

GIS-BASED EMERGENCY AND EVACUATION PLANNING FOR VOLCANIC HAZARDS IN NEW ZEALAND

**J.W. Cole¹, C. E. Sabel², E. Blumenthal¹, K. Finnis³, A. Dantas⁴,
S. Barnard¹ and D.M. Johnston⁵**

ABSTRACT

Geographic Information Systems (GIS) provide a range of techniques which allow ready access to data, and the opportunity to overlay graphical location-based information for ease of interpretation. They can be used to solve complex planning and management problems. All phases of emergency management (reduction, readiness, response and recovery) can benefit from GIS, including applications related to transportation systems, a critical element in managing effective lifelines in an emergency. This is particularly true immediately before and during a volcanic eruption.

The potential for volcanic activity in New Zealand is high, with 10 volcanoes or volcanic centres (Auckland, Bay of Islands, Haroharo, Mayor Island, Ruapehu, Taranaki, Tarawera, Taupo, Tongariro (including Ngauruhoe) and White Island) recognised as active or potentially active. In addition there are many active and potentially active volcanoes along the Kermadec Island chain. There is a great deal of background information on all of these volcanoes, and GIS is currently being used for some aspects of monitoring (e.g. ERS and Envisat radar interferometry for observing deformation prior to eruptions). If an eruption is considered imminent, evacuation may be necessary, and hence transportation systems must be evaluated. Scenarios have been developed for many centres (e.g. Taranaki/Egmont and Bay of Plenty volcanoes), but so far the use of GIS in planning for evacuation is limited.

This paper looks at the use of GIS, indicates how it is being used in emergency management, and suggests how it can be used in evacuation planning.

Keywords: volcanic hazard, GIS, emergency management, evacuation planning.

INTRODUCTION

When a volcano erupts, emergency services need prompt, accurate information in order to fulfil their role. There must be an effective Emergency Plan for the area affected and there must be ready access to information which allows good decisions to be made despite rapidly changing circumstances. Advances in computer systems over the past 25 years have provided an excellent opportunity to provide databases which give the sort of information required. In particular Geographic Information Systems (GIS) allow ready access to both spatial and attribute data, on a national or local scale,

and provide the opportunity to overlay information for ease of interpretations. Yet, little use has been made of this suite of techniques so far within New Zealand for volcanic hazard management.

This paper sets out some background on active volcanoes in New Zealand, evacuation planning and we go on to explore some of the opportunities available using GIS and how they could be used to supplement emergency management plans prepared by Civil Defence and Emergency Management Groups (CDEM) , in particular when planning for effective evacuation during a volcanic crisis.

¹ Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

² Department of Geography, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

³ Department of Geology, University of Otago, P.O.Box 56, Dunedin, New Zealand

⁴ Department of Civil Engineering, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

⁵ Institute of Geological and Nuclear Sciences, P.O.Box 30368, Lower Hutt, New Zealand

Hazardous volcanic phenomena range from passive gas emission and slow effusion of lava to volcanic explosions accompanied by the development of a stratospheric ash plume with associated dense descending currents of incandescent volcanic ash and rocks that race at high speeds along the surface away from the volcano (Greene, 2002). In many cases, the loss of life could have been reduced if public safety officials and the general population were aware of the potential effect of the phenomena on their local environment.

BACKGROUND TO EMERGENCY MANAGEMENT

Emergency Management activities can be grouped into four tasks: risk reduction, readiness, response, and recovery. These terms capture the types of activities society must undertake in an effort to coexist with a variety of natural and man-made hazards (Lindell & Perry, 1992). The tasks can be described as follows:

Risk reduction: Activities that actually eliminate or reduce the probability of a disaster, such as preventative land-use zoning and the establishment of comprehensive emergency management programs.

Readiness: Development of plans to save lives and minimise the effects of the emergency, such as evacuation plans, and the creation and maintenance of up-to-date spatially referenced data such as property boundaries, utility lines and emergency headquarters locations.

Response: Activities immediately following the emergency. These activities provide assistance to those in need, to stabilise the situation and speed recovery.

Recovery: Activities needed to return all systems to normal or better. These include short-term recovery to provide vital life-support systems (e.g. shelter, food, water), and long term recovery that may continue for many years.

Each of these phases needs careful planning, and all would benefit from the use of GIS analyses and databases.

In New Zealand, a series of reviews in the 1990s looked at how Civil Defence and Emergency Management (CDEM) was carried out, and a new Ministry (Ministry of Civil Defence and Emergency Management; MCDEM) was set up on 1 July 1999. MCDEM provides overarching policy advice to the Government and the consolidation and oversight of CDEM provision, funding and monitoring (MCDEM, 2004). The CDEM Act 2002 established a framework for CDEM in New Zealand, aimed at building resilient communities. A National CDEM strategy is a part of the framework, and will be supported by a National CDEM Plan, with regional plans developed by CDEM Groups. There is a National Contingency Plan for volcanic eruptions, highlighting the need for and awareness of managing volcanic hazards, and CDEM Groups must hold contingency plans, many of which are in the process of being updated. A Volcanic Impacts Study Group (VISG) has been set up within the Auckland Engineering Lifelines Group (AELG) to provide an opportunity for volcanic hazard scientists to interact with

emergency managers and consultants and discuss topics of common interest in workshops and seminars.

GIS IN EMERGENCY PLANNING

A GIS is a system of hardware, software and procedures designed to support the capture, management, manipulation, sophisticated analysis and modelling and display of spatially-referenced data suitable for solving complex planning and management problems. GIS has its roots in the early 1960s although it really began to take off in the 1980s when the price of computing hardware had fallen below a critical threshold. It is now a maturing mix of technology and expertise, being applied within a wide range of fields, with applications in the fields of government, utilities, financial, natural resource and transportation.

All four emergency planning tasks identified by Lindell & Perry (1992) can benefit from the application of GIS. Access to appropriate data is the key. In an emergency, it is critical to have the right data, at the right time, displayed logically, to respond and take appropriate action. By utilising GIS, this data can be shared across agencies or departments through spatial databases held in one central location. GIS provides a mechanism to centralise and visually display critical information during an emergency.

With regard to *risk reduction*, GIS can be used to identify and model hazards and begin to evaluate the consequences of potential emergencies. It can initially be used for land-use planning as a tool for consultation, zone delineation etc. The relative safety of routes, structures and populations can then be evaluated with respect to potential natural hazards. This would involve more complex modelling of the hazard itself. When the hazards are viewed in relation to other spatially organised data, such as streets, buildings, or power lines, emergency plans can be formulated. GIS can also be used to implement legislation that limits development in areas identified as high risk. Vitality, human life and other values such as property, wildlife or habitat, at risk from the emergency can be quickly identified and targeted for protective action.

Readiness is concerned with activities that prepare for actual emergencies. Here network planning comes to the fore. GIS can be used to provide answers to questions such as the optimum location for fire stations if a 10-minute response time is required, or the safest location for new hospitals, emergency facilities and headquarters. What evacuation routes should be selected based on anticipated or actual volcanic plumes? Will the road networks handle the anticipated traffic? GIS can also be used to display real-time monitoring for early warning systems. It is now possible to deliver these types of information and maps over the internet for public information delivery.

Immediately following a disaster, GIS can aid the *response* phase by determining the closest emergency vehicles to the

incident and assigning them to the area using the optimum or shortest path. This is increasingly possible as emergency vehicles carry GPS units enabling them to be accurately located. In a complex emergency, GIS can help manage the overall status and provide timely information updates. This necessitates GIS datasets being established and maintained in advance of the disaster. The City of Napier has gone some way to establishing spatial data sets and to implement these concepts with their civil defence internet based GIS public information service (City of Napier, 2005), although it is not yet possible on this system to dynamically route vehicles on the existing road networks.

Recovery efforts begin when the emergency is over, and are often in two phases, short- and long-term. Short-term recovery restores vital services and systems. GIS can play a role in damage assessment and information management. Using GPS and telecommunication devices, locations and assessments of damage can be geo-referenced and transmitted back to the emergency headquarters for real-time update of the recovery. For more long-term efforts, such as reconstruction of utilities, GIS can be used to locate new services and to track the construction and rebuilding efforts.

Throughout the process planning is essential. Here GIS can be used to identify and model hazards and begin to evaluate the consequences of potential emergencies. The relative safety of routes, structures and populations can be evaluated with respect to potential natural hazards. This would involve more complex modelling of the hazard itself. When the hazards are viewed in relation to other spatially organised data, such as streets, buildings, or power lines, emergency plans can be formulated.

There are a number of emergency management applications which have incorporated GIS into their design. Dunn (1989) describes the creation of a system in NW England to facilitate command and control decision-making in the event of an environmental disaster, such as a chemical explosion. Three main roles were envisaged: to coordinate emergency service activities; to make decisions regarding evacuation; and to monitor the progress of the emergency. The value was soon recognised of centralised banks of integrated information which might be interrogated to yield responses within a pressured situation. The Configurable Evacuation Management and Planning Simulator (CEMPS) aimed to integrate GIS with a traffic simulation models to simulate the behaviour of evacuees (de Silva, 2000; de Silva & Eglese, 2000). Cova & Johnson (2002) also developed traffic simulation models to model evacuation behaviour in an emergency situation.

Capabilities of GIS in transport and traffic engineering

A critical element in conducting emergency evacuation before, during or immediately after a volcanic eruption is planning and operation of the transportation system at high efficiency levels to minimize damage and casualties. In developed areas, a volcanic eruption event may damage

critical parts of the transportation system such as bridges and tunnels. This damage may interfere both in self-evacuees behaviour and in emergency services response, because panic associated with lack of information about alternative escape routes may result in chaotic and disorganized travel patterns that may generate multiple inefficiencies such as bottlenecks, network congestion and long response times. Therefore, travel behaviour understanding, modelling and forecasting can play a major part in saving lives and resources in volcanic eruption events.

Due to the nature of volcanic eruption events, GIS is an instrument that can contribute to the analysis of transportation systems performance subject to a large variety of interfering factors. Mostly from recent experience in the last two decades, it is observed that transportation engineers have employed GIS in transportation (GIS-T) to store, manipulate and incorporate geo-spatial reality to solve and help decision-makers on their crucial tasks (Galimore *et al.*, 1992; Souleyrette & Strauss, 1999). Several applications in planning (travel demand modelling, logistics, etc) (O'Neil, 1991; Ding *et al.*, 1993; Bennion & O'Neil, 1994), traffic engineering (accident analysis, traffic control and coordination, etc) (Nyerges, 1994; Yong & Taylor, 1991; Waerder & Timmermans, 1994) and asset management (pavement maintenance and monitoring) (Johnson & Demetrsk, 1994; Viviani & Soria, 1995) have completely transformed transportation studies. In the emergency management context and more specifically in volcanic eruption evacuation, GIS-T can be employed to quickly apply the travel demand modelling state-of-the-art which incorporates travellers' probabilistic behaviour in route choices. Also, a few GIS-T software packages have now incorporated advanced functionalities such as vehicle/network routing and facility location, that emergency services such as firefighters, ambulance and police can be used to achieve significant benefits in terms of assessing scenarios and operational procedures during evacuation activities (Partyka & Hall, 2000), necessary for such events as volcanic eruptions.

Despite considerable progress achieved in recent years, research and implementation efforts towards utilizing the full potential available in GIS-T should be contemplated. Many scholars have indicated that geo-spatial modelling provided in most commercial GIS-T desktop software is inefficient, because they are based on very simplistic representation of transportation system characteristics, and do not include multiple inter-relationships observed in reality (Stokes & Marruci, 1995). For example, current network analysis techniques are limited to computing travelling costs solely based on the characteristics of each link of the transportation system, without considering variations over time from nearby interfering systems such as rivers, vegetation, topography, etc. This provides a very static representation of the variables that contribute to decision-making activities, which may under or over estimate benefits, costs, behaviours, etc. On the other hand, there are serious concerns about the isolationist

tendency adopted by some emergency services. It is very often observed that each organisation will have its own GIS-T developed according to its specific needs, without contemplating data/information sharing needs. In a few cases, organisations will purchase GIS-T software without even analyzing whether or not the package will suit its needs during emergency events. A volcanic evacuation emergency will potentially require all emergency services to work together from the outset, and GIS-T packages must be integrated.

ACTIVE VOLCANOES IN NEW ZEALAND

All of the active and potentially active volcanoes in New Zealand are sited in the North Island, west of a line from Whakatane in the Bay of Plenty to Wanganui (Figure 1). Most are associated with subduction of the Pacific plate beneath the Australian plate, and specifically associated with the <1.6Ma Taupo Volcanic Zone (Wilson *et al.*, 1995a). Taranaki may be associated with deeper parts of this subduction system (Stewart *et al.*, 1996), and Bay of Islands and Auckland are intra-plate.

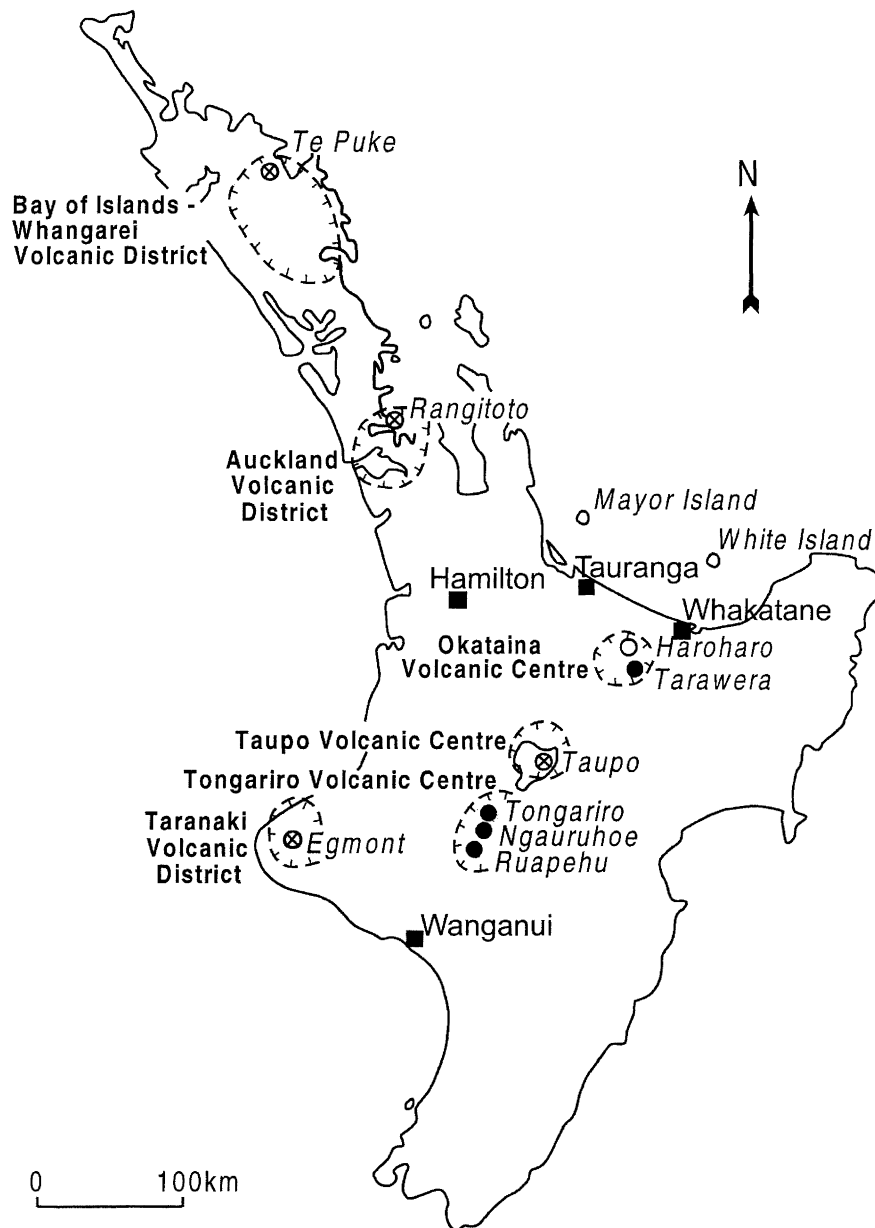


Figure 1. Distribution of active volcanoes, volcanic districts and volcanic centres in North Island, New Zealand. Closed circles - Volcanoes that have erupted since 1850 (recorded history); Circles with cross - Volcanoes that have erupted during the last 2,000 years (dated by C^{14}). Open circles - Volcanoes that have erupted during the last 5,000 years and are presumed active. Volcanic districts or centres are indicated by dashed lines. (From: Cole & Nairn, 1976).

A problem with defining an active volcano in New Zealand is that written history is short, extending back only to the mid-19th century. In contrast Mediterranean countries extend back for thousands of years. As a consequence Cole & Nairn (1975) defined three categories of active volcano in New Zealand; 1) Volcanoes which have erupted since 1850 (recorded history), 2) Volcanoes which have erupted in the last 2,000 years (Dated by C¹⁴), 3) Volcanoes which have erupted in the last 5,000 years, and are potentially active. Using these criteria, ten volcanoes or volcanic centres were regarded as active or potentially active (Fig. 1); White Island, Tarawera, Tongariro, Ngauruhoe and Ruapehu fall into category 1; Bay of Islands, Auckland, Taranaki, and Taupo into category 2; Haroharo into category 3. Since this publication, dates from Mayor Island (Houghton *et al.*, 1992) suggest the last volcano should be added to category 2 (Fig. 1), and it has become apparent that there are many active volcanoes along the Kermadec arc to the north of New Zealand (e.g. Wright *et al.*, in press), which come under New Zealand administrative control.

Most historic eruptions in New Zealand have been explosive. Basaltic centres such as the Bay of Islands and Auckland

have a restricted distribution of the resultant pyroclastic ejecta, producing cinder cone and maar volcanoes. The explosions are usually larger in andesitic centres such as Tongariro, Ruapehu and Taranaki, and may be cataclysmic in the rhyolite centres of Tarawera, Haroharo and Taupo. Ballistic blocks and thick ash will be a hazard close to the volcano, and widespread ash further away. The distribution of this ash will largely depend on the wind direction at the time of the eruption, which could change several times during the eruptive event. The dominant high level wind direction in the North Island is from the west, therefore areas to the east of the volcanoes are more likely to be covered with ash, with even small amounts causing severe disruption to all forms of transportation (Table 1). Associated with explosive eruptions, particularly from rhyolitic and andesitic volcanoes, there could be pyroclastic density currents, which would form ignimbrites and block-and-ash flow deposits around the volcano, and when the ash is remobilised by rain, cause lahars. There could also be an extrusive eruption of lava forming flows or domes. Lavas will only affect areas on the volcano or within the volcanic centre.

Table 1

Thickness of ash	Effects on roads
0-2 mm	Road markings obscured, traction reduced (wet and dry ash), visibility reduced as dry ash is remobilised by traffic and wind. Steep hills difficult for 2WD vehicles to climb
2-20 mm	Moderate hills become difficult for 2WD vehicles to climb, steep hills impossible. Drifts cause larger humps in road. Once dampened and compacted it becomes firmer, easier to drive on.
20-100 mm	Slight inclines may be impassable to 2WD vehicles, 4WD vehicles need differential or hub locks to climb moderate hills. Larger drifts (eg 300 mm) may hinder or stop 2WD vehicles on flat roads
100-300 mm	Uneven surfaces in the ash stop any 2WD vehicles, compacted damp ash on flat surfaces is still able to be driven on. 4WD utility type vehicles (not cars) may be able to slowly progress on the flat. Drifts may need to be cleared. Moderate inclines difficult, but may be possible for experienced 4WD drivers. Steep inclines generally impassable. Ruts easily formed on hills.
>300 mm	Compacted ash may be driven on by 4WD vehicles, softer patches may easily bog vehicles. Gradual inclines possible on compacted ash, but after a few vehicles ruts in the ash will form, hindering uphill progress for further vehicles.

TYPES OF INFORMATION CURRENTLY AVAILABLE TO EMERGENCY MANAGERS RELATING TO VOLCANIC ACTIVITY IN NEW ZEALAND

There is a great deal of information available about individual volcanoes in New Zealand (e.g. Wilson *et al.*, 1995b) and an increasing amount of information available about periodicity of eruptions (e.g. Houghton *et al.*, 1995). Much of the information is however background material which helps to indicate the 'personality' of volcanoes in New Zealand rather than provide direct information that will be of value to Emergency Managers in the next eruption. There is

also an increasing amount of information available as a result of the GeoNet programme (GeoNet, 2002). This is providing monitoring information based on seismic, deformation and geochemistry. In addition satellite imagery is allowing broad, near real-time data to be available over a wide area. For example, differential radar interferometry (DinSAR) can be used to identify surface deformation, with C-band radar wavelengths allowing resolution to a few tens of metres (Stevens, 2003). The best results of this technique are however in arid, flat unvegetated areas; not in a country such as New Zealand.

Hazard maps indicate the most dangerous areas associated with each volcano, and what style of activity may be

experienced in each area on and around that volcano. Such maps are available for Taranaki (Neall & Alloway, 1996), Ruapehu (Latter, 1987; Neall *et al.*, 2001) and Okataina (Scott & Nairn, 1998).

Information has also been compiled for Auckland by Johnston *et al.* (1997) and Paton *et al.* (1999), and a summary of this is given below.

Volcanic risk for Auckland Volcanic Field

The first phase of the study (completed in 1997) involved developing five eruption scenarios to illustrate what might happen in Auckland should an eruption occur, and a qualitative assessment of the effects of these scenarios on selected infrastructure, population (Table 2) and the environment (Johnston *et al.*, 1997). The study highlighted the value of emergency management planning that will identify in advance likely impacts on community lifelines and strengthen the links between agencies that will have to respond to such events. The second phase was undertaken in 1998-1999 and involved some quantitative GIS risk assessment, including economic and social considerations of the eruption scenarios (Paton *et al.*, 1999). The study explored several factors that create vulnerability in the community (e.g., patterns of interaction between physical and social vulnerability, number and distribution of vulnerable groups) and found that:

- Physical hazard characteristics can be used to anticipate the nature, intensity and duration of the

social threat to communities, but more detailed vulnerability analysis is required to provide a comprehensive picture of social vulnerability;

- Vulnerable groups are evenly distributed throughout the Region, creating a complex threat communication and mitigation environment;
- To accommodate the diversity of vulnerable groups, communication and mitigation strategies must cater for the specific needs and resources of each group;
- Destruction and disruption to the social and physical infrastructure caused by volcanic eruption will also affect the short- and long-term economic status of the community;
- Economic vulnerability is influenced by the capability of local and central government agencies (e.g., need for income support, grants etc) and charitable organisations to manage these consequences, particularly in the light of the revenue implications of lost productivity over a period of months or even years.

The study concluded that accurate and comprehensive vulnerability analyses must identify the nature, number and distribution of vulnerable groups within the community. This study contributed to the Contingency Plan for the Auckland Volcanic Field (Auckland Regional Council, 2002).

Table 2

	Auckland				
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
1 km		384	5100	8733	7350
2 km	1803	16635	15297	32076	35652
5 km	30096	119922	123459	144084	171054
10 km	263367	300228	431742	454434	446895

EVACUATION EVENTS IN NEW ZEALAND

Large-scale evacuation events have occurred in many countries throughout history, and lessons can be learnt from them. Fortunately, no large-scale events (taken for convenience as >12,000 evacuees) have been necessary in New Zealand, possibly due to the short history of European settlement (160 years). The common incidents in New Zealand have been short-lived, and relatively small scale, associated with storms and floods, but there have been three events: the 1886AD eruption of Tarawera, 1931 Hawkes Bay earthquake and 1968 Inangahua earthquake, where significant numbers were evacuated. In 1886 ~500 people evacuated on a voluntary basis when Tarawera began eruption on 10 June (Blumenthal, 2003); in 1931, ~11,000 people were evacuated from Hawkes Bay because of building damage, fire, and shortage of water and food; 301 people were evacuated from Inangahua in 1968 largely because of the threat of a flood if the river burst its banks. All of these

events were before the development of computers and the possibility of using GIS-based data, so usage of GIS-based planning before evacuation from a large-scale event is yet to be tested.

Considerations prior to evacuation

Prior to an eruption, plans for evacuation, identifying major routes and suitable destinations must be in place well before any evacuation is necessary. Emergency response facilities, such as hospitals and fire-stations must be identified and if new facilities need to be constructed, optimum locations can be determined using road network analysis, spatial interaction and location-allocation algorithms within GIS to maximise population or aerial coverage and spread overall risk. Plans for evacuation of hospitals, schools and nursing homes should already have been implemented by each authority, but individual facilities and institutions also need to have an evacuation plan which should be coordinated with

those of local authorities. To achieve this, communication links must be established early in the pre-eruption stage. Locations of evacuation shelters should be confirmed and made accessible/known to agencies and the public. Information on vehicle protection, ash clearance, bulk ash disposal, contractor resources and arrangements, and availability of fuel are also important. Lists of special equipment/supplies should be compiled, including tow trucks and taxi companies/private bus companies. Plans for potential receiving cities need to be updated, and suitable accommodation will need to be readily available.

Evacuation route information

Evacuation can be either pre-eruption or during-eruption. Due to a lack of viable transportation alternatives, the primary method of evacuation movement in New Zealand has to be by road, although there are some rail links, and there would be the possibility of using 'Interislander' ferries in coastal areas with deep enough harbours. Before the eruption, road conditions are unaffected by ash, but apprehension may affect driving skills. Evacuation movement during periods of ash fall is drastically changed by road conditions and drivers should be made aware of this. Most compulsory evacuations should take place before any substantial ash falls in the area, and where possible people advised to evacuate themselves by car. Special population groups (such as hospital patients, residential schools, nursing homes and retirement villages) will need to travel on buses, but each organisation will need to confirm their own evacuation procedures.

Security of evacuated area

The security of the evacuated area is intimately linked with authority and responsibility. It is extremely important that measures are taken to secure evacuated areas, and that evacuees are aware that this will be done. This process can be

greatly aided with reference to a large-scale GIS-based buildings register. Security of the evacuated area is essential to continue sustainability of lifelines in the area, to encourage clean-up and return of evacuees after the event. During many past evacuations overseas (e.g. Rabaul 1994), looting and other socially destructive actions occurred, and this must be avoided at all costs.

POTENTIAL EVACUATION SCENARIOS FROM TWO AREAS IN NEW ZEALAND

These scenarios are based on postgraduate studies leading to two theses; an MSc thesis by Erica Blumenthal (Blumenthal, 2003) on the Bay of Plenty and a PhD thesis due to be finished by Kirsten Finnis in 2005 on Taranaki.

Bay of Plenty

In about 1315AD the Kaharoa eruption from Tarawera volcano deposited rhyolitic ash over much of the northern North Island, New Zealand. Columns of ash were erupted for days or weeks, and these were followed by slow extrusion of lava domes, with intermittent ash eruptions, which may have continued for 4 years (Nairn *et al.*, 2001). If such an event occurred today it would cause major disruption to the surrounding area, and evacuation of some areas would be inevitable.

The next eruption of this type to affect the Bay of Plenty will also most probably be from Tarawera or from Haroharo volcano to the north. When this happens, the highest risk is within a 10 km zone around the vent area, and this becomes a Primary Evacuation Zone (Zone 1; Figure 2), including the Rotorua Lakes district (bordering Lakes Rotokakahi, Tikitapu, Okareka, Tarawera, Okataina). Residents of this area would have to be evacuated prior to commencement of the eruption.

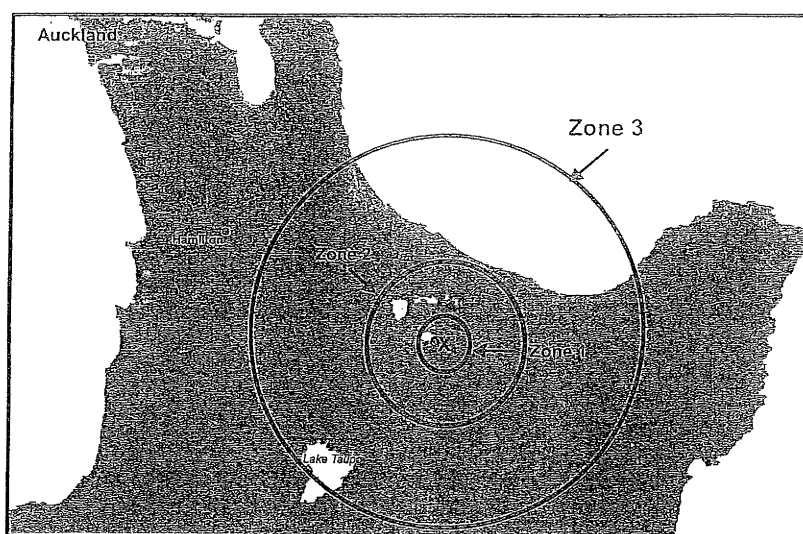


Figure 2. Evacuation Zones for a projected eruption of Tarawera. Zone 1 = 10 km radius (primary) zone; Zone 2 = 40 km radius (secondary) zone; Zone 3 = 100 km radius (potentially 'unsafe' zone). (From Cole & Blumenthal, 2004).

Residents on the northwest shore of Lake Tarawera (along Spencer Road) would be the most vulnerable to any eruption from Tarawera (Fig. 3A). This area is likely to be completely devastated in a Kaharoa-type eruption from Tarawera or Haroharo, particularly from ballistic ejecta and thick near-vent ash fall (Nairn *et al.*, 2001). Therefore, it is imperative that this area evacuates pre-eruption. An added problem is the single evacuation route into and out of the area. Spencer Road ends at the edge of Lake Tarawera and is a long narrow road that extends for ~17 km, along Tarawera Road to Rotorua (Fig. 3A), making large-scale evacuation on this road hazardous. There is also the likelihood of landslips associated with pre-eruption seismicity, which could close the road and sever the link to Rotorua. The construction of a loop road extending northwest from Spencer Road to Millar Road, Lake Okareka, should be considered. This would be of benefit to the local residents at any time, but particularly so if an eruption is imminent. The use of a loop road as a mitigation measure was implemented by officials at Mammoth Mountain (Long Valley, California, USA) during a recent eruption scare (Mader & Blair, 1987).

Further out is the Secondary Evacuation Zone (Zone 2; Fig 2) and would include the urban areas of Rotorua, Kawerau and Murupara. Effects on these towns will depend very much on the wind direction, but this variability puts all in potential danger. The larger population of the towns means that any decision to evacuate becomes a major operation and requires careful planning.

Rotorua is situated 25 km west-northwest of Tarawera volcano (Fig. 3B). The population of Rotorua district is 64,473 (Statistics New Zealand, 2001), and a compulsory evacuation notice may be given if the eruption is large enough or wind direction is from the east. Because of the larger population, it would be advisable that voluntary evacuation is encouraged earlier, to decrease the number of potential evacuees where the compulsory order is given. The importance of the timing of any evacuation order is critical: too soon, and people will start to return, believing the emergency is over; too late, and many evacuees will try to evacuate at once, causing panic.

Viable destinations for evacuees from Rotorua include Hamilton, Auckland and possibly Tauranga and Taupo. However, evacuation to Tauranga and Taupo, or to any other city within the Bay of Plenty region, is better only as an interim measure. These centres could need to be evacuated themselves if the eruption escalated or wind direction changed. If the route to Taupo is taken, the recommendation given to evacuees will be to travel south along State Highway (SH) 30 through to SH 1, as SH 5 passes close to the Primary Evacuation Zone and may be closed prior to the eruption. If the route to Hamilton is taken, the recommendation given to evacuees will be to travel via SH 5 to SH 1 (Fig. 3B).

Kawerau is situated 20 km northeast of Tarawera volcano (Fig. 3C), with a population of 6,975 (Statistics New

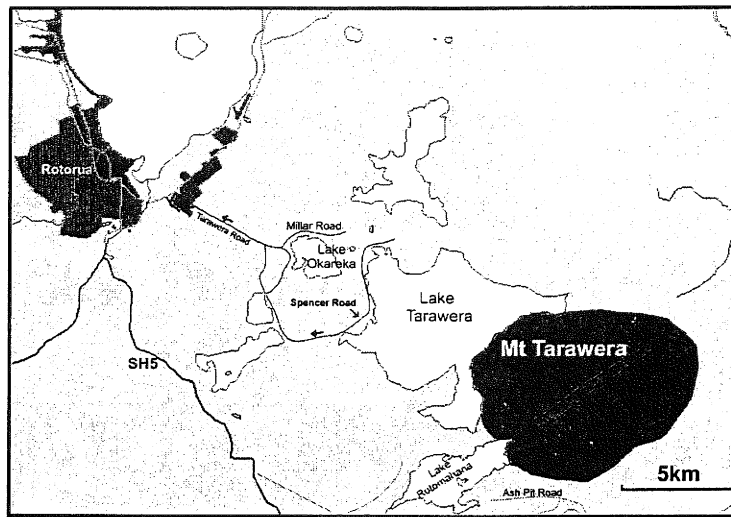
Zealand, 2001). Kawerau has three main road exits from its township. Rotorua and Te Teko could also have been ordered to evacuate at this time. This puts pressure on some roads and other evacuation routes, although only Te Teko's population (630) will affect the roads in the immediate vicinity.

If the population leaves Kawerau via Kawerau Road to SH 30, the choice lies in either going to the west or east (along SH 30). The best option is to take SH 30 to the east; they could then travel to Te Teko, turn south and follow the south route and travel on to Taupo via Murupara; or could turn north from Te Teko, or to Matata, on the coast, and then northwest to Tauranga. Following this route would be slow, and would involve travelling in ash fall-prone areas, once the eruption has commenced. Going to the west will compound the problems in the Rotorua area. A second option is to leave Kawerau by the southern forestry road to Ngamotu Road, although this comes in close proximity to Tarawera volcano, just outside of the Primary Evacuation Zone. This option is only possible pre-eruption, and is likely to be closed as soon as the eruption begins. The options from here are east and then south to Murupara and south to Taupo (Fig. 3C).

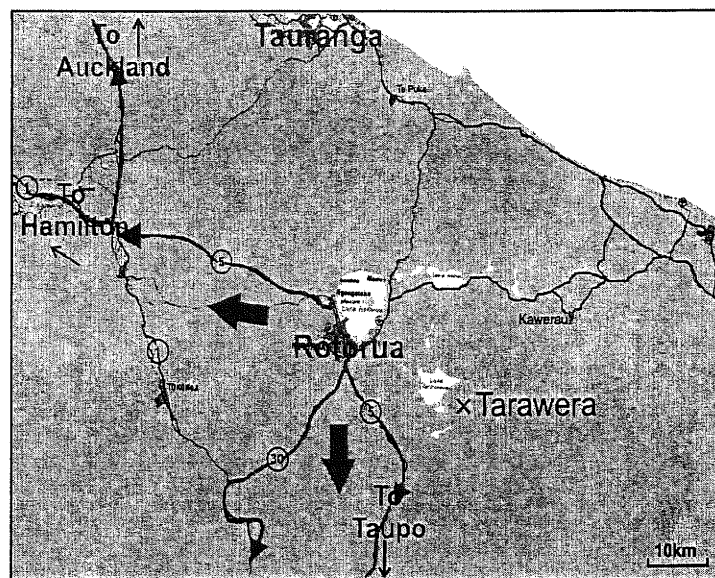
Rotorua district has 32,311 registered cars in the district; 32,479 including rental cars and taxis, together with 260 buses and coaches. Assuming a population of 64,473, the number of cars would appear to be adequate, assuming two people per car. Those without a household car, or without the opportunity to travel with friends or relations, will need to rely on buses and coaches. Measures must be taken to ensure these are organised in advance, with meeting points and drivers prearranged.

According to the 2001 census, 90.9% of households in the Bay of Plenty region have access to a motor vehicle (Statistics New Zealand, 2001). As there are 86,793 households in the Bay of Plenty, there are therefore 7,899 households without access. With an average household population there of 2.6 persons, this will result in about 20,535 people in the region without access to a motor vehicle. From these figures it appears that Rotorua has ~6,420 people whom do not have access to a motor vehicle, while Kawerau District has ~939 people without access to a motor vehicle. The assumption is made that most of the 7,359 people, from these key areas, will need public transport.

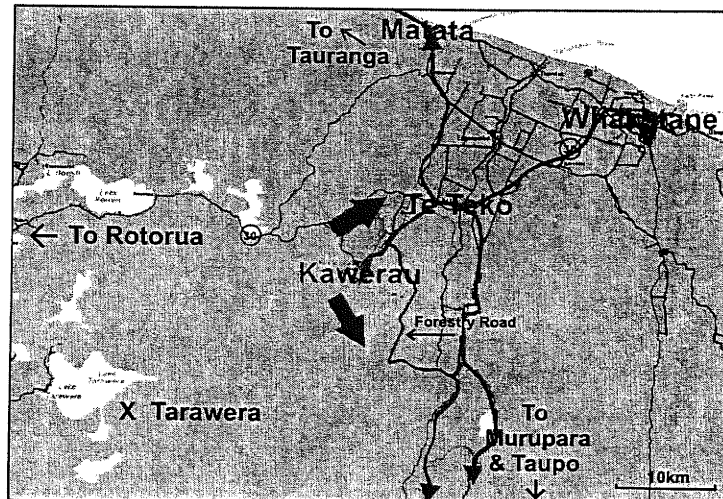
Initial destinations for evacuees are likely to be Auckland, Hamilton, Tauranga, and Taupo. However, many smaller destinations will receive evacuees, with many people wishing to choose their own destination because of relatives or friends. It is also possible that some of the cities (e.g. Tauranga and Taupo) could need to be evacuated themselves and are therefore not recommended as ideal final destination points. After initial destinations have been reached, it will be possible to transfer evacuees to other points around the country, and to family and friends outside evacuated zones. This subsequent transfer is recommended to decrease the effect on public resources, and for the preservation of mental



A



B



C

Figure 3. A. Lake Tarawera potential area evacuation route; B. Rotorua potential evacuations routes; C. Kawerau potential evacuations routes (From Cole & Blumenthal, 2004).

health and emotional support, as it is essential to counteract subsequent negative impacts on the evacuees, as happened in Baños, Ecuador (Lane *et al.*, 2003). A registration system is recommended once final destinations are known, so that enquiries from friends and relations can be dealt with effectively.

As the largest city in New Zealand, Auckland has the largest accommodation resource of the cities considered, with numerous hotels, motels, and schools. The short-term accommodation sources include friends and family, motels, camping grounds, and dormitories. Most evacuees are expected and are recommended to travel to these sources once leaving the evacuation shelters. Auckland is also thought to be a good medium and longer-term shelter (and relocation) destination, because of the accommodation resources and potential employment opportunities available (Auckland Regional Council, 1996). For short-term shelter purposes, Hamilton can provide up to 900 beds, which would include both motel and Marae accommodation. Longer-term shelter resources include various hotels, motels and camping grounds. Hamilton would be a good medium-term sheltering destination, however less so for short-term shelter.

Taupo may be an interim destination, and as such will be able to provide a small amount of support shelter. Taupo and the surrounding district has welfare centers, including the Great Lake Centre and the Events Centre (which can accommodate ~100 each), plus primary schools (22) and motels, which are available for short-term shelter.

The Tauranga-WBOP Emergency Management Civil Defence Plan (2002) states that the preferred option for short-term emergency accommodation for smaller numbers of evacuees is the use of the combined district/region's hotels and motels. It states that should large numbers be involved, other facilities will be used. It also states that registers of locations and premises suitable for short-term shelter for evacuees are held by the Emergency Operations Centre. Major shelter facilities (able to provide catering, showers, car-parking, accommodation) include Tauranga Racecourse, Greerton; Papamoa Sports Club, Papamoa; Bay Park Stadium, Te Mauna; QEII Memorial Hall, Tauranga; Blake Park Stadium, Mt Maunganui; and Community Centre, Waihi Beach. Medium-term facilities (greater than 72 hours) include motels, campground cabins, caravan parks and sites, with total capacity estimated to be around 8,000 people. However, Tauranga is not the best medium- or long-term sheltering location.

Taranaki/Egmont

The most recent volcanic activity from Mt Taranaki/Egmont (in 1755; Neall *et al.*, 1986) produced small tephra eruptions which only affected areas inside the Egmont National Park boundary (9.6 km from the source). However, approximately 700 years ago, at the beginning of the volcano's present

eruptive cycle, two pyroclastic flows travelled down the Stony River channel, extending ~15 km from the summit (Neall *et al.*, 1986), into what these days is predominantly farmland. Ash clouds on the side of these flows extended kilometres further to the west and south. Although only small in a geological scale, a similar eruption today would have the potential to directly impact about 500 residents. Tephra eruptions from Mt Taranaki/Egmont have exceeded volumes of 10^7 m³ (Alloway *et al.*, 1995), depositing material as far as 250 km away (Eden *et al.*, 1993). Tephra from a moderate sized eruption, depending on wind speed and direction, could be deposited up to 1 m thick (Martin, 1999) in areas within the Taranaki region, and it would only take a small amount of ash (<10 mm) to have a major impact on transportation and infrastructure (Table 1). Should Mt Taranaki/Egmont produce its greatest hazard, a flank collapse, thousands would be impacted. The flank collapse that produced the Opua Formation 7,000 years ago left deposits 5 m thick over 25 km from its source, that covers an area over 100 km² (Neall *et al.*, 1986). Today, that collapse would destroy everything between the source and a 15 km stretch of coast including Opunake (Fig. 4).

Due to the radial nature of the Taranaki Region, the highest eruption threat is considered to be to the towns which lie within 40 km of Mt Taranaki/Egmont's summit. The area to the northwest of the volcano, from Okato to New Plymouth (Fig. 4) is considered to be a safe area due to protection from 'ground hazards' by the Pouakai Range, but could still potentially be affected by ash fall. The major towns within this 40 km radius include New Plymouth, Waitara, Stratford, Inglewood, Eltham, Opunake, Manaia and Hawera which in total have a combined population of approximately 100,000.

The Taranaki Regional Volcanic Contingency Plan (TRVCP; Taranaki Regional Council, 2000) includes a section outlining evacuation issues and procedures. Evacuations fall into two categories, encouraged and enforced, and are determined by the Scientific Alert Level (SAL) and 'forecasts' by scientific advisers. Encouraged evacuations from at risk areas are to occur during later stages of SAL 2, and enforced evacuations during SAL 3. An evacuation zone map has been developed (Fig. 4), based on the volcanic hazard zone map, which shows the locations of the four colour coded zones, major roads, district boundaries and proposed direction of evacuation. Although this map has been distributed throughout the Taranaki Region, less than a quarter of residents know which zone they live in.

The highest priority zone (Red Zone) is the area most likely to be affected most frequently and most severely by lahars and debris avalanches. This zone covers all of Egmont National Park, extending to Wairemu Rd, Eltham Rd and SH 3 and down most rivers. Inglewood is located within the zone, and rivers in the red zone flow through the towns of New Plymouth, Waitara, Stratford, Eltham and Opunake.

Otherwise, these towns, and the majority of the region west of Stratford is located in the next highest zone (Blue Zone). This area has been affected by historic ground hugging flows and in a large eruption may be affected in a similar way to the red zone. The next zone (Orange Zone) covers the rest of the Taranaki region lying to the east of Stratford and includes towns such as Hawera and Patea. This area would only need to be evacuated if the effects of an eruption are significant. The fourth zone (Yellow Zone) which is the 'protected' area from Okato to New Plymouth and would also only need to be evacuated if the eruption effects were significant or if the area became isolated.

The contingency plan also contains an evacuation route map (Fig. 4), which is to be placed on signs around the region in the event of volcanic activity, to show residents the fastest way to safe ground. The routes have been pre-determined in an attempt to have people from the high-risk areas take the shortest time to evacuate and gain as much distance from the volcano as possible (Taranaki Regional Council, 2000).

The radial and coastal nature of the area also creates problems for those living to the west of the volcano. The TVRCP has identified that some areas of the region may become uninhabitable if lahars down the Waiwhakaiho and Stony Rivers cut off the Yellow Zone which includes the city of New Plymouth. In this scenario, road access, water and electricity would no longer be available and evacuation by sea would have to be considered. A similar situation would arise if SH 45, the main road which follows the coast from New Plymouth to Hawera, was cut in multiple places. This road, which crosses at least six major rivers capable of channelling pyroclastic flows and lahars, is the primary road in and out for western communities south of New Plymouth and north of Opunake. There is a secondary road, Wiremu Rd, which runs parallel to SH 45 closer to the mountain, however should the highway be cut, this road would also be of no use. Residents stranded in these areas would also have to be evacuated by sea.

There are only 3 main roads out of the Taranaki Region; SH 3 to the north and south, and SH 43 to the east, which has extensive unsealed sections. If SH 45 and SH 3 south of Stratford were to be cut, SH 3 south to Wanganui is the only option. Stratford residents, depending on road closures have the option of going north or south on SH 3 or east to Taumaranui on SH 43. Residents from Stratford north have the option of continuing to north on SH 3 to Te Kuiti, or turning on to SH 40 to Taumaranui. The cities of Hamilton, Wanganui and Palmerston North or Wellington would be the most viable destinations for evacuees. The towns of Te Kuiti, Taumaranui, Raetahi and Ohakune are options for the short-term.

Data from the 2001 census shows that of the 38,500 households in the Taranaki Region, 90% have access to a motor vehicle, therefore leaving 3820 without access to a vehicle. By district, 2685 households in the New Plymouth

District, 276 households in the Stratford District and 867 households in the South Taranaki District do not have access to vehicles. On average, there are only 2.6 people per household, so if neighbours or relatives without cars wanted to travel to the same destination car-pooling could be an option. Public transportation, however, would be required for the remainder.

The TRVCP states that those who leave during the encouraged evacuation period are responsible for finding their own accommodation. People who leave during the forced evacuation will also be encouraged to find their own accommodation, but for those who are unable, to the designated civil defence organisation ensures that people are appropriately accommodated (Taranaki Regional Council, 2000). District civil defence organisations are responsible for providing evacuee welfare in district evacuations, regional civil defence organisations in regional evacuations and for evacuations beyond the region, the Ministry of Civil Defence & Emergency Management co-ordinates evacuee welfare. So far, TRVCP has only suggested accommodation sources such as family and friends, hotels and motels, holiday parks and other camping or dormitory complexes such as youth camps and university campuses, but a more exhaustive list, such as compiled for the Bay of Plenty should be considered.

POTENTIAL FOR GIS USE IN EVACUATION PLANNING PRIOR TO AND DURING AN ERUPTION

Volcanoes are intuitively appealing for GIS modellers since unlike earthquakes, their location (usually) is known, although the relative magnitude and timing may be harder to predict. Nevertheless, the current use of GIS methods for emergency and evacuation planning related to volcanic eruptions is limited. Most papers discuss mass movement events, with few considering more sophisticated themes such as the use of large data sets for interactive modelling and analysis.

According to a typology proposed by Pareschi *et al.* (2000), GIS data of utility for volcanic studies can be categorised into one of three forms:

- Digital Elevation Models (DEMs)
- Satellite imagery
- Vector data on natural and man-made features

DEMs are raster layers in which data values represent elevation. Increasing resolution of DEMs to sub-metre vertical and horizontal accuracy can now enable accurate modelling of the terrain surface. Satellite digital images again of sub-metre spatial resolution can be integrated with DEMs to reveal landscape features such as soil type, vegetation and, with multiple images, an analysis of change over time of such features. Vector data could range from energy supply lines, strategic buildings, roads to population centres.

In a rare example of applying GIS to the management of volcanic crises, Gomez-Fernandez (2000) aimed to identify

areas on the Spanish Canary Island of Tenerife where the next events would occur, together with the kind and magnitude of the phenomena and the resulting eruptive distribution. Environmental and socio-economic databases were integrated to model volcanic processes and produce potential risk maps. Areas were then identified of high risk, potential evacuation routes calculated and safe locations identified for services and resources.

In New Zealand, much GIS-related activity associated with volcanoes has used satellite imagery, with extensive evaluation of ERS and Envisat interferometry (e.g. Stevens *et al.*, 2004; Stevens & Wadge, 2004). Most of this work has related to deformation prior to eruptions, and hence is more related to surveillance than specifically to evacuation. However accurate eruption forecasting is clearly required before reliable evacuation procedures can be put in place. This work will continue over the next 3+ years, as part of the 'Regional Riskscape' model (King *et al.*, 2004), to be carried out by the Institute of Geological and Nuclear Sciences (GNS) and National Institute of Water and Atmosphere (NIWA), and funded by the Foundation for Research Science and Technology (FRST).

More specifically related to evacuation planning, GIS can be used both prior to and during an eruption. Prior to an eruption, the suite of tools available within network analysis are invaluable. Questions which can be answered would

include what evacuation routes should be selected based on the location of the hazard, the population to evacuate, and to where they were being evacuated. Testing a variety of scenarios, perhaps under simulated emergency conditions can also be greatly aided by GIS data and techniques. Locating optimum sites for planning and management of the eruption and subsequent evacuation can also be aided by GIS analysis. Here, priorities would include picking a site which was safe, yet also not too isolated from the situation.

During an eruption, provided there is an established and well-maintained database of resources, populations, transportation routes and utilities, GIS should be an important aid to emergency evacuation. By overlaying and analysing a variety of maps, personnel can quickly estimate populations needing to be evacuated. This has been started, both for Auckland (Johnston *et al.*, 1997; Table 2) and for other active volcanoes (Table 3) where populations living within zones specific distances from the volcano have been estimated. Evacuation routes can be also assessed for risk, and safe routes selected. If the hazard or meteorological conditions change, perhaps effecting new areas, new evacuation plans or scenarios can also be implemented. The results of the GIS-generated analysis, whether as a map or report, can be distributed instantaneously to relevant authorities over the internet for fast and accurate public information delivery.

Table 3

	White Island	Okataina V.C.	Taupo	Ruapehu	Taranaki	Bay of Islands	Mayor Island	Mt Edge- cumbe	Ngauruhoe
10 km	15	1,017	429	96	300	7,098	6	8,781	129
25 km	15	65,700	26,277	4,035	42,465	21,243	6	19,386	4,173
50 km	825	119,904	31,053	15,957	98,040	43,533	108,795	112,032	18,003
100 km	161,157	350,544	160,551	113,043	105,030	135,207	349,251	302,079	88,782
200 km	635,898	1,216,155	1,065,528	1,062,825	546,708	1,069,800	1,770,117	857,136	1,056,996

CONCLUSIONS

- GIS is an extremely valuable tool for emergency management in New Zealand.
- Use has already been made of GIS in New Zealand as a prediction tool for eruptions (using radar interferometry), and has contributed to scenario development for Auckland, and potential size of evacuation zones for other volcanoes.
- GIS can be used effectively for evacuation planning and greater usage should be included in future plans for volcanic hazard research in New Zealand.

ACKNOWLEDGEMENTS

Funding for this study for JWC, EB, SB and DMJ has come from FRST Contract UOCX0207, for which the authors are most grateful. The authors thank Drs Ian Nairn and Nicki Stevens for discussion related to the paper and to the anonymous reviewer who made many helpful comments.

REFERENCES

- Alloway, B., Neall, V.E. & Vucetich, C.G. (1995). "Late Quaternary (post 28,000 year B.P. tephrostratigraphy of northeast and central Taranaki, New Zealand". *Journal of The Royal Society of New Zealand*, **25**(4): 385-458.
- Auckland Regional Council, (1996). "Strategy for evacuees from outside Auckland region. Auckland Regional

- Council Civil Defence Plan for the northerly evacuation of Ruapehu District by resources wholly from the Auckland region". *Auckland Regional Council*. 25p.
- Auckland Regional Council, (2002). "Contingency Plan for the Auckland Volcanic Field". *Auckland Regional Council Technical Publication* **165**. 72p.
- Barnard, S. (2004). "Results of a reconnaissance trip to Mt. Etna, Italy: The effects of the 2002 eruption of Etna on the province of Catania". *Bulletin of the New Zealand Society for Earthquake Engineers* **37** (2): 47-61.
- Bennion, M.W. & O'Neill, W. A. (1994). "Building Transportation Analysis Zones Using Geographic Information Systems". *Transportation Research Record* **1429**: 49-56.
- Blumenthal, E. (2003). "Evacuation planning needed for any future rhyolite eruption from Tarawera volcano". *Unpublished MSc Thesis, University of Canterbury, Christchurch*.
- Cole, J.W. & Nairn, I.A. (1975). "Catalogue of Active Volcanoes of the World including solfatara fields. Part 22; New Zealand". *International Association of Volcanology and Chemistry of the Earths Interior*. 156p.
- Cole, J.W. & Blumenthal, E. (2004). "Evacuate! What an evacuation order given because of a pending volcanic eruption could mean to residents of the Bay of Plenty". *Tephra* **21**: 46-52.
- Cova, T.J. & Johnson, J.P. (2002). "Microsimulation of neighborhood evacuations in the urban - wildland interface". *Environment and Planning A* **34** (12): 2211-2229
- De Silva, F. N. (2000). "Challenges in designing spatial decision support systems for evacuation planning". University of Colorado, USA, Natural Hazards Research and Applications Information Center, *Institute of Behavioral Science*: 13.
- De Silva, F. N. & Eglese, R.W. (2000). "Integrating simulation modelling and GIS: spatial decision support systems for evacuation planning". *Journal of the Operational Research Society* **51**: 423-430.
- Ding, C., Choi, K. & Kim, T. J. (1993). "GIS-Based Traffic Analysis Zone Design". *Third International Conference in Computers in Urban Planning and Urban Management, Atlanta, Georgia, USA*.
- Dunn, C. E. (1989). "Cumbria Graphical Information System for emergency planning". *Mapping Awareness* **3**(6): 15-17.
- Eden, D.N., Froggatt, P.C., Trustrum, N.A. & Page, M.J. (1993). "A multiple-source Holocene tephra sequence from Lake Tutira, Hawke's Bay, New Zealand". *New Zealand Journal of Geology and Geophysics* **36**: 233-242.
- Gallimore, W.P., Hartgen, D.T. & Li, Y. (1992). "Applications of GIS-Transportation Analysis Packages in Super-Regional Transportation Modeling". *Annual Meeting of the Transportation Research Board, Washington, USA*.
- GeoNet, (2002). "Geonet News 1" (June 2002), *Institute of Geological and Nuclear Sciences, Lower Hutt* [information also available on www.geonet.org.nz].
- Greene, R. W. (2002). "Confronting Catastrophe: A GIS handbook". *ESRI Press*.
- Gomez-Fernandez, F. (2000). "Contribution of geographical information systems to the management of volcanic crises". *Natural Hazards* **21**(2-3): 347-360.
- Houghton, B.F., Weaver, S.D., Wilson, C.J.N. & Lanphere, M.A. (1992). "Evolution of a Quaternary peralkaline volcano: Mayor Island, New Zealand". *J. Volcanol. Geotherm. Res* **51**:217-236
- Houghton, B.F., Wilson, C.J.N., McWilliams, M.O., Lanphere, M.A., Weaver, S.D., Briggs, R.M. & Pringle, M.S. (1995). "Chronology and Dynamics of a large silicic magmatic system: Central Taupo Volcanic Zone, New Zealand". *Geology* **23**: 13-16.
- Johnson, B.H. & Demetsky, M.J. (1994). "Geographic Information System Environment for Transportation Management Systems". *Transportation Research Record* **142**: 67-73,
- Johnston, D.M., Nairn, I.A., Thordarson, T. & Daly M. (1997). "Volcanic Impacts Assessment for the Auckland Volcanic Field". *Auckland Regional Council Environment Division, Technical Publication Number* **79**.
- Kerr, J.E. & Johnston, D.M. (2003). "Land use planning as a tool for managing volcanic hazards, New Zealand". *Abstract for the Cities on Volcanoes 3 Conference, 14-18 July 2003, Hilo, Hawaii, USA*: 71.
- King, A., Bell, R. and Heron, D. (2004). "Towards a Riskscape model". *Abstract, Natural Hazard Management Conference, Tauranga, 10-11 August, 2004*: 17.
- Lane, L.R., Tobin, G.A. & Whiteford, L.M. (2003). "Volcanic hazard or economic destitution: hard choices in Baños, Ecuador". *Environmental Hazards* **5**: 23-34.

- Latter, J.H. (1987). "Volcanic hazard map of Tongariro National Park Region. 1:100,000". *Department of Scientific and Industrial Research, Wellington*.
- Lindell, M.K. & Perry, R.W. (1992). "Behavioral Foundations of Community Emergency Planning". *Hemisphere Publishing Co., New York*. 309p.
- Mader, C.G. & Blair, M.L. (1987). "Living with a volcanic threat: Response to volcanic hazards, Long Valley, California". *William Sprangle, Portola Valley, California*. 105p.
- Martin, B. (1999). "Likely impacts within the Taranaki Region of future eruptions from Mt Taranaki". *Masters Thesis, University of Auckland, Auckland*, 133 p.
- MCDEM, (2004). "Resilient New Zealand; A Aotearoa manahau. National Civil Defence Emergency Management Strategy 2003-2006". *Ministry of Civil Defence and Emergency Management*, 35p.
- Nairn, I.A., Self, S., Cole, J.W., Leonard, G.S. & Scutter, C. (2001). "Distribution, stratigraphy, and history of proximal deposits from the c.AD 1305 Kaharoa eruptive episode at Tarawera Volcano, New Zealand", *New Zealand Journal of Geology and Geophysics* **44**: 467-484.
- Napier City Council (2001). Napier City Council GIS Application
[www.gis.napier.govt.nz/encounter/ncc/index3.html?workspace=CivilDefenceMaps&context=civildefence].
Date accessed, 28th July 2005.
- Neall, V.E. & Alloway, B.V. (1996). "Volcanic hazard map of western Taranaki". *Massey University Department of Soil Science Occasional Report* **12** (map only).
- Neall, V.E., Stewart, R.B. & Smith, I.E.M. (1986). "History and petrology of the Taranaki Volcanoes". *Royal Society of New Zealand bulletin*, **23**: 251-263.
- Neall, V.E., Cronin, S.J., Donoghue, S.I., Hodgson, K.A., Lecointre, J.A., Palmer, A.S., Purves, A.M. & Stewart, R.B. (2001). "Lahar hazards map for Ruapehu Volcano". *Institute of Natural Resources – Massey University, Soils and Earth Sciences Occasional Publication* **1** (map only).
- Nyerges, T. L. (1994). "Locational Referencing and Highway Segmentation in a Geographic Information System". *ITE Journal*; 27-31
- O'Neill, W. A. (1991). "Developing Optimal Transportation Analysis Zones Using GIS". *ITE Journal*: 33-36.
- Papacostas, C.S. (1995). "GIS Application to the Monitoring of Bus Operations". *Compendium of Technical Papers, Institute of Transportation Engineers, USA*.
- Pareschi, M. T. & Cavarra, L. (2000). "GIS and Volcanic Risk Management". *Natural Hazards* **21**(2-3): 361-379.
- Partyka, J.G. & Hall, R.W. (2000). "On the Road to Service: OR/MS Today". www.lionhrtpub.com.
- Paton, D., Johnston, D., Gough, J., Dowrick, D., Manville, V., Daly, M., Batistich, T., & Baddon, L. (1999). "Auckland Volcanic Risk Project: Stage 2". *Auckland Regional Council, Technical Publication Number 126*.
- Scott, B.J. & Nairn, I.A. (1998). "Volcanic hazard map of Okataina Volcanic Centre". *Environment Bay of Plenty resource planning publication* **97/4** (map only).
- Souleyrette, R. & Strauss, T. R. (1999). Transportation. In: Easa, S. and Chan, Y. (eds.) "Urban Planning and Development applications of GIS"; *ASCE; Virginia, USA*.
- Statistics New Zealand, (2001). "Census of Population and Dwellings", [www.stats.govt.nz/census/]. Date accessed, 29th July 2005.
- Stevens, N.F. (2003). "Anticipating pre-eruptive volcanic deformation in Auckland from space, using differential radar interferometry (DinSAR)". *Geological Society of New Zealand Annual Conference Abstracts, Dunedin, December 1-4, 2003. Geological Society of New Zealand Miscellaneous Publication* **116A**: 139.
- Stevens, N.F., Garbell, H. & Mouginiis-Mark (2004). "NASA EOS Terra ASTER: Volcanic topographic mapping and capability". *Remote Sensing of Environment*, **90**: 405-414.
- Stevens, N.F. & Wadge, G. (2004). "Towards operational repeat-pass SAR interferometry at active volcanoes". *Natural Hazards* **33**: 47-76.
- Stewart, R.B., Price, R.C. & Smith, I.E.M. (1996). "Evolution of high-K magma, Egmont volcano, Taranaki, New Zealand: evidence from mineral chemistry". *J. Volcanol. Geotherm. Res.* **74**: 275-295.
- Stokes, R.W. & Marucci, G. (1995). "GIS for Transportation Current Practices, Problems and Prospects". *ITE Journal*: 28-37.
- Taranaki Regional Council, (2000) . "Taranaki Regional Volcanic Contingency Plan". New Plymouth, 56p.

- Tauranga-WBOP Emergency Management, (2002). "Civil Defence Plan 2002". *Emergency Management Office, Western Bay of Plenty District Council, Tauranga.*
- Viviani, E. & Soria, M.H.A. (1995). "Aplicação de um SIG no desenvolvimento de sistema de gerência de vias não-pavimentadas"; *Anais do IX Congresso da Associação Nacional de Ensino e Pesquisa em Transportes – ANPET, III*: 1148-1153.
- Waerden, P. & Timmermans, H. (1994). "Parking Simulation using a Geographical Information System". *Second Design & Decision Support Systems in Architecture & Urban Planning Conference*: 1-12.
- Wilson, C.J.N., Houghton, B.F., McWilliams, M.O., Lanphere, M.A., Weaver, S.D. & Briggs, R.M. (1995a). "Volcanic and structural evolution of Taupo Volcanic Zone: a review". *J. Volcanol. Geotherm. Res.* **68**: 1-28.
- Wilson, C.J.N., Houghton, B.F. & Scott, B.J. (1995b). "Volcanoes of New Zealand". *Tephra*, **14**(2): 2-11.
- Wright, I.C., Worthington, T.J. & Gamble, J.A. in press. "New multibeam and geochemistry of the 30° – 35°S sector, and overview, of southern Kermadec arc volcanism". *J. Volcanol. Geotherm. Res.*
- Young, W. & Taylor, M. (1991). "A parking Model hierarchy". *Transportation* **18**: 37-58.