Vulnerability of farm water supplies to volcanic ash

T.M. Wilson
C. Stewart
J.W. Cole
D.M. Johnston
S.J. Cronin

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T. M. Wilson, Natural Hazard Research Centre, University of Canterbury, Private Bag 4800, Christchurch

C. Stewart, Private Consultant, Brooklyn, Wellington

J. W. Cole, Natural Hazard Research Centre, University of Canterbury, Private Bag 4800, Christchurch

D. M. Johnston, Joint Centre for Disaster Management, GNS Science and Massey University, Private Box 756, Wellington

S. J. Cronin, Volcanic Risk Solutions, Massey University, Private Bag 11 222, Palmerston North

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Volcanic ashfall can have serious impacts on water supplies. Freshly-fallen volcanic ash may result in short-term physical and chemical changes in water quality, increased wear and damage to water delivery systems and a high demand for water during cleanup operations. Modern farming operations are critically dependent on their water supplies, particularly dairying, which has very high rates of water consumption, particularly during summer months.

The aim of this project was to characterise the vulnerability of farm water supplies in New Zealand to volcanic ashfall, and to make management recommendations to reduce this vulnerability. In this report, we have:

- reviewed the literature on the impacts of volcanic eruptions on rural water supplies worldwide;
- characterised the water use regimes and identified the vulnerability of the water supply systems of eight case study farms from across the North Island, New Zealand;
- devised a scheme to rate the overall vulnerability of each farm;
- reviewed international agricultural water quality guidelines; and finally,
- made a series of management recommendations for reducing vulnerability of farms to a volcanic eruption.

Literature review

Two particular eruptions have been studied with respect to impacts on agricultural or rural water supplies: the 1980 eruption of Mt St Helens, in the northwestern United States, and the 1991 eruption (VEI 4+) of Hudson Volcano, in southern Chile. For these relatively large eruptions, it is clear that physical impacts of ashfall tend to overwhelm more subtle chemical impacts (such as changes to water quality). Particular points of vulnerability are open systems such as irrigation channels and drinking water ponds, which become clogged with ash, and ash damage to electrical components such as switch panels, to motors and other components such as sprinkler heads.

Impacts of ash from the Mt St Helens eruption on two contrasting regions showed that as expected, groundwater-fed systems are much more resilient to volcanic ash than surface water-fed systems. However, even groundwater-based water supplies can be vulnerable to ashfalls; in Ritzville Country, ashfall still caused disruption to groundwater-fed irrigation systems as airborne ash disabled pumps by shorting out electrical panels. In coastal Santa Cruz province, Patagonia, windmills used to extract groundwater were disabled by airborne ash from the 1991 eruption of Hudson Volcano.

Vulnerability assessment of case study farms

Eight case study farms in the central North Island covering a diverse range of locations and land uses and access to water supplies were characterised with respect to their water use, with the aim of assessing the vulnerability of their water supplies. Overall vulnerability is determined by the following factors:

- the type of water supply (whether groundwater or surface water-fed);
- water storage capacity;
- water use;
- independence of supply;
- pumping capability;
- other stresses on the water supply.

Overall vulnerability index
An overall vulnerability index for each farm was calculated by assigning weighted scores to the six factors described above. The largest single factor contributing to vulnerability is whether a water supply is derived from groundwater or surface water. The overall vulnerability of the study farms ranged from 'extremely vulnerable' (a score of 87 out of a maximum of 100 for a dairy farm in Taranaki) to 'moderately vulnerable' (a score of 42, for a sheep and beef farm in Hawkes Bay).

Overall volcanic risk to water supplies
Vulnerability indices for individual farms were combined with predictions from a probabilistic volcanic risk model of the accumulated thickness of volcanic ash over the central North Island over a period of 10,000 years. This gives an overall indication of the volcanic risk to farm water supplies. Study farms 4 (a dairy farm in Rerewhakaaitu, near Rotorua) and 6 (a dairy farm in south Taranaki) were assessed as being most at risk.

Review of international agricultural water quality guidelines
Agricultural water quality guidelines from South African, Canada and New Zealand/Australia (ANZECC), as well as guidelines produced by the FAO, were reviewed. This was a useful exercise as it identifies the water quality issues important to farm water use and primary production. Our preliminary analysis suggests that the following are likely to be the key issues for farm water supplies in the event of volcanic ashfall:

- high levels of suspended ash (turbidity) will make surface waters unsuitable for irrigation because of clogging of pipes and nozzles; abrasional damage is a further hazard; pumping of suspended volcanic sediments (such as at Study Farm 3) suggest damage will occur to impellors; water pumps can be expected to suffer accelerated wear if pumping volcanic sediment suspended in water over a long period of time (months to years) following an ashfall event;
- surface water contaminated by ash may show a tendency to be corrosive towards concrete;
- the palatability of drinking water for livestock may be affected due to the presence of iron and manganese which impart a bitter metallic taste; and
- there may be toxic effects on livestock from volcanic elements such as fluoride and aluminium; however, intake of fluoride from drinking water may be insignificant compared to ingestion from contaminated feed.

It is important to bear in mind that guideline values for protection of agricultural water uses are primarily based on sustainable use of a water supply over a long period of time, whereas an ashfall is likely to be a short-term event. As guideline values are set on the basis of long-term use, short-term incursions may not be a problem. However, palatability issues are an obvious exception to this observation. Also likely to be problematic are the clogging of equipment with suspended ash, abrasion of irrigation nozzles and distribution systems by ash, and possibly also corrosion effects due to high levels of acidity.

Management recommendations
A series of recommendations arising from the findings of this report were drawn up, with the purpose of enabling individual farm managers to increase their resilience to a volcanic eruption. *Reduction* recommendations are designed to increase resilience by taking steps well in advance of a volcanic crisis, and include: increasing water storage capacity, diversifying water supplies as far as is practicable, maintaining water supplies in a good state of repair and considering the purchase of a diesel generator to maintain pumping capacity if

volcanic ashfall causes power outages. *Readiness* recommendations include ensuring the water supply is in a good state of repair, moving stock to paddocks with a gravity-fed water supply, stocking up on filters and fittings and ensuring maximum storage levels. *Response* recommendations include advice on coping during an ashfall with an emphasis on protecting and conserving water supplies. *Recovery* recommendations range from short-term considerations of clean-up and repair of water supply systems, to longer-term considerations of rebuilding with an emphasis on greater resilience.

KEYWORDS

Volcanic hazards, volcanic ash, water, agricultural water guidelines, New Zealand, agriculture

1.0 INTRODUCTION

The aim of this project was to characterise the vulnerability of farm water supplies in New Zealand to volcanic ashfall, and to make management recommendations to reduce this vulnerability. In this report, we have reviewed the literature on the impacts of volcanic eruptions on rural water supplies worldwide; characterised the water use regimes and identified the vulnerability of the water supply systems of eight case study farms from across the North Island, New Zealand; constructed a ‘vulnerability model’ from the findings of these case studies; reviewed international agricultural water quality guidelines; and finally, made a series of management recommendations for reducing vulnerability of farms to a volcanic eruption.

Water demands of modern farms are wide-ranging, and include stock watering, irrigation and cleaning as well as the household supply. With increasing productivity on most New Zealand farms, water demands have increased over time and are likely to continue to do so in the future (especially with a high rate of conversion to dairy farming). This increasing dependence on water supplies makes it important to understand their vulnerability to volcanic and other natural hazards and to identify mitigation strategies.

It is well-established that even small quantities of volcanic ashfall can disrupt water supplies. Impacts include physical blockages of intake structures by ash, damage due to abrasion or corrosion, and increased levels of turbidity, acidity and soluble components caused by the suspension of ash in water. Indirect impacts include water shortages caused by the increased water demand for cleanup (Stewart et al., 2006; Blong, 1984). However, most studies in this area have focused on the urban environment, often on comparatively large-scale water supply, sewerage and storm water systems (Blong et al., 1984; Johnston et al., 2000). In general there has been little attention given to the impact of volcanic ash on farm water supplies, other than a recent literature review and modelling study (Stewart et al., 2006) which considered impacts of volcanic ashfall on rain-fed roof water tanks typical of rural households in New Zealand.

Other volcanic hazards such as lahars, pyroclastic flows and lava flows also have the potential to damage or contaminate farm water supplies. For instance, during the 2006 eruption of Merapi volcano in Java, a block-and-ash flow devastated part of Kaliadem village. Thousands of people lost their water supply as a result of damage to springs and other parts of the distribution system such as pipes (Wilson et al., 2007). These hazards are beyond the scope of this report and are not discussed further.

1.1 Volcanic hazards in the central North Island

All of New Zealand’s potentially active volcanoes (many of which are located in the Taupo Volcanic Zone in the central North Island; Figure 1.1) are capable of producing explosive eruptions. Many of these volcanoes could potentially erupt in such a manner that distributes volcanic ash across the North Island and beyond. Volcanic ash is the most widely-distributed product of explosive volcanic eruptions, with even relatively small explosive eruptions potentially distributing ash hundreds of kilometres distance from the volcano. Much of New

Zealand's highly productive farmland is also located within the central North Island, particularly in the Waikato, Bay of Plenty, Taranaki, Hawke's Bay and Manawatu. All of these regions are vulnerable to volcanic ash hazards due to their relatively close proximity to the numerous volcanic centres and New Zealand's variable climatic conditions.

Volcanism in the central North Island is dominated by the Taupo Volcanic Zone (TVZ), and Taranaki volcano (Figure 1.1). The TVZ extends southward from White Island, in the Bay of Plenty, to Ruapehu volcano, and has been active for ~1.6Ma. It is one of the most active (in terms of frequency and material erupted) volcanic zones on Earth, with the total erupted volume of pyroclastic material estimated to be 15-20,000 km^3 (Wilson et al., 1995). The broad range of volcanism means that the magnitude of possible eruptions range from minor andesitic events (such as the 1995-1996 Ruapehu eruptions, which had significant effects on agriculture in the region despite their small size), to a plinian rhyolitic event (such as the 1.8 ka Taupo eruption).

1.1.1 Cone volcanoes

Whilst an eruption is possible from any of the active volcanoes in the central North Island, it is more likely the next eruption will be from one of the central North Island cone volcanoes due to their higher eruptive frequency. These volcanoes are characterised by frequent eruptive activity (e.g. Wilson et al., 1995; Neall and Alloway, 1996; Neall, 2003; Cronin and Neall, 1997; Alloway et al., 1995). Future eruptive episodes may be effusive (i.e. development of lava flows and domes which potentially could produce block and ash flows and debris flows during collapse events), or explosive, with small to large explosive eruptions producing ashfalls, pyroclastic flows or lahars.

Volcanic hazards from New Zealand's cone volcanoes can be grouped into two categories:

- Hazards from ground-hugging flows (lava flows, lava domes, pyroclastic flows, lateral blasts, landslides, lahars and associated floods).
- Hazards associated with the injection of pyroclastic material and gases into the air (ashfalls and volcanic gases).

1.1.1.1 Ruapehu Volcano

Ruapehu Volcano (Figure 1.1) is one of New Zealand's most frequently active volcanoes. It is a complex composite andesite volcano built in at least four cone-building episodes involving both central (summit) and flank events during the last 260 000 years. The volcano rises to 2797 m and recent activity has been from a single vent occupied by Crater Lake. Major phreatomagmatic eruptions have occurred in 1969, 1971, 1975, 1995, 1996 and 2007 (Cronin et al., 1996). Volcanic ash from prehistoric eruptions has been found in lake sediment cores in Taranaki, Hawke's Bay and Auckland, suggesting that ashfall hazards from Ruapehu volcano could potentially affect much of the North Island (Froggatt and Lowe, 1990; Sandiford et al., 2001; Eden et al., 1993). The 1995-1996 eruptive episode caused widespread and substantial disruption and economic losses to New Zealand despite its relatively small size (Johnston et al., 2000).

1.1.1.2 Tongariro Volcano

The multiple stratovolcano Tongariro includes the satellite cone of Ngauruhoe, which commenced erupting about 2,500 years ago. The last major eruption of Ngauruhoe was on 19 February 1975, when strong explosive activity sent eruption columns to 10 km and pyroclastic flows moved down the flanks (Hobden et al., 2002).

Episodes of vigorous cone growth occurred between 210-200 ka and 130-70 ka, and from 25 ka to the present day. Cronin and Neall (1997) have summarised the recent eruptive history of Tongariro as follows:

- *22.5 - 10 ka:*	One large volume, large magnitude eruption
- *10 - 9.7 ka*:	Very frequent (one eruption at least every 50 years) large volume, large magnitude eruptions
- *9.7 ka - present*:	Frequent low volume, low magnitude eruptions.

1.1.1.3 Taranaki Volcano

Taranaki Volcano represents the primary volcanic hazard to farm water supplies in the Taranaki region, given its close proximity and frequent eruptive activity in the past. Recent studies also indicate ashfall from Taranaki Volcano has impacted much of the North Island, including Auckland and Hawke's Bay (Turner et al., 2007). The volcano has been active for about 130,000 years. The most recent eruptive episode was the relatively small Tahurangi eruptive episode in ~1755 A.D. The much larger Burrell eruptive episode occurred in 1655 A.D. (Neall, 2003).

Between 28 ka and 3 ka at least 76 eruptions (>10^7 m^3) producing widespread ashfall have occurred, giving a minimum eruption frequency of one large eruption every 330 years. It is likely that frequent smaller eruptions have also occurred (similar to the magnitude of the 1995/96 Ruapehu eruptions) that have left no traces in the stratigraphy. Eruptions from Taranaki volcano appear to be clustered rather than occurring at regular intervals (Neall and Alloway, 1993). This is supported by new unpublished data which suggests the eruptive record of Taranaki Volcano may have been dramatically underestimated (S. Cronin, pers comm., 2007). For example, the most recent ash eruption of Taranaki (~1755 A.D.) was the culmination of eight eruptions in the preceding 300 years, including a large eruption (the Burrell eruptive episode) which distributed ash across eastern Taranaki in approximately 1655 A.D. Taranaki Volcano is thus regarded as simply in a period of quiescence that has lasted for the past 200 years. It is considered extremely likely to erupt again in the future.

1.1.1.4 Caldera Volcanoes

New Zealand caldera volcanoes such as Taupo and Okataina (which includes Tarawera) have a history of infrequent but moderate to large eruptions. The caldera-forming eruptions typically create collapse structures 10-25 km in diameter and deposit >100 km^3 of ash and pumice. They are also capable of producing moderate to large eruptions (1-10 km^3) between caldera collapse events, such as the 1315 A.D. Kaharoa eruption.

Eruptions from these volcanoes are usually significantly larger than from the cone volcanoes and have the potential to significantly impact much of the central North Island and associated water supplies. The Okataina and Taupo volcanoes have been the most active over the past several thousand years and are discussed below.

1.1.1.5 Okataina Volcanic Centre

Okataina Volcanic Centre (OVC) lies east of Rotorua and includes the large rhyolite complexes of Haroharo and Tarawera, with other centres at Mt Edgecumbe, Okareka and Rotoma. During the last 22,000 years approximately 80 km^3 of magma has been erupted. The most recent eruption was on 10 June 1886 when Tarawera erupted, forming the Tarawera Rift (Leonard et al., 2002).

In contrast to other New Zealand volcanoes such as Ngauruhoe and White Island which have relatively small eruptions every few months or years, the volcanoes at OVC have erupted at intervals which have varied between 700 and 3000 years. However, when eruptions do take place at OVC, they are 100 to 10,000 times larger than those at White Island or Ngauruhoe (Nairn, 2002). It is the size of most Okataina eruptions, despite their infrequency, that creates a significant volcanic hazard in the Bay of Plenty region (Nairn, 2002).

1.1.1.6 Taupo Volcanic Centre

The Taupo Volcanic Centre consists of a large basin, about 50 km across and 300-500 m deep. TVC has been sporadically active over the last ~300 ka, and in that time it has shown a random pattern of exceptionally large events interspersed by smaller eruptions. In particular the Taupo Volcanic Centre has been frequently and voluminously active in the past ~65 ka, with approximately 30 major eruptions, at intervals of between 50 and 5000 years (Sutton et al., 2000; Wilson et al., 1986; Houghton et al., 1995). The largest (Oruanui) event at 22.6 ka erupted ~400 km^3 of magma (Wilson et al., 1988). The last major eruption (Taupo eruption) occurred 1800 years ago (Wilson et al., 1988). There is no obvious pattern to these eruptions that would suggest when or where the next event might occur (Stirling and Wilson, 2002).

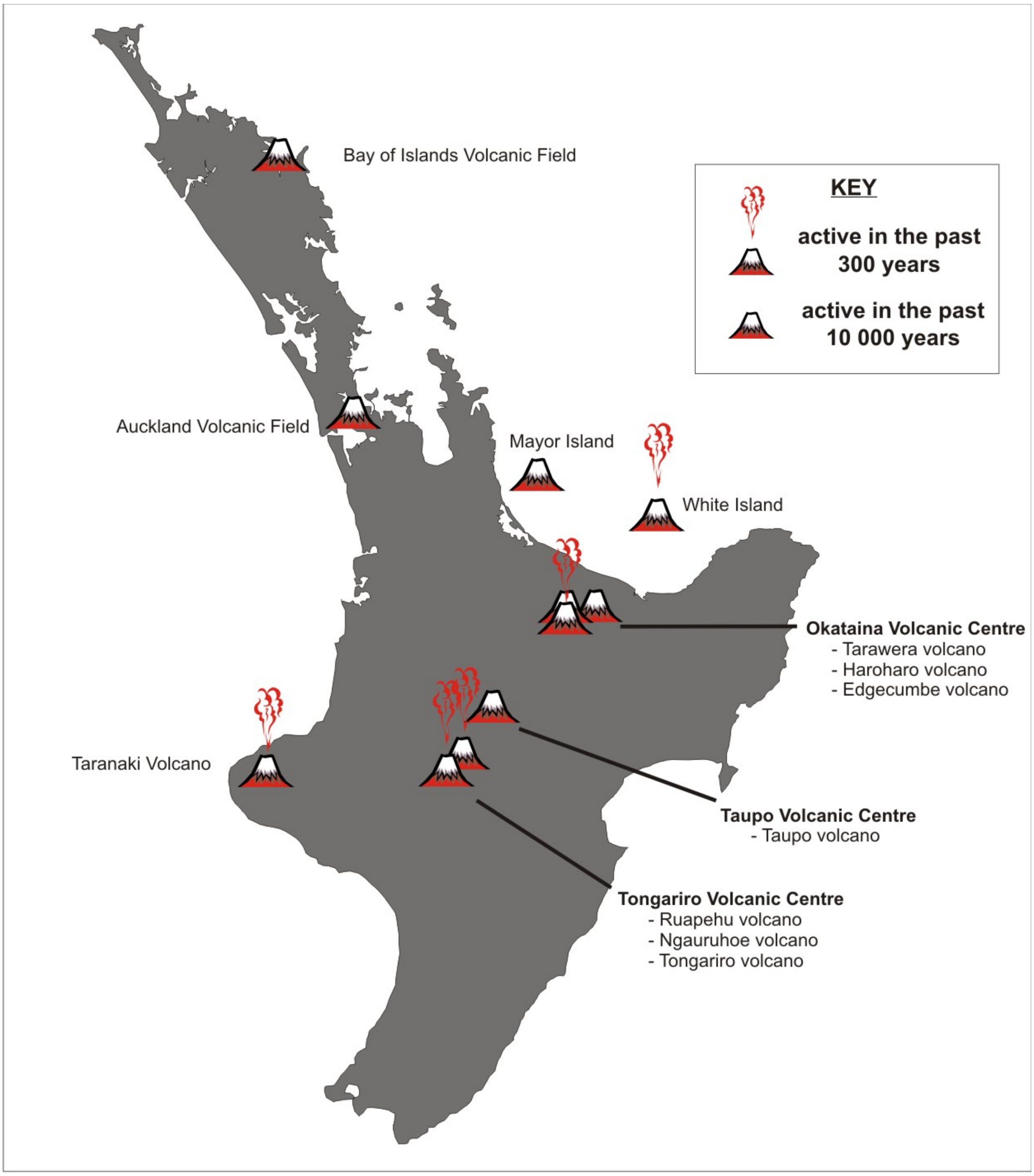


Figure 1.1 Volcanic centres in the North Island, New Zealand.

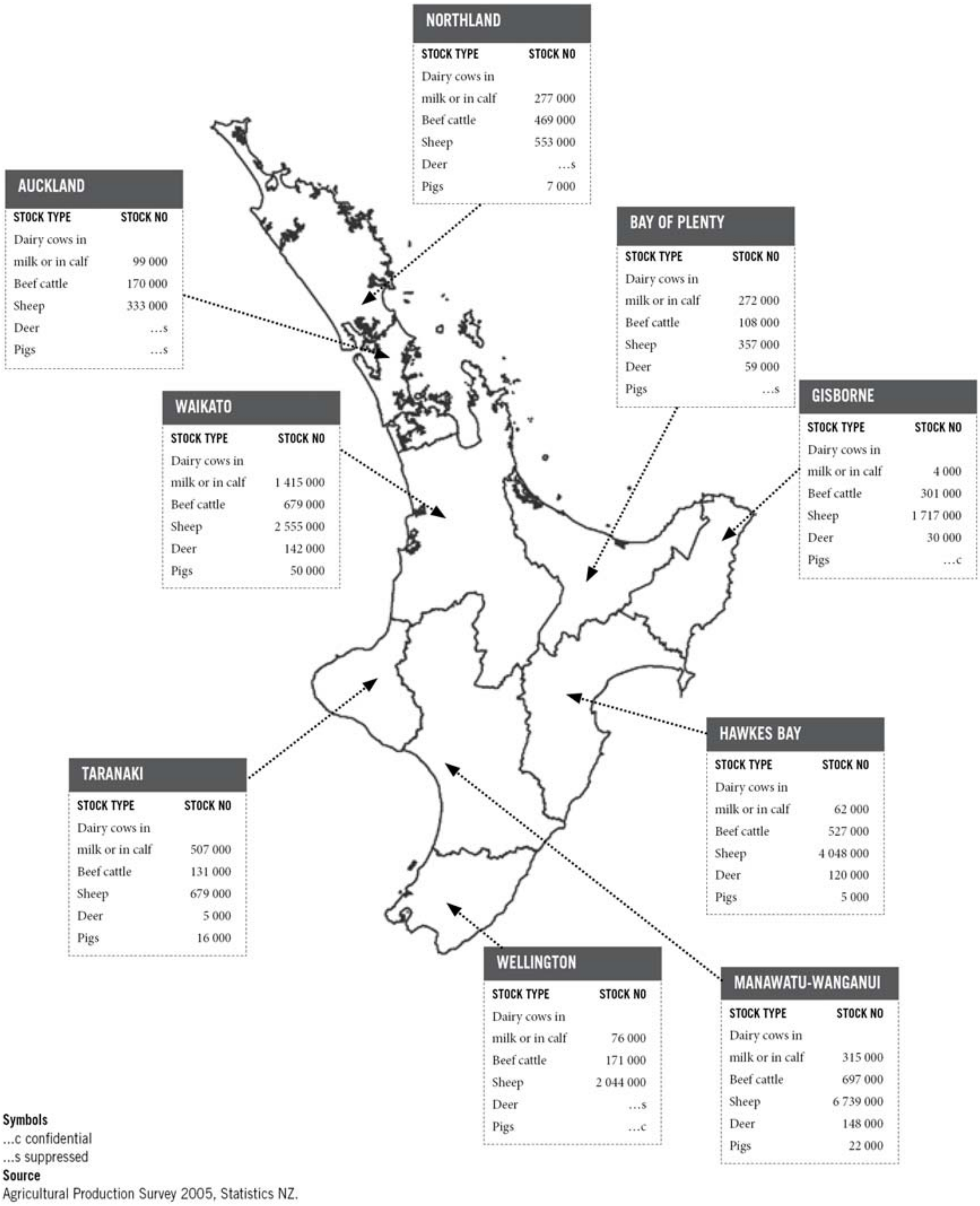
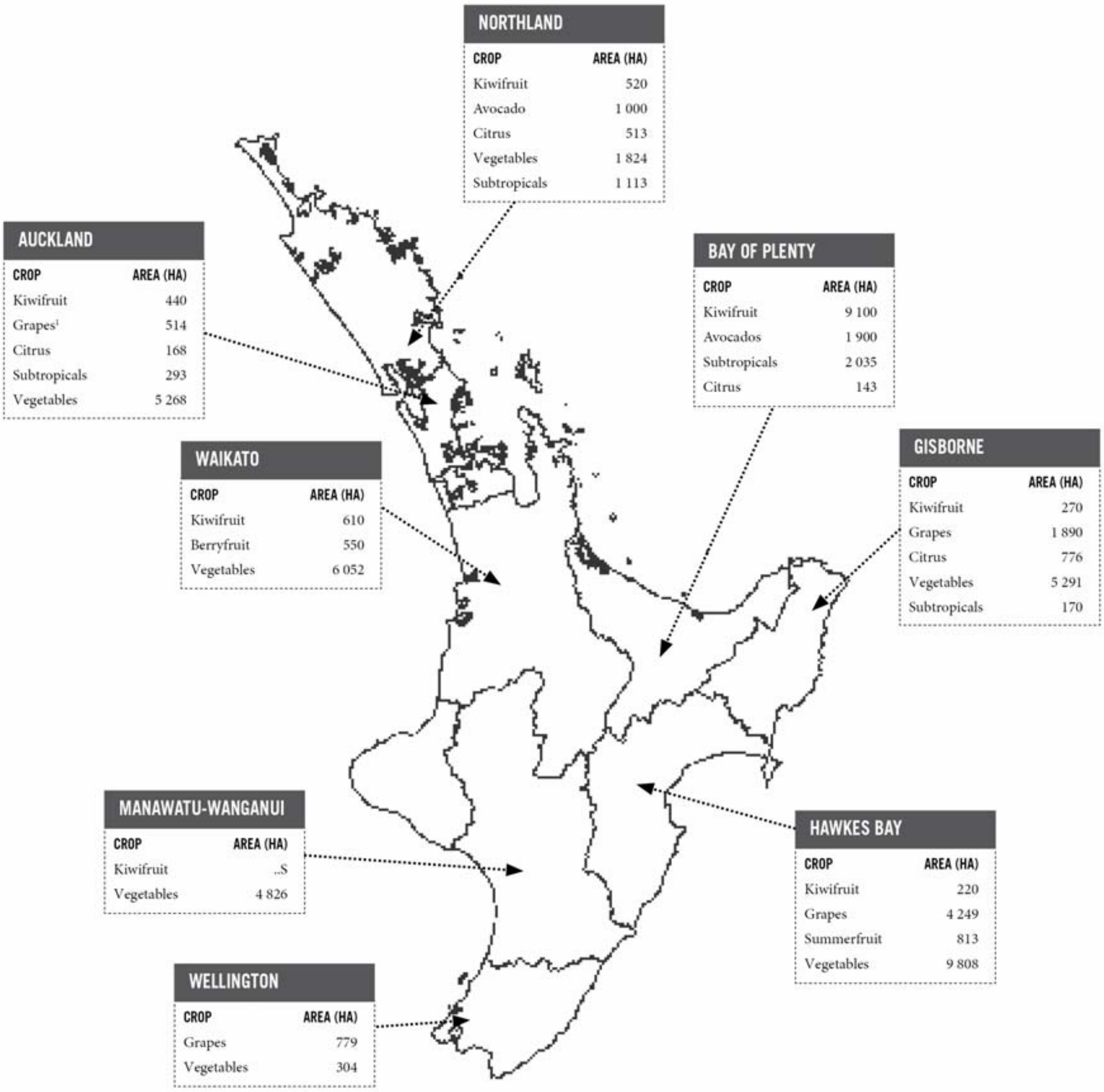


Figure 1.2 North Island agricultural livestock production statistics, June 2005 (MAF Sheep and Beef Monitoring Report, 2006)



Source
Agricultural Production Survey, June 2005, Statistics NZ.
[1] Grape statistics have been sourced from the New Zealand Winegrowers Vineyard Surveys.
Symbol
..S Suppressed

Figure 1.3 North Island horticulture production statistics, June 2005 (MAF Horticulture Monitoring Report, 2006)

2.0 IMPACTS OF VOLCANIC HAZARDS ON FARM WATER SUPPLIES: INFORMATION REVIEW

2.1 Overview

Volcanic ash (see Appendix 1 for further information) is the most widely-distributed product of volcanic eruptions. Historically ashfalls have been responsible for the majority of impacts on water supply systems. A recent review of volcanic ash impacts on water supplies was carried out by Stewart et al. (2006); the focus was on municipal water supply systems. Witham et al. (2005) reviewed the literature on volcanic ash-leachates, and included an evaluation of the use of ash-leachate data in environmental impact assessment. These previous reviews have been used as a basis for the following review in which we consider the impacts of ashfall on agricultural water supplies.

2.2 General impacts of volcanic ash on water supplies

Impacts on water supplies have been reported subsequent to a number of historic eruptions. Studies describing these impacts are described fully in Stewart et al. (2006) and a summary table from this report is reproduced here as Table 2.1. Effects include physical blockages of intake structures by ash and damage due to abrasion or corrosion of equipment. The major public health concerns are thought to be the potential for outbreaks of waterborne infectious diseases due to the inhibition of disinfection by high levels of turbidity, and elevated concentrations of fluoride increasing risks of dental and skeletal fluorosis. Physical impacts of ash and problems due to high levels of acidity, turbidity and fluoride are well-documented; however, little attention has been paid to the other soluble components of volcanic ashfall and their potential consequences for water supplies.

Table 2.1 Summary of volcanic ash impacts on water supplies (from Stewart et al., 2006)

Impact	Comment	Examples	Reference
Physical impacts of ash	Ash can clog intake structures	Irazú, Costa Rica (1963)	**Blong (1984)**
	Abrasive nature of ash can cause increased wear on equipment	Fine ash clogged filters at the intake to San José's river-fed water supply. Water had to be trucked in.	**Blong (1984)**
	Corrosive nature of ash can damage electrical equipment and corrode metallic structures such as pipes	Mt Ruapehu, New Zealand (1995/96) Rotorua's water supply cut when a resident washed ash into a power transformer and cut electricity supply to pumps.	**Johnston (1997)**
Water shortages	Heavy demands on water for clean-up of ashfall	Mt Spurr Volcano, Alaska (1992) City of Anchorage experienced severe water shortages because of demand for ash cleanup; one reservoir completely emptied; no water available for firefighting.	**Johnston (1997)**
Increased turbidity	Suspension of ash in water increases turbidity; this can make water undrinkable and compromise terminal disinfection	Mt St Helens, USA (1980) Increased occurrence of waterborne Giardiasis due to turbidity from volcanic ash inhibiting disinfection.	**Weniger et al. (1983)**
Acidification	Surface coatings on fresh ash are highly acidic, due to adsorbed volcanic aerosols H_2SO_4, HCl, HF	Copahue Volcano, Argentina (2000) pH 2.1 reported in nearby Lake Caviahue; pH 2.5 reported in streams 60 km from source.	**Smithsonian Institution (2000)**
Fluoride contamination	Fluoride from HF readily leached from fresh ash; can exceed safe limits for people and animals	Lopevi, Vanuatu (2003) 10 mg/L fluoride reported in rainwater-fed tanks.	**Cronin et al. (2003b)**
		Hekla, Iceland (1947–1948) 9.5 mg/L fluoride recorded in Merkjá stream.	**Stefánsson and Sigurjónsson (1957)**
Contamination by other soluble components	Freshly-fallen ash releases soluble components into receiving waters	Copahue Volcano, Argentina (2000) Increased concentrations of iron, fluoride, sulphate in water supplies.	**Smithsonian Institution (2000)**
	Many studies made of ashfall leachates, but few have focused on receiving waters		
	Major leachate components: sulphate, Cl, Na, Ca, Mg, F	Soufrière Hills, Montserrat (1997) Increased concentrations of sulphate, chloride and fluoride	**Smithsonian Institution (1997)**
	Minor leachate components: Mn, Zn, Ba, Se, Br, B, Al, Si, Cd, Pb, As, Cu, Fe		

2.3 Reported impacts: case studies of volcanic ashfall impacts on agricultural water supplies

For this report we located published reports of the impacts of volcanic ashfall specifically on farm water supplies and agricultural water uses. From the outset it was clear that there is a general lack of published information in this area. The United States Geological Survey (USGS) website is a comprehensive and authoritative resource on the impacts of ashfall hazards, but contains little coverage of effects on agricultural water use. Similarly, while the New Zealand Ministry of Agriculture and Forestry (MAF) website has wide coverage of the impacts of volcanic eruptions on agriculture, horticulture and forestry in New Zealand, it contains very little specific information on the impacts on water supplies for these primary industries.

Two particular eruptions have been studied with respect to impacts on agricultural or rural water supplies: the 1980 eruption of Mt St Helens, in the northwestern United States, and the 1991 eruption (VEI 4+) of Hudson Volcano, in southern Chile. Information on impacts of the Hudson eruption comes both from reports published at the time, and also from a field visit conducted by the authors of this report in January 2008 (Wilson et al., 2008).

2.3.1 1991 eruption of Hudson volcano, Chile

After 20 years of quiescence, Hudson volcano (Cerro Hudson) in the southern Andean volcanic zone ejected basaltic ash during a phreatomagmatic, partially subglacial eruption that had prolonged paroxysmal activity between 12-15 August 1991. This magnitude VEI 4+ Plinian eruption produced at least 4 km^3 and possibly as much as 17 km^3 bulk volume of ash (Naranjo and Stern, 1998) and was one of the largest eruptions of the 20th century. Due to prevailing winds, most of the ash deposits fell to the east through the Patagonian meseta, reaching the Atlantic coastal zone. The depth of deposited tephra exceeded 80 cm in areas proximal to the volcano. Los Antiguos village, located approximately 100 km southeast of Hudson volcano, was covered by a 20 cm layer of ash. Ash was deposited over a wide sector of Santa Cruz province in Patagonia, with 2 cm falls being recorded at the Atlantic coast and trace quantities deposited in the Falkland Islands (Inbar et al., 1995).

The most severe agricultural impacts were recorded in the Los Antiguos Valley. Heavy stock losses were reported, and horticulture was disrupted with the entire 250-ton cherry crop lost the year of the eruption (Inbar et al., 1995). Over larger areas, there were reports of sheep herd numbers declining and farms being abandoned (La Nacion, 1993). Impacts on sheep herds are believed to have occurred as far away as the Falkland Islands, despite only traces of ashfall recorded there.

In areas with extensive systems of open channel flood irrigation systems, such as Los Antiguos and Puerto Ingeniero Ibáñez (Figures 2.1 and 2.2), irrigation ditches reportedly became blocked and had to be dug out manually. Problems persisted for a period of one to two years after the eruption owing to windblown ash recontaminating ditches. There were reportedly some problems with abrasional and corrosional damage to metal fittings in irrigation systems.

Figure 2.1 Intake from stream for flood irrigation system, Puerto Ingeniero Ibáñez, Chile

A further major problem was with livestock drinking water, as in general livestock drink from ponds. Watering holes became clogged with ash, and turned to mud. These then became a trap for animals when they attempted to get access to the watering holes; their fleeces became saturated with ashy mud (Figure 9) and this added to their exhaustion and stress (Bitschene et al., 1993).

Figure 2.2 Open channel flood irrigation system, Puerto Ingeniero Ibáñez, Chile

In general, municipal supplies were relatively unaffected by the ashfall as they are derived from either springs or groundwater wells. In Los Antiguos, water supply wells are dug to a depth of at least 6 metres, and the water supply was reportedly continuous (Inbar et al., 1995). However, an exception to this was in the coastal zone of Santa Cruz, where there is very little surface water and a heavy reliance on groundwater extracted using wind-driven pumps (Figure 2.3). Ash damaged the bearings of the windmills and thus disabled the water supply.

Figure 2.3 Wind-driven groundwater pump, Tres Cerros, coastal Santa Cruz

2.3.2 1980 eruption of Mt St Helens

There were significant impacts on agriculture in Washington State following the May 1980 Mt St Helens eruption, although damage was much less than initially expected (Warrick et al., 1981). The initial surprise of the ashfall was compounded by lack of information, rumour and speculation about the likely impacts and appropriate responses. Farmers and experts alike could not readily identify the proper course of action to mitigate effects. Mitigation strategies evolved out of trial and error, rather than authoritative information. With high stakes involved, such as farmers' livelihoods, such experimentation was accompanied by concern and often high anxiety (Warrick et al., 1981).

Kittitas County, located around 150 km from the volcano, had irrigation systems fed by surface waters and distribution by open irrigation ditches. This region received between 5-20 mm ashfall. Irrigation systems suffered a range of effects from this level of ashfall (Warrick et al., 1981). Electrical panels shorted out and pump motor components (such as brushes and commutators) had increased wear, and seals and bearings on sprinkler heads and pumps wore down faster also. Other effects were that worn sprinkler heads increased the load on pump motors, and there were also some reports of ash clogging sprinkler heads. Farmers were advised to keep systems running at a minimum rate to keep flushing ash through the system (FEMA, 1980).

Other methods used in mitigation were to keep switch panels clear, and to attempt to keep ash out of motors in any way possible. Blowing ash off with air compressors was a common method. Farmers were also advised to run water destined for pumped irrigation systems through settling basins before it reached the pumps.

There were problems with rapid sedimentation of irrigation ditches in Kittitas County. Larger ditches could be flushed easily, but smaller ditches needed to be shovelled out (Warrick et al., 1981).

Ritzville County is located 300 km distant from Mt St Helens, but received a greater depth of ashfall (20-40 mm) due to variations in the ash plume and climatic conditions. However, irrigation systems in this region were disrupted less than in Kittitas County, because they are primarily fed by groundwater, with water from bores being pumped directly to sprinkler systems. Thus there was no direct ash contamination of the water supply.

There were, however, some problems when ash penetrated electrical panels and switchboards and caused electrical shorting, following heavy rain on 25-26 May 1980 which increased the conductivity of the ash. This disabled pumps and curtailed irrigation operations.

The fate of the deposited ash was also studied (Warrick et al., 1981). The ash was found to form a layer on the soil surface within a few days of the eruption, which remained in place for some time unless disturbed by erosion or cultivation equipment. This layer retarded capillary action and evaporation, slowing infiltration and leading to excess runoff. Irrigation rates were therefore reduced to prevent soil erosion. Rainfall was reportedly a major aid in the recovery process, washing ash from crops, settling unconsolidated ash deposits and increasing their integration into the soil profile.

The contrasting experiences in Kittitas and Ritzville counties illustrate the relative vulnerabilities of groundwater and surface water, and the systems they support, to volcanic ashfall.

2.4 Inferred impacts from other studies

The following studies were not directly concerned with impacts of volcanic ash on agricultural water supplies, but are included here (covered under various topics) as their findings are likely to be relevant.

2.4.1 Disruption of electricity supply

The vulnerability of electrical power supply networks to volcanic hazards, particularly volcanic ashfall, is well documented (Sarkinen and Wiitala, 1981; Warrick et al., 1981; Johnston, 1997; Heikin et al., 1995). Refer to Appendix 3 for more information. Increasingly high dependence of modern farming on electricity, particularly for pumping water, makes disruption of electrical supplies a major vulnerability for farms. If the electricity supplies are lost for an extended period, and if there is no backup power generation, water supplies reliant on electrical pumps will be disrupted creating significant implications for human and animal welfare, irrigation, and dairy shed hygiene.

Damage to electrical equipment was a commonly reported cause of irrigation supply failure to farmers impacted by the 1980 Mt St Helens eruption (Warrick et al., 1981).

2.4.2 Damage to farm water supply infrastructure

Because of its highly abrasive and corrosive nature, ash can damage intake structures and increase levels of wear on other plant or machinery it comes into contact with. Ash washed into the upper Tongariro River during the 1995/1996 Ruapehu eruptions caused considerable abrasional damage to turbines at the Rangipo hydroelectric power station (Malcolm and van Rossen, 1997). Such mechanical fragility has led to speculation that ash-laden water will damage water pumps if pumped through them (Neild et al., 1998).

2.4.3 Rainwater-fed household water supplies

Many households in rural areas rely on rainwater tanks with a roof catchment. These are particularly vulnerable to aerial contamination because of their large surface area to volume ratio. Unless downpipes leading to water storage tanks are disconnected, contamination of roof-fed supplies can be expected (Johnston, 1997b). Stewart et al. (2006) modeled contamination scenarios for different thicknesses of ash on a range of water supplies, and found that as little as 1 mm ashfall will probably be sufficient to make roof-fed tank water undrinkable due to a bitter, metallic taste, and possibly also toxic.

2.4.4 District water supplies and treatment plants

Some farms are supplied by district or regional water supply schemes. Reported impacts on water supply schemes include (Johnston et al., 2004):

- suspended ash blocking intake filters, particularly for river-fed water supplies;
- suspended ash in water can cause wear and tear on components of water treatment plants due to its abrasive and corrosive nature;
- high turbidity levels can compromise the effectiveness of disinfection of pathogenic micro-organisms;
- high water demand for cleanup depleting water storage in reservoirs;
- contamination of water supplies with high levels of turbidity and acidity (low pH).

The suspension of volcanic ash in water can easily exceed acceptable limits for turbidity. Following the May 1980 eruption of Mt St Helens in the USA, increases in the occurrence of waterborne *Giardiasis* were reported for months afterwards, as far away as Montana. These events were linked to heavy rainfall washing the deposited ash into water supplies (Weniger et al., 1983).

Suspended ash within surface water supplies can block intake structures, as occurred during the 1963 eruption of Irazú in Costa Rica when fine ash clogged filters at the intake to the capital city's river-fed water supply. As a result, water needed to be brought in by truck to San José (Blong, 1984).

On 23 November 1945, the water supply for the community of Taumarunui, New Zealand (population 2700), 50 km north-northwest of the vent at Ruapehu, was disrupted by large quantity of ash being washed into the Wanganui River where the sediment blocked water-intake filters. Pumping was reduced from 90,000 L/h to 32,000 L/h due to the high turbidity of the river water. Eventually filtration became impossible and pumping ceased. By the following day water quality had improved sufficiently for pumping to resume (Johnston et al., 2000). Numerous disruptions to both water and electricity supply were reported over several months at Whakapapa, 9 km north of the vent, due to ash in the streams feeding the water supply and ash in the electricity generating plant. Staff members reported that the fine ash in the stream made the filters useless and water was no longer able to pass through the settling ponds. The reworking of ash further affected water supplies in 1946 and during the warmer than average summer of 1955 (Houghton et al., 1987; Johnston et al., 2000).

2.4.5 Increased solvation potential due to acidification of surface water

Many of New Zealand's waters are soft, with moderate to low levels of alkalinity and pH. These properties can give the water a high solvation potential, so that the water may dissolve metals from plumbing fittings if it lies in the plumbing, for example, overnight (MOH, 2008). Water with a pH<5.0 can also have an increased tendency to be corrosive towards concrete.

Freshly-fallen volcanic ashfall frequently is capable of acidifying waters, and may therefore increase their solvation potential., This may in turn increase the dissolution of metals from plumbing fittings, which can cause a health hazard in household supplies if fittings contain lead, and may damage metallic fittings.

However, most pipes used in farm water supply systems are made of PVC or alkathene (polythene), which are corrosion-resistant.

This topic is complex and further analysis is beyond the scope of this study.

2.4.6 Water demands during cleanup phase

Water usage can be expected to increase significantly as affected communities begin cleanup operations (Johnston, 1997b; Johnston et al., 2004).

Following the 1980 Mt St Helens eruption, there were fears that ash deposits on pastures would cause harmful effects on animal health in Kittitas County. Farmers who had access to irrigation water irrigated pastures heavily in an attempt to settle and compact the ash to decrease the respiratory hazard to livestock. Some orchardists in the Spokane Valley attempted to wash off trees using hoses with nozzles (Warrick et al., 1981).

The August 1992 eruption of Mt Spurr volcano, Alaska, deposited about 3 mm of ash on the city of Anchorage. The cleanup of ash resulted in excessive demands for water, increasing the peak demand by 70%. This in turn caused widespread pressure and supply problems which led to several storage reservoirs dropping to dangerously low levels, and at least one reservoir being completely emptied, with insufficient reserves for firefighting had they been required (Johnston, 1997b; Johnston et al., 2004).

2.5 Summary of literature review

Two particular eruptions have been studied with respect to impacts on agricultural or rural water supplies: the 1980 eruption of Mt St Helens, and the 1991 eruption (VEI 4+) of Hudson Volcano, in Chile. For these relatively large eruptions, it is clear that physical impacts of ashfall tend to overwhelm more subtle chemical impacts (such as changes to water quality). Particular points of vulnerability are open systems such as irrigation channels and drinking water ponds, which become clogged with ash. In the case of Hudson Volcano, redistribution of ash by strong winds in the area (Santa Cruz province, Patagonia) led to continuing problems lasting for years afterwards. Other problems included airborne ash shorting out switch panels and causing increased wear on pumps, and clogging sprinkler heads.

Impacts of ash from the Mt St Helens eruption on two contrasting regions showed that as expected, groundwater-fed systems are much more resilient to volcanic ash than surface water-fed systems. However, even groundwater systems can be vulnerable to ashfalls; in Ritzville Country, ashfall still caused disruption to groundwater-fed irrigation systems as airborne ash disabled pumps by shorting out electrical panels. In coastal Santa Cruz province, Patagonia, windmills used to extract groundwater were disabled by airborne ash from the 1991 eruption of Hudson Volcano.

3.0 CHARACTERISATION AND VULNERABILITY ASSESSMENT OF FARM WATER SUPPLIES

3.1 Overview

Agriculture is critically dependent on water quality and quantity. Water supplies may be obtained from both surface[1] and groundwater[2] sources. Rainfall, along with other important factors, has a significant influence on the type of farming that particular regions can sustain (Figure 3.1). However, as farmers strive to increase profitability, there has been a large

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[1] Surface water is defined here as any water resource that is exposed to the atmosphere, such as rivers, reservoirs, and lakes. Surface water supplies can be accessed at any point where there is sufficient volume for extraction.

[2] Groundwater is defined here as rainwater that has travelled through the soil to underground aquifers (areas of fractured rocks or porous sediments such as sand and gravel). Access can be gained to groundwater through wells or (less commonly) where it outcrops at the earth's surface at springs.

increase in demand for water. This has put increasing pressure on water resources, particularly for irrigation and stock water, requiring that the resource be actively managed. Water resources under the Resource Management Act 1990 (RMA) are generally managed by councils. The RMA allows individuals to take water for stock drinking water and domestic needs provided it does not, or is not likely to have, an adverse effect on the environment. If farms require a greater allocation of water they must apply for a resource consent (B. Jenkins, *pers comm*., 2007).

Unless a farm extracts significant amounts of ground or surface water requiring a resource consent (i.e. exceeding relevant allocation limits), the managing authority will have no record of that particular extraction. Thus it is difficult to measure water use throughout a district or region, and to assess water supply vulnerability on a regional basis.

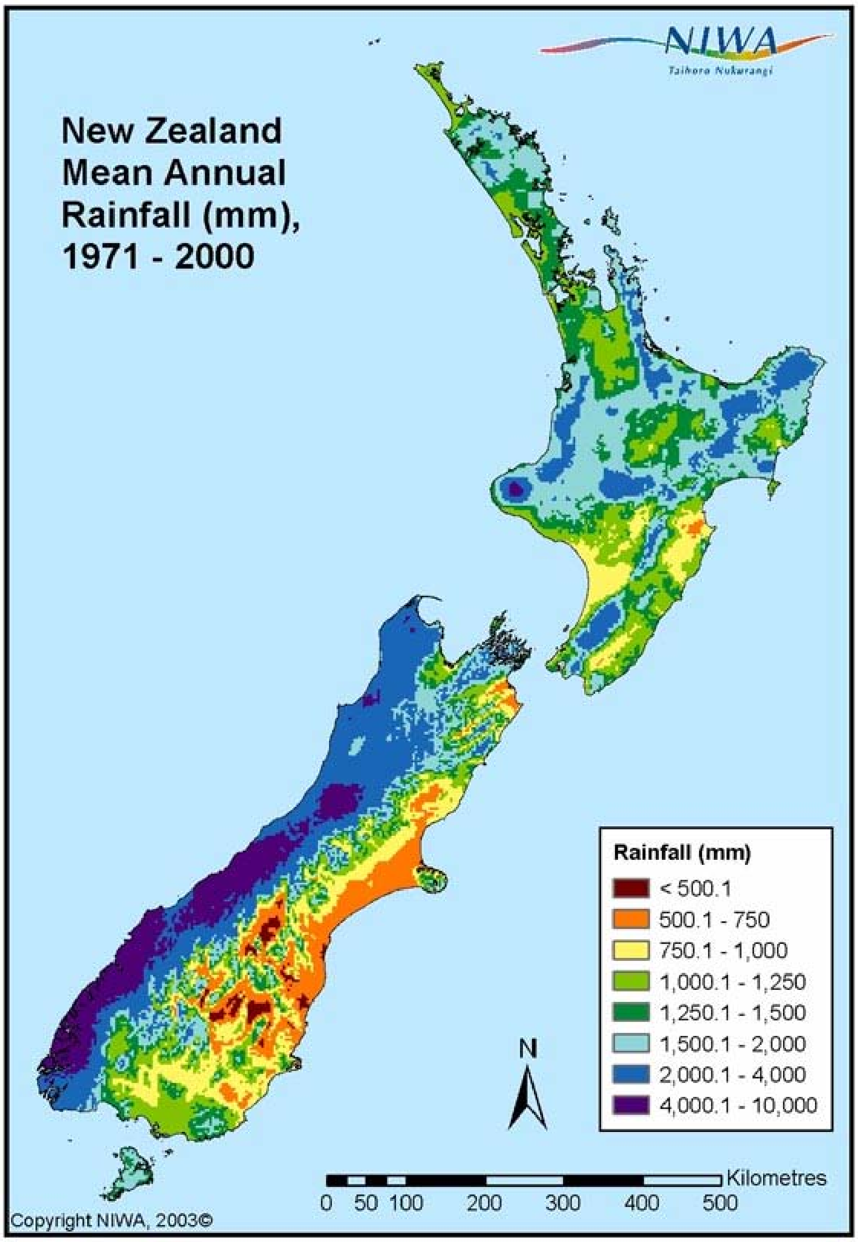

Figure 3.1 Mean annual rainfall in New Zealand (NIWA, 2003)

3.2 Assessment of vulnerability of farm water supplies

Initially an assessment of regional water vulnerability was made using regional council water allocation and monitoring information. Given the difficulties with defining farm water usage at a regional scale, only a brief attempt has been made to give a general picture using water allocation statistics[3]. This information is presented in Appendix 2.

The second vulnerability assessment approach was to investigate water supply usage and vulnerability for individual farms, using a range of case studies. These farms were identified by drawing on personal and professional contacts. The location of these farms is shown in Figure 3.2. The study farms span the diverse range of land uses and water supplies in the central North Island. We decided to cover fewer case studies in more detail, by visiting farms and interviewing farmer and farm managers following a semi-structured interview schedule (Appendix 4) rather than using a broader-scale approach such as a postal questionnaire distributed to a greater number of farms. The interview schedule was designed to assess general farm characteristics, farm water supply system, vulnerability to volcanic hazards and experience with previous natural hazards.

General characteristics of the case study farms are shown in Table 3.1, and their location is shown in Figure 3.2. The farms span a range of locations relative to active volcanoes (such as Study Farm 6, close to Mt Taranaki), to more distally-located (such as Study Farms 1, 2 and 7 in Hawke's Bay). Many of the farms received ashfalls during the 1995/96 Ruapehu eruptions, and interviewees were able to describe their past experiences and any actions they had taken to minimise the impacts.

Field visits were carried out between 2 and 8 May 2007, apart from Study Farm 4, which was the subject of a week-long detailed assessment of its overall vulnerability to volcanic hazards in December 2005. Contact was made with farmers and farm managers several weeks ahead of time, to set up interviews which lasted between one and two hours. Limited tours of the study farms were also made as time permitted.

In addition to information on water supplies, we collected additional data on points of vulnerability to farms. This was considered appropriate given inter-relationships within farm systems. The data collected, much of it based on primary accounts from the 1995/96 Ruapehu eruptions, is rare in volcanic hazard literature so has been included here within the report. Many of the accounts also serve to illustrate the interdependencies water supplies have with other farm input and output processes.

[3] For further details about the management of water resources in each region contact regional councils or refer to respective websites.

Table 3.1 General characteristics of study farms

Study farm	Farm type	Location	Water supply	Date visited
1	Sheep and Beef	Tikokino, Hawke's Bay	Groundwater	2 May 2007
2	Sheep and Beef	Bridge Pa, Hawke's Bay	Surface water (& groundwater)	2 May 2007
3	Sheep and Beef	Western Taupo, Waikato	Surface water	3 May 2007
4	Dairy	Rerewhakaaitu, Bay of Plenty	Groundwater	18 Dec 2005
5	Dairy	Reporoa, Bay of Plenty	District scheme (groundwater)	3 May 2007
6	Dairy	Eltham, Taranaki	District scheme (surface water)	7 May 2007
7	Horticulture: vineyard	Near Hastings, Hawke's Bay	Groundwater	2 May 2007
8	Horticulture: kiwifruit	Cambridge, Waikato	Groundwater	5 May 2007

4.0 STUDY FARM 1: TIKOKINO

4.1 General information

Study Farm 1 is located near Tikokino, in southern Hawke's Bay (Figure 3.2). It is an approximately 650 ha (with a further 325 ha leased) sheep, beef and deer farm running up to 10,000 stock units. Approximately 100 ha are devoted to crops annually. Current livestock numbers are given in Table 3.2. Supplementary feeding occurs during the spring (Table 3.3), between June and August. Shearing of ewes occurs in May and December, hoggets in October and lambs in January. Deer fawning occurs in mid-November to December.

4.1.1 Water supply

The farm is supplied by a shallow 6 m (20 ft) deep, 2 m wide bore with a suction pipe. The water table is at approximately 3 m depth. The bore is approximately 100 m from the northern creek on the farm (Figure 3.3) and only supplies stock drinking water for the farm. Water is pumped to two 20,000 L tanks located at the northern and western ends of the farm (Figure 3.3) for water storage on topographic high points. These tanks feed the stock water troughs by gravity. The troughs are rectangular with a capacity of 200 L and are kept full by a ballcock tap (Figure 3.4). There are still some older-style 400 L troughs, but they can cause problems as deer like to wallow in the troughs; however they are easier to keep clean. The troughs are all concrete, and there are 159 altogether, placed at a frequency of one or two per paddock (blue dots in Figure 3.3).

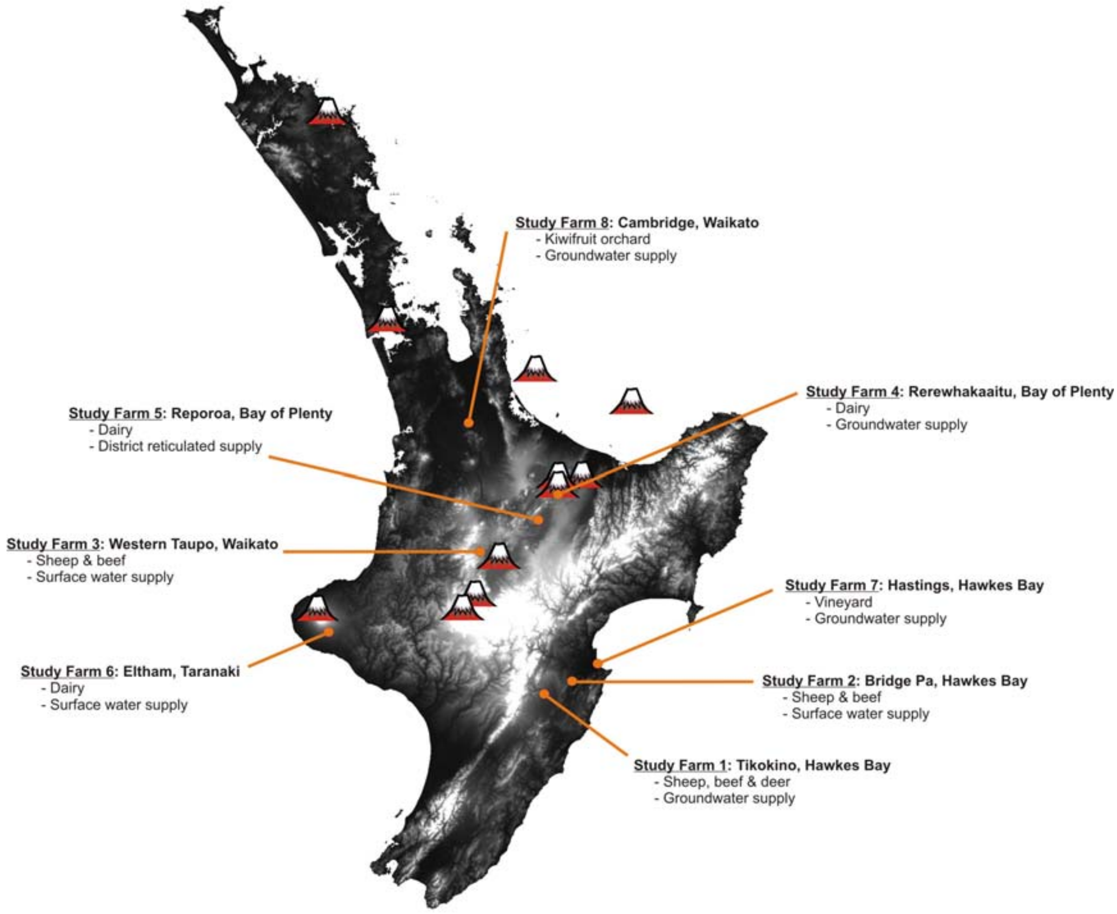

Figure 3.2 Location of study farms

Table 3.2 Livestock numbers and types on Study Farm 1, Hawke's Bay

Sheep	4,400
Beef	1,200
Deer	900

Table 3.3 Supplementary feed produced on Study Farm 1, Hawke's Bay

Silage	300-400 t (dry matter)
Grain (barley and maize)	50 t
Hay	600 round bales

The bore pump is electrically powered. However, it can be run off the PTO on the tractor if required. It is enclosed within a pump shed to protect it from the weather; this should also protect it from ashfalls. In summer, when stock drinking needs are high, the pump is under considerable demand and the farmer estimated could be in operation up to 24 hours per day. In winter, the pump operates on demand to keep the storage tanks full. From past experience, there is one to two days worth of reserve water in the storage tanks during peak water use in the summer, with water flowing out to troughs under gravity.

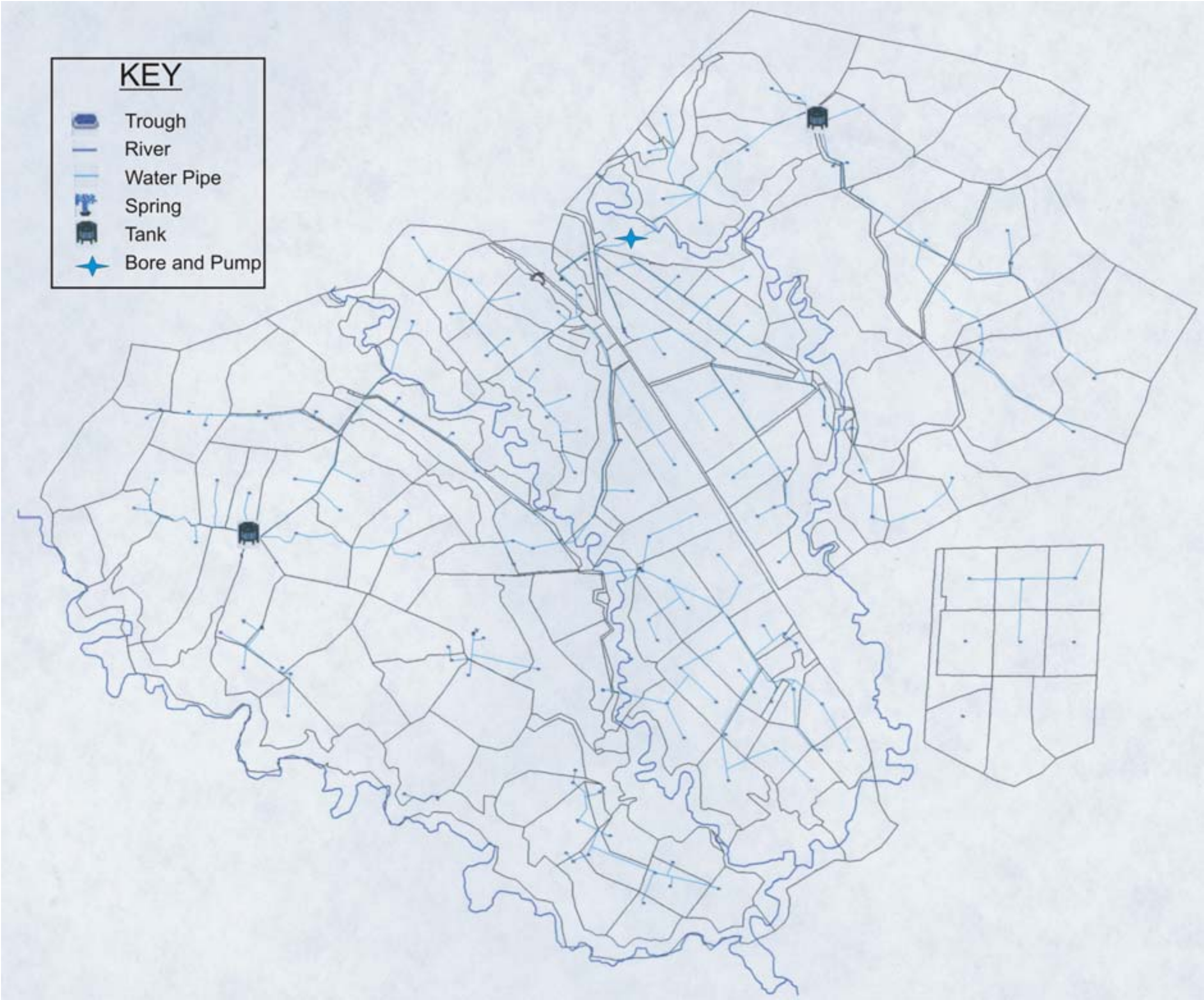

Figure 3.3 Water supply and distribution system, Study Farm 1

There are four dams (small reservoirs) on the farm, although these are not preferred as a water source as stock (deer and cattle in particular) walk into them, eroding their banks and making the water turbid. A number of dams have been filled in as a result. The main dam is still in use and can be linked back into the farm water supply system if required.

Figure 3.4 200 L stock water troughs

There is also a stream on the farm, which is only used for stock water. There has never been a period when this has dried up, even during dry summer periods. This is also used by neighbouring farms.

The homestead is supplied from a 20,000 L rain water tank. This can be disconnected and connected to the farm water supply if required.

There has been significant investment in the water system to build reliability, resiliency and reduce the continued maintenance that was required on the dams. Before this upgrade to the bore (groundwater supply), the farm had relied solely on dams for water supply (Figure 3.5). The farmer estimates spending 0.5 days per week on maintaining the water system and rates it as an essential part of the farming operation.

4.1.1.1 Stock water

Water is essential in summer for stock consumption. In winter the demand for water is greatly reduced, as stock take up more moisture through feeding and lose less through perspiration. Livestock can go for up to several weeks without feed (although they will lose condition), but they are likely to begin suffering potentially irreversible effects after several days without water (Macfarlane et al., 1961; OSH, 2003).

4.1.1.2 Previous problems

The current groundwater supply is very stable and the farmer reported no previous problems.

Figure 3.5 Dam, Study Farm 1

4.1.2 Natural hazard experience

4.1.2.1 Ruapehu eruption, 1995

This farm received an estimated 1-5 mm of ashfall during the 25 September 1995 Ruapehu eruption. The ash fell over a period of several hours, and remained until the next rainfall four or five days later. Sheep were put off eating pasture by the coating of ash. There were no other physical impacts to the livestock, however the farmer noted the sheep were distressed by the lack of feed. Supplementary feed was distributed to the stock, and because of the short duration of the event, this was a satisfactory solution for ensuring the food supply. There was no noticeable impact on the farm's water supply, stock water troughs, or on the household supply.

Despite the general lack of impact on farming operations, the farmer reported he and his family felt a considerable level of uncertainty and nervousness at the time. Radio and television news media was regularly monitored to keep up to date. The farmer considered the most critical information needs to be: firstly, how long the ashfall might continue for, and secondly, the nature of the impacts on livestock. The farmer said that he had waited for official information to be distributed through the media, but didn't receive any official warning. One of the fears held by the farmer was that a much larger ashfall could occur.

The farmer had the following suggestions to make about the type of information that he would have found useful at the time:

- Information on the duration of the ashfall would have assisted with planning the supplementary feed schedule;
- Any information on animal health mitigation;
- Information on impacts of ashfall on the water supply and distribution system; and
- Any information on pasture rehabilitation.

There do not appear to have been any long-term harmful effects from this eruption to this farm. It is possible there were some minor soil fertility benefits from the sulphur-rich ash (see Cronin et al., 1997; 1998).

4.1.3 Seasonal vulnerability

On the basis of the information provided by the farmer about seasonal operations on this farm, the following comments can be made about seasonal vulnerability. Spring would be a difficult time if there was an eruption because this is when supplementary feed is produced. The period in early spring, before grass has grown and there is no supplementary feed left would be difficult; lambing would occur at the same time. Shearing would be a problem in May and December, when ewes are shorn, October with hoggets, and lambs in January. Wool would be full of ash which would probably lower the quality and create significant wear on the combs (see Section 1.4), but it may be possible to scour out. Deer fawning from mid-November to December is also a vulnerable time.

Whilst the diverse water supply (i.e. access to groundwater and surface water supplies which should continue flowing during an ashfall) increases the farm's resilience to manage an ashfall, the key vulnerability of water supplies on this farm is reliance on electrical power for operation of the submersible pump for ground water extraction. If groundwater supplies were disrupted there would be sufficient storage in the tanks for stock for at least several days in summer conditions. If it was cooler and there was sufficient moisture in the pasture then water supplies may extend for up to 1-2 weeks. Reserve water storage in the form of dams would also be vulnerable to contamination by ashfall. If the surface water supplies were turbid and/or undrinkable, drastic management options may need to be considered (evacuation or destruction).

4.1.4 Potential mitigation of volcanic hazards

If there was warning of an imminent eruption, key equipment (including the water supply infrastructure) would be checked and rainwater pipes disconnected.

4.1.4.1 Water supply

If sufficient warning was given or at the beginning of an ashfall the farmer believes he would check over the water supply and ensure it was in good condition and operating as designed. During any ashfall he would attempt to clean and refill stock water troughs. If the power supply went out, he would use the power-take-off (PTO) attachment on his tractor to power the pump, hence using a diesel supply. If the pump was to fail for mechanical reasons, the farmer would try and buy another one straight away. The house supply would be disconnected.

The creeks which run through the property (Figure 3.3) would also be a potential drinking source for the animals, especially if aquifer-derived. However surface water supplies would rapidly become contaminated by ash (from either falling or remobilised from ground deposits).

The farmer would resist putting covers on the troughs, as they would be quite labour intensive to put on. He believes the stock would probably knock them off anyway, so would prefer the extra effort cleaning the troughs out by hand.

In an emergency, the farmer would probably fence off the dam and gravity feed the troughs from it if required. This may not be possible during an ashfall, with suspended ash in the water potentially blocking inlets and pipes. The main dam can be connected to water supply network and used to supply the paddocks below it (to the east).

The farmer noted that ensuring stock have access to drinkable water would be one of the top priorities following an ashfall. There is more time available with feed, as stock can last for several days without food, and supplementary feed is also available. However water would be required almost immediately, especially as dry dusty ash is likely to cause discomfort for the animal's mouth and throat. Supplementary feed, hay and grain in particular, will not have the same moisture content as pasture and its consumption will increase the water requirements for the animal.

4.1.4.2 *Information requirements*

The farmer listed five specific pieces of information he would like to receive at the onset of a volcanic eruption:

- how long the eruption will go on for;
- how much ash is likely to fall;
- what would the likely impacts to animal health be and how best would you to mitigate such impacts;
- pasture rehabilitation and how best to mitigate such impacts;
- protection of the water supply and how best to mitigate such impacts.

He believed a checklist (before/during/after) would be highly useful.

4.1.4.3 *Stocking rates*

Stock numbers fluctuate during the year, allowing farmers to regulate their stocking rate in relation to feed availability. If there is stress on feed and supplementary feed reserves, then less stock will be carried. This would be an important management tool during the recovery from a future ashfall which impacted feed reserves over the long term.

The farmer suggested that if sufficient (and convincing) warning was given during before a large eruption (such as a period of sustained unrest in a volcano), then he would consider lowering stock numbers, although he noted that this is a risky course of action.

> *'If you de-stock too far you get a low price and then when you try to buy them back, if you aren't badly affected, you will pay a very high price.'*

He believed young stock would be retained, whilst expendable older stock would be sold to the works or market.

4.1.4.4 *Labour*

The farmer believed additional labour would be required following an eruption, and that he would be able to organise this rapidly himself.

4.1.4.5 *Covered yards*

The woolshed and covered yards have the capacity to hold 1,300 ewes if required. This would be used if ashfall became an issue, especially for sheep about to be shorn or recently birthed.

4.2 Study farm 2: Bridge Pa

4.2.1 General information

Study Farm 2 is an 850 ha (2,100 acre) sheep and beef farm located close to Bridge Pa, central Hawke's Bay, which typically runs 6,200 sheep and 400 cattle (Figure 3.2). The farm is split into two blocks with a 500 ha block running 3,200 sheep and the 400 cattle, the other 350 ha block runs 3,000 sheep. As with any stock farm, stocking rates vary throughout the year depending on the availability of feed. At the time of interviewing (2 May, 2007) most of the cattle were away due to the dry conditions.

The farm has 3 barns, each with a capacity for ~230 large square bales (4x3x7 ft), giving the farm a supplementary feed reserve of ~700 hay bales. As much hay as possible is made on the farm during the November-January period, although in dry years it must be bought in, particularly when it is a dry season (such as had to occur during the 2006/07 season). Power for the farm and house is mains supply from overhead wires.

4.2.2 Water supply

The farm has several springs which feed creeks running through the farm. The "main spring" has never dried up, but the other 2-3 springs dry up during summer months requiring a trough system. Water for the trough system is supplied from the "main" spring at an open 4 x 4m surface water body where one hydro-ram pumps ~9,500 L (2500 gal) per day from 1.5 m below the surface to two storage tanks. It lifts the water ~200 m (550 ft) to four 20,000 L concrete storage tanks. A 4 inch drive line falls about 10 m (30 ft) to give sufficient head to distribute water to the troughs.

The water from the springs is limey, although there are no scaling problems reported with the farm water system. The house uses a roof water supply collected in a 40,000 L (10,000 gal) tank (Figure 3.6). There is the ability to switch the house onto the farm supply if required.

Figure 3.6 Rain water collection tank – for house supply

4.2.2.1 Stock drinking water

Stock drinking water is the primary water use on the farm. This demand is met by a trough system throughout the farm and is supplemented by the spring-fed creeks when they are flowing. Modern 750 L round troughs are used predominantly, whilst there are also some of the older style 750 L rectangular troughs.

Water demand varies throughout the year, although it peaks during the hot summer months creating a significant demand. The farmer noted it is critical to have water during the summer months with temperature highs at times reaching >30˚C for several days in a row. Water consumption is also related to the feed quality. If livestock eat a lot of rough dry feed (such as hay, or pastures after a dry summer) then stock require a lot more water from the trough system. During the summer period, monitoring of the water supply system is one of the key farm tasks, ensuring there are no leaks and that all stock has adequate access to water. During cooler periods of the year stock don't require so much water and gain more through their feed.

The trough water system has no resiliency in the system, with only one break or leak potentially disrupting water supply to one or more paddocks. If unnoticed, such leaks can potentially drain the storage tanks too, further reducing the resilience of the system.

No irrigation is carried out on the farm.

4.2.3 Natural hazard experience

4.2.3.1 Ruapehu eruption of 1995

The farm experienced one very light (less than 1mm) ashfall during the 1995 eruption from Ruapehu. The eruptions essentially caused no problems at all to the farm's infrastructure. It caused minor irritation to eyes, collected in the guttering of the homestead and was noticed on the surface of machinery left out in the open. There was no noticeable deposition onto pasture and or impacts to the stock. Livestock were not put off eating or drinking. There was also no noticeable impact to the farm water supply or any machinery.

No warning was given of the eruption, although it was certainly visible from the farm. There was very little known about it by the farmers or within the rural community at the time. The farmer cannot remember any information that was distributed to the rural sector following the eruption.

4.2.4 Vulnerability to volcanic hazards

The farm's water supply is very vulnerable if electrical power is lost during an ashfall event, particularly as there is no back-up generator capacity on the farm. The loss of the pump outside of summer may not be a significant issue, as stock could drink from creeks and springs which would probably be relatively free of ash if outflow volume is sufficient. Vulnerability is greatest during the summer months when water demand is at a peak and surface water resources are at their minimum.

The surface water area at the "main spring" is vulnerable to ashfall and may result in detrimental effects to water turbidity and chemically quality. It may also cause accelerated wear to the pump or even mechanical failure. Again, vulnerability is highest during the summer months when the trough network is relied on to meet a very high water demand.

4.2.5 Potential mitigation of volcanic hazards

The farmer said he would use common sense, ensuring firstly that people on the farm were safe and catered for. Then stock would be considered, although he was unsure exactly what could be done for them. It is likely he would monitor impacts and respond with problems as they arose on a priority basis. If warning was given that an eruption was likely or ash was on the way he would not alter farm plans greatly.

4.2.5.1 Roof water supply

The first thing the farmer said he would do during an ashfall would be to secure the roof water supply and switch over to the farm supply.

4.2.5.2 Farm water supply

There was some concern that the pump intake may block or clog from ashfalls. The farmer believed little could be done about the water supply, other than hope it does not block up.

4.2.5.3 Power supply

There is no back-up power; no diesel backup generators. However the house has a barbeque and wet backs for self-sufficiency.

4.2.5.4 Stock evacuation

The farmer considered that stock evacuation is unlikely to be a feasible option. He commented that there is no guarantee that stock could be evacuated to areas free of ashfall, and that there are major logistical issues with evacuating stock. He reported that if the situation warranted it, he would 'open the gates and let the stock go.'

The farmer did not consider destocking, pointing out that it typically takes seven to ten days to organise grazing during non-crisis periods, and that warnings of an impending eruption could potentially be shorter than this (depending on the level of volcanic activity).

4.2.5.5 Sources of information

Any information distributed by emergency management authorities on preparing and recovering from a volcanic eruption would be appreciated by the farmer, especially if it could be used as a check-list or reminder. The farmer was unsure of what could be done to mitigate the effects of ashfall and believed a checklist would be useful.

4.2.5.6 External assistance

The farmer had a low level of expectation of external assistance. Nothing is expected from central or local government agencies. The farmer noted:

> *'You are on your own on a farm - you wouldn't get any help until they had dealt with Napier and Hastings!'*

4.3 Study farm 3: Western Bays, Lake Taupo

4.3.1 General information

This farm includes two blocks with 280 ha on the Western Bays site (Figure 3.7) and a further 1700 ha near Raetihi. This study only includes information for the Western Bays block (Figure 3.2). There are 4000 stock units on the farm, with approximately 3000 sheep and 300 beef cattle.

Figure 3.7 Study Farm 3, Western Bays, Taupo

4.3.2 Water supply

This farm obtains its water supply from a spring several kilometres to the west. Water is pumped from a pool below a culvert (Figure 3.8). The intake is out of the main flow, making it less susceptible to flooding (it was not affected by a small flood in 2003 during which 60mm of rain fell in 40 minutes). Due to the turbulent nature of the stream, the intake is largely self-cleaning. Water is extracted by submersible pump to a settling tank, filtered and three multi-stage pumps pump water back to the farm (Figure 3.8).

Figure 3.8 Intake area from surface water supply; multistage pumps

The farmer gave a brief account of how the farm's water supply has evolved over time:

In the 1960s when the area was being developed for farming by Lands and Survey, ground water bores were put down. Extraction was at a faster rate than recharge, and as bores dried up, new bores were put down. As a result there are approximately six redundant bores on the farm. A larger bore was drilled in the early 1980s by Landcorp but this well collapsed. Other water supply options were trialled, such as a stream supply located 9 km away. This was supply was impacted during the 1996 Ruapehu eruption (discussed below). Access and supply security issues led to this supply being abandoned, not the eruption impacts. It was finally decided that the best option would be to obtain water from a spring-fed creek. This required seven consents and cost approximately $130,000 to set up. The system was initially established in partnership with two other sheep and beef farms, but these have since been sold and combined into a dairy farm. This has put pressure on the water resource with around 95% of the extracted water going to the dairy farm.

The system is designed for extracting 140 m^3/day of water, with a consented take of 200 m^3/day of water allowed. The study farm only requires 4% of the 200 m^3/day of water. The system is closely monitored due to the number of consents issued, so the farmers keep the system in very good repair.

The stream water is of excellent quality and is suitable for human consumption.

4.3.2.1 Stock drinking water

Stock drinking water is the primary use of water on the farm. The homestead also draws water from the farm system. Water is pumped to the tanks and then gravity-fed to the troughs. There are 90 troughs which consist of a mix of round and rectangular types (most are 200 L). The ballcock valves are protected from the stock and are constantly serviced every time the farmer is out around the farm. There is storage on the farm for 100,000 L of water, independent of the water extraction system. The period of maximum water demand is during late summer, when temperatures are high and pastures have dried out so that livestock are not gaining significant hydration from grazing. Water consumption has been measured at approximately 20,000 L/day during this period. This gives five days water supply for the farm if the supply is lost, assuming maximum water consumption (i.e. hot dry summer days); during winter or rainy periods this would last for 2-3 weeks (depending on conditions).

4.3.2.2 Power supply

The reliability of the power supply has been a problem in the past. The longest outage experienced has been eight hours, which prompted consideration of purchasing a generator for the water supply. No generator had been purchased at the time of the interview.

4.3.2.3 Pumice fragments

Fine pumice fragments in the water are highly abrasive to the impellors within the pumps, wearing them out over a period of years. They also block the filters at the extraction site, degrading their effectiveness. The pumps consist of a series of vertically-stacked impellors, with the greatest wear on the bottom impellor at the water inlet. Replacing only the worn impellors has been attempted, but it was found to be easier to simply replace the entire pump. Pumice fragments ranging from silt-sized to pebble-sized have been found in the filters.

These problems have prompted a redesign of the water system. Water is now taken from an extraction point one third of the way down the settling tank to allow for some settling of the pumice fragments (which generally are waterlogged and tend to settle to the bottom) to avoid blocking the filters.

Volcanic ash is also highly abrasive, and an ashfall would be expected to have similar effects on this type of system as the pumice fragments.

4.3.3 Natural hazard experience

4.3.3.1 Ruapehu eruption of 17 June 1996

The farm was directly in the path of an ashfall during the 17 June 1996 Ruapehu eruption, and received approximately 1 mm ash. The farmers reported that it was 'a frightening experience', and that the ash irritated their eyes and lungs, such that they had to go indoors and shower.

During the eruption the farmer recalls the previous water supply that supplied the farm (9 km away) was contaminated by ashfall falling on and washing into the water supply. Restrictions were reportedly declared on water usage, but all the farms in the region during the eruption were dry stock farms, so there was considerably less draw than exists now.

Stock were unable to feed for 5-6 days until rains washed the ash off the pastures, although no detrimental effects on their health were noted by the farmers. There was no feeding out of supplementary feed at the time, but the farmer was beginning to seriously consider it before the rain came. Other than being put off their food, the farmers could recall no other impacts at the time on the stock or on pasture.

Clearing ash from house gutters was difficult as the ash consolidated into a hard, putty-like material that was difficult to wash out. Wind-blown ash impacted sheep, clogging wool and subsequently causing damage to shearing combs during shearing. The roof water supply was disconnected during the ashfall. .

Logging contractors were on the farm at the time and had to stop operations as the ash got in their saw chains causing problems.

4.3.4 Vulnerability of water supply (and farm) to volcanic hazards

This water supply is fed by surface waters so is more vulnerable than a groundwater-fed system. However, the extraction point is close to the spring, which should reduce the surface area of the stream exposed to direct ashfall and ash washing into the stream.

The most vulnerable time for impact to water supplies would probably be in middle to late summer when water demand is highest and the storage capacity on the farm will be exhausted most rapidly. The household supply holds 20,000 L and would probably last several weeks.

4.3.4.1 Feed

Annually, 200 t of grass silage and 70 bales of hay are produced. Swedes and kale are usually also grown. Cattle can go on to silage, but if the pastures are covered in ash then sheep would also have to go on to supplements. This would significantly reduce stores for later in the year, either requiring destocking or purchase of more feed.

4.3.5 Potential mitigation of volcanic hazards

The first action would be to disconnect the drain pipe to prevent ashfall on the roof entering the household supply tank. Based on previous experience, the farmer would not bother trying to cover troughs but would wait and monitor the situation. If there was any warning (official or visual) then he would make sure the water storage was at maximum capacity. As the main water supply intake is in an open stream, it is impossible to prevent ashfall from entering this system. Once the stored water supply ran out, backup options include using a diesel generator to get one of the disused groundwater bores operating.

In the event of an eruption beginning to cause significant detrimental effects on livestock, the farmer believed he would go into survival mode, cut fences and as a last resort take stock down to Lake Taupo for watering. If feasible he would truck water in and/or truck stock out. The farmer is strongly aware of the vulnerability of this location, close to the Tongariro volcanoes, and reported that he would consider buying in supplementary feed in the event of a warning.

4.3.5.1 Expectations of external assistance

The farmer reported that he would not expect any immediate external assistance from emergency management agencies. However, he had an expectation that power supplies would be restored as quickly as possible if they failed, and also that Federated Farmers could play a useful role in donating feed and assisting with transport. Any stock destruction would be handled by MAF.

4.3.6 Other users of the water supply system

The water supply system described above also services a neighbouring dairy farm, which reportedly uses 95% of the allocated take for stock drinking water and cleaning the dairy shed. Although we did not visit this dairy farm, it is reasonable to predict that it will be highly vulnerable to any disruptions to its water supply as it has limited water storage.

4.4 Study farm 4: Rerewhakaaitu

4.4.1 General information

Study Farm 4 is located on Brett Road, Rerewhakaaitu (Figure 3.2). It is a 116.7 ha dairy farm that carries 350 cows in two herds. The farm is supplemented by a rented 24 ha 'run-off' block for the purpose of supplementary feed production and extra grazing area. This is located several kilometres east of Lake Rerewhakaaitu.

The farm is directly in the shadow of Tarawera Volcano (8 km to the north) and has received significant ashfalls from this centre, including the 1886 A.D. Tarawera eruption.

4.4.1.1 Annual farm activities

Calving begins in August which continues through to September. The beginning of calving signals the start of milking, the central economic activity of the farm. About September, grass silage (supplementary feed) starts to run out and supplies of maize silage are approximately half used. September, October and November are the months of peak milk production for the cows, following calving and elevated pasture growth in spring. Maize silage is used up in October. Grass silage making begins in November and may continue through to December. This usually consists of 50 t of grass silage in pits (silage covered by protective plastic sheeting) and 160 round bales wrapped in protective plastic. Mating of the cows is carried out in November and December. From January to May milking continues but at a reduced rate. Approximately 100 t of maize silage is purchased in March and stored in bunkers on the farm. Cows are dried off (ceased milking) from May to July. Grass silage is fed out from June till end of August to assist the cows through the winter months when in calf.

4.4.1.2 Supplementary Feed

The quantity of supplementary feed usually stored and consumed on the farm consists of:

- Round wrapped bales - 270[4]
- Chopped Silage - 30-40 t
- Dry matter maize - 100 t

[4] Round silage bales weigh ~0.5-0.8 tonnes each

4.4.2 Water supply

Water is a critical element of any dairy farm. It is required for consumption by stock (drinking water) and is used in large amounts for washing down the milking shed and associated structures to keep them in a hygienic and acceptable working environment.

The farm is supplied from two artesian pumps servicing the farm's (including the homestead) water supply needs. It consists of a submersible pump in each bore supplying four 22,500 L tanks. Currently the eastern pump supplies all troughs on the farm and the homestead, whilst the western pump supplies water to the milking shed, but the two can be merged into one system if required. The key vulnerability of this system is the reliance on electrical power.

4.4.2.1 Stock drinking water

If electrical power was cut to the farm, there is the potential to set up gravity fed troughs from the tanks, from which stock could access water from. This could provide several days of water to the herds, depending on climatic conditions. Dry and hot conditions would mean the cows are each drinking 40-50 L of water daily equating to 17,500 L for the herd. Cold and wet conditions would mean a minimal amount of water is consumed with the cows deriving hydration through pasture consumption. Water would also be required for washing down the milking shed (albeit not under high pressure, potentially reducing the effectiveness of cleaning).

Volcanic ashfall would contaminate the uncovered, round 350 L stock-water troughs in each paddock, causing problems as cows drank suspended volcanic ash and any aerosols dissolved within the trough water. Lake Rerewhakaaitu was suggested by the farmer as a possible emergency water option; however it would also be filled with suspended volcanic ash from direct fall and drainage systems.

4.4.2.2 Cleaning the dairy shed

Contamination of the milking shed was identified as a possible hazard by the farmer. He believed water would be the best way to wash down the shed, equipment and cows (especially their teets). The farmer was also concerned that ash washed from the milking shed would block drains or cause problems in the effluent sump (with its associated pump).

4.4.2.3 Effluent sump

The effluent sump is located beside the milking shed to allow the animal effluent washed from the milking shed to settle out of the washing water. The remaining water is then sprayed onto paddocks. In normal operation the sump occasionally blocks with silt. The large sediment pulse of suspended volcanic ash created by washing down the milking shed and associated surfaces during or following an ashfall would probably have a similar effect, blocking drainpipes, and potentially damaging the sump pump.

Grills cover the drains at the milking shed which would stop large clasts (>20 mm) and some consolidated wet volcanic ash from entering the pipes, but may block as a result causing flooding so would need to be regularly cleaned during wash down. If the pipes were to block with volcanic ash, removing volcanic ash from them is a difficult, time consuming and costly effort.

4.4.3 Natural hazard experience

4.4.3.1 1995/96 Ruapehu eruptions

The farm did not receive ashfalls during the eruptions, although ash fell close by. The farmers remembered the cold and dark conditions that were created by the plume. They recalled discussing the effects on farms that were impacted, with the main complaints being that stock were put off eating ash cover pastures and increased supplementary feed was fed out. No official warning of the eruption was received, but the eruption plume was observed as it came north.

4.4.3.2 2004 Bay of Plenty floods

During the 2004 BOP floods up to 500 farms were affected by flooding, with approximately 50 severely damaged (New Zealand Herald, 20/7/2004). This sparked an industry driven (Dexcel and Federated Farmers) evacuation of stock from the badly effected farms (P. Journeaux, *pers comm*., 2005). About 20,000 cows were moved out of the area generally further north into the Waikato and Bay of Plenty (www.maf.govt.nz). The dairy herds were received by non-impacted farms which in return for grazing and care of the animals were entitled to the milk produced by the evacuated herd. The Ministry of Agriculture and Forestry provided financial assistance for the transportation of these animals.

During this flooding event the farm took on approximately 20 cows for a large part of the milking season from one of the severely impacted farms. Initially it was only meant to be for 4-5 weeks, but they stayed on for upwards of 10-12 weeks. This allowed the dairy cows to continue lactating and did not need to be destroyed or sent to the works, thus maintain the asset and reducing the disruption to the effected farms. The farmers felt like they were helping out fellow farmers, although others in the area which also took on cows felt it was for purely economic gain.

4.4.4 Vulnerability to volcanic hazards

An eruption in summer would have the greatest impact on water supplies to the farm, due to high stock drinking water demands. Whilst the supply would be secure (groundwater) the potential loss of electricity during an eruption would create major difficulties.

It would be unlikely that farmers would be able to buy any supplementary feed at the end of winter, as most would have used it up. They could probably buy ‘meal’, but this would be dependent on how much is stockpiled by farm supply stores.

4.4.4.1 External assistance

The regional council, MAF, Federated Farmers and Dexcel were all agencies the farmers believed they would look to for assistance during or following a volcanic eruption. Information on what to do following an eruption would be the biggest initial demand. There was also some uncertainty on what happens to land severely impacted by ashfall, such as will they be allowed to rehabilitate it, what should they do and do they still even own the land?

4.5 Study farm 5: Reporoa

4.5.1 General information

Study Farm 5 is a 160 ha dairy on Settlers Road, Reporoa in the centre of the Taupo Volcanic Zone (Figure 3.2). It is at high risk from nearly all volcanic centres in the North Island.

The farm runs 500 dairy cows, with 100 rising. Milking begins in August (at the same time as calving) and continues for 9 months through to mid-May. 600 t (200 t dry matter) of grass silage is produced annually and stored under cover.

4.5.1.1 Water supply

The farm is supplied by water from the Reporoa Water Supply (RWS), which flows under gravity to the farm. The biggest water demands on the farm come from stock drinking water requirements and cleaning the dairy shed following milking. It is not used for irrigation. The farm has no storage for stock water drinking supplies, but does have a 22,500 L water tank at the dairy shed for storing cleaning water. There is no storage for the household, also connected to the RWS, and no alternate rainwater supply. All pipes on the farm are underground, indeed water is only exposed to the atmosphere when it reaches the troughs, which are 1125 L rounds.

The water supply is distributed throughout the farm with sufficient head (pressure) that losing the power is not an issue, but some neighbouring farmers at the same elevation as the RWS spring need to pump water to higher reaches of their farms for distribution.

4.5.1.2 Reporoa water supply

The RWS supply serves 361 properties, supplying 6,800 hectares of farmland and the Fonterra Reporoa dairy processing plant (RDC, 2006). The scheme is supplied by two sources; water is gravity fed from Wharepapa Spring located approximately 8.5 km northwest of Reporoa township, serving Reporoa township, Fonterra dairy factory and beyond; and the Deep Creek spring to the south which is pumped into the Broadlands and Mihi area. It is lightly chlorinated and has no reservoir capacity. An average of 5,900 m^3 of water was used daily in 2005 with a peak consumption of 8027 m^3. It is supplied through 65 km of pipe work. The largest consumer is the Fonterra Co-operative Group Ltd factory. The farmer is not aware of any storage tanks related to the scheme itself.

Different levels of extraction have been set for Farming, Residential and Dairy Factory consumers (Table 3.4). The following is taken from RDC (2006):

- The sources, pumps and network are designed to supply a steady flow to each farm over 16 hours with each farm requiring its own on-site storage and if necessary, pumping equipment.

- The flow for each property is calculated from a daily allocation based on farm area.
- The allocation is enforced by the use of a flow restrictor at each connection point.
- The Dairy Factory has one connection supplying a steady flow, plus an extra allocation during night hours which it stores in its own reservoirs for use during the day.
- Residential users receive an unrestricted 24 hour flow.
- The supply is self-funding, with all costs and revenues identified in a separate stand-alone account.

Table 3.4 Maximum allowable extraction from the Reporoa Water Supply (from RDC, 2006)

Individual User	Extraction
Farming	505 L/Ha/day
Residential	20 L/min
Dairy Factory	3600 m^3/day

4.5.1.3 Stock drinking water

Stock drinking water demands peak in the summer months, with the farmer quoting that dairy cows require up to 70 L/day when they are lactating, depending on the temperature.

The farmer believes that the cows could last without water supplies for up 12 hours in summer and 24 hours in winter (maybe 36 hours), but little more. This will be dependent on the ambient temperature and moisture content within feed (i.e. they will last longer on lush pasture compared to if they were on dry hay). During winter supplements are usually fed out, which can be quite dry.

4.5.1.4 Cleaning the dairy shed

Cleaning of the dairy shed is a large water use and is required following milking (twice daily). Water use is intensive during this period, requiring a 22,500 L tank to ensure sufficient supply. This tank is recharged from the RWS between milkings.

4.5.1.5 Loss of supply

The water supply is only ever lost for several hours at a time, usually the result of someone digging up the pipe and severing it. This has never significant disruption to the farm.

4.5.2 Natural hazard experience

4.5.2.1 Ruapehu eruption of 1996

The farm received a dusting of ash during the 1996 eruptions. The farmers remember it getting dark and cold, even though it was a fine day. There was no warning; rather they saw the plume coming towards them from the south (Figure 3.3). They could remember light ash deposits on clean surfaces, however there were no problems with the gutters and no impacts to the farm or stock.

There was slight irritation to the eyes when outside and exposed to the falling ash. The farmers were concerned about how much ash they would receive on the farm and how it would affect the pasture feeding regime (feed security and subsequent stock health). They did nothing unusual on the farm to prepare for the ashfall.

Water was the last thing on their mind, the supply being assumed to be unaffected. Indeed the farmers were more concerned during previous earthquakes because of the potential for broken pipes.

The Ministry of Agriculture and Forestry at the time advised that the ash may be toxic to animals. The farmers felt there was plenty of information available, although as they weren't seriously impacted by the eruption they were not overly concerned. The noted a lot of information following the event in the media and also in farming magazines such as "Straight Furrow".

The farmers reported that for several years following the eruptions, many of the grazing and land purchase contracts had clauses with an option to back out of the agreement "subject to volcanic activity".

4.5.2.2 Flooding and geothermal hazards

Occasionally the farm is affected by short periods of flooding from a creek draining from the Waiotapu thermal area, which flows on the eastern border of the farm. The flooding events are usually short lived, but occur every few years. As the water is from the geothermal area, it has high arsenic (As) concentrations, so that the remnant flood water (puddles) in the paddocks are highly toxic. The toxic salts are concentrated in the soil; not the grass as might be expected. When the cows lick or consume the soil (often due to salt deficiency) they are poisoned and usually die within 1-2 days. Because of the salt deficiency, selenium (Se) and copper (Cu) supplement salt blocks have been put out in the paddocks to try and alleviate this deficiency.

There used to be problems when cows drank from naturally occurring surface water springs in the paddocks. If the cows just drank from the surface of the water it would be ok, but if the cows walked through the water, stirred up the As, and then drank they would be poisoned (As is a heavy element which rests at the bottom of the water body). These springs no longer occur in the paddocks however.

4.5.2.3 Earthquake hazards

The farmers indicated the farm is "occasionally" affected by earthquakes which can be up to 4.8 on the Richter scale. They reported that no disruption has occurred to the RWS and farm water supply during following seismic events. The farm experienced moderate shaking during the Edgecumbe earthquake, but the water supply to the farm was unaffected following the event.

4.5.2.4 2004 Bay of Plenty flooding

Following the 2004 Bay of Plenty floods the farm took in 10-15 additional cows from farms impacted by the floods. In return for the cows maintenance the farm was entitled to the milk produced by the cows.

4.5.2.5 Snow hazards

The farmers reported there had been several snow falls during their time on the farm, but it has only been on the ground till the afternoon and not caused any problem.

4.5.3 Vulnerability to volcanic hazards

The main vulnerability will be if the RWS pumps (assumed to be electrically powered) at the spring intake loses electrical power resulting in district wide disruption of water supplies. There is no resilience in the form of stored water on the farm; rather there is total reliance that the RWS will continue to function. There are no alternatives to this supply, with surrounding surface water bodies toxic to stock consumption.

During a volcanic ashfall, there is unlikely to be any problems with the water supply on the farm, provided that the RWS continues to operate normally. The only exposed water is in troughs which may be contaminated by ash leaching soluble aerosols into the water and turbidity. If the supply is disrupted however, stock water troughs will be rapidly emptied by thirsty cows. Survival time is therefore in the order of hours, rather than days. Once the supply is lost there is no resiliency anywhere in the district, with all farms relying on the same water supply.

The farmer noted that cows will hunt water if they are thirsty and will happily break through fences. If they are water stressed they may panic and break fences to reach the hydrothermally enriched stream on the eastern boundary.

Cleaning down of the dairy shed may create some problems, with the ash turning into a paste when wet. It may cause some problems to drains and in the effluent sump (Wilson and Cole, 2007).

4.5.4 Potential mitigation of volcanic hazards

The farmer was unsure to what extent he would prepare for an eruption. He thought buying in extra feed would be the first action if there was sufficient warning. He believed grazing could not be arranged in ‘safe’ areas before an eruption due to the uncertainty of which way the wind will distribute ash. The farmer noted the time of the year becomes a critical variable, with the worst scenario if cows were in full lactation. He further noted that if he needed to cull animals, he wouldn’t know which to take out first; the top 10% are almost as good as the bottom 10%. They believed the destruction of genetic stock would be a terrible loss to them and to the country.

4.5.5 External assistance

The farmers said any information on how to deal with the effects of a volcanic eruption would be highly appreciated. The local paper was suggested as an excellent means to distribute information to farmers. If brochures were sent around, there are so many in the mail that people would probably just throw them out. The MAF website was also identified as a good place to look for information.

Federated Farmers would be the first choice in an emergency as an agency to assist and advise farmers, especially in terms of:

- co-ordination of relief supplies
- trucking stock out (i.e. advice whether livestock should be moved immediately or later)
- what the impacts will be
- what to do to mitigate the effects
- how quickly you need to do things

4.6 Study farm 6: Eltham

4.6.1 General information

Study Farm 6 is a dairy farm located on Kaponga Rd, South Taranaki, around 6 km west of Eltham and 10 km north of Manaia. The farm has 125 ha (112 ha effective) running 410 Jersey cows, on Taranaki brown loam soil, with an average annual rainfall of 1,400 mm, and supplies milk to the Fonterra Co-operative. It is part of the Waoikura model catchment - a water catchment study conducted by Fonterra and MAF.

Milking begins in early August and continues through to mid-late May (finishing on 24 May in 2007). Approximately 8 ha of silage is produced on the farm; 145 t of maize silage and 300 big square (4 by 3 ft) hay bales are also purchased.

The electricity supply is from overhead power lines situated along the road. There is no backup generator if the power was disrupted.

4.6.2 Water supply

4.6.2.1 Waimate West Water Supply

Water is supplied to the farm from the Waimate West Water Supply (WWWS). This scheme is one of eleven run by the district councils in Taranaki (South Taranaki DC in this case). It supplies a population of ~4,000 (802 metered connections; 622 properties rated for water supply, which includes 27,000 ha of dairy farmland), including the towns of Manaia and Kaponga. The supply is metered with users paying on a per m^3 basis. There is also a base charge for each intake (or connection) from the supply.

4.6.2.1.1 Intake

The scheme has three intakes; the main intake is in the Mangawheroiti stream, with the other intakes in the Otakeho and Mangawhero streams, diverting flow to the Mangawheroiti. The intake structure on the Mangawheroiti stream coarsely filters water through a boom, metal screen and a bag, which removes unwanted material such as pine needles (Figure 3.9 and 3.10). The water flows under gravity (with some additional boost pumping) to the WTP.

Figure 3.9 General view of intake with stream in foreground

4.6.2.1.2 Water Treatment Plant (WTP)

The water is gravity fed from the intake structure down to the water treatment plant (WTP) in Rowan Rd where it is treated (coagulation, flocculation, clarification, filtration, chlorination, and pH correction; Figure 3.11). There are two absorption clarifiers with a combined rating of ~730 m^3/hr. There are five automatic valveless gravity sand filters also rated at ~730 m^3/hr.

Figure 3.10 Filter bag

Each of the supplying streams and their intake structures are highly vulnerable to ashfall, lahar and pyroclastic flow hazards which may impact the area during an eruption of Taranaki volcano.

Figure 3.11 Water Treatment Plant – Waimate West Water Scheme

The site has significant electrical power demands for the treatment process. If the power stops, chemical dosing stops, clarifiers and filters cannot be backwashed and raw water booster pump stops. Production would reduce markedly during one day. The plant can be bypassed if required, but some equipment can be run with a portable generator and tractor PTO. There is also the capacity for emergency disinfection (chlorinator).

4.6.2.1.3 Storage

Near the WTP there are two reservoirs, with a total capacity of 13,500 m^3 (Figure 3.12). The daily water demand is 17,700 m^3/day, giving less than one day's supply in the reservoirs. Water is pumped to users, but this can be bypassed to give a maximum gravity fed of ~500 m^3/hr.

There is enough storage capacity for 18 hours supply (during high demand periods) or 3-4 days during winter when stock drinking water requirements are reduced. During peak demand (washing down the dairy shed) each reservoir will be drained by a third as the system cannot keep up with demand.

Figure 3.12 One of the two Waimate West scheme storage tanks

4.6.2.1.4 Vulnerability

Staff at the WTP mentioned that the system can barely handle the demand at present and are exploring for groundwater to supplement the supply, although there has been Fe and Mn contamination in the exploratory boreholes. Motivation for diversifying the supply comes from the significant pressure on the current supply and the additional benefit of providing greater resilience to volcanic hazards. This would greatly increase the resilience of the supply, offering an alternative to the vulnerable surface water takes.

4.6.2.2 Farm water supply

There are three intakes to the farm from the WWWS. The intakes feed an interconnected system which supplies all water requirements on the farm, including domestic supply, stock drinking water and dairy shed cleaning water. Water is piped directly to stock water troughs; there are 30 paddocks with four 150 L round troughs in each (120; Figure 3.13).

Figure 3.13 150 L round stock water trough

A 4,000 gallon storage tank (~18,000 L) behind the milking shed is the only water storage on the farm, and is used to store water for washing the dairy shed (Figure 3.14). Supply to this tank is supplemented by rainwater from the roof of the dairy shed (the only catchment of rainwater for any use on the farm, including domestic supply).

As the farm is only several kilometres from the WWWS storage tanks, during past periods of water stress the farm has continued to receive water when others further from the scheme have not.

4.6.2.2.1 Water Use

Stock watering is essential throughout the year. The heavy water use period is from the end of December through to March. It is estimated by the farmer that the dairy herd consumes between 50-60 m^3 of drinking water daily during the summer (100 L/cow), but this reduces to ~15 m^3 of water daily in winter (40 L/cow). Water use for dairy shed cleaning is estimated to be ~22 m^3 per day. Cleaning following each milking uses approximately two thirds of the 4000 gal water storage tank at the dairy shed.

Figure 3.14 The dairy shed looking north towards Taranaki volcano – note the rain collection tank in the centre

The peak water consumption for the farm is from mid-December through to mid-March, when up to 120-140 L/cow/day is used, largely due to essential stock drinking water requirements. The total daily water demand just for the farming operations is therefore 410 cows x 120 L/cow/day in summer = 49,200 L/day or 49.2 m^3/day. In winter usage will be ~15-18 m^3/day. So there is clearly not enough storage on site to keep them going for long, even in winter, if the supply was to stop.

Washing the dairy shed is essential during the milking season to maintain a hygienic and clean shed, but is not required during non-milking periods.

The annual water bill for the farm usually adds to several thousand dollars per year.

4.6.2.2.2 Unused bores

There are several old wells on the farm which were abandoned when the new WWWS was put in. There is a submersible pump (stored on the farm) which the farmer assumes could be used to reactivate these wells, although notes it could be risky to rely on them and would only be a last resort.

4.6.2.3 Effluent ponds

Effluent drains from the dairy shed to two ponds. These ponds store the effluent, and cleaning water washed from the dairy shed following cleaning, allowing settling of solids. It is then pumped out onto the pastures by an effluent pump (designed to pump solids). Each pond measures 20m by 20m and 4 m deep, although only one pond is currently used (Figure 3.15).

4.6.2.4 Loss of supply

The water supply has never been lost to the farm in living memory, although there have been restrictions declared (such as over the 06/07 summer). Other users of the same and other schemes have lost water supplies however.

During the 06/07 summer the reservoir got down to 17-18% of capacity, so the managing authority reduced the water pressure to try and reduce consumption and build back up the capacity. Users were told to conserve water. A good rainfall soon cleared the problem – but there was significant concern for a period.

There is no experience of dealing with natural hazards on the farm.

4.6.3 Vulnerability to volcanic hazards

The farm's water supply is extremely vulnerable to volcanic hazards as the catchments that feed the regional scheme (the WWWS) are vulnerable to lahars and pyroclastic flows from Taranaki volcano, in addition to ashfall. The increased sediment load that could be deposited within the catchments by volcanic hazards, may result in catastrophic failure of the water intake or the WTP and disrupt water supply to users. As the system is under stress during normal operation; demand is likely to be exaggerated during and following an eruption further putting pressure on water supplies.

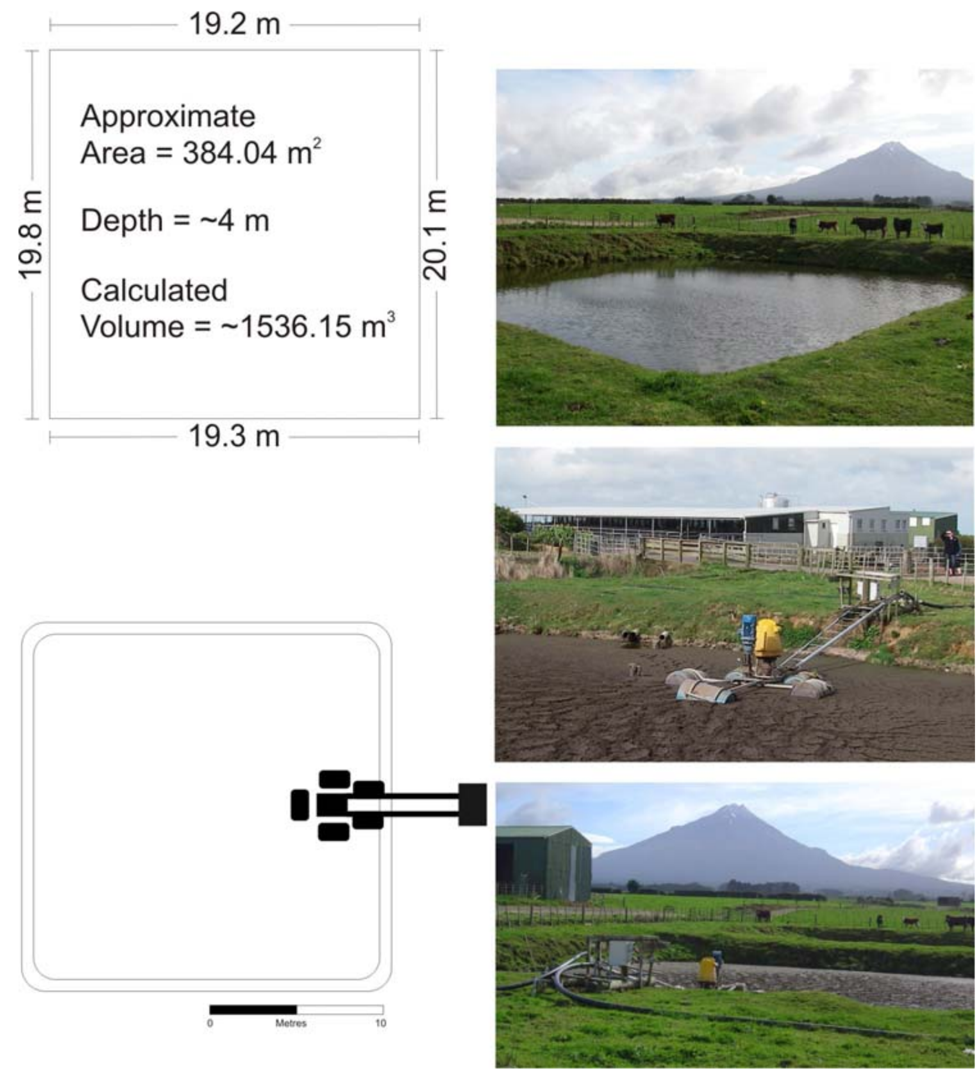

Figure 3.15 The effluent ponds

Water demand is likely to increase during an ashfall as additional water is required to remove/clean the ash/effluent mix from the dairy shed. Water may even be required to wash ash from the cow's teats to reduce inflammation during milking (Wilson and Cole, 2007).

The WWWS is reliant on electrical power supplies for all water treatment systems and pumps to work at maximum capacity. However if power was lost to the plant, and water supplies were still relatively clean, a gravity feed of 600 m^3/hr is possible from the intake structure. The WTP can be bypassed and water gravity fed to farms. Such a situation would have to be closely monitored to ensure that ash did not build up and block the water supply. There may also be the option of choosing which stream to take water from, depending on relative levels of turbidity.

Staff at the WWWS said that there had been no contingency planning for volcanic flow hazards (lahars and debris flows). However, they anticipated that the system would probably deal with light ash showers, but moderate-heavy ash showers would cause significant problems for the water treatment process.

On the study farm, the roof feed to the dairy shed cannot be disconnected so would probably be severed by hacksaw in the event of an ashfall to protect the rain-fed water tank from ash contamination.

4.6.4 Potential mitigation of volcanic hazards

The farm didn't receive any ash during 1995/1996, and when asked what they would do in the event of an impending ashfall, they were uncertain what the best action would be. The farm manager believes they would carry on as normal on the farm – assessing what impacts occur and responding as needed. Plans would be made, but would depend on the level of warning and severity of the ashfall.

They are entirely dependent on the water scheme, with a limited amount of potential to use rainwater (could collect it from the roof of the main house, and they already collect it from the milking shed). There is no PTO facility for water pumps, and there is no generator on the farm.

Stock troughs would be cleaned out. If the water supply was lost, stock would be moved to troughs with water, although this would only extend supplies in the order of hours, rather than days – as may be required.

The farmers believed Fonterra would be the best source of information, working on the assumption that the company is a large and well-resourced organisation with multiple information channels. They expect that water would be brought in by tanker to keep them going if the supply was lost. They didn't have any expectations of help from MAF, Federated Farmers, the regional council or MCDEM.

4.7 Study farm 7: Hastings Vineyard

4.7.1 General information

Study Farm 7 grows 35 acres of Merlot and Malbec grapes. A further 10 acres is grown off the main site. These grapes are processed onsite along with ten acres of grapes from a neighbouring vineyard. The vineyard includes a restaurant which draws water from the same supply as the vineyard. The Property Manager was interviewed for approximately 1.5 hours, and a tour was made of part of the vineyard.

The vineyard is sited on Matapiro sandy loam, which is a free-draining soil. There is a hard pan 800mm below the surface which creates difficulty for post driving.

Vines are established on 500m lines each with two wires (Figure 3.16).

Figure 3.16 Vines

4.7.2 Water supply

The vineyard is supplied from a 20m bore at the western border of the vineyard. Water is pumped out of the bore with a single-phase submersible pump. The pump and bore are enclosed by a casing inside a shed. The pump is electrically powered with the power supply coming from standard sub-aerial power lines which run along the road on the western boundary of the vineyard. There is no provision for emergency backup power (i.e. a generator or tractor PTO). Water is pumped as required, with no pressure or storage tank providing any resiliency if the pump fails. If the water supply was out for any period of time during the vintage then there would be a significant loss of production. All water requirements for the property (including the restaurant) are met from the bore, and if the water supply failed, the restaurant would be unable to operate significantly impacting economic performance of the vineyard.

The only storage facility for water on the property is a tank of approximately 20,000 L capacity which collects water from the roof of the wine-processing shed. This could be used as a short term measure, and the tank can be disconnected from the roof.

The water from the bore (and in this area) has high hardness. Scale deposits are a problem for the hot water system in the restaurant and a deioniser is used. The irrigation lines get scale deposits within them, reducing flow efficiency and can ultimately block. Recently the town water supply has been extended out to the vineyard, and this could be an option for the future as it may have a lower hardness than the groundwater.

4.7.2.1 Vine irrigation

Irrigation has been installed throughout the vineyard. ‘Drippers’ have been installed below the canopy of the vines at 1.5m intervals and drip onto the roots of the vines. Each dripper provides ~4L per hour for four hours per day, usually five days per week, during dry periods which usually occur between September and February. This rate is reduced if there has been sufficient rainfall, with 10 mm rainfall being sufficient to replace a week of irrigation.

Stony high ground needs the most water, other areas less. The establishment of new vines has the highest water demand of any farm activity. Irrigation of new vines promotes growth and the development of deep root systems, and can have a strong influence on the ripening of the first crop on time for harvest. New vines are irrigated during the growing season from November to February.

The vineyard uses a manual system which pumps water on demand. There is not enough capacity in the system to meet the demands of both the restaurant and the irrigation system, so irrigation is done during the night, which also reduces evaporative losses.

4.7.2.2 Winemaking

Water demand is high during the winemaking process, particularly during the vintage (typically between March and May). The main use is for cleaning out equipment such as the tanks.

4.7.2.3 Restaurant

The restaurant has a high water demand for food preparation, washing and cleaning. Six septic tanks have been installed to deal with wastewater from the restaurant, toilets, and winemaking process.

4.7.3 Natural hazard experiences

4.7.3.1 Effects of Ruapehu eruption in 1995

The Property Manager was not working at the vineyard during the 1995 eruption, but was at a vineyard further inland which experienced traces of ashfall. No warnings were received. He reported that the quantity of ash received had little effect, despite the fact that this event occurred during the growing season. No changes to operational decisions or mitigation methods were required. Even the sensitive leaves of the vines were not impacted.

4.7.3.2 Volcanic activity in 1991?

The property manager recalled that the summer of 1991/92 was a poor grape growing season for the Hawkes Bay region. He said the low sunshine hours resulted in a heat deficit which delayed the ripening of the grapes and reduced the quantity and quality of the crop produced that year. The property manager estimated that “at least” 20-30% of production value was lost. If the cooler conditions had occurred during flowering then the effects could have been significantly worse.

The property manager attributed this cool summer to the result of increased particles in the atmosphere (aerosols and fine ash) from the eruption of Pinatubo volcano in the Philippines [in June 1991]. It is more probable that these effects were caused by the Hudson eruption in Chile, South America [in August 1991], as distribution of volcanic plumes are usually largely constrained to the hemisphere they erupt in.

4.7.3.3 Frost in 2003

In 2003 a heavy frost led to estimated losses of 50-60% in production value for the study farm and surrounding vineyards. The property manager reported this had a significant impact to the local industry and prompted significant information sharing on how to mitigate frost damage following the event.

4.7.3.4 Salt spray

There are problems with easterly storms blowing salt spray (sea water vapour) onto the vines. This causes sensitive areas of the leaf to die (brown tipping; Figure 3.17). New leaves are reported to be most vulnerable, such as in those forming in the spring growth period. This is a coastal issue, impacting only vineyards in close proximity to the beach.

To mitigate the effects of the salt spray, the irrigation system is turned on to try and dilute the salt spray. Trees have also been planted as windbreaks to try and block the wind/spray.

This is only really a problem for vineyards close to the sea. Some other vineyards have installed large (25mm diameter pipe) irrigators which they turn on to wash off the salt spray whenever the easterly storm is coming in. This may also be useful in event of an ashfall.

Figure 3.17 Vine leaves suffering damage from salt spray

4.7.4 Vulnerability of water supply (and farm) to volcanic hazards

The water supply on this orchard is relatively invulnerable to volcanic ashfall as it is derived from groundwater, and the pumping equipment is housed in a shed, and the irrigation system is enclosed. The main vulnerability is the potential loss of power. The heads of the irrigation drippers could accumulate with ash and block up, although as they are facing downwards the ash should not settle on them.

4.7.5 Potential mitigation of volcanic hazards

The Property Manager believes the management approach (unless otherwise advised) would be to wait and see what the impacts were and then to respond as appropriate. He thinks it would have to get pretty bad before they would actively look for outside assistance.

The property manager wanted accurate, rapidly distributed information on likely effects and what can be done to mitigate effects would be the most useful action emergency response agencies could provide. The Regional council would be the first source approached for information. Later, financial aid would be appreciated, but not expected.

He thought the vineyard would make changes if useful information was provided in advance. His belief is that present natural hazard literature in the viticulture community is about frost control (after the 2003 event). He noted that it usually takes a severe impact from a hazardous event before good information is distributed.

4.7.5.1 Possible methods for removing ash from vines

The use of the irrigation system may wash some of the ash off the vines. There is also the possibility of blowing and shaking the ash off with a mechanical harvester. Such machines have a leaf plucking system which reduces the leaf/stem ratio. This is usually done in the late spring to reduce the leaf area to let more light in to other areas of the canopy. The disturbance of blowing air and mechanical shaking these machines would probably remove at least some ash, but there could be potential damage to the machinery (increased wear on moving parts and congestion of engine). Alternatively harvesting pods could be put on the machines, which shake the vines quite vigorously and may stir up the ash less. They are very fast, so would be able to cover a big area. It was estimated by the property manager there are 20-30 grape harvesters in the Hawke's Bay region – they run 24/7 during the harvest season (late February-late April). Alternatively, a sprayer could be used to spray water onto the vines to try and clean the leaves and grapes of ash.

If the ash was wet these methods may be less successful. Factors that might affect ash removal include: how recently the ash fell, and a possible window when it is best to attempt removal.,

4.7.5.2 Labour

As a small operation, it was perceived that additional labour could be rapidly recruited if required. However, this is likely to be much more difficult for larger acreages.

4.7.5.3 Machinery

Many of the viticulture tractors have full cabs and have carbon filters for spraying operations. This would probably mitigate intake of ash if operated during an ashfall, although would probably require regular, time consuming cleaning. Most other machinery is under cover.

4.7.5.4 Sourcing information

The Property Manager said he would look on the internet for information, then follow up with the regional council. He understood that the weather would be the key for any event and would want data on what the likely impacts would be, with examples from other areas. He said he would phone other areas closer to the volcano which would be hit first and harder than they would, so hoped that information would flow back from these areas to the wider viticulture community. He believed that such information would be sent to the relevant authorities for distribution.

In the event of a large eruption he would wait and see what the impacts were and then react. However if information was available before the event it would be very useful, and would be rapidly distributed throughout the viticulture community (good infomation distribution networks).

4.8 Study Farm 8: Cambridge Kiwifruit Orchard

4.8.1 General Information

Study Farm 8 is a 5.5 ha kiwifruit orchard, 4 ha of which is in kiwifruit. The orchard is sited on river terraces along the Waikato River, 8 km from Cambridge, on light loam soil which is very free draining.

The farmers grow the 'Green' variety of kiwifruit, with approximately 1000 plants per hectare; each plant supported on a 6 ft pagoda system (Figure 3.18). Two out of three rows are female plants. When the plants are established the canopy of leaves develops like a roof, with the fruit protected below.

Bud development begins from the end of September through to the end of October. Flowering and pollination occurs in November, with fruit set taking place in December. Pollination is highly reliant on bees ($130/hive). Spring is therefore a time of major growth, with new cane and leaf growth (irrigation is important during this time). A rule of thumb is that fruit development and growth period usually takes 150 days (from fruit-set through to harvesting). Harvest occurs from late-February through to May, depending on variety and the season. The ‘Gold’ variety is a month earlier than the ‘Green’ variety usually, so require more extensive frost protection systems.

Figure 3.18 Kiwifruit plants and pagoda system.

The time from planting to full maturity is seven years. During the initial 2 years no fruit is produced, but from the third year on fruit is produced in increasing volume. Estimated production for the 2007 season was 15,000 trays of fruit. As the orchard is in second year of production, this figure is estimated to double (~30,000 trays) when the crop is fully mature.

The location of the farm means only ashfall hazards will ever impact the farm during a volcanic eruption.

4.8.2 Water Supply

Environment Waikato did not allow the farmers any extraction of water from the Waikato River, despite several other properties having consents (first in first served type basis). There are two water uses on the farm, irrigation and domestic supply for the house.

Irrigation of the orchard is serviced by a 4-inch cased bore at a depth of 100m. Maximum consented extraction is 120 m^3/day. There is sufficient aquifer pressure to raise water to a 20 m depth. A submersible at 45 m depth pumps the water out of the bore. Water quantity is excellent; during well tests (maximum pumping for a sustained period) the water table dropped 5m, but recovered within 24 hours. The water contains no sediment; however it has a high concentration of Manganese (Mn) and Iron (Fe; at least initially) making it unsuitable for household.

4.8.2.1 *Irrigation*

Irrigation typically occurs from mid-January through to late February, and typically lasts for 2 h/daily. In dry years irrigation may begin in late December. The irrigation system uses 'drippers' situated below the canopy to irrigate water onto the roots of the plant (Figure 3.19). There is a 25,000 L storage tank for ensuring there is enough water for irrigation. Water is taken directly from the bore to the tank and then pumped to the irrigators. At no time is the supply exposed to the atmosphere (and thus ashfall hazards), so should be relatively resilient to ashfall hazards.

4.8.2.2 *Domestic Supply*

The house is supplied by rain water collection from the roof. Water is stored in a second 25,000 L tank. There is the provision to switch over to the irrigation supply if required in an emergency.

4.8.2.3 *Frost Protection*

Late spring frosts would be quite devastating to the flowering of the kiwifruit crop. There are currently no provisions for frost protection, although this is a likely development in the future. It would involve setting up a series of small spray nozzles above the canopy of the kiwifruit. It could potentially just involve extending the existing canopy dripper tube above the canopy. However it is a very expensive to set up such a capability, as the bore would need to be widened to a 6 inch casing (the current 4 inch cased bore cost over $10,000).

Figure 3.19 Drippers

4.8.3 Natural Hazard Experience

4.8.3.1 *1995 Ruapehu Eruption*

When the farmers were dairy farming at Matamata they received a dusting of ash. There were no problems to the farm at all and it was regarded simply as an interesting experience, mainly because the rain simply washed it all off.

There was no information distributed during this period that they can remember. If they had been impacted further then more information would have been greatly appreciated.

4.8.3.2 Vulnerability to Volcanic Hazards

An ashfall during bud development and flowering of the plants is likely to cause significant damage to the plant and have a serious impact on the yield (potentially destroying all fruit development by the plant). If the ashfall occurred after fruit set, then ash could potentially be washed off and some of the crop saved. However, cleaning of ripe fruit that have been ashed on would be a challenge, given the huge number of fruit and the hairy nature of the fruit. The Gold variety is less hairy so may be more resilient from this respect; however they are more sensitive to fluctuations in environmental conditions and go to mush very easily.

Once leaves develop, the fruit below is protected. This would provide some protection during light ashfalls, however rainfall and remobilisation of dry ash (from the plant or ground) may cause the fruit to become contaminated.

As mentioned earlier, bees are an essential part of the kiwifruit pollination process. Ash particles are particularly destructive to insects, mostly due to abrasion to the epicuticular wax layer, which caused rapid desiccation and death. The greatest damage to insects occurs to beneficial species such as honey and pollinator bees, and predatory and parasitic wasps (Cook et al., 1981). These insects are highly mobile and many have a dense covering of body hairs that trap volcanic dust. An ashfall may be devastating to pollinator insect populations causing significant disruption in pollination. Artificial pollination may need to be used, at greatly increased costs (~$1000/ha) and subject to the risk that widespread impacts from ashfall may create large demand for this service that outstrips supply.

The export market for kiwifruit is extremely sensitive to damaged or marked fruit, so it is unlikely that fruit damaged by the ash would be acceptable for export. Ash on the plant can be incorporated into the fruit as the skin grows (as observed occurring to citrus fruit during the 2006 Merapi eruption; Wilson et al., 2007), This may make it uneconomic to pick the fruit, even crops survive through to harvesting.

4.8.4 Potential Mitigation of Volcanic Hazards

The farmers are aware they are in a vulnerable part of the country. They would look to the regional council and scientific community for advice. They would want information quickly and rapidly, especially if there were significant warnings about a possible eruption.

The farmers would think about insurance and what cover they had. They would disconnect the down pipe – they didn't do this during the eruption in 95/96 as the ashfall was too light to worry about.

4.9 Summary of Study Farm Assessments

Water is a critical element on New Zealand farms. The major uses are for stock drinking water, irrigation, cleaning (e.g. of dairy sheds, tanks used for winemaking), the homestead supply, and making up agricultural chemical preparations such as pesticides, fertilizers and dips.

Where there is a significant ashfall, uncontaminated surface water would be in short supply. Ash would contaminate supplies by increasing the turbidity, pH and potentially leach toxic chemicals into the water resource (Wilson and Cole, 2007).

It is difficult to assess how much ashfall will contaminate water supplies or render them useless. Factors that affect this vulnerability include:

- intended use of the water (some applications don't require the same level of water quality as others)
- ability of the water supply network to cope with increased levels of suspended sediment (includes water pump, any filters, pipes, etc)
- capacity to filter or treat contaminated supplies
- seasonal and climatic vulnerability.

Recovery of water supplies will be dependent on:

- volume of remobilized ash being added to the water body
- ability of the water body to flush out contaminating ash
- volume of the water body
- chemistry of the water
- buffering capacity of the water body (different reservoir/river beds have different buffering capacity)

4.9.1 Reserve Water Supplies

If water supplies become contaminated or disrupted by power failure, the ability of a farm to meet its water demands depends on stored water. Ideally, stored water should be in enclosed tanks (as open reservoirs will be vulnerable to ashfall) and located on topographic high points so that water may be gravity fed into the farm system.

Following electrical supply loss, pump damage or surface water contamination, gravity fed water from water tanks may become the only option for many farms.

4.9.2 Contamination of Stock Drinking Water

The amount of water consumed by a livestock herd is largely controlled by weather conditions. Dry and hot conditions will greatly increase water consumption (Table 3.5), whilst cold and wet conditions would mean a minimal amount of water is consumed as livestock derive hydration through pasture consumption (Wilson and Cole, 2007). Whilst demand would be slightly lower in cooler temperatures, an ashfall will cover pastures causing stock to drink more from farm water troughs to make up their water demands.

Table 3.5 Water Use Estimates (from Piper, 2005)

Water Use	Water Use (m^3/day)
Household use (4 people)	0.74
Dairy shed wash down [1]	0.07
Dairy [1]	0.1
Beef [1]	0.0625
Deer [1]	0.0385
Sheep [1]	0.0055

[1] Water use per animal

Water consumption is also related to the feed quality. If livestock eat a lot of rough dry feed (such as hay, or pastures after a dry summer) then stock require a lot more water from the trough system. It is likely that supplementary feed consumption will increase following a moderate ashfall (often rough, dry feed).

General pastoral farm vulnerability is greatest however in early spring, as supplementary feed supplies are at their lowest and farmers are expecting vigorous spring pasture growth with the warmer weather. Stock would also be under considerable stress following birthing and rearing/milking demands. They would also be attempting to put on condition following the demands of winter, creating high feed demands on pastures.

Ashfall would contaminate uncovered stock-water troughs in paddocks, causing problems as cows drink suspended ash and any aerosols dissolved within the trough water. However, mixing 1 kg of ash from the 1995 Ruapehu eruption with a typical 1000 L water trough did not raise the fluorine levels of the water above health standards, although the water was acidic (pH 4.6) potentially putting stock off drinking (Neild et al., 1998).

Potential mitigation of this would be to clean the tephra out of the trough and replace the water regularly (adjusting the buoy-cock so the troughs are refilled to a lower level would mean less water needs to be replaced, but may concentrate harmful aerosols if left too long). This would be time consuming, especially in remote paddocks and/or if there were many troughs (Wilson and Cole, 2007). It would also increase the volume of water required. A management option would be to cover and/or disconnect troughs from the farm water supply in paddocks not containing stock, although this would involve getting out to the paddocks somehow and then working with wet tephra (Wilson and Cole, 2007).

Any large, nearby water bodies are a potential watering option for stock. The volume of lakes may stay dilute enough to give a period of acceptable stock drinking water supply, perhaps at least until another more permanent source is developed. Over time during a large ashfall event, or with remobilisation of ash being transported into such water bodies, this may not be for very long.

4.9.3 Cleaning

4.9.3.1 Milking Sheds

The lack of water for washing down the milking shed would be a serious issue for successful operation, potentially degrading milk quality to a point it cannot be sold (Wilson and Cole, 2007). Milking sheds are generally open, allowing ash to easily enter the building. This would cause problems for humans, cows and equipment, if it was decided to continue milking during an ashfall. It would (Wilson and Cole, 2007):

- decrease the quality of the working environment causing health hazards to humans (as it would get into the eyes and throats), and animals alike
- dirty the cups between milkings, as well as get onto the teats of the cows during milking (potentially causing discomfort and health implications for the cow, such as the onset of mastitis; M. Pacey *pers comm*., 2004). This may allow ash to enter the pump and milk storage equipment of the milking shed, potentially causing damaging or contaminating the milk.

4.9.3.2 Vineyards

During the vintage significant water use is required for cleaning tanks used in the production of wine. Lack of water would also be a serious issue for the successful production of wine, potentially degrading quality or indeed halting production.

4.9.4 Irrigation

Irrigation is essential for many farms to achieve a higher level of production than possible on normal rainfall alone. Irrigation is a major water use and is likely to be compromised during an ashfall event. Even if additional groundwater can be sourced, the supply will be vulnerable to power failure or possibly required to assist in watering animals from nearby farms. It raises the question whether farmers would stop irrigating to assist other farmers to save their animals from dehydration (likely to be related to the strength of social linkages and sense of community).

4.9.5 Ponds/Reservoirs

Volcanic ashfall on the surface of ponds (irrigation, stock water or effluent sumps) would increase the concentration of suspended volcanic ash, increasing the possibility of blocking the outlet of the sump or damaging the effluent pump. Volcanic ash entering the sump is likely to increase the acidity and turbidity of the water, but would probably not restrict the usual practice of spraying the water on to paddocks, assuming there were no blockages in the pipes and the pump was still operational., This would be similar to problems that waste water systems and sewage treatment plants face during volcanic ashfalls, but on a smaller scale.

4.9.6 Drains

To avoid blockages the best practice would be to remove as much of the suspended volcanic ash and effluent sludge before being washed into the sump, with a tractor’s frontal attachments (bucket or blade) and/or hand shovels. Remaining deposits will hopefully be small enough in size and volume not to cause blockages.

4.9.7 Vulnerability of Individual versus District Water Supply Schemes

It is difficult to judge whether a district water supply scheme is more vulnerable than individual water supplies on farms (such as a bore hole or reservoir). A significant point is that if the district scheme fails there is potentially no water supplies anywhere else in the district, whereas if each farm had a water supply a certain degree of resiliency for the district can be created by sharing that resource. Alternatively if power supplies fail then the district may indeed be shut down anyway.

An advantage of district supply schemes is that most of the distribution network is usually underground and there would only be one site to repair if damaged. For areas that are not serviced by a reticulated supply, there could potentially be hundreds of individual farm schemes requiring repair following a widespread eruption fail during a eruption.

4.9.8 Water for general farm operations

Many non-critical functions, such as drenching, require some water usage. It is possible such functions would be halted during a water supply crisis (either through lack of water or lack of farmer time) reducing the quality of farm practices.

The key vulnerability of many farm water systems is the reliance on electrical power. Electrically powered pumps are used to pump water around the farm (to stock water troughs, irrigation networks, etc.). If power is lost, water supplies are also lost, unless pumps can be driven by another power source, such as a fuel generator or power-take-off (PTO) from a tractor.

4.10 Information Availability

Volcanic hazards in the central North Island of New Zealand can generally be defined as high impact, low probability events. Because events are so few and far between, communities quickly forget the disruption and impacts. Predicting where the ash will go is extremely difficult due to variable climatic conditions (wind directions and strengths), even when an eruption is imminent or occurring. Therefore reduction and readiness is rarely carried out specifically for volcanic hazards by farmers, but it can be part of on-going hazard mitigation strategies that will benefit the business during any adverse events.

The distribution of information before, during and after a volcanic crisis will be essential., As volcanic eruptions are infrequent events with which few farmers have had experience. Memories tend to be very short when it comes to remembering the consequences and effects of natural disasters. The average time Hawke's Bay farmers are on their land is 8.5 years for example, so many farmers will have forgotten or never experienced the eruptions over 10 years ago (Garth Eyles, *pers comm*., 2007). Information therefore needs to be readily available to quickly distribute to people when required. During the 1995/96 Ruapehu eruption there was a significant gap of information being supplied, especially for the rural sector. The Ministry of Agriculture didn't have the information required and the few advisors they had available were too busy to put any time into researching likely impacts.

Farmers interviewed during this project identified five specific pieces of information they would like to receive at the onset of a volcanic eruption:

- how long the eruption will go on for;
- how much ash is likely to fall;

- what would the likely impacts to animal health be and how best would you to mitigate such impacts;
- pasture rehabilitation and how best to mitigate such impacts;
- protection of the water supply and how best to mitigate such impacts.

One way to reduce lack of preparedness during an extreme geophysical event is to rapidly distribute hazard mitigation information out via mass media. Clear, intensive ‘last minute’ hazard education and post-event recommendations can be distributed if a volcanic eruption is imminent, or has occurred with little warning. The media must be included as a legitimate partner in any hazard education program, with many farmers placing a high reliance on this source for information. It will also be important that information is conveyed in a consistent manner by all agencies during a crisis.

5.0 OVERALL VULNERABILITY INDEX AND INTEGRATION INTO RISK ESTIMATION

5.1 Factors influencing vulnerability of farm water supplies to volcanic hazards

On the basis of the detailed characterisations of farm water use regimes and identification of points of vulnerability within water supply systems described in the previous chapter, six factors that influence vulnerability of water supplies to volcanic hazards were identified. These are as follows:

5.1.1 Type of supply

- Groundwater
- Surface water

The type of water supply is the key determinant of vulnerability to volcanic ashfall, with groundwater-fed supplies considerably less vulnerable. However, the above-ground components of groundwater-fed systems are still vulnerable to ashfall, as was reported in the literature review (Sections 2.3.1 and 2.3.2). In one case, airborne ash penetrated the bearings of a windmill used to extract groundwater in coastal Santa Cruz; this area is totally dependent on groundwater thus were severely disabled. Another common cause of failure is airborne ash penetrating switchboards and causing short-circuiting.

5.1.2 Pumping capability

- Total reliance on pumped water – no backup power
- Total reliance on pumped water – backup power
- Some reliance on pumped water – no backup power
- Some reliance on pumped water – backup power
- No reliance on pumped water

The ability to pump water is critical to water distribution on most farms. This is usually powered by electricity, the distribution networks of which are vulnerable to failure during a volcanic eruption. Groundwater supplies usually require pumping facilities, unless there is a significant head of water. Surface water supplies may be less vulnerable to loss of pumping facilities as normal flow may be able to continue.

5.1.3 Independence of supply

- Individual access to supply
- Share with several users
- District scheme

This vulnerability indicator is designed to capture the resilience of an area. In general, farms with their own water supplies tend to have a higher degree of resilience because farmers in these situations are used to being self-reliant. Also, if an individual water supply fails, backup from neighbouring farms may be possible. This will not be the case with large-scale schemes (see Section 3.8.2.1): all farms served by the scheme will be affected in the event of supply disruption.

5.1.4 Water usage

- Small water user
- Large water user at specific times of the year
- Large water user for most of the year

Small water users are less vulnerable than larger users. If the supply fails, it will generally be less difficult to find an alternative supply, and stored supplies will last longer.

5.1.5 Level of stress on water supply

- Constant stress on farm water supply
- Seasonal stress on farm water supply
- Occasional stress on farm water supply
- Unstressed water supply

An eruption will intensify existing stresses on a water supply.

5.1.6 Storage capacity

- No storage capacity
- Storage capacity to operate for 1-3 days (in high demand periods)
- Storage capacity to operate for 5+ days (in high demand periods)

Storage capacity will allow a farm to continue to function following failure or disruption of the water supply, and will provide a buffer period to repair the distribution system or obtain alternative supplies. Conversely, a farm with no storage capacity will be immediately in crisis following disruption of supply.

5.2 Overall farm vulnerability index

A scheme for assessing the overall vulnerability of a farm to volcanic ash impacts on water supplies was drawn up (Table 4.1) by considering the findings both of our literature review (Chapter 2) and our case studies of individual farms (Chapter 3). Detailed assessments for each farm are provided in Appendix 5. A scheme for assigning relative vulnerabilities was also drawn up (Table 4.2).

Summary results for individual farms are shown in Table 4.3.

Table 4.1 Scheme for deriving an overall farm vulnerability index[1]

CONTRIBUTING FACTOR		SCORE	TOTAL
Type of supply	Groundwater	10	**30**
	Surface water	30	
Pumping capability	No reliance on pumped water	0	**20**
	Some reliance on pumped water – backup power option for pump	5	
	Some reliance on pumped water – no backup power option for pump	10	
	Total reliance on pumped water – backup power option for pump	15	
	Total reliance on pumped water – no backup power option for pump	20	
Storage capacity	Storage capacity to operate for 5+ days (in high demand periods)	5	**20**
	Storage capacity to operate for 1-3 days (in high demand periods)	10	
	No storage capacity	20	
Independence of supply	Individual access to supply	0	**5**
	Share with several users	2	
	District scheme	5	
Water usage	Small water user	5	**15**
	Large water user at specific times of the year	10	
	Large water user for large periods of the year	15	
Level of stress on supply	Constant supply of water to farm	0	**10**
	Occasional pressure on farm water supply	3	
	Seasonal pressure on farm water supply	7	
	Constant pressure on farm water supply	10	
OVERALL VULNERABILITY INDEX		**RATING OUT OF**	**100**

[1] For a farm water supply to volcanic hazards

Table 4.2 Relative vulnerability classification scheme

Overall vulnerability index	Relative vulnerability classification
10-40	Low
41-60	Moderate
61-80	High
81-100	Extreme

Table 4.3 Overall vulnerability indices for each study farm

Study farm	Farm type	Location	Water supply	Vulnerability index	Relative vulnerability classification
1	Sheep and Beef	Tikokino, Hawke's Bay	Groundwater	42	Moderate
2	Sheep and Beef	Bridge Pa, Hawke's Bay	Surface water (& groundwater)	58	Moderate
3	Sheep and Beef	Western Taupo, Waikato	Surface water	67	High
4	Dairy	Rerewhakaaitu, Bay of Plenty	Groundwater	45	Moderate
5	Dairy	Reporoa, Bay of Plenty	District scheme (groundwater)	65	High
6	Dairy	Eltham, Taranaki	District scheme (surface water)	87	Extreme
7	Horticulture: vineyard	Hastings, Hawke's Bay	Groundwater	60	Moderate
8	Horticulture: kiwifruit	Cambridge, Waikato	Groundwater	50	Moderate

5.3 Assessing volcanic risk to study farms

Volcanic risk encompasses the likelihood and magnitude of a volcanic hazard event impacting a particular location. Integrating this information with the inherent vulnerability of a particular farm gives an overall estimation of risk.

Volcanic risk depends on the proximity to active volcanic centres. Depth of ashfall normally declines with distance away from the vent. The size distribution of ashfall also changes as the plume travels away from the vent, with coarser particles falling closer to the vent and finer particles transported furthest (Figure 4.1). However, at any particular location the characteristics of the ashfall deposited can vary widely.

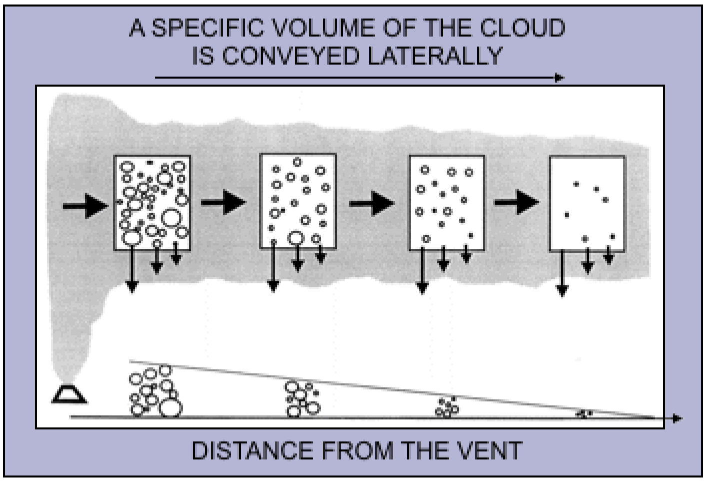

Figure 4.1 Changes in volcanic ash size distribution with distance from the vent

The thickness of ashfall received at a particular site will depend on:

- The magnitude (size) of the eruption: the larger the eruption the greater the volume of material erupted.
- Distance from the volcano: areas close to the volcano will receive the thickest ash falls.
- Wind and climatic conditions: these control the dispersal of the ash plume.

A probabilistic ashfall map (Hurst and Smith, 2004) has been used here to define volcanic risk for each study farm (Figure 4.2). This model is derived from a method for quantifying the probability of a particular thickness of volcanic ash at any particular site using Monte Carlo methods and an ash dispersal model *("ASHFALL*"). Hurst and Smith's model uses a large number of eruption iterations and considers the mean accumulated ash thicknesses from multiple volcanic centres (including the Tongariro, Taupo and Okataina volcanic centres, White Island and Taranaki volcano; see Figure 1.1). Predicted accumulations of ashfall over a 10,000 year period are shown in Figure 4.2. Data for each study farm are shown in Table 4.4.

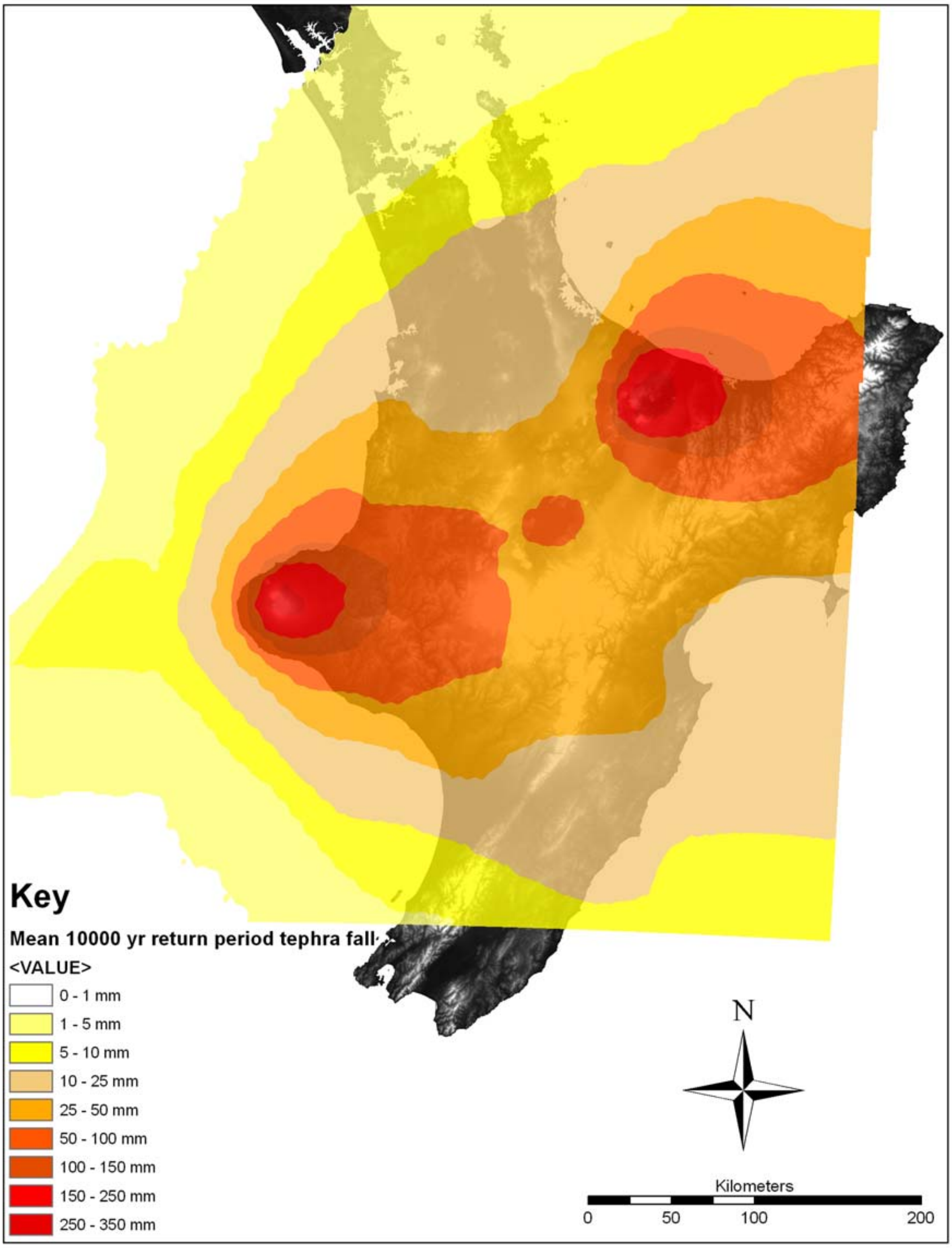

Figure 4.2 Mean 10,000 year return period ashfall thicknesses (Hurst and Smith, 2004)

Table 4.4 Mean ashfall depths over 10,000 years

Study farm	Farm type	Location	Water supply	Mean ashfall depth over 10,000 years
1	Sheep and beef	Tikokino, Hawke's Bay	Groundwater	30 mm
2	Sheep and beef	Bridge Pa, Hawke's Bay	Surface water (and groundwater)	25 mm
3	Sheep and beef	Western Taupo, Waikato	Surface water	50 mm
4	Dairy	Rerewhakaaitu, Bay of Plenty	Groundwater	180 mm
5	Dairy	Reporoa, Bay of Plenty	District scheme (groundwater)	40 mm
6	Dairy	Eltham, Taranaki	District scheme (surface water)	150 mm
7	Horticulture: vineyard	Hastings, Hawke's Bay	Groundwater	20 mm
8	Horticulture: kiwifruit	Cambridge, Waikato	Groundwater	18 mm

However, it should be noted that this model does not include proximal hazards such as lahars or pyroclastic flows, which are also capable of causing major damage to rural water supplies.

5.4 Overall risk of volcanic hazards to farm water supplies

In this section, the vulnerabilities of individual farm water supplies has been combined with their predicted volcanic risk, to estimate the overall risk. This is presented in a summary diagram (Figure 4.4), in which the risk fields have been defined from the literature review of water supply sensitivity to volcanic hazards.

Study farms 4 and 6 clearly have a relatively high overall risk of volcanic hazard impacts on their water supplies. Study Farm 6 has both a high level of innate vulnerability in its water supply, and also is considered relatively highly at risk from volcanic hazards. Study Farm 4 is less vulnerable but also is highly at risk from volcanic hazards.

The other study farms plot more closely together, with Study Farm 8 probably the least at risk overall due to a lower risk from volcanic hazards, and only moderate vulnerability in its water supply.

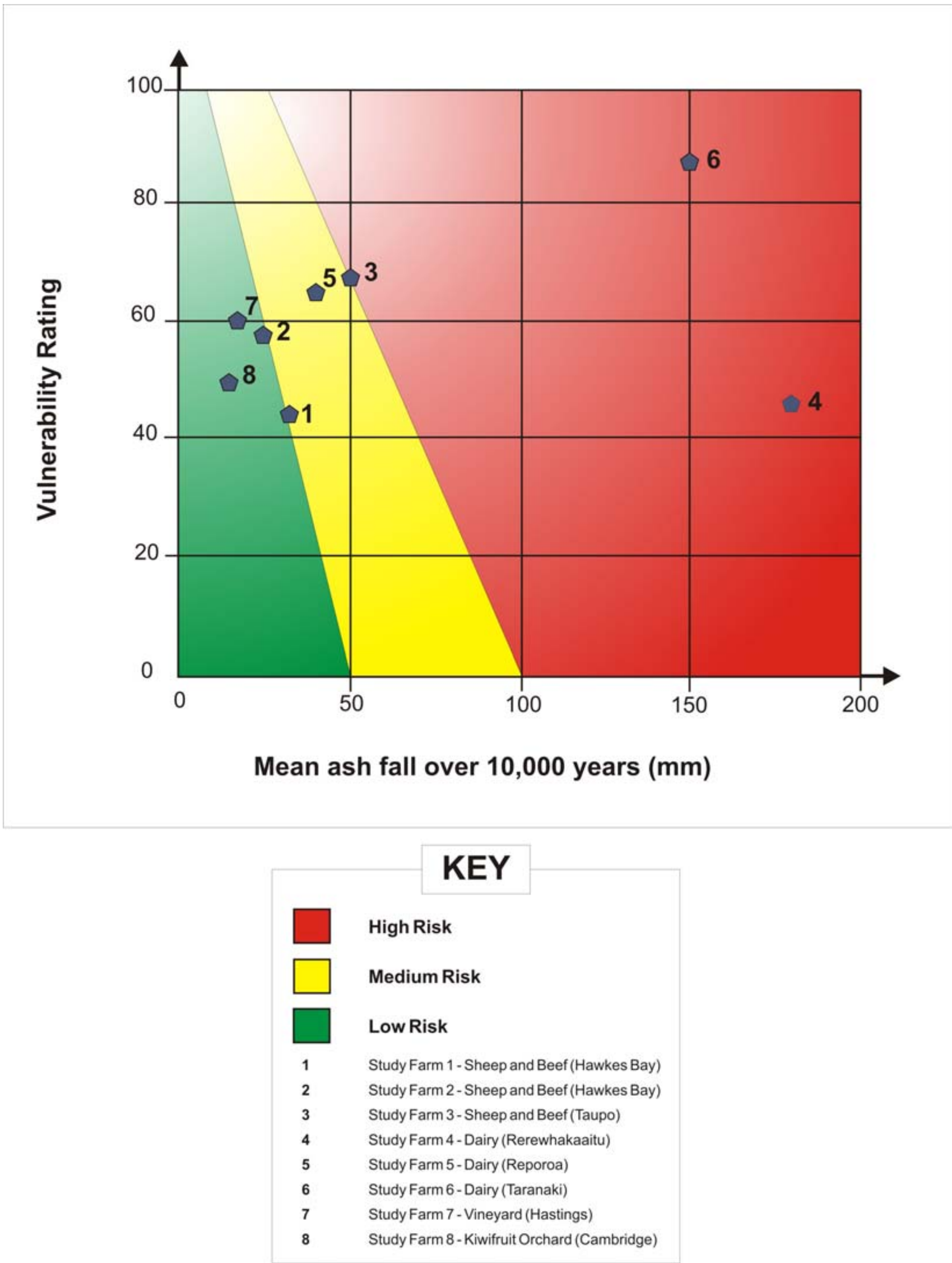

Figure 4.3 Overall risk of study farms of volcanic ashfall impacts on their water supplies

6.0 REVIEW OF AGRICULTURAL WATER QUALITY GUIDELINES

Both the quantity and quality of water resources are critically important issues for agriculture and aquaculture. As shown in the case studies (Chapter 3), volcanic ashfall can disrupt the water supply by blocking intakes and pipes, and also by interrupting the power supply, leading to pump failures. Volcanic ashfall also has impacts on water quality as fresh volcanic ash releases acidity and other soluble components such as fluoride, calcium and sulphate into surface waters. Chapters 5 and 6 address the likely impacts of volcanic ashfall on water *quality* in relation to agricultural uses, firstly by reviewing relevant water quality guidelines to identify the critical issues, and then by using available information to attempt to model impacts using the simple model of Stewart et al. (2006).

Water quality guidelines for primary production were found by searching the internet and the relevant literature. Four sets of guidelines were readily found; we decided not to search further as this set contained sufficient information for comparison. In this chapter, these guidelines will be briefly described, then comparisons will be made between the contents of the guidelines under the headings of agricultural water quality for: irrigation, general use and livestock drinking water. Tables comparing numerical standards have been compiled where possible.

6.1 Overview of agricultural water quality guidelines

6.1.1 ANZECC guidelines

The Australian and New Zealand Guidelines for Fresh and Marine Water Quality are produced jointly by two ministerial councils: the Agriculture and Resources Management Council of Australia and New Zealand (ARMCANZ), and the Australian and New Zealand Environment and Conservation Council (ANZECC). They were last updated in October 2000. These guidelines relate to the sustainable use of water resources in the two countries for various end uses, including primary production. It should be noted that the New Zealand Drinking Water Standards (2005) are separate, and are produced by the New Zealand Ministry of Health.

The ANZECC guidelines (2000) have the following primary objective:

> *“To provide an authoritative guide for setting water quality objectives required to sustain current, or likely future, environmental values [uses] for natural and semi-natural water resources in Australia and New Zealand.”*

These guidelines are available online through multiple sources, such as the New Zealand Ministry for the Environment website www.mfe.govt.nz.

The primary production guidelines have sections on water quality for irrigation and general water use, and livestock drinking water quality. An important point to note about these guidelines is that they are not intended to be used as mandatory standards. Rather, the guidelines are ‘trigger values’, whereby exceedences of these values trigger further investigations.

6.1.2 FAO guidelines

The Food and Agriculture Organisation of the United Nations, based in Rome, has produced a set of guidelines entitled 'Water Quality for Agriculture' (Ayers and Westcot, 1985). These were updated in 1994, and are available online through the FAO's corporate document repository at: http://www.fao.org/DOCREP/003/T0234E/T0234E00.HTM.

This document was originally published as 'Irrigation and Drainage Paper 29', and was primarily derived from case studies and research findings from farming in arid and semi-arid climates (Ayers and Westcot, 1985). As a result, the guidelines have a very strong focus on water quality issues in irrigation-dependent farming systems and, in particular, salinity build-up and control. However, the more recent version does contain a short section on water quality for livestock and poultry drinking water.

The FAO guidelines are the nearest thing we found to international guidelines, and are based on case studies from many regions of the world, albeit with a focus on arid areas (Jensen et al., 2001).

6.1.3 Canadian guidelines

The Canadian Water Quality Guidelines (CWQG) for Agricultural Water Uses contain values for livestock watering and irrigation (CCME, 2005). They are national values designed to protect the health of livestock and crops and are developed according to a national protocol under the auspices of the Canadian Council of Ministers of the Environment (CCME, 1993). In general, guideline values are based on animal (livestock watering) or plant (irrigation) toxicity studies. Some irrigation guidelines, however, are intended to protect human health. Where data are limited, interim livestock watering guidelines may be calculated from human health drinking water values.

CWQGs are voluntary tools for the assessment and management of agricultural water uses. At levels below the guideline, adverse effects on livestock or crops are not expected. At levels above the guideline, there is an increased probability of observing adverse effects. Further investigation may be necessary.

A branch of the Canadian government (Agriculture and Agri-Food Canada) has produced an excellent series of fact sheets about agricultural water quality. These are available on its website http://www.agr.gc.ca/pfra/water/quality_e.htm#protect.

6.1.4 South African guidelines

The South African Water Quality Guidelines are produced by the Department of Water Affairs and Forestry, the custodian of South Africa's water resources. Part of its mission is to:

"maintain the fitness for use of water on a sustained basis".

Agricultural use is one of the four categories of water use defined by the South African Water Act. The guidelines are organised along similar lines to the ANZECC guidelines, and have volumes on both irrigation and livestock watering for agricultural water use. They are

available online at:
http://www.dwaf.gov.za/IWQS/wq_guide/irrigat.pdf
http://www.dwaf.gov.za/IWQS/wq_guide/livestoc.pdf

The guidelines described above are all broadly divided into coverage of water quality requirements for irrigation and livestock drinking water, so the following discussion will also use this structure. The ANZECC guidelines also contain coverage of water quality for ‘general farm use’, which will also be covered here.

6.2 Livestock drinking water quality

Good water quality is essential for successful livestock production. Poor quality water may reduce animal productivity, growth and fertility, and in extreme cases animals may die. Contaminants in drinking water can also produce residues in animal products such as meat, milk and eggs.

Daily water intake varies widely among different types of livestock, and is also influenced by factors such as the climate, diet and the physiological state of the livestock. Daily intake rates can be as high as 85 litres/cow/day for dairy cows in milk.

6.2.1 Toxic effects

Many elements are essential nutrients for animal health, but may cause toxic effects at high concentrations. The ANZECC guidelines have set the following trigger values for toxicity effects of major and trace elements in livestock drinking water (Table 5.1). Where available, levels set by other guidelines are included for comparison.

Table 5.1 A comparison of guideline values for trace elements in livestock drinking water

Parameter	ANZECC	FAO	Canadian	South African	Comments
			mg/L		
Aluminium	5	5	5	5	Relatively non-toxic, but may have neurotoxic effects at high levels
Arsenic	0.5	0.2	0.25	1	Pigs and poultry are most sensitive and may suffer dehydration and haemorrhagic diarrhea although short term doses are usually tolerated
Beryllium	-	0.1	0.1	-	Little information available
Boron	5	5	5	5	Short term exposures are little problem, but long term exposures may cause weight loss and decrease in feed intake
Cadmium	0.01	0.05	0.08	0.01	Cd is of concern because it bioaccumulates; high Cd levels may cause teratogenic, mutagenic and carcinogenic effects
Calcium	1000	-	1000	1000	Essential element for bones and teeth; excess Ca can reduce absorption of other nutrients.
Chromium	1	1	0.05	1	The South African guidelines specify that this limit is for chromium (VI), the hexavalent form
Cobalt	1	1	1	1	Co is an essential micronutrient (component of vitamin B_{12}) but toxic at higher concentrations
Copper	0.4 to 2	0.5	0.5 to 5	0.5	There is quite a narrow window between essential and toxic levels of Cu. This varies with the type of livestock, hence the ranges of GVs, and also depends on molybdenum and sulphate levels

Table 5.1 continued

Parameter	ANZECC	FAO	Canadian	South African	Comments
			mg/L		
Fluoride	2	2	1 to 2	2	Excessive F causes dental and skeletal fluorosis. Intake from feed is also important; the Canadian guidelines recommend using the lower GV if feed is high in fluoride
Iron	-	-	-	10	Some discoloration of meat at 0.1 mg/Lin veal calves; also can taint milk at low levels; however GVs generally not set as iron not considered a health hazard
Lead	0.1	0.1	0.1	0.1	Acute lead poisoning is more common (eg via contaminated feed) and affects the nervous system; chronic effects include anorexia and emaciation
Magnesium	2000	250-500[1]	-	500	Mg is essential but high doses cause scouring and diarrhea.
Manganese	-	0.05	-	10	Deficiency problems are of much more concern than toxicity problems; FAO level is based on human drinking water guideline which is not based on health hazards
Mercury	0.002	0.01	0.003	0.001	Hg is of concern as it bioaccumulates and causes severe neurotoxic effects
Molybdenum	0.15	-	0.5	0.01	An essential micronutrient toxic at high concentrations; causes diarrhea and loss of appetite
Nickel	1	-	1	1	Interacts metabolically with iron
Nitrate	400	100	100	100	Nitrate is readily converted to nitrite, which is much more toxic to animals. Nitrite oxidizes haemoglobin to methaemoglobin which cannot transport oxygen. Symptoms include vomiting, convulsions, cyanosis and death.
Nitrite	30	10	10	-	
Selenium	0.02	0.05	0.05	0.05	Component of enzyme glutathione peroxidase; deficiencies more common than toxicity and feed supplementation is common
Sodium	-	-	-	2000	Decreased palatability tends to occur prior to any toxic effects
Sulphate	1000	-	1000	1000	Sulphur is essential for animal nutrition but high levels cause diarrhea and are unpalatable.
TDS[2]	2000 to 4000	1000	3000	1000	High levels primarily affect the palatability of the water which in turn causes indirect health effects[3]
Uranium	0.2	-	0.2	1	Little information available
Vanadium	-	0.1	0.1	1	Possibly an essential element; interacts metabolically with Cr and Fe; high levels lead to reduced growth
Zinc	20	24	50	20	Essential micronutrient; many enzymes contain Zn; tolerance generally high

[1]These suggested limits range from 250 mg/L for poultry and swine to 500 mg/L for sheep
[2]Total dissolved solids (salinity)
[3]See discussion on palatability effects below

As with the irrigation guidelines, these values are generally intended to be used as ‘triggers’. Livestock drinking water concentrations less than these values are considered unlikely to cause any adverse effects, while exceedences are intended to trigger, or indicate the need for, further investigations. Toxicological effects are complex and depend on many factors such as the dietary intake of trace elements and metabolic interactions between elements (for instance, an adequate level of dietary calcium tends to suppress the uptake of lead, and zinc-deficient diets aggravate mercury toxicity).

6.2.2 Palatability effects

Palatability is an important issue for livestock drinking water. Direct effects of an unpalatable water supply are a refusal to consume water, consumption of water at levels inadequate for physiological requirements, or a refusal to consume water followed by a period of excessive consumption if no alternative supply is provided and animals are driven to do so by thirst signals. Indirect health effects can arise because there is a direct relationship between water intake and feed intake, and if water intake is inadequate, animal condition will decline along with production parameters such as milk production, average daily gain and feed conversion ratio. This is known as dehydration-induced hypophagia.

The scenario in which animals refuse to drink, but then consume excessive quantities, can lead to acute toxicity effects. For instance, high levels of sodium in the water can cause osmotic stresses and hypertension.

Livestock generally find highly saline water unpalatable; also, the types of salt present are important in addition to the total dissolved solid content. Magnesium sulphate (Epsom salts) is more harmful than sodium chloride or sulphate. The main water constituents implicated in palatability effects are chloride, sulphate, magnesium, bicarbonate and calcium. Other factors, such as dust, temperature, levels of hydrogen sulphide, ammonia, organic compounds such as toluene and xylene, and the presence of algae, can also contribute to the palatability of water to livestock.

The ANZECC guidelines set the following ranges for tolerances of livestock to salinity in drinking water (Table 5.2). It is important to note that livestock may be able to adapt physiologically to intermediate levels of salinity if they are exposed gradually over several weeks. These guideline values are generally less conservative than the South African and FAO guidelines, which set their lower threshold (below which no adverse effects are expected) at 1000 mg/L.

Table 5.2 Tolerances of livestock to salinity in drinking water

Livestock	**TDS (mg/L)**		
	No adverse effects expected	*Animals may have initial avoidance but should adapt*	*Loss of production, decline in condition and health*
Beef cattle	<4000	4000-5000	>5000
Dairy cattle	<2400	2400-4000	>4000
Sheep	<4000	4000-10000	>10000
Horses	<4000	4000-6000	>6000
Pigs	<4000	4000-5000	>6000
Poultry	<2000	2000-3000	>3000

A further issue not addressed by any of the agricultural guidelines reviewed, but arising from a review of the human drinking water standards (Stewart et al., 2006), is the presence of metallic elements such as iron, zinc, copper and manganese, which can impart dark staining and a ‘bitter, metallic taste’ to drinking water. This adversely affects its palatability to human consumers, particularly at low pH values. There is little information about the levels of these contaminants that will cause avoidance responses in animals, and we can therefore identify this issue as an information gap. As a preliminary approach to this issue, we propose using the aesthetic guideline values from the Drinking Water Standards for New Zealand (2005) as indicative of potential problems in livestock.

The Canadian fact sheet *Water Quality and Cattle* discusses taste and odour issues for cattle, and lists several constituents that are thought to affect beef cattle performance (Table

5.3). The fact sheet also notes that the presence of iron and manganese may cause cattle to show a preference for one water source over another, but that the levels causing this response are unknown at this stage.

6.3 Water quality for irrigation

Approximately 80% of allocated water in New Zealand is used for irrigation. The net contribution of irrigation to GDP at the farmgate was estimated to be approximately $920 million in 2002/03 (MAF Technical Paper 04/01). The area of irrigated land is doubling approximately every decade (ANZECC, 2000).

Table 5.3 Water quality constituents affecting beef cattle performance due to taste and odour[1]

Constituent	Reduced performance	Unsuitable for beef cattle
Nitrate (mg/L)	450-1300	>1300
Salinity (mg/L)	3000-7000	>7000
Sulphate (mg/L)	500-3300	>3300
Fecal coliforms (no./100 ml)	1000-2500	>5000
pH	>8.5	>10

[1]Source: http://www.agr.gc.ca/pfra/water/wqcattle_e.htm

The region of New Zealand (shown in Figure 1.1) considered to be most at risk from volcanic activity has a relatively high rainfall (Figure 3.1). Agriculture is therefore, in general, less reliant on irrigation in these regions. An important exception is Hawke's Bay, which has 18,100 ha of irrigated land, and has experienced many ashfalls due to its location east of the Tongariro volcanoes.

Poor quality water may cause the following problems in irrigation systems:
- Reduced crop yield and/or quality as the result of the buildup of salinity or toxic constituents;
- Impairment of soil quality (e.g. buildup of contaminants or adverse effects of sodicity on soil structure);
- Damage to irrigation equipment such as corrosion or blockages.

6.3.1 Salinity problems

Salinity is the presence of soluble salts in soils or waters. Salts originating from the dissolution or weathering of rocks and minerals are present in irrigation waters, and remain behind in the soil as the water evaporates or is taken up by crops. This can lead to a buildup in salts in the soil over time. A salinity problem exists if salt accumulates in the crop root zone to a concentration that reduces water availability to plants, which in turn impairs plant growth. Salinisation is an issue of concern on a large scale in Australia, but is currently considered to be only of minor importance in New Zealand (ANZECC, 2000).

Salinity is a complex issue because it is influenced not only by the properties of irrigation water but also by soil characteristics, climate and rainfall, soil management practices and the type of crop being cultivated and its salt tolerance. As a result, generally-applicable water quality trigger values are not set by the ANZECC (2000) guidelines; instead a flowchart procedure is given whereby salinity impacts of irrigation water can be evaluated by considering the above factors.

A simple, field-based preliminary assessment of the likely salinity hazard of irrigation waters can be made using the following formula:

$$EC_{rzs} = EC_i/(2.2xLF) \qquad (1)$$

where ECrzs is the electrical conductivity (this is a measure of the dissolved salt content) in the root zone, ECi is the conductivity of the irrigation water, and LF is the average leaching fraction. The units of electrical conductivity are dS/m (where 1 dS/m = 1000 μS/cm). Leaching fractions vary between 0.6 for sandy soils to 0.2 for heavy clay soils. The resulting root zone salinity (ECrzs) can then be compared to tables of values for crops of different sensitivities to assess the salinity hazard.

Similar approaches are used in the other guidelines reviewed here. The Canadian water quality guidelines recommend that total dissolved solids (TDS) concentrations in irrigation waters should not exceed 500 mg/L for sensitive crops such as carrots, beans, strawberries and raspberries, or 3500 mg/L (for tolerant crops such as barley, wheat and oats). The FAO guidelines state that TDS levels of <450 mg/L should not impose any restrictions on the use of water for irrigation, levels of 450-2000 mg/L may impose slight to moderate restrictions on use, and levels exceeding 2000 mg/L are likely to impose severe restrictions. The South African guidelines are generally similar to the Canadian approach. Irrigation water TDS levels of <260 mg/L are not expected to impair crop yield, even for sensitive crops. There is a range of intermediate categories, and at the other end of the scale, TDS levels >3510 mg/L are expected to pose severe challenges for sustainable irrigation, even for tolerant crops.

6.3.2 Sodicity problems

As well as the total salt content of irrigation waters, the relative ion composition is important. In particular, high-sodium waters can cause problems for the structural stability of soils, as sodium ions can break up clay aggregates into smaller particles which can then clog pores and reduce the permeability of the soil, which in turn reduces water infiltration. This property is known as '*sodicity*'. Water infiltration is also influenced by total salinity (TDS), with higher levels of salinity increasing infiltration. Thus, these two factors (sodicity and TDS) must both be taken into account when assessing likely effects of irrigation waters on water infiltration. The ANZECC guidelines contain a method for determining the risk of soil structure degradation caused by irrigation water quality. This method involves calculating a 'sodium adsorption ratio' (SAR) from the concentrations of sodium, calcium and magnesium in the irrigation water, and considering this together with the electrical conductivity (EC) of the irrigation water to produce an overall assessment of risk (ANZECC, 2000).

The other guidelines reviewed here take a related but slightly different approach by setting threshold values for both the SAR and the EC to evaluate risk. The FAO guidelines are shown in Table 5.4 to illustrate the use of these thresholds, together with the salinity guidelines described in Section 5.2.1. This table shows that water infiltration problems increase with increasing sodicity (SAR), and with decreasing salinity.

Table 5.4 FAO guidelines on interpretation of water quality parameters for irrigation (from Ayers and Westcot, 1985)

Problem in irrigation water		Units	Degree of restriction on use None	Slight to moderate	Severe
Salinity					
TDS		mg/L	<450	450-2000	>2000
EC[1]		dS/m	<0.7	0.7-3.0	>3.0
Water infiltration (evaluated using EC and SAR together)					
SAR <3	and	EC =	>0.7	0.7-0.2	<0.2
SAR = 3-6	and	EC =	>1.2	1.2-0.3	<0.3
SAR = 6-12	and	EC =	>1.9	1.9-0.5	<0.5
SAR = 12-20	and	EC =	>2.9	2.9-1.3	<1.3
SAR >20	and	EC =	>5.0	5.0-2.9	<2.9

[1]EC (electrical conductivity) is also a measure of water salinity; the TDS and EC measures are equivalent.

6.3.3 Specific ion toxicity problems

Toxicity problems can occur if certain ions in the soil-water system are accumulated by crops; the degree of damage depends on the concentration accumulated and the crop sensitivity. The major ions of primary concern are chloride and sodium.

There are two main problems related to the presence of chloride: foliar injury, and that high levels of chloride can increase the uptake of cadmium (which is toxic) by crops. Tobacco leaves are particularly sensitive to chloride, and concentrations of >40 mg/L are considered unsuitable for irrigation of tobacco. Trigger values set by the ANZECC guidelines for chloride in relation to both these issues are shown in Table 5.5. Also shown in the same table are the trigger values for prevention of foliar injury due to sodium in irrigation waters.

Chloride can accumulate in foliage as it is highly soluble and readily taken up with soil water, moves in the transpiration stream and hence accumulates in leaves. It can also be absorbed directly through leaves. Plants vary in their sensitivity to chloride, but plant injury will occur when accumulation in leaves exceeds the tolerance of the crop. Typical signs of damage are leaf burn and drying of leaf tissue. Plant injury occurs first at leaf tips and progresses back along the edges as severity increases. Necrosis is often accompanied by early leaf drop.

Table 5.5 Trigger values for preventing toxic effects of chloride and sodium in irrigation water (from ANZECC guidelines)

Toxicity problem		Chloride concentration	Sodium concentration
		mg/L	mg/L
Foliar injury[1]	*Sensitivity of crops*		
	Sensitive	<175	<115
	Moderately sensitive	175-350	115-230
	Moderately tolerant	350-700	230-460
	Tolerant	>700	>460
Risk of increasing cadmium uptake			
	Low risk	<350	-
	Medium risk	350-750	-
	High risk	>750	-

[1]These values are for chloride concentrations in water applied to foliage (i.e. sprinkler irrigation)

Similar approaches are used in the other guidelines. The Canadian guidelines recommend that concentrations of chloride in irrigation water should not exceed 100 mg/L for sensitive crops and 700 mg/L for tolerant crops. The South African guidelines state that levels of <100 mg/L should protect all but the most sensitive plants from foliar damage, but that levels >700 mg/L will lead to increasing problems with chloride accumulation.

Guideline values are also set for trace metals and metalloids in irrigation water. The ANZECC guidelines set trigger values for both long-term use (LTVs, up to 100 years) and short-term use (STV, up to 20 years). The long-term and short-term values have been developed to address the problem of contaminant buildup in soils over time, and also to prevent direct toxicity of contaminants in irrigation to crops (Table 5.6). A marked disparity between an LTV and STV for a particular contaminant indicates that there is a risk of contaminant accumulation in soils. Conversely, if the STV and LTV are the same (e.g. for lithium), this indicates that direct toxicity is the main concern.

The FAO guidelines are shown for comparison in the same table. They recommend a single value (a recommended maximum concentration) for each trace element. The Canadian guidelines are almost identical, so are not shown although points of difference are noted. The South African guidelines are more complex in that they generally recommend a range of acceptable values for each trace element, from a concentration that will be tolerated by even the most sensitive crops, through to a concentration that will be toxic to even the most tolerant crops. This information has been omitted from Table 5.6 for clarity.

6.3.4 Scaling and corrosion problems

Corrosion and scaling are opposite tendencies, and are primarily, but not only, affected by the levels of calcium carbonate in a water supply relative to its saturation potential., If water is supersaturated it will be scale-forming, whereas if it is undersaturated it will be non-scale forming or corrosive (aggressive).

Scaling is a problem in irrigation systems as it can leave white deposits on fruit or leaves if a sprinkler system is used and can cause fine nozzles to block and reduce flow rates. It is also a problem for general water use as scale deposits can form in boilers and pipes. Corrosion can lead to the deterioration of groundwater well and pumping equipment, pipelines, sprinklers and storage tanks. It is primarily a problem for metal surfaces but plastic and concrete may also be affected by the presence of certain constituents.

Various indices are used to quantify the tendency of a water supply to be either corrosive or scale forming. The Langelier index is the primary index used. This index is defined as follows:

$$LI = pH_a - pH_c \qquad (2)$$

where pH_a is the actual pH of the water, and pH_c is the theoretical pH of the water if it was in equilibrium with solid calcium carbonate. The pH_c value is derived from the alkalinity (concentrations of carbonate and bicarbonate ions) and the concentrations of calcium, magnesium and sodium ions in the water. The Langelier Index is temperature-sensitive, and there is a greater tendency towards scale formation at higher temperatures. A simplified version of the ANZECC guidelines for assessing corrosiveness and scaling potential are shown in Tables 5.7 and 5.8.

Table 5.6 Long-term and short-term trigger values for trace metals and metalloids in irrigation water (from ANZECC guidelines 2000)

Element	**ANZECC guidelines**		**FAO guidelines**[1]	**Comments**
	LTV[2] mg/L	STV[3] mg/L	mg/L	
Aluminium	5	20	5	Can cause non-productivity in acid soils (ph<5.5), but more alkaline soils will precipitate the ion and reduce toxicity
Arsenic	0.1	2.0	0.1	Toxicity varies widely; toxic to rice at < 0.05 mg/L
Beryllium	0.1	0.5	0.1	Toxicity to plants varies widely
Boron	0.5	<0.5-6[4]	0.7[5]	Causes foliar damage in a similar manner to Na and Cl
Cadmium	0.01	0.05	0.01	Toxic to plants at 0.1 mg/L; more conservative LTV reflects its tendency to accumulate in soils and plants
Chromium	0.1	1	0.1	Conservative limits because of lack of knowledge of toxicity to plants
Cobalt	0.05	0.1	0.05	Toxic to tomato plants at 0.1 mg/L
Copper	0.2	5	0.2	Toxic to plants in range 0.1-1.0 mg/L
Fluoride	1	2	1	Inactivated in neutral and alkaline soils; effects on humans and animals consuming plants that have accumulated F^-
Iron	0.2	10	5	Not toxic in aerated soils but can contribute to soil acidification; also iron oxide deposits can build up and clog equipment
Lead	2	5	5	Lead is strongly retained by soils, and is not readily taken up or translocated by plants. However, some plants are known to accumulate lead.
Lithium[6]	2.5	2.5	2.5	Tolerated up to 5 mg/L by most plants, though citrus crops very sensitive. Has effects on soil structure similar to sodium.
Manganese	0.2	10	0.2	Toxic to some crops in acid soils
Mercury	0.002	0.002	-	
Molybdenum	0.01	0.05	0.01	Not normally toxic to plants, but can be toxic to livestock if fed forage grown on high-Mo soils
Nickel	0.2	2	0.2	Toxic to a number of crops at 0.5-1 mg/L
Selenium	0.02	0.05	0.02	Toxic to some crops at 0.025 mg/L; also to livestock if forage is grown in soils with high levels of selenium
Uranium	0.01	0.1	-	
Vanadium	0.1	0.5	0.1	Toxic to many crops at low levels
Zinc	2	5	2	Toxicity to crops varies widely; more toxic in acid soils

1 Recommended maximum concentrations
2 Long-term trigger values, based on up to 100 years of use
3 Short-term trigger values, based on up to 20 years of use
4 The ANZECC guidelines recommend setting a range for the STV of boron depending on crop sensitivity; the same range is recommended by the Canadian guidelines
5 From FAO guidelines, irrigation water containing 0.7 mg/L B should have no restrictions on use, 0.7-3 mg/L will have slight to moderate restrictions, and >3 mg/L will have severe restrictions on use.
6 Lithium is very toxic to citrus, in which case a trigger of 0.075 mg/L is set

Table 5.7 Trigger values for assessing the corrosiveness of water

Parameter	Value	Comments
pH	<5	High corrosion potential
	5-6	Likelihood of corrosion
	>6	Limited corrosion potential
Hardness	<60 mg/L $CaCO_3$	Increased corrosion potential
Langelier index	<-0.5	Increased corrosion potential
	-0.5 to 0.5	Limited corrosional potential

Table 5.8 Trigger values for assessing the scale-forming potential of water

Parameter	Value	Comments
pH	<7	Limited scaling potential
	7 to 8.5	Moderate scaling potential
	>8.5	Increased scaling potential
Hardness	>350 mg/L $CaCO_3$	Increased scaling potential
Langelier index	>0.5	Increased scaling potential
	-0.5 to 0.5	Limited scaling potential

Concrete corrosion is a special case of the above; concrete is susceptible to corrosion by three mechanisms. These are leaching, ion exchange and expansion. Briefly, the water constituents leading to high aggressivity towards concrete are: pH<4.5, carbonic acid (CO_2) >60 mg/L, ammonium (NH_4^+) >60 mg/L, magnesium >1500 mg/L and sulphate >3000 mg/L. The reader is referred to the FAO guidelines for further discussion of this topic.

6.3.5 Other causes of fouling

Other properties of water can also lead to fouling or clogging of irrigation systems. For instance, high levels of suspended solids can clog intake structures, pipelines or fine nozzles. Neither the ANZECC nor the Canadian guidelines recommend any guideline values for suspended solids in relation to fouling potential, but the FAO and South African guidelines both state that levels of <50 mg/L suspended solids should cause no problems with clogging drip irrigation systems, levels of 50-100 mg/L can be expected to cause slight to moderate problems, and levels of >100 mg/L are expected to cause severe problems. The South African guidelines note that the abrasive action of particles can also lead to accelerated wear of sprinkler nozzles and other components in the distribution system. This is particularly relevant in relation to volcanic ash which is highly abrasive.

Other chemical processes can also cause fouling, particularly the presence of high levels of dissolved iron and manganese. An additional problem with high levels of dissolved iron is that plant foliage can be damaged by iron deposits. For iron, the FAO guidelines recommend a value of 0.1 mg/L as being the threshold below which no significant fouling effects are expected. The South African guidelines are similar, and stipulate a value of 0.2 mg/L as being the level below which only minor fouling problems are expected. The ANZECC guidelines do not set a guideline for iron in relation to fouling effects, but set a trigger value of 0.2 mg/L for the long-term (100 year) use of irrigation water, which will provide protection against fouling effects. Similar comments apply to manganese; thresholds below which fouling effects are not expected are set at 0.1 mg/L by both the FAO and South African guidelines. The ANZECC trigger value for long-term use in irrigation water for manganese is 0.2 mg/L.

Biological processes can also cause fouling, if a biological slime layer forms. The main parameter affecting this process is the presence of dissolved organic matter.

6.4 General water uses

Other uses of water in agriculture are washing equipment, and the preparation of agricultural chemicals such as pesticides, dips and fertilizers. In general, deteriorating water quality is associated with a reduced effectiveness in pesticide preparations. While none of the guidelines reviewed set guideline values for water used to prepare agricultural chemicals, the Canadian fact sheets provide some useful examples of water quality impacts on the efficacy of pesticides. For example, the effectiveness of RoundUp herbicide is reduced by the presence of clay and organic particles, by high pH and by high levels of dissolved calcium, magnesium and iron.

6.5 Comments on guidelines in relation to likely effects of volcanic ashfall

It is important to bear in mind that guideline values for protection of agricultural water uses are primarily based on sustainable use of a water supply over a long period of time, whereas an ashfall is likely to be a short-term event. As guideline values are set on the basis of long-term use, short-term incursions may not be a problem. However, palatability issues are an obvious exception to this observation. Also likely to be problematic are the clogging of equipment with suspended ash, abrasion of irrigation nozzles and distribution systems by ash, and possibly also corrosion effects due to high levels of acidity.

Ashfall deposition on surfaces is likely to greatly outweigh the effects of contamination of the water supply by ash for crop foliage and on dietary intake if livestock feed is contaminated by ash. An obvious example is from the 1995/1996 eruptions of Ruapehu where many sheep died due to probable ingestion of fluoride via ash-contaminated grass (Cronin et al., 1998).

Findings from Stewart et al. (2006) gives some indication of likely 'problem areas' for agricultural water uses. Ashfall-contaminated water is characterized by high levels of acidity, aluminium, calcium, iron, manganese, sulphate and fluoride. Thus, this water may have corrosive tendencies, although effects of low pH may be offset by the high calcium content, and may be unsuitable for mixing agricultural chemical preparations. The palatability of the water to livestock will be an important consideration; generally, for humans, the water is likely to become unpalatable before it presents a health hazard. However, if livestock continue to drink contaminated water, problems such as fluoride toxicity may become important. These issues will be investigated further in the next chapter.

7.0 MODELLING OF ASHFALL CONTAMINATION OF FARM WATER SUPPLIES

Open water supplies are vulnerable to ashfall contamination. In farm areas, these include stock watering troughs, dams, roof-fed tanks and irrigation races. A simple model for predicting the effects of ashfall contamination on receiving waters is used here for a range of situations commonly encountered in farm water supplies, using examples derived from our field work.

7.1 Model for predicting concentration increases in receiving waters from volcanic ashfall

Freshly-fallen ash releases soluble components into receiving waters, with over 55 soluble components known to occur in volcanic ash leachates (Witham et al., 2005). The anions chloride (Cl^-), sulphate (SO_4^{2-}) and fluoride (F^-) and the cations calcium (Ca^{2+}), sodium (Na^+) and magnesium (Mg^{2+}) generally occur at the highest concentrations. Surface coatings on fresh ash are also highly acidic, due to the presence in the plume of aerosols composed of the strong mineral acids H_2SO_4, HCl and HF.

The model developed by Stewart et al. (2006) for predicting the effects of volcanic ashfall on the chemical composition of receiving waters can be concisely expressed as follows:

$$C_{water} = C_{ash}TDA/V \qquad (1)$$

where C_{water} is the predicted concentration increase of a soluble contaminant in the receiving water body in mg/L, C_{ash} is the concentration of the contaminant in the ash in mg/kg, T is the thickness of the ash in metres, D is the density of the ash in kg/L, A is the area of the receiving water body in square metres and V is the volume of the receiving water body in cubic metres. The quantity A/V is also known as the contamination potential of a water body in m^{-1}.

It should be noted that this model predicts concentration *increases* in receiving waters, rather than final concentrations. This is because the soluble components on volcanic ash are also present in natural waters.

7.2 Stock watering troughs

In general, livestock on New Zealand farms drink from concrete watering troughs. A range of troughs commonly used in New Zealand are shown in Figure 6.1. The water level is maintained with a float and cutoff valve several centimetres below the top to avoid overflow which can lead to boggy conditions around the trough.

Figure 6.1 Stock watering troughs used in New Zealand

Dimensions and capacities of a range of troughs used in New Zealand are provided in Appendix 6. These values have been used to calculate contamination potentials, which range from approximately A/V = 2 to 5. Oblong troughs have higher values of A/V than round ones, and small troughs have higher values of A/V than large ones. To illustrate the use of the model we have used troughs illustrating either end of this range; the 60-gallon oblong trough shown in the upper right hand side of Figure 6.1 has an A/V of 4.9, and the 250-gallon round trough shown in the upper left hand side has an A/V of 2.7.

Predicted concentration increases in these two troughs are shown in Tables 6.1 and 6.2. Ashfall composition data for the 1995/96 eruptions of Mt Ruapehu has been used in this model. This is derived primarily from a study by Cronin et al. (1998), and supplemented where necessary from other studies of volcanic ash leachate composition. The provenance of these data is described in Stewart et al. (2006) and is not repeated here. The predicted concentration increases have been compared with the ANZECC livestock drinking water guidelines, and exceedences have been highlighted in yellow.

Table 6.1 Predicted concentration increases (C_{water}) in a 60-gallon oblong water trough (A/V=4.9) with different thicknesses of volcanic ashfall

		C_{ash} (mg/kg)	C_{water} (mg/L) for oblong 60-gallon (270-litre) trough			
			1 mm ash	5 mm ash	10 mm ash	50 mm ash
Livestock drinking water parameters						
Acidity	H+	0.00041	0.000002009	0.000010045	0.00002009	0.0001005
	pH[1]		5.70	5.00	4.70	4.00
Aluminium	Al	195	0.96	4.8	9.6	48
Arsenic	As	0.032	0.00016	0.00078	0.0016	0.0078
Boron	B	2.6	0.013	0.064	0.13	0.64
Cadmium	Cd	0.0038	0.000019	0.000093	0.00019	0.00093
Calcium	Ca	5392	26	132	264	1321
Chromium	Cr	0.044	0.00022	0.0011	0.0022	0.011
Cobalt	Co	0.132	0.00065	0.0032	0.0065	0.032
Copper	Cu	4	0.020	0.098	0.20	0.98
Fluoride	F	86	0.42	2.1	4.2	21.1
Iron	Fe[2]	46	0.23	1.1	2.3	11.3
Lead	Pb	0.0014	0.0000069	0.000034	0.000069	0.00034
Magnesium	Mg	419	2.1	10.3	20.5	103
Manganese	Mn[2]	14.3	0.07	0.35	0.70	3.5
Molybdenum	Mo	0.001	0.0000049	0.000025	0.000049	0.00025
Mercury	Hg	0.0087	0.0000426	0.00021	0.00043	0.0021
Nickel	Ni	0.35	0.0017	0.0086	0.017	0.086
Nitrate	NO3	25.6	0.13	0.63	1.25	6.3
Selenium	Se	0.1	0.00049	0.0025	0.0049	0.025
Sodium	Na	413	2.0	10.1	20.2	101
Sulphate	SO4	5722	28	140	280	1402
Zinc	Zn	5.6	0.027	0.14	0.27	1.4

[1]pH values of <5 are associated with an increased potential for corrosion (Table 5.7).
[2]The aesthetic guideline values for Fe and Mn in the Drinking Water Standards of New Zealand (2005) are used here for comparison in an attempt to predict impacts on palatability of livestock drinking water. They are 0.2 m/L for Fe and 0.04 mg/L for Mn.

For a 60-gallon trough, at 1 mm ashfall the only parameters that appear to exceed guideline values are iron and manganese. It is important to note that the guidelines for Fe and Mn are not based on health hazards, but are based on likely effects on the palatability of the water. The relevant guideline values are taken from the Drinking Water Standards of New Zealand (2005) and it is important to note that the applicability of these values to livestock is entirely speculative at this stage.

With 5 mm ashfall, toxicity effects of fluoride contamination become apparent, as well as an increased likelihood of effects on palatability. While short-term ingestion of relatively low levels of fluoride (a predicted increase of 2.1 mg/L) may not be harmful as the guideline values refer to longer-term intake, the possibility that livestock may also be ingesting fluoride with their feed is a strong one. With 10 mm ashfall, problems due to aluminium toxicity also arise, along with increasing severity of palatability effects and fluoride toxicity. Water receiving 50 mm ashfall cannot be regarded as drinkable.

For a 250-gallon round trough (Table 6.2), it can immediately be seen that there are no predicted impacts on the quality of the water for livestock drinking with 1 mm ashfall. Even at 5 mm ashfall, only the putative impacts on palatability arise. With increasing thicknesses of ashfall, the predicted effects increase in the same manner described for the 60-gallon trough.

Increasing thicknesses of ashfall are also associated with increasing levels of acidity (pH) in receiving waters. Values of pH<5 have been highlighted in yellow, as possibly increasing the corrosiveness of the water towards metal fittings and pipes and towards the concrete (Section 5.3.4). However, it is important to note here that concrete tanks are thought to provide buffering capacity due to the dissolution of carbonate minerals from the hardened concrete (Cronin and Sharp, 2002). Concrete corrosion is a complex issue and it is beyond the scope of this study. For instance, high levels of sulphate may also contribute to concrete corrosion, as sulphate can combine with the calcium and aluminium compounds in the concrete causing them to swell and exert mechanical stresses.

While these findings must be regarded as indicative, and are subject to the limitations and cautions described in Stewart et al. (2006), an obvious recommendation that arises is that using larger and deeper troughs reduces vulnerability to contamination of stock drinking water. A further comment is that palatability effects may become apparent at lower levels of ashfall in comparison to toxicity effects. However, as noted in Chapter 5, there are no relevant guidelines in relation to the presence of metallic contaminants such as iron and manganese; there is an information gap for this issue.

Table 6.2 Predicted concentration increases (C_{water}) in a 250-gallon round water trough (A/V=2.7) with different thicknesses of volcanic ashfall

		C_{ash} (mg/kg)	C_{water} (mg/L) for round 250-gallon (1125-litre) trough			
			1 mm ash	5 mm ash	10 mm ash	50 mm ash
Livestock drinking water parameters						
Acidity	H+	0.00041	0.0000011	0.0000055	0.000011	0.000055
	pH[1]		6.0	5.3	5.0	4.3
Aluminium	Al	195	0.53	2.6	5.3	26
Arsenic	As	0.032	0.000086	0.00043	0.00086	0.0043
Boron	B	2.6	0.0070	0.035	0.070	0.35
Cadmium	Cd	0.0038	0.0000103	0.000051	0.00010	0.00051
Calcium	Ca	5392	15	73	146	728
Chromium	Cr	0.044	0.00012	0.00059	0.0012	0.0059
Cobalt	Co	0.132	0.00036	0.0018	0.0036	0.018
Copper	Cu	4	0.0108	0.054	0.108	0.54
Fluoride	F	86	0.23	1.2	2.3	12
Iron	Fe[2]	46	0.12	0.62	1.2	6.2
Lead	Pb	0.0014	0.0000038	0.000019	0.000038	0.00019
Magnesium	Mg	419	1.13	5.7	11.3	57
Manganese	Mn[2]	14.3	0.039	0.19	0.39	1.9
Molybdenum	Mo	0.001	0.0000027	0.0000135	0.000027	0.000135
Mercury	Hg	0.0087	0.000023	0.00012	0.00023	0.0012
Nickel	Ni	0.35	0.00095	0.0047	0.0095	0.047
Nitrate	NO_3	25.6	0.069	0.35	0.69	3.5
Selenium	Se	0.1	0.00027	0.00135	0.0027	0.014
Sodium	Na	413	1.1	5.6	11	56
Sulphate	SO_4	5722	15	77	154	772
Zinc	Zn	5.6	0.015	0.076	0.15	0.76

[1]pH values of <5 are associated with an increased potential for corrosion (Table 5.7).
[2]The aesthetic guideline values for Fe and Mn in the Drinking Water Standards of New Zealand (2005) are used here for comparison in an attempt to predict impacts on palatability of livestock drinking water. They are 0.2 m/L for Fe and 0.04 mg/L for Mn.

7.3 Farm reservoir

Ponds formed by damming streams are used as reservoirs for livestock watering and irrigation. We have applied the model to the reservoir illustrated in Figure 6.2; results are shown in Table 6.3.

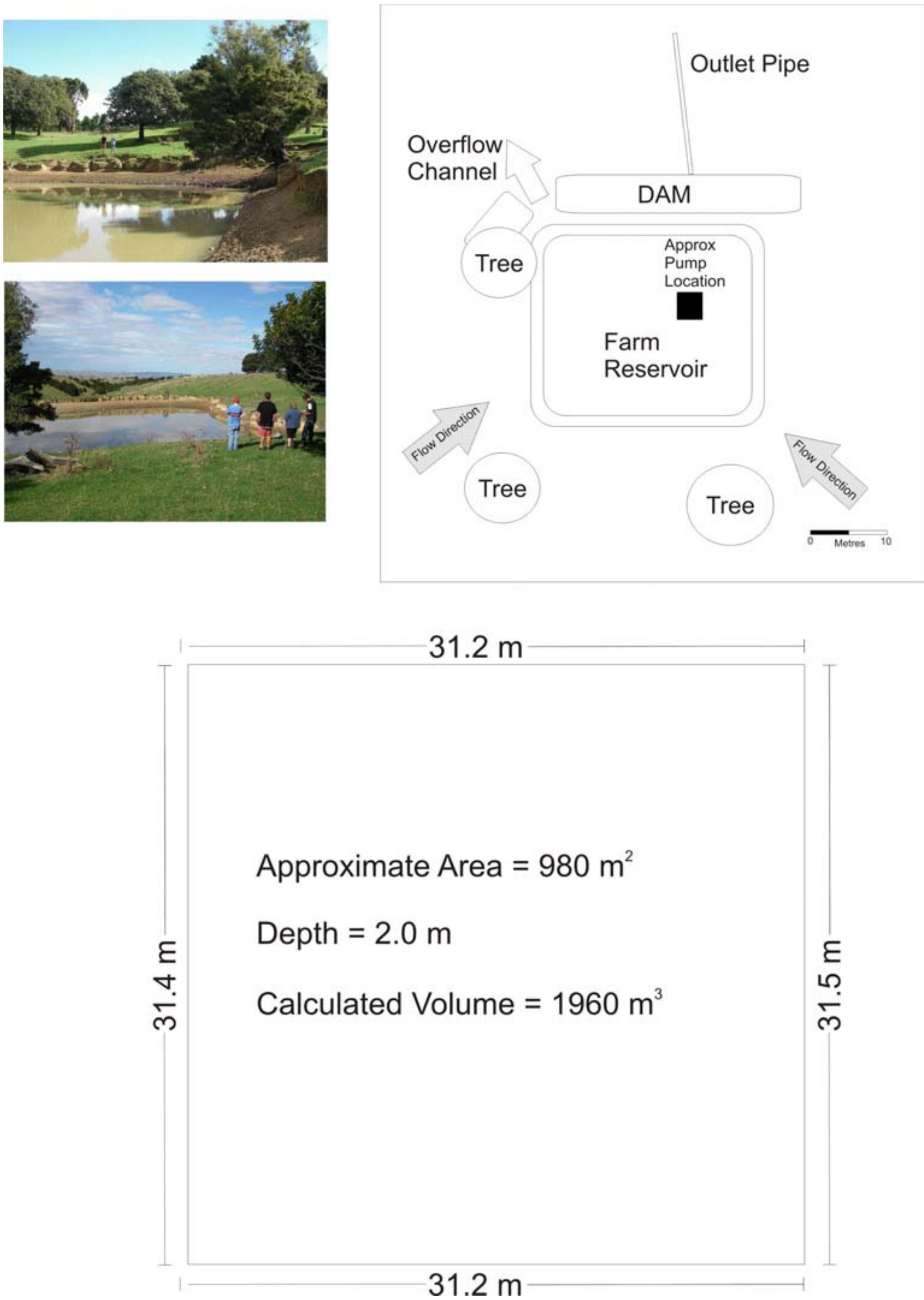

Figure 6.2 Study Farm 1 reservoir, Hawke's Bay

Table 6.3 Predicted concentration increases (C_{water}) in a farm reservoir with different thicknesses of volcanic ashfall

		C_{ash} (mg/kg)	C_{water} (mg/L) for farm reservoir (A/V=0.5)			
			1 mm ash	5 mm ash	10 mm ash	50 mm ash
Livestock drinking water parameters						
Acidity	H+	0.00041	0.000000205	1.025E-06	2.05E-06	0.00001025
	pH[1]		6.7	6.0	5.7	5.0
Aluminium	Al	195	0.098	0.49	0.98	4.9
Arsenic	As	0.032	0.000016	0.00008	0.00016	0.0008
Boron	B	2.6	0.0013	0.0065	0.013	0.065
Cadmium	Cd	0.0038	0.0000019	0.0000095	0.000019	0.000095
Calcium	Ca	5392	2.7	13.5	27.0	135
Chromium	Cr	0.044	0.000022	0.00011	0.00022	0.0011
Cobalt	Co	0.132	0.000066	0.00033	0.00066	0.0033
Copper	Cu	4	0.002	0.01	0.02	0.1
Fluoride	F	86	0.043	0.22	0.43	2.2
Iron	Fe[2]	46	0.023	0.12	0.23	1.2
Lead	Pb	0.0014	0.0000007	0.0000035	0.000007	0.000035
Magnesium	Mg	419	0.21	1.0	2.1	10
Manganese	Mn[2]	14.3	0.0072	0.036	0.072	0.36
Molybdenum	Mo	0.001	0.0000005	0.0000025	0.000005	0.000025
Mercury	Hg	0.0087	0.0000044	2.2E-05	0.000044	0.00022
Nickel	Ni	0.35	0.00018	0.00088	0.0018	0.0088
Nitrate	NO_3	25.6	0.013	0.064	0.13	0.64
Selenium	Se	0.1	0.00005	0.00025	0.0005	0.0025
Sodium	Na	413	0.21	1.03	2.07	10.3
Sulphate	SO_4	5722	2.9	14	29	143
Zinc	Zn	5.6	0.0028	0.014	0.028	0.14

[1]pH values of <5 are associated with an increased potential for corrosion (Table 5.7).
[2]The aesthetic guideline values for Fe and Mn in the Drinking Water Standards of New Zealand (2005) are used here for comparison in an attempt to predict impacts on palatability of livestock drinking water. They are 0.2 m/L for Fe and 0.04 mg/L for Mn.

Clearly reservoirs of this size are less vulnerable to changes in composition due to ashfall than small water troughs, because of the greater depth available for dilution. Effects on palatability (which are very much putative at this stage) become apparent at 10 mm ashfall, and at 50 mm ashfall problems with fluoride toxicity may also be expected. While a pH value of 5 is predicted by this model for an ashfall of 50 mm, some buffering capacity from the underlying soils and sediments can be expected.

7.4 An irrigation reservoir

Increasing turbidity is a well-characterised consequence of the contamination of water supplies by volcanic ashfall. The suspension of ash in water has led to a range of effects such as the clogging of water intakes and abrasive damage to turbines (Blong, 1984; Johnston, 1997). High levels of turbidity can also compromise the effectiveness of disinfection in water treatment, causing a public health risk.

Irrigation systems are clearly vulnerable to high levels of turbidity. As discussed in Section 5.3.5, high levels of suspended solids can clog intake structures, pipelines or fine nozzles. Guideline values for suspended solids state that levels of <50 mg/L suspended solids should cause no problems with clogging drip irrigation systems, levels of 50-100 mg/L can be expected to cause slight to moderate problems, and levels of >100 mg/L are expected to cause severe problems. The South African guidelines note that the abrasive action of particles can also lead to accelerated wear of sprinkler nozzles and other components in distribution systems; this is particularly relevant in relation to volcanic ash which is highly abrasive.

Irrigation systems vary in their vulnerability to volcanic ashfall. Systems that rely on groundwater abstraction and that do not have above-ground storage are relatively invulnerable. However, storage reservoirs are vulnerable to ashfall. An example of a storage reservoir on a Hawke's Bay vineyard is shown in Figure 6.3. The dimensions of this reservoir are 30 m x 20 m x 5 m deep, giving a contamination potential A/V of 0.2.

For 1 mm ashfall, the total volume of ashfall on the surface of this reservoir will be 0.6 m^3. This is equal to 600 kg ash, using a density of 1 kg/L for freshly fallen ash (Stewart et al., 2006). When divided by the volume of the reservoir, this gives a suspended solid concentration of 600/3000 kg/m^3, or 200 mg/L. Comparing this to the guideline values described above, this level of suspended solids is expected to cause problems, assuming the deposited ashfall remains in suspension.

Thus, just 1 mm ashfall on a five-metre deep irrigation reservoir can be expected to cause problems owing to the presence of suspended particles. Problems will intensify with greater thicknesses of ashfall and for shallower reservoirs.

Figure 6.3 Irrigation reservoir, Hawke's Bay

8.0 CONCLUSIONS

Volcanic ashfall can have serious impacts on water supplies. Freshly-fallen volcanic ash may result in short-term physical and chemical changes in water quality, increased wear and damage to water delivery systems and a high demand for water during cleanup operations. Modern farming operations are critically dependent on their water supplies, particularly dairying, which has very high rates of water consumption, particularly during summer months. The aim of this project was to characterise the vulnerability of farm water supplies in New Zealand to volcanic ashfall, and to make management recommendations to reduce this vulnerability.

8.1 Literature review

Two particular eruptions have been studied with respect to impacts on agricultural or rural water supplies: the 1980 eruption of Mt St Helens, in the northwestern United States, and the 1991 eruption (VEI 4+) of Hudson Volcano, in southern Chile. For these relatively large eruptions, it is clear that physical impacts of ashfall tend to overwhelm more subtle chemical impacts (such as changes to water quality). Particular points of vulnerability are open systems such as irrigation channels and drinking water ponds, which become clogged with ash, and ash damage to electrical components such as switch panels, to motors and other components such as sprinkler heads.

Impacts of ash from the Mt St Helens eruption on two contrasting regions showed that, groundwater-fed systems are much more resilient to volcanic ash than surface water-fed systems. However, even groundwater-based water supplies can be vulnerable to ashfalls; in Ritzville Country, ashfall still caused disruption to groundwater-fed irrigation systems as airborne ash disabled pumps by shorting out electrical panels. In coastal Santa Cruz province, Patagonia, windmills used to extract groundwater were disabled by airborne ash from the 1991 eruption of Hudson Volcano.

8.2 Vulnerability assessment of case study farms

Eight case study farms in the central North Island covering a diverse range of locations and land uses and access to water supplies were characterised with respect to their water use, with the aim of assessing the vulnerability of their water supplies. Overall vulnerability is determined by the following factors:

- the type of water supply (whether groundwater or surface water-fed);
- water storage capacity;
- water use;
- independence of supply;
- pumping capability;
- other stresses on the water supply.

8.2.1 Overall vulnerability index

An overall vulnerability index for each farm was calculated by assigning weighted scores to the six factors described above. The largest single factor contributing to vulnerability is whether a water supply is derived from groundwater or surface water. The overall vulnerability of the study farms ranged from 'extremely vulnerable' (a score of 87 out of a maximum of 100 for a dairy farm in Taranaki) to 'moderately vulnerable' (a score of 42, for a sheep and beef farm in Hawkes Bay).

8.2.2 Overall volcanic risk to water supplies

Vulnerability indices for individual farms were combined with predictions from a probabilistic volcanic risk model of the accumulated thickness of volcanic ash over the central North Island over a period of 10,000 years. This gives an overall indication of the volcanic risk to their water supplies. Study farms 4 (a dairy farm in Rerewhakaaitu, near Rotorua) and 6 (a dairy farm in south Taranaki) were assessed as being most at risk.

8.3 Guidelines review

Agricultural water quality guidelines from South African, Canada and New Zealand/Australia (ANZECC), as well as guidelines produced by the FAO, were reviewed. This was a useful exercise as it identifies the water quality issues important to farm water use and primary production. Our preliminary analysis suggests that the following are likely to be the key issues for farm water supplies in the event of volcanic ashfall:

- high levels of suspended ash (turbidity) will make surface waters unsuitable for irrigation because of clogging of pipes and nozzles; abrasional damage is a further hazard; pumping of suspended volcanic sediments (such as at Study Farm 3) suggest damage will occur to impellors; water pumps can be expected to suffer accelerated wear if pumping volcanic sediment suspended in water over a long period of time (months to years) following an ashfall event;
- surface water contaminated by ash may show a tendency to be corrosive towards concrete;
- the palatability of drinking water for livestock may be affected due to the presence of iron and manganese which impart a bitter metallic taste; and
- there may be toxic effects on livestock from volcanic elements such as fluoride and aluminium; however, intake of fluoride from drinking water may be insignificant compared to ingestion from contaminated feed.

There are considerable uncertainties associated with these issues. For instance, although guideline values for iron and manganese in drinking water are set for the human drinking water supply in New Zealand, there are no guideline values for livestock drinking water and little indication available of the sensitivity of different livestock to the palatability of their water supply.

8.4 Broader considerations for farm managers in a volcanic crisis

This report addresses impacts of volcanic ash on farm water supplies. However, in the event of a volcanic crisis, impacts on soil and vegetation, livestock, human health and lifelines (particularly electricity supplies and transport and communication networks) will also occur. Thus, minimising disruption of farm water supplies should be part of an integrated and comprehensive farm response .

Neild et al. (1998) provide a comprehensive summary of potential impacts on agriculture and horticulture. Wilson and Cole (2007) take this further, summarising potential ashfall impacts for pastoral farms (specifically dairy farms) and addressing key farm management vulnerabilities and recommending strategies for risk management. Wilson et al. (2007) provide a useful summary of impacts on tropical horticulture for the 2006 eruption of Merapi volcano, Indonesia.

For more information on the impacts of volcanic eruptions on agriculture, horticulture and forestry, and potential mitigation measures, refer to http://www.maf.govt.nz/mafnet/rural-nz/emergency-management/volcanoes/volcano-erruption-impact/httoc.htm

For more information on the impacts of volcanic eruptions to infrastructure and communities refer to http://volcanoes.usgs.gov/ash – volcanic ash impacts website.

For more information on health hazards of volcanic ash and guidelines on household preparedness before, during and after an ash fall refer to http://www.ivhhn.org.

For more information on volcanic monitoring in New Zealand refer to http://www.geonet.org.nz/.

9.0 RECOMMENDATIONS TO REDUCE FARM WATER SUPPLY VULNERABILITY TO VOLCANIC HAZARDS

The purpose of these recommendations is to increase resilience to a volcanic eruption. They have been divided into components corresponding to the ‘4R’ model (reduction, readiness, response and recovery) that is currently used as the basis for emergency management in New Zealand. An indicative timeframe is also provided for each section.

9.1 Reduction (years to months in advance of an eruption – during periods of quiescence)

Risk reduction refers to steps that can be taken well in advance of any crisis to reduce vulnerability.

- Take steps to protect the farm’s household water supply. If the household relies on a roof-fed rainwater tank, install a disconnect valve to prevent ash washing into the tank. Alternatively stockpile bottled water.
- Ensure farms have adequate tank water storage. Five to seven days’ supply for stock in hot dry conditions is ideal, but 3-5 days is a reasonable target. Ensure that stored water can be distributed if pumping facilities are disrupted, by locating tanks on top of topographic highs so water can be gravity-fed.
- Diversify water supplies if possible; an ideal situation is to have access to both surface and ground water supplies.

- Be aware that an already overstretched water supply will be more vulnerable in the event of a volcanic crisis; if possible take steps to address the problem prior to an event occurring.
- Maintain water distribution systems in a good state of repair to reduce the need for attention from the farmer during a crisis when time and resources will be scarce. If the distribution system has separate sources, consider connecting them into a single network to provide extra resilience.
- Using larger stock watering troughs should provide some mitigation against contamination by ashfall, as there is more volume available to dilute soluble components.
- Consider purchasing a diesel generator to ensure that water pumps can continue to operate during power outages. A further option is to ensure that pumps can be run from tractor PTOs, but this has the disadvantage of immobilising tractors.

9.2 Long-term readiness (weeks to days in advance of an eruption; volcano showing some signs of unrest)

- Make sure maintenance of water distribution and supply system is up to date and that storage tanks are full.
- Plan what to do in the event of an eruption. Decide how to best locate livestock for access to fresh water. Consider alternative supplies of water if your own supply becomes unusable (e.g. neighbours with a groundwater supply).
- Stock up on filters and water supply fittings (for pumps and other machinery)

9.3 Short-term readiness (days to hours in advance of an eruption: volcano showing strong signs of unrest, or has erupted and ashfall is possible)

- If your household water supply is from the roof, disconnect the down-pipe so that ash does not wash into the storage tank. Consider water rationing if supplies are limited.
- Move stock to paddock(s) with good access to water supplies, e.g. gravity-fed from storage tanks, or running water such as springs or creeks, and preferably close to homestead.
- Decide on management options for stock watering troughs
    - Move stock to secure supply if possible
    - Cover troughs during ashfall
    - Leave troughs uncovered, but ensure they are full to dilute ashfall contamination
- Be prepared for false alarms - predicting a volcanic eruption prediction is not an exact science.
- Ensure sump, drain pipes, and drain grills are clear.

9.4 Response (during and immediately after an eruption)

- Monitor and assess impact of volcanic ash on water supplies. If possible, service pump to ensure any damage is minimised.
- Prioritise farm activities as being critical, required or optional., These may change from day to day. Develop a priority list of facilities that must be kept operative versus those that can be shut down during and after ashfalls.

- If possible, and appropriate, move stock into covered yards.
- If water supply is compromised or disrupted, begin to practice water conservation.
- Expect little outside help during the response period, other than information on radio, television and the internet.
- Conserve water when cleaning up ash. Best practice guidelines are to lightly wet the volcanic ash and then shovel it out. Choose a disposal site well away from critical farm areas. This is preferable because if ash is washed into drains it may block them as well as increasing water use.

9.5 Recovery (following the eruption)

- Be aware that volcanic eruptions may not be short-term disturbances but may last for periods of years or even decades.
- Take the time to assess all components of water supply systems.
- Build back better: if your supply was damaged or disrupted, reconstruct it in a more resilient manner to prevent the same problem occurring in the future. Use Reduction recommendations as guidelines.

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APPENDICES

APPENDIX 1 INFORMATION ON VOLCANIC ASHFALL

Thickness and grain size of the ash deposit

The thickness of the ashfall is determined by the magnitude of the eruption, the wind direction during the eruption, and proximity to the volcano. The grain size of the ash deposit is similarly determined by these characteristics. The presence of water during the eruption also has a significant influence, causing magma to be super-cooled and quench, rapidly releasing energy and causing vesicles in the magma to shatter. The resulting ash is usually comprised of fine and blocky fragments (Heiken and Wohletz, 1985).

Components of volcanic ash

Volcanic ash is composed of glass shards, crystal/mineral fragments, and lithic particles (fragments of older material such as rock stripped off the magma chamber walls) in varying proportions depending on the style of eruption (Figure 2.1 and Figure 2.2; Heiken and Wohletz, 1985). The proportions of each may change throughout the duration of the eruption. Volcanic ash is generally hard (ranging from 3-8 on Moh's scale of hardness) and has sharp broken edges making it very abrasive. Mineral fragments reflect the magma type, as they are derived from phenocrysts with in the magma. The chemical composition and rate of cooling of the erupting magma will determine the different mineral assemblages. Glass shard shapes and sizes depend upon the shape and size of vesicles present within the magma immediately before eruption (Heiken and Wohletz, 1985; Blong, 1984). These differences in ash components and grain types, alters the physical impacts of ash deposition. Individual volcanoes may have a typical composition of magma which is unique to that volcano.

Volcanic ash is readily remobilised when dry, very electrically conductive when wet, and highly abrasive, particularly as most ash is made up primarily of glass shards (Figure 2.1; Heiken and Wohletz, 1985).

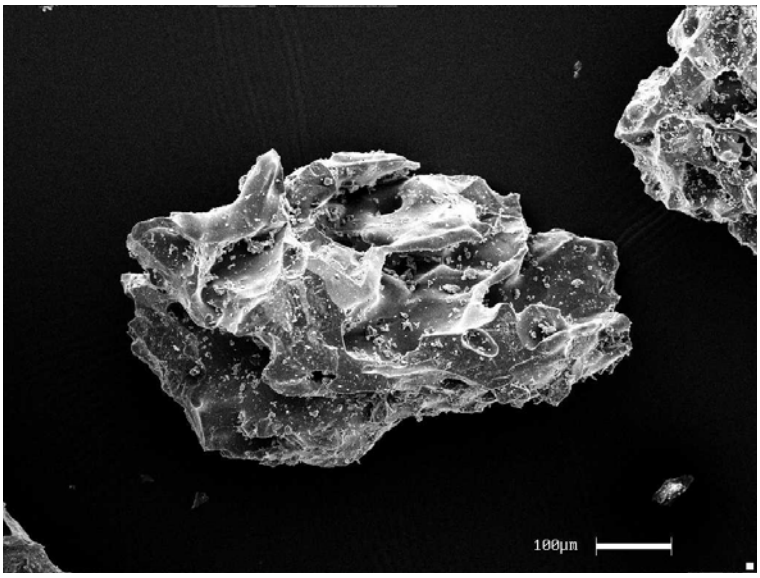

Figure A1 Scanning Electron Microscope image of a basaltic ash particle from the 1886 Tarawera eruption from Tarawera Volcano, New Zealand (Scott Barnard, pers comm., 2007)

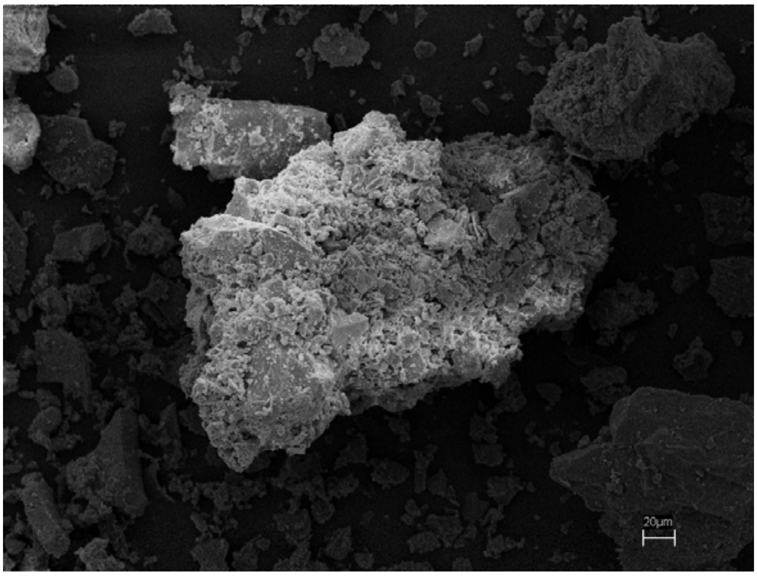

Figure A2 Scanning Electron Microscope image of a basaltic-andesite ash particle sampled from a block-and-ash flow of the 2006 eruption from Merapi Volcano, Indonesia (Wilson and Kaye, unpublished data)

Adsorption of volatiles

The most chemically reactive components of ash are thin films of compounds derived from magmatic gases that adhere to ash grains, forming reactive surface coatings (Witham et al., 2005; Rose, 1977). Scavenging of aerosols within volcanic plumes is complex, and is controlled by:

- magma type and ash composition
- mode of eruption
- gas-pyroclast dispersion immediately following fragmentation
- concentration of the plume
- ratio of particles to gas
- particle size fractions
- particle surface area, porosity and texture
- temperature and chemical history or the particle trajectory through the plume
- environmental conditions (including wind and humidity)
- extent of hydrothermal interaction at the volcano.

Fine ash particles have large surface areas relative to their mass, allowing transport of significant amounts of soluble aerosols given the size of the ash particle. As the finest ash particles travel the greatest distance from a volcano, relatively thin ashfalls many contaminate water bodies with potentially toxic concentrations of aerosols (Cronin et al., 2003a).

Many adsorbed elements are highly soluble, and rainfall or surface water flow onto freshly deposited ash will readily leach these materials into the environment. The concentration of the leachate itself is highly dependent on the volume of water that comes into contact with the ash (Witham et al., 2006). Ash may fall directly onto water bodies where soluble salts can rapidly dissolve within the water. It is also common for aerosols and ash particles to dehydrate as they are transported away from the volcano, or after they have settled onto the ground surface. When this ash is remobilised into water bodies (wind or water erosion) the soluble salts can contaminate water supplies, especially if there hasn't been rain to leach the ash (Stewart et al., 2006). During a rainy season, for example, the volume will be high and, hence, concentrations will be lower. Pulses of high F, Cl and SO_4^{2-} concentration and low pH have been recorded in rivers following deposition of ash during volcanic activity (Oskarsson, 1980; Smithsonian Institution, 2000), as have high lake SO_4^{2-} levels (Markhinin, 1988; Weaire and Manly, 1996).

Acidification

Surface coatings on fresh volcanic ash are highly acidic, due to the influence in the volcanic plume of aerosols composed of the strong mineral acids H_2SO_4, HCl and HF. Therefore, when freshly-erupted ash comes into contact with water, it has the potential to lower the pH beyond acceptable limits for drinking water supplies or for the protection of aquatic life or livestock (Stewart et al., 2006; Cronin et al., 2003a; Witham et al., 2005).

There are many examples of the acidification of natural waters and water supplies following volcanic ashfall (summarised in Stewart et al., 2006). At Iwikau village, located at the base of Whakapapa skifield, pH levels ranging from 4.4 to 6.0 were recorded in roof tank supplies following the 1969 Ruapehu eruptions. Further down the mountain, Whakapapa Village received 1–6 mm of ash; the pH of its stream-fed water supply was recorded as 5.6 (Collins, 1978). Similar pH levels in receiving waters following volcanic ashfall have been reported in many other studies (e.g. Wilcox, 1959; Smithsonian Institution, 1997; Cronin and Sharp, 2002). Very low pH values are associated with greater thicknesses of ashfall.

APPENDIX 2 REGION FARM WATER USAGE

Information was accessed from council websites (Waikato, Bay of Plenty, Taranaki and Hawke's Bay regions), regional council publications, and interviews were held with hydrologists from Environment Waikato and Taranaki Regional Council, the Manager of Land Management for Hawke's Bay Regional Council, Fonterra field managers and scientists in Taranaki, and the Emergency Management Officer for Taranaki Regional Council.

Regional water use

To establish a general overview of water usage by region, information on the management of water resources was obtained for five regions (Waikato, Bay of Plenty, Gisborne, Hawke's Bay and Taranaki). It was hoped this information would give farm water usage information at a regional level so that conclusions could be drawn on which regions are most vulnerable to volcanic ashfall impacting farm water supplies. However it became rapidly clear that councils had relatively poor understandings of farm water use in the region due to non-consented allocation rights to farmers under the RMA. Council databases only included users who exceeded allocation limits and required a consent, giving an incomplete and inaccurate record. This lack of data prompted more attention to be focused on the case-study farms.

Analysis was undertaken on consented water takes by Lincoln Environmental (2000) investigating water allocation in each region, and percentages of surface and groundwater. Whilst slightly out of date, this is a useful proxy to investigate water usage in each region. It is also useful to investigate allocated water users because as the largest water users, they would be most impacted by disruption of water supplies from volcanic ashfall.

Total weekly allocation and type of supply are presented in Table A2.1. There is a high reliance on surface water supplies the central and western parts of the North Island, with approximately two thirds of allocated water derived from surface water takes in the Waikato and Bay of Plenty regions (Lincoln Environmental, 2000). Reliance is significantly higher in Taranaki. This is of concern as surface water supplies are most vulnerable to disruption by volcanic ashfall, particularly in Taranaki given the high volcanic hazard of that region. In marked contrast 67% of water allocations in the Hawke's Bay is made up of groundwater supplies (Lincoln Environmental, 2000). This indicates a higher resiliency as supplies are unlikely to be contaminated by ashfall.

Table A2.1 Water allocation by region in groundwater and direct surface water takes (from Lincoln Environmental, 2000)

Council	Total weekly allocation (m^3/s)	Weekly allocation % allocated from groundwater	% allocated from surface water
Waikato	10.3	39%	61%
Bay of Plenty	8.9	29%	71%
Hawke's Bay	16.8	67%	33%
Taranaki	3.4	4%	96%

Usage of allocated water is presented in Table A2.2. Note that public water supply includes municipal, stock water, domestic, community and farm household water supplies (Lincoln Environmental, 2000). This indicates that for all regions, farm water supplies (irrigation and a component of public water supply) make up a large component of water allocations. Hawke's Bay is notable for its high total weekly allocation and high allocation for irrigation. This indicates a potentially increased vulnerability to farm water users in that region through contamination of surface water supplies (includes irrigation reservoirs which rely on groundwater reserves) or power cut disrupting access to groundwater resources. Taranaki has a very low allocation for irrigation, suggesting less vulnerability. This variability in water sources between regions suggests farm water supply sources are highly diverse and there is likely to be strong variation within regions.

Table A2.2 Uses of allocated water by region (from Lincoln Environmental, 2000)

Council	Total weekly allocation (m^3/s)	% of allocation for irrigation	% of allocation for industrial use	% of allocation for public water supply
Waikato	10.3	32%	42%	26%
Bay of Plenty	8.9	40%	19%	41%
Hawke's Bay	16.8	68%	11%	21%
Taranaki	3.4	13%	41%	46%

A further breakdown of water allocation for irrigation and irrigated area by region and land-use type is presented in Table A2.3. Much of the irrigated area in each region is for horticultural practices. Dairy farming makes up a large component of irrigated land in Taranaki, whilst arable farming is a large component in Hawke's Bay. These land-uses in each respective region are likely to suffer greater disruption if their water supplies are contaminated by volcanic ashfall due to their greater reliance on water. They also have greater likelihood of disruption, as irrigating farms often have uncovered water storage ponds for storing extracted ground water for times of irrigation or have large extractions from surface water resources. The greatest area irrigated is also in Hawke's Bay suggesting a high reliance on agricultural irrigation in this region to maintain productivity. This vulnerability may be somewhat mitigated by the high percentage of groundwater extraction for allocated water extractions in the region (67%; Lincoln Environmental, 2000).

Allocation limits for water extraction on a per farm basis (farms being defined as farm properties larger than 1 ha) in each region are presented in Table A2.4 to give reference to the size of extraction allowable without a consent.

Table A2.3 Water allocation limits for individual farms in different regions

Council	Maximum allowed surface water abstraction	Maximum allowed groundwater abstraction	Source
Waikato	▪ 15 m^3/day	▪ 15 m^3/day ▪ 1.5 m^3/day for properties entirely within 600m of coastal marine area	www.ew.govt.nz/
Bay of Plenty	▪ 15 m^3/day ▪ 2.5 litres per second or 10% of the estimated five year low flow from river or stream ▪ intake velocity shall not exceed 0.3 metres per second	▪ 35 m^3/day	www.ebop.govt.nz/
Hawke's Bay	▪ 20 m^3/day for takes > 4 weeks ▪ 200 m^3/day for takes < 4 weeks ▪ Must not exceed 0.3 m^3/sec and not exceed 10% of the instantaneous flow	▪ 10 L/sec or 20 m^3/day	www.hbrc.govt.nz/
Taranaki	▪ 1.5 L/sec or 50 m^3/day	▪ 1.5 L/sec or 50 m^3/day	TRC, 2006

Table A2.4 Water allocation for irrigation and irrigated area by region and land-use type (adapted from Lincoln Environmental, 2000)

Council	Water allocation for irrigation ($m^3/s/wk$)	Consented irrigation area (ha)	Irrigated area - MAF estimate (ha)	Average allocation (mm/ha/wk)	% of irrigated area in different land uses (MAF estimate)				
					Dairy pasture	Other pasture	Arable	Horticulture	Viticulture
Waikato	3.3	n/a	4,500	44	14%	-	-	84%	2%
Bay of Plenty	3.6	9,435	9,435	23	23%	-	-	76%	-
Gisborne	1.2	n/a	5,000	15	8%	-	2%	90%	<1%
Hawke's Bay	11.4	23,242	23,242	30	8%	8%	35%	41%	8%
Taranaki	0.4	n/a	2,000	13	88%	-	12%	-	-

APPENDIX 3 ELECTRICAL POWER SUPPLY VULNERABILITY

Tephra can many problems for electrical distribution systems, which consequentially disrupt water pumps. The most common problems are supply outages from insulator flashover, flashover in electrical switch boards, line breakage (weight of tephra and tephra laden flora falling onto the lines) and controlled outages during tephra cleaning (Heiken et al., 1995; Johnston, 1997; Warrick et al., 1981).

Insulator flashover is a serious threat to electrical supplies and equipment on farms. Flashover occurs as electricity arcs from a conductor to earth or from conductor to conductor (www.transpower.co.nz). This damages the insulators and the lines, electrical equipment, or transformers; ultimately leading to a power cut. Flashover potential is determined primarily by the ash conductivity, ash adherence and physical dimensions of equipment. Dry volcanic tephra is not known to be conductive enough to be a problem. However when enough moisture is present to increase the conductivity of the ash flashover may occur. The moisture may come from the atmosphere (in the form of rain, before or after the eruption), or from the eruption plume itself (Wilson and Cole, 2007).

Substation insulators are more vulnerable to flashovers than line insulators, because of their shape and orientation, so it is likely the regional electrical distribution network will fail at critical nodes creating widespread outages during moderate to severe tephra falls. This will cause large disruption, potentially including farms not affected by ashfall.

Electrical storms are commonly associated with tephra falls due to the static build up from the millions of ash particles rubbing together. This creates lightning strike hazards for electrical supply networks. This was observed in the Tarawera area during the 1886 eruption, with telegraph poles and lines struck, cutting communications (Smith, 1886). Such strikes also occurred during the 1980 Mt. St. Helens eruption and during the May 1924 Kilauea eruption, when 21 consecutive poles were hit (Blong, 1984).

The best way to mitigate tephra fall hazards to electrical power supply is to bury power-lines, and install insulators and power lines resistant to tephra accumulation. These however are highly costly options difficult to justify to New Zealand’s current energy sector. A controlled power outage to allow cleaning of the insulators is commonly used; however this is costly, both in terms of cleaning and the loss of power to consumers. Cleaning by Transpower during the 1995-96 Ruapehu eruptions involved water blasters at ~1500 psi to quickly clean off tephra, followed by manual cleaning using a dry cloth (www.transpower.co.nz). Drying the insulators gave much better results but greatly increased cleaning time (Johnston, 1997). It is also unlikely power supply maintenance personnel would be available to rural customers immediately, with urban centres and higher voltage lines getting priority (P. Joureaux, *pers comm.*, 2005). The installation of a personal generator on a farm would give a degree of resilience to volcanic hazards.

APPENDIX 4 STUDY FARM INTERVIEW LOG SHEETS

Natural Hazards RESEARCH CENTRE

UC UNIVERSITY OF CANTERBURY Te Whare Wānanga o Waitaha CHRISTCHURCH NEW ZEALAND

INTERVIEW LOGS – Farms

Interviewer:

Date:

Location (GPS):

Farm Type:

Stock Numbers/Rate:

Acres/Hectares:

1) Please describe in detail how you access water supplies for your farm:
- nature of farm water supply (groundwater, stream, reservoir, regional or local schemes etc)
- pumps, storage facilities (tanks/reservoirs)
- how many others do you share your water supply with?

2) What key farm functions/operations require water? Is this supply required through out the year? (*rate 1-4, with 4 being essential*)

3) Characterise water use throughout the year – what is water used for and when (*defining seasonal vulnerability*):
- when are the heavy water periods?
- how much do you use (*during the year and during specific times*)
- how long are these periods?
- how critical are they (*rate 1-4, with 4 being essential*)

4) Has there been any events/or actions that have threatened or disrupted your farm water supply?
- What implications did they (potentially) have on your farm and the way you run your farm?
- Has this experience modified the way you farm now?

5) Were you ashed on during the 1995/96 Ruapehu eruptions?

- If so, could you please describe the experience
  - = what did you do (before, during, after)?
  - = what was impacted?
  - = how much information was available?
  - = what could have been better?
  - = what parts of the experience were good?

- If not…could you please describe the experience (what did you do and what was impacted, how much information was available)
  - = what did you do (readiness)?
  - = what did you hear was impacted?
  - = how much information was available?
  - = what could have been better?
  - = what parts of the experience were good?

6) What do you think would happen to your water supply if it was affected by volcanic hazards, such as an ashfall, lahar, pyroclastic flow (*may need to describe what these events could do to the water supply – talk through their entire water supply and look for weakness and vulnerabilities*):

- water quality and supply
- supply infrastructure (pumps, pipes, hoses, tanks, troughs).
- end uses (stock drinking, irrigation, washing down, domestic use, etc)

Please try to identify key points of vulnerability – such as open tanks/dams/reservoirs, pumps, pipes that can get blocked

7) What actions would you do to protect your farm and its water supply if you were informed (*talk through general farm stuff as well as water supply – entire supply – would they try and secure/protect supplies)*:

- a volcano was showing signs of unrest and a volcanic eruption was possible within the next month
- a volcanic eruption was imminent (likely within the next couple of days-week)
- a volcanic eruption had occurred and your farm was likely to be affected by ashfall hazards within 2-10 hours

8) Do you have a roof-fed water tank for household supply?

- If so…do you have a disconnect valve between the roof and the tank?

9) What assistance would expect from the emergency management agencies (such as MAF or Federate Farmers or regional council or MCDEM) in the volcanic crisis (*in general and then in regard to water supplies*)

- before
- during
- after

APPENDIX 5 APPLICATION OF FARM WATER SUPPLY VULNERABILITY MODEL (VOLCANIC HAZARDS)

- **Study Farm 1: Water Supply Vulnerability Rating**

VULNERABILITY CLASS	INDICATOR	VULNERABILITY RATING
Supply	Groundwater	10
Pumping Capability	Total reliance on pumped water – back up power option for pump	15
Storage Capacity	Storage capacity to operate for 1-3 days (in high demand periods)	10
Independence of Supply	Share with several users	2
Water Usage	Small water user	5
Previous/Current Water Stress	Constant (un-stressed) supply of water to farm	0
VULNERABILITY RATING	SUM TOTAL	42 (100)

- **Study Farm 2: Water Supply Vulnerability Rating**

VULNERABILITY CLASS	INDICATOR	VULNERABILITY RATING
Supply	Surface water	30
Pumping Capability	Some reliance on pumped water – no back up power option for pump	10
Storage Capacity	Storage capacity to operate for 1-3 days (in high demand periods)	10
Independence of Supply	Individual access to supply	0
Water Usage	Small water user	5
Previous/Current Water Stress	Occasional pressure on farm water supply	3
VULNERABILITY RATING	SUM TOTAL	58 (100)

- **Study Farm 3: Water Supply Vulnerability Rating**

VULNERABILITY CLASS	INDICATOR	VULNERABILITY RATING
Supply	Surface water	30
Pumping Capability	Total reliance on pumped water – back up power option for pump	15
Storage Capacity	Storage capacity to operate for 5+ days (in high demand periods)	5
Independence of Supply	Share with several users	2
Water Usage	Small water user	5
Previous/Current Water Stress	Constant pressure on farm water supply	10
VULNERABILITY RATING	SUM TOTAL	67 (100)

- **Study Farm 4: Water Supply Vulnerability Rating**

VULNERABILITY CLASS	INDICATOR	VULNERABILITY RATING
Supply	Groundwater	10
Pumping Capability	Total reliance on pumped water – back up power option for pump	15
Storage Capacity	Storage capacity to operate for 1-3 days (in high demand periods)	10
Independence of Supply	Individual access to supply	0
Water Usage	Large water user at specific times of the year	10
Previous/Current Water Stress	Constant (un-stressed) supply of water to farm	0
VULNERABILITY RATING	SUM TOTAL	45 (100)

- **Study Farm 5: Water Supply Vulnerability Rating**

VULNERABILITY CLASS	INDICATOR	VULNERABILITY RATING
Supply	Groundwater	10

Pumping Capability	Total reliance on pumped water – no back up power option for pump	20
Storage Capacity	No storage capacity	20
Independence of Supply	District scheme	5
Water Usage	Large water user at specific times of the year	10
Previous/Current Water Stress	Constant (un-stressed) supply of water to farm	0
VULNERABILITY RATING	SUM TOTAL	65 (100)

- **Study Farm 6: Water Supply Vulnerability Rating**

VULNERABILITY CLASS	INDICATOR	VULNERABILITY RATING
Supply	Surface water	30
Pumping Capability	Total reliance on pumped water – back up power option for pump	15
Storage Capacity	No storage capacity	20
Independence of Supply	District scheme	5
Water Usage	Large water user at specific times of the year	10
Previous/Current Water Stress	Seasonal pressure on farm water supply	7
VULNERABILITY RATING	SUM TOTAL	87 (100)

- **Study Farm 7: Water Supply Vulnerability Rating**

VULNERABILITY CLASS	INDICATOR	VULNERABILITY RATING
Supply	Groundwater	10
Pumping Capability	Total reliance on pumped water – no back up power option for pump	20
Storage Capacity	No storage capacity	20
Independence of Supply	Individual access to supply	0

Water Usage	Large water user at specific times of the year	10
Previous/Current Water Stress	Constant (un-stressed) supply of water to farm	0
VULNERABILITY RATING	SUM TOTAL	60 (100)

- **Study Farm 8: Water Supply Vulnerability Rating**

VULNERABILITY CLASS	INDICATOR	VULNERABILITY RATING
Supply	Groundwater	10
Pumping Capability	Total reliance on pumped water – no back up power option for pump	20
Storage Capacity	Storage capacity to operate for 1-3 days (in high demand periods)	10
Independence of Supply	Individual access to supply	0
Water Usage	Large water user at specific times of the year	10
Previous/Current Water Stress	Constant (un-stressed) supply of water to farm	0
VULNERABILITY RATING	SUM TOTAL	50 (100)

APPENDIX 6 DIMENSIONS OF STOCKWATER TROUGHS USED IN CHEMICAL MODELLING

Humes trough dimensions					area (m^2)	volume (m^3)	**A/V (m^{-1})**
Shape	*Capacity*	*Length*	*Width*	*Depth*			
Rectangular	200 (44gal)	1300	710	380	0.92	0.2	**4.6**
Rectangular	300 (66gal)	1900	710	380	1.35	0.3	**4.5**
Rectangular	400 (90gal)	2740	710	380	1.95	0.4	**4.9**
Shape	*Capacity*	*Diameter*	*Depth*				
Circular	500 (110gal)	1484	380		1.73	0.5	**3.5**
Circular	750 (165gal)	1794	380		2.53	0.75	**3.4**
Circular	1000 (220gal)	1634	600		2.10	1	**2.1**
Circular	1500 (330gal)	2000	600		3.14	1.5	**2.1**
Circular	2500 (550gal)	2500	600		4.91	2.5	**2.0**
Hynds round troughs							
	Capacity (l)	*Diameter*	*Depth*				
Round 100 gallon	450	1350	430		1.43	0.45	**3.2**
Round 175 gallon	780	1600	510		2.01	0.78	**2.6**
Round 250 gallon	1125	1960	510		3.02	1.125	**2.7**
Hynds oblong trough	*Capacity (l)*	*Length*	*Width*	*Depth*			
60 gallon oblong protector trough	270	2000	660	380	1.32	0.27	**4.9**
						Average A/V	**3.4**

www.gns.cri.nz

Principal Location

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657