model also does not account for the attenuation of erosion rates on the edges of the lahar path. Additionally, further understanding of turbidity tolerance levels for WSS during volcanic events is required to better inform system shutdown guidance.

Indirect impacts such as outages to power and transportation were incorporated in the L1 eruption scenario, however, assumptions were made to anticipate the impacts on individual water supply schemes. Firstly, outages to the telecommunication network were expected to occur as a result of any electricity outages. This aligns with previous investigations into the dependency of the telecommunication network on electricity [37,43], however, this may not be the case in some instances where back-up generators are available to power specific components. It was also assumed that water supply operators were unable to return to sites during evacuations. Water supplies are essential during emergencies and in some scenarios, authorities may facilitate controlled site access to maintain supply. To reduce the uncertainty of these indirect impacts there needs to be an integration of relevant emergency management plans within eruption scenarios in future applications of this model. This approach could also be applied to more accurately predict spatiotemporal spikes in water supply demand in a future eruption, where areas where clean-up would commence in and areas hosting large numbers of evacuees are identified.

This vulnerability model is designed to be used in a range of volcanic risk contexts to illustrate water supply vulnerability and estimate likely impacts during eruption scenarios. It is recommended that when using this model, local water supply infrastructure managers and engineers are consulted to accurately develop specific FTA inputs for individual supplies.

## 7. Conclusions

The proposed impact assessment framework allows for multi-hazard volcanic impact assessments to be undertaken for complex, multi-component WSS. Current water supply impact models are not suitable for use in contexts with varying system designs. We present a whole-of-system vulnerability model for WSS that can be applied to a range of scenarios and systems. This can be applied globally by emergency managers, water supply engineers, and planners to identify WSS vulnerabilities to volcanic hazards and identify options to increase resilience. Here, we apply the impact assessment framework to a large explosive eruption from Taranaki Mounga, Aotearoa New Zealand, with a range of WSS affected across the Taranaki region. This analysis allowed for the impacts of a large-scale, long-duration eruption scenario on water sources and intake structures, aerial pipelines, and open-air filters and clarifiers to be undertaken. Risk reduction strategies such as back-up generator and water storage availability were also considered. This analysis forecasted water supply outages of weeks to months during a large eruption scenario; and highlights significant regional water supply vulnerabilities, facilitating ongoing discussions on increasing the resilience of WSS to volcanic eruptions.

## CRediT authorship contribution statement

**Harley Porter:** Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Thomas M. Wilson:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Alana Weir:** Software, Methodology, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Carol Stewart:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Heather M. Craig:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software. **Alec J. Wild:** Validation, Software, Methodology. **Ryan Paulik:** Software, Methodology. **Roger Fairclough:** Resources, Project administration, Methodology, Investigation. **Maria Buzzella:** Methodology, Investigation, Conceptualization.

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## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Heather M. Craig reports financial support was provided by New Zealand Ministry of Business Innovation and Employment. Thomas M. Wilson reports was provided by New Zealand Ministry of Business Innovation and Employment. Alana Weir reports financial support was provided by New Zealand Ministry of Business Innovation and Employment. Roger Fairclough reports financial support was provided by New Zealand Ministry of Business Innovation and Employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

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