Modelling livestock evacuation following a volcanic eruption: an example from Taranaki volcano, New Zealand

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Abstract Livestock evacuation from farms affected by volcanic ashfall during or following a moderate to large volcanic eruption of Taranaki volcano would pose serious logistical challenges for emergency organisations. The volcanic hazards present during the eruption (such as volcanic ashfall) have the potential to significantly disrupt farming and transport operations in widespread areas both near to and far from the volcano. This paper presents a simplistic model that estimates the time and resources required to evacuate dairy cows from a large eruption from Taranaki volcano in New Zealand. Whilst intended to highlight the scale of time, money and logistics required for a large livestock evacuation, the model also provides a first step towards a model which can be run during periods of volcanic crisis to aid decision making. The model estimates that for a total evacuation of cows from dairy farms impacted by 100 mm of ashfall 208,000 cows would need to be evacuated and it would take at least 43,600 man-hours and cost >NZ$2,000,000. It would take 264 livestock truck and trailer units to evacuate this number of cows in 7 days, or 88 units in 21 days. It is therefore recommended that large-scale livestock evacuation and relocation should not be considered in future volcanic crisis planning, due to the large logistical requirements a large livestock evacuation would require in terms of time, livestock evacuation transport units, and lack of capacity of farms in surrounding regions to support the massive influx of additional livestock.

Keywords  agriculture; livestock evacuation; modelling; New Zealand; Taranaki volcano; volcanic hazards

INTRODUCTION

Agricultural production provides a significant proportion of New Zealand’s economy (4.3% of GDP; Statistics New Zealand 2007). Within the agricultural industry, livestock farming represents a significant component and livestock evacuation following a moderate to large volcanic eruption would pose serious logistical challenges to emergency organisations. The volcanic hazards produced during the eruption (such as volcanic ashfall, pyroclastic flows and lahars) have the potential to significantly disrupt farming and transport operations. Under these conditions, evacuation of the large number of livestock necessary from the impacted areas will be extremely difficult because of feed cover by ashfall, potential damage to farm equipment and transport infrastructure, and the very limited transportation capacity and availability of farmland to receive and sustain evacuated livestock.

The efficient evacuation of livestock involves significant planning, and one of the significant key decisions faced by emergency managers with agricultural responsibilities when faced with a volcanic crisis is whether to commit resources to evacuating livestock from impacted farms. This has prompted hazard managers and agricultural experts to express concern over whether livestock evacuation would be possible during a volcanic eruption. For example, during the 1995 Ruapehu eruption, New Zealand Ministry of Agriculture and Forestry (MAF) discussed the feasibility of evacuation for affected pastoral farms, but ultimately discarded it as impractical (P. Journeaux pers. comm. 2006).

Two case studies of livestock evacuations in New Zealand following natural hazard events are
analysed. A review of available literature indicated there have been no other studies investigating livestock evacuation in New Zealand. The paper then presents findings from a pilot study evaluating the feasibility of evacuating livestock following a moderate to large sized explosive eruption from Taranaki volcano, New Zealand. The model uses geospatial platforms and traffic simulation software as tools to gain a quantitative understanding of the number of animals required to be evacuated utilising a farm animal database, the time it would take to evacuate livestock (loading/unloading and travel time), and the transportation resources required for such an operation. These provide insight for a foundation upon which to base future planning in the event of a real crisis.

CASE STUDIES OF RECENT NATURAL HAZARD EVENTS IN NEW ZEALAND WHICH REQUIRED LIVESTOCK EVACUATION

Two case studies are presented as examples of previous livestock evacuations that have occurred in New Zealand following severe “rapid onset” natural hazard events. The first illustrates potential impacts following a large volcanic eruption and the second details a modern livestock evacuation due to flooding.

1886 AD Tarawera eruption

Ashfall from the 10 June 1886 eruption from Tarawera volcano, Bay of Plenty (Fig. 1) had a significant impact on young, developing pastoral farms and gives some insight into how a large modern day volcanic eruption may impact pastoral livestock. Most of the pastoral farms affected were located in eastern Waikato and Bay of Plenty and were exposed to basaltic ashfalls ranging from 12 mm at Tauranga to 75 mm at Te Puke, and 75–100 mm between Matata and Whakatane (Fig. 1; Nairn 2002).

Pastoral farmers in the distal Bay of Plenty region found that up to 10 mm of ashfall did not completely prevent livestock from grazing. However, in the heavier ashfall areas closer to the volcano pastures were totally covered by ashfall preventing grazing. Matters were made worse by severe problems in finding feed for the affected livestock (primarily sheep, cattle and horses; Keam 1988).

Those farms with supplementary feed were able to maintain the majority of their livestock, but many farmers became desperately short on extra feed stocks within days of the eruption. Farmers either had to bring in supplementary feed from outside the affected area to offset shortfalls in local supplies, evacuate livestock for pasturing elsewhere, or sell the livestock (Keam 1988).

Many farmers chose to evacuate livestock to Tauranga and Whakatane ports (Fig. 1), but many animals died while walking to these ports. Government assistance was sought for evacuation and in providing funding for supplementary feed purchase. A recommendation was made by agricultural officers that badly affected (starving and in extreme poor condition) animals be slaughtered and two-thirds of livestock in the Whakatane district be evacuated (Keam 1988). Several thousand livestock (mostly sheep and cattle) were evacuated by steamer from Whakatane and the government-owned reserves of Tiritiri and Motuihe islands were used for pasturing some of the evacuated animals (Keam 1988). Many large farms outside the affected area accepted livestock or provided supplementary feed. The total number of livestock evacuated may have exceeded 20 000 (Keam 1988).

After the first week, rain in the Bay of Plenty removed much of the ash. This allowed access to a substantial amount of grass and greatly reduced the pressure on livestock. Evacuations continued by ship well into July, nearly 6 weeks after the eruption (Keam 1988).

2004 southern North Island floods

One of the most common natural hazards to impact farms in the past 5 years in the central North Island has been flooding. In 2004, 111 dairy and 1550 sheep and beef farms in the southern North Island were directly affected by flooding (MAF 2004). Road closures from flooding damage affected milk collection from a further 1400 dairy farms (MAF 2004). This necessitated an industry-driven (Dairy NZ and Federated Farmers) evacuation of dairy cows from badly affected farms by truck and trailer units (P. Journeaux pers comm. 2005). Approximately 20 000 dairy cows were moved out of the area, generally further north into the Waikato and Bay of Plenty (Fig. 1; MAF 2004). The dairy herds were taken to unaffected farms which received the milk produced by the evacuated herd in return for grazing and care of the animals. When the impacted farm was operational again, the cows returned. The Ministry of Agriculture and Forestry provided financial assistance for the transportation of these animals (MAF 2004).
LIVESTOCK EVACUATION

Any livestock evacuation as a result of a natural hazard event will be carried out under significantly different conditions to normal transportation or logistical operations. The evacuation and emergency logistics response to Hurricane Katrina in the United States (i.e., bringing in aid to New Orleans) illustrated that normal logistical systems and planning are dramatically affected by extreme natural events (Holguin-Veras et al. 2007). They compound impacts and significantly reduce the efficiency of components of logistics systems because of the: (1) large volumes to be transported; (2) short time frames of response to prevent loss of lives and property; and (3) major uncertainties about what is actually needed and what is available at the site (Holguin-Veras et al. 2007).

Decision to evacuate livestock

The decision by a farmer to evacuate livestock during a volcanic crisis from their farm is likely to be influenced by: (1) financial considerations, i.e., the cost of transport and lost production versus the risk of suffering livestock losses; and (2) the volcanic hazard, i.e., the style and magnitude of the eruption, and the direction and strength of wind at the time of the eruption which will control where and how much ash falls. There are also emotional considerations, as most farmers have a close bond with their livestock and are unlikely to want to lose them (even for a short period of time).

Where and when ash will fall is usually highly uncertain before any volcanic eruption, so it is unlikely any farmer or emergency manager will decide to evacuate livestock before ash has fallen on farmland.
Therefore, a key factor in evacuation decisions is what thickness of ashfall a farmer (and/or emergency manager) will decide is too great to continue keeping livestock on the farm. Further factors that will influence a decision to evacuate include the accessibility of hazard information and farmers’ understanding of how volcanic ashfall may impact their farm. Whilst it is unlikely volcanic monitoring systems will provide forecasts or predictions for duration or magnitude of future volcanic activity, any information the farmer receives (whether official or gossip) on further ashfalls is likely to have a bearing on the validity of the decision to evacuate.

Physical constraints will also influence the evacuation decision. Availability of evacuation transportation (such as livestock truck and trailer units), road network availability (as evacuation of people will take top priority), and availability of unaffected farms to receive evacuated livestock will be key factors. If all are available, even at an early stage in an eruption, the evacuation decision may be made at a much lower ashfall thickness.

Evacuation time

The total time required to evacuate livestock will be dependant on efficient and effective co-ordination between farmers and emergency managers, which includes impact assessment and transport deployment systems. It will be crucial for all parties to know:

- what livestock require evacuation (i.e., those able to survive for a period of time versus others too incapacitated for evacuation or have perished).
- what transportation resources are available and suitable.
- which transportation resources can be employed. Transport networks are likely to be disrupted following an eruption by impacts from volcanic hazards and other transport network users.
- where destinations for evacuated livestock are situated.

Communication of this knowledge will be a significant challenge. Communication networks may be disrupted with many people and organisations operating at a reduced level of situational awareness. For example, bridges which carry telephone lines may be destroyed by lahar hazards and cell tower operation on Taranaki volcano may be disrupted.

All of these issues have the potential to change dramatically throughout any evacuation as roading, vehicle, animal health, farm availability and volcanic hazard conditions change over the duration of evacuation. They will be further complicated by additional concerns such as priority assignment for certain livestock holding higher genetic and monetary value, and government assistance (which could range from transport subsidies through to livestock replacement assistance).

Impacts to evacuation vehicles and people

Volcanic ash is highly abrasive, potentially corrosive, very fine grained and easily remobilised (Blong 1984). It can easily enter or be sucked into engines and mechanical parts, causing damage and even failure (Neild et al. 1998). The risk of further volcanic activity or subsequent lahar hazards would also be a significant health and safety concern for people and animals (Neild et al. 1998).

Development and dissemination of traffic management plans

The difficult task of rapidly organising a large scale evacuation is highlighted by the logistical problems experienced during and following Hurricane Katrina (Holguin-Veras et al. 2007). When faced with supplying New Orleans with aid supplies, the US Federal Emergency Management Agency (FEMA) struggled to adequately identify enough staging and drop off points, suffered problems with asset visibility (location, status and movement of assets), could not track movement of trucks, and found it difficult to secure enough transport to adequately supply requirements (Holguin-Veras et al. 2007). Problems were further complicated by truck operators evacuating the New Orleans area due to fears of damage and injury before the landfall of Hurricane Rita (which followed Hurricane Katrina several weeks later, although it did not greatly impact New Orleans). This severely hampered readiness efforts (Holguin-Veras et al. 2007). A similar experience may occur during a volcanic eruption induced livestock evacuation if on-going eruptive activity occurs (e.g., Jenkins et al. 2007; Turner et al. 2007).

USING A TRAFFIC MODELLING PACKAGE TO ESTIMATE LIVESTOCK EVACUATION BEHAVIOUR

Emergency managers and transportation officials are increasingly using traffic modelling packages to aid in evacuation planning and operation. Such tools provide a means of estimating evacuation times, developing traffic management and control strategies, and identifying evacuation routes (Rathi & Solanki 1993; Chang 2003; Moriarty et al. 2007).
Southworth (1991) has recommended several informational requirements for realistically simulating traffic flow during emergency conditions:

- accurate description of the transportation infrastructure, especially the highway network;
- accurate description of the spatial distribution of the population by time of day and type of activity;
- accurate representation of vehicle utilisation during an emergency;
- accurate representation of the timing of the public response to an emergency, and how the timing varies by location and current activity at the time of learning of the threat;
- accurate representation of evacuee route and destination selection behaviour;
- accurate representation of any traffic management controls that may be incorporated within the evacuation plan; and
- accurate representation of any non-evacuation based protective action taken by a significant number of population subgroups within the at-risk area.

TARANAKI ERUPTION LIVESTOCK EVACUATION SCENARIO

The model uses an eruption scenario based on the 5700 BP Inglewood eruption of Taranaki volcano. This eruption scenario has been selected due to the high concentration of dairy farms near Taranaki volcano, the high likelihood of a future eruption at Taranaki (Turner et al. 2007), and the relatively large magnitude of the eruption (Neall 1972).

Inglewood eruption

Eruptions from Taranaki volcano (TV) are the primary volcanic hazard for the Taranaki region, given its close proximity to urban and rural communities and frequent eruptive activity in the past (Turner et al. 2007). The ash from the Inglewood eruption was mapped and discussed by Neall (1972), and Franks (1984). Alloway et al. (1995) presented an isopach map of its distribution (Fig. 2), with ash distributed to the north-east of the volcano as far as the Waikato lakes (Lowe 1988).

Livestock evacuation scenario

The evacuation scenario makes a number of assumptions:

- a decision has been made to evacuate dairy herds affected by the eruption (i.e., it is not a preventative or readiness measure);
- farms impacted by 50 mm of ashfall have been selected to be evacuated;
- ash thicknesses are assumed to have fallen in one discrete event or the farm has been able to maintain the dairy herd up until the 50 mm thickness of ash was reached;
- dairy cows are evacuated by existing livestock truck and trailer units, designed specifically for cow transport (with 40 dairy-cow transport unit in double stacked configuration);
- dairy cows are assumed to be assembled in livestock yards ready to be loaded as soon as livestock transport arrives;
- only dairy cows are accounted for within this livestock evacuation;
- only the state highway network is used for the evacuation;
dairy cows are evacuated to urban centres more than 200 km from Taranaki volcano, as it is prudent to evacuate a significant distance from the volcano (this also assumes livestock will be redistributed from urban centres); and

• no urban centre (destination) that had received 2 mm of ashfall from the eruption is considered as a destination.

Some of these assumptions simplify the complex nature of a large livestock evacuation. The reality is that evacuation conditions and resources could be much worse.

Methodology

The number of farms and dairy cows within the 50 mm ashfall isopach of the Inglewood eruption are presented in Table 1.

Evacuation transport

The number of trucks assigned to each farm is based on each truck and trailer unit carrying 40 cows. If the number of animals per truck is lower than this, the product will be rounded up or down depending on the livestock evacuation plan being used (see below).

The scenario assumes the livestock trucks operate on a 24 h basis (i.e., using a rotation of drivers to keep the trucks operating at 100% efficiency). There has been no specific consideration within the model for downtime of trucks for fuelling or maintenance—for simplicity these are included within the loading time parameter.

The availability of livestock transportation vehicles in the Taranaki region is a key constraint on any large scale evacuation of livestock. Depending on the amount of warning time and preparation time additional of transportation units could be obtained from surrounding regions.

Loading time

The model assumes that dairy cows are in the yards ready to be loaded onto trucks when they arrive. It assumes all farms and destination centres have a livestock loading ramp and livestock yards. Loading/unloading time is assumed to be 1.5 h per truck and trailer unit at each farm. This includes loading/unloading the cows onto/off both the truck and trailer and manoeuvring time (i.e., backing onto the loading ramp).

Destination

The livestock evacuation model assumes that each destination centre is 200 km from the volcano and has received less than 2 mm of ashfall. It also assumes stockyards that can unload trucks and allow redistribution of livestock. The model assumes the need for a rapid evacuation with limited transport assets, so livestock are taken to these destination centres for later distribution to surrounding farms. This also removes the need to consider the capacity of destination farms to receive livestock within the model.

Road network

The model for evacuation uses the state highway network (Fig. 3). Dairy farms that required evacuation of livestock were linked to the nearest node of the state highway network by a geographic information system (GIS) and this distance was included in the distance required to be travelled by each truck from the evacuation origin (farm) to the evacuation destination (urban centre). This creates a network between all evacuation origins and evacuation destinations.

By evacuating livestock to urban centres (Fig. 3) livestock are immediately removed from the danger zone. They may be later distributed to destination farms as livestock are removed from danger zones and more transport becomes available.

Livestock evacuation scenarios

The unique abilities of a traffic modelling, GIS based package allows for effective management of the evacuation, by planning the most efficient routes, calculating impedance within the traffic network (congestion), and prioritising livestock pickup and delivery. The traffic modelling can be continuously updated as the situation on the ground changes and be used to plan for future contingencies. Several livestock evacuation scenario options have been

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Dairy farms within the 50 mm isopach of the Inglewood eruption.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dairy farms impacted by 50 mm or more of ash</td>
<td>528</td>
</tr>
<tr>
<td>Total area (ha) of dairy farms impacted by 50 mm or more of ash</td>
<td>77 199</td>
</tr>
<tr>
<td>Population of dairy cows impacted by 50 mm or more of ash</td>
<td>208 438</td>
</tr>
</tbody>
</table>
investigated with the model to determine which is the most successful. These are described below:

**Scenario 1—Full evacuation**

Trucks that do not receive a full load of cows from one farm travel to the next available farm and load until they are full.

**Scenario 2—Full efficient evacuation**

This provides only enough trucks to each farm so truck and trailer units receive a full load. For example, if a farm has a herd of 346 dairy cows, then eight truck and trailer units will be provided (to take 320 cows).

**Scenario 3—Partial herd evacuation**

This option assumes that only 50% of each herd is evacuated, rounded up to a multiple of 40 (creating full transport units). This plan attempts to reduce the huge logistical challenge a large animal evacuation would entail and allow for a more rapid evacuation and reduce pressure on destination farms. It allows impacted farms to attempt to manage with a minimal dairy herd and allows for the possibility of low-value livestock being culled.

**Evacuation transport network analysis:**

**calculation of estimated truck travel time and cost**

**Traffic assignment options**

A key benefit of using a traffic modelling, GIS based package to assist in managing a livestock evacuation is the ability to factor in the traffic loadings on the roads used by the transport units for evacuating livestock. Given the small number, it is unlikely there will be enough livestock truck and trailer units on the road in any one place to cause undue congestion, other than at evacuation centres. For this reason it may be more efficient to distribute trucks to a number of evacuation destination centres, rather than just the centre closest to the farm.

Traffic assignment models are used to estimate the flow of traffic on a network (Ortuzar & Willumsen 1994). These models input a matrix of trips that indicate the volume of traffic between origin and destination. Trips are loaded onto the network based on the travel time or impedance of the alternative paths that could carry this traffic.
Three different types of traffic assignment methods were applied to the traffic network (see below). Each method assumes different driver behaviour and control on the traffic network. For further information and applications on traffic assignment methods refer to Ortuzar & Willumsen (1994).

(1) All or nothing. All trips are assigned to the lowest travel cost path without any consideration of traffic capacity or traffic control within the network;

(2) User optimum. Trips are assigned to paths taking into consideration that drivers will attempt to minimise individual travel costs (or travel time), which incorporate delays and road traffic capacity (i.e., vehicles per lane per hour);

(3) System optimum. Trips are assigned to paths in order to minimise the total travel costs of all drivers, based on the assumption that traffic can be controlled or managed in such a way that the most efficient operation occurs within the network.

Mathematically the traffic assignment optimisation problem can be described as shown in Eqn 1.

\[ T = \sum_{a \in A} \int_0^{f_a} c_a(f_a) \, dx \]

subject to

\[ \sum_{a \in A} h_{pq} = d_{pq}, \quad p \in P, q \in Q \quad (1a) \]

\[ f_a = \sum_{p \in P} \sum_{q \in Q} \sum_{r \in R_{pq}} h_{pq} \delta_{pq} \quad a \in A \quad (1b) \]

where

- \( T \) = total network cost;
- \( h_{pq} \) = traffic flow from origin \( p \) to destination \( q \) on the route \( r \);
- \( c_a(f_a) \) = travel cost on the link \( a \) for a flow \( f_a \);
- \( d_{pq} \) = demand for trips from origin \( p \) to destination \( q \);
- \( \delta_{pq} \) = 1 (if the link \( a \) is on the route \( r \) from \( p \) to \( q \)) or 0 (otherwise);
- \( L \) = set of links in the network;
- \( P \) = set of origin nodes;
- \( Q \) = set of destination nodes; and
- \( A \) = set of links as part of route; and
- \( dx \) = infinitesimal increment in flows on the network.

**Calculation of travel time**

Based upon the network traffic assignment, individual traffic routes between the evacuating farms and the evacuation destination centres are computed. The routes judged to be the most acceptable by the particular traffic assignment were presented as the travel time component of total livestock evacuation time requirement (Eqn 2). This figure was doubled (reflecting the original trip from the destination centre).

\[ TE_{pq} = TL_{pq} + 2 \times c_{pq} \]

where

- \( TE_{pq} \) = total travel time evacuation for a route from origin (farm) \( p \) and destination (evacuation centre) \( q \);
- \( TL_{pq} \) = loading/unloading time for a route from origin (farm) \( p \) and destination (evacuation centre) \( q \);
- \( c_{pq} \) = travel time evacuation for a route from origin (farm) \( p \) and destination (evacuation centre) \( q \);

The network total time (NTT) in man-hours required for each evacuation plan is calculated with Eqn 3.

\[ NTT = \sum_q \sum_p TTE_{pq} \]

**Results**

**Total time (duration) required for evacuation scenarios (in man-hours)**

Each evacuation scenario (Table 2) shows each evacuation plan will take a very long time to complete. As expected, reducing the required number of livestock to be evacuated dramatically reduces the time required. For example, Scenario 1 requires a total of 44 383 man-hours compared to Scenario 3 which requires a total of 23 146, when using the “user optimal” traffic assignment method.

The model shows that traffic congestion causes an extra 762 h in Scenario 1, 536 h in Scenario 2 and 427 h in Scenario 3 for travel times when the “all or nothing” assignment is compared with “user optimal” assignment (Table 2). When the system optimal assignment is used, efficiencies of 63 h in Scenario 1, 57 h in Scenario 2, and 27 h in Scenario 3 are achieved.

The “all or nothing” traffic assignment method takes the shortest path without considering congestion or other external parameters. Congestion ratings were applied to the road network to simulate congestion at evacuation centres, although these had little influence given the low traffic numbers (50 trucks over the network). Whilst the most efficient, this traffic assignment method is also the most unrealistic and should not be used when more realistic assignments are available.
The “user optimum” traffic assignment is more realistic as it considers capacity of the road network and thus allows each part of the transport network to have different behaviour, which is similar to what occurs in reality. In the model, an increased congestion rating was given to roads close to final destinations reflecting the congestion livestock trucks would create at favourable evacuation centres. This resulted in the GIS assigning some evacuation trips to evacuation centres further away from origin farms for greater time efficiency.

“System optimal” traffic assignment allows for coordination by assuming complete external control, and therefore it should be the most efficient assignment. However, this becomes unrealistic as people will not behave totally in accordance with external control, unless they are operating under command of an evacuation controller (external control of the network).

Little difference to the “user optimal” traffic assignment was achieved given the low traffic numbers on the network (Table 2). Benefits would be greatest if significant congestion occurred on the network, such as human evacuation traffic or bridge collapse (e.g., from lahar hazards).

### Cost of evacuation transport

The cost of using evacuation transport has been calculated using travel time base values from Land Transport New Zealand (2005), and these costs are presented in Table 3. Heavy commercial driver time cost ($20.10/h) and heavy commercial vehicle II vehicle and freight time cost ($28.10/h) have been combined to give a total time cost of $48.20/h (Land Transport New Zealand 2005). The results show there would be significant costs associated with any evacuation. Note that this does not include economic disruption costs, which for example would be

<table>
<thead>
<tr>
<th>Scenario plan</th>
<th>Loading/unloading time</th>
<th>Traffic assignment method</th>
<th>Travel time</th>
<th>Total time</th>
<th>Stock evacuated</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scenario plan</strong></td>
<td><strong>Truck pickups</strong></td>
<td>(h)</td>
<td><strong>Traffic assignment method</strong></td>
<td>(h)</td>
<td>(days)</td>
</tr>
<tr>
<td>1 (Full evacuation)</td>
<td>5520</td>
<td>16 560 690</td>
<td>All or nothing</td>
<td>27 061</td>
<td>1127.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>User optimal</td>
<td>27 823</td>
<td>1159</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>System optimal</td>
<td>27 760</td>
<td>1157</td>
</tr>
<tr>
<td>2 (Full efficient evacuation)</td>
<td>5004</td>
<td>15 012 625.5</td>
<td>All or nothing</td>
<td>24 162</td>
<td>1007</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>User optimal</td>
<td>24 698</td>
<td>1029</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>System optimal</td>
<td>24 641</td>
<td>1027</td>
</tr>
<tr>
<td>3 (Partial evacuation)</td>
<td>2902</td>
<td>8706 363</td>
<td>All or nothing</td>
<td>14 013</td>
<td>584</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>User optimal</td>
<td>14 440</td>
<td>602</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>System optimal</td>
<td>14 413</td>
<td>601</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario plan</th>
<th>Estimated loading/unloading time cost (NZ$)</th>
<th>Traffic assignment method</th>
<th>Estimated travel time cost (NZ$)</th>
<th>Total estimated evacuation transport cost (NZ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Full evacuation)</td>
<td>798,192.00</td>
<td>All or nothing</td>
<td>1,304,340.20</td>
<td>2,102,532.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>User optimal</td>
<td>1,341,068.60</td>
<td>2,139,260.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>System optimal</td>
<td>1,338,032.00</td>
<td>2,136,224.00</td>
</tr>
<tr>
<td>2 (Full efficient evacuation)</td>
<td>723,578.40</td>
<td>All or nothing</td>
<td>1,164,608.40</td>
<td>1,888,186.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>User optimal</td>
<td>1,190,443.60</td>
<td>1,914,022.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>System optimal</td>
<td>1,187,696.20</td>
<td>1,911,274.80</td>
</tr>
<tr>
<td>3 (Partial evacuation)</td>
<td>419,629.20</td>
<td>All or nothing</td>
<td>675,426.60</td>
<td>1,095,055.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>User optimal</td>
<td>696,008.00</td>
<td>1,115,637.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>System optimal</td>
<td>694,706.60</td>
<td>1,114,335.80</td>
</tr>
</tbody>
</table>
Table 4 Total time required for each evacuation plan under different transport availability scenarios.

<table>
<thead>
<tr>
<th>Deadline</th>
<th>Stock trucks required</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7 days</td>
</tr>
<tr>
<td>Evacuation Scenario 1</td>
<td>264</td>
</tr>
<tr>
<td>Evacuation Scenario 2</td>
<td>236</td>
</tr>
<tr>
<td>Evacuation Scenario 3</td>
<td>137</td>
</tr>
</tbody>
</table>

expected from the dedicated use of transport assets for only evacuation use, disruption to dairy farming, and other wider economic effects.

Transport assets required for time-pressure/ deadline evacuation

Different evacuation deadlines were analysed to determine the number of transport assets required to successfully complete the evacuation (Table 4) using the “user optimal” traffic assignment travel times. The matrix presented in Table 4 demonstrates the enormity of the logistical challenge of rapid evacuation (7–10 days) following an ashfall. After that period has passed, it is probable that livestock would die from dehydration or starvation without sufficient clean water supplies or supplementary feed. Even if livestock on farms could survive for 28 days, a sizeable portion of New Zealand’s livestock truck assets would be required to remove livestock under each evacuation scenario.

DISCUSSION

Implications and lessons from previous livestock evacuations in New Zealand

Farmers and stakeholders within the agricultural sector may demand evacuation of livestock, particularly if livestock are suffering significant welfare impacts from ashfall hazards. Farmers may perceive that evacuation is a valid management option given the precedent that has been set with recent livestock evacuations during floods in the Manawatu and Bay of Plenty (MAF 2004; P. Journeaux pers. comm. 2005; P. O’Flaherty pers. comm. 2005). However, ashfall hazards cannot be treated in the same way as flooding hazards. Moderate to large volcanic eruptions could affect hundreds to thousands of farms in the central North Island, while flooding events such as the 2004 Manawatu floods would impact a comparatively smaller area. Because of the difference in hazard scope, many more farms would need to be evacuated in an eruption, putting significant pressure on transport system capacities and capacities of other farms to absorb further livestock. During a flood crisis, livestock can be immediately evacuated to higher ground, but during an ashfall there will be nowhere for livestock to be immediately evacuated, other than farm sheds or perhaps shelter belts in some instances (Wilson & Cole 2007).

Discussion of results

The model presented above illustrates the extreme difficulty, if not impossibility, inherent in evacuating the required number of dairy cows in an acceptable period of time from Taranaki farms impacted by 50 mm of ashfall from an Inglewood style eruption. Livestock evacuation would be even more difficult if the roading system does not perform according to the many assumptions considered in the modelling exercise. For example, the model does not take into account roads blocked by ashfall or whether there is the capacity to receive over 200 000 cows in surrounding districts. It is doubtful whether enough farms could be found to relocate the cows following evacuation of the dairy herds, as most New Zealand farms run at maximum possible stocking rates for maximum efficiency (P. Journeaux pers. comm. 2006). Introducing dairy cows for more than a short period will place significant stress on the resources of the receiving farm, especially its feed resources.

It is more likely and feasible that a small, limited evacuation of livestock of high genetic value and diversity could be undertaken from a farm facing an imminent ashfall. The reality for most farms and their livestock is that they will be left to manage as best they can with whatever supplementary feed and clean water supplies they can find. It is highly likely some farms (especially those badly impacted by ashfall i.e., >100 mm) will lose a significant number of livestock (e.g., Wilson & Kaye 2007). Indeed by the time pastures have recovered or been re-established a significant breeding programme is likely to be required to fill the void of the potentially crippling losses that could be inflicted.
The time required to evacuate livestock as estimated by this model suggests the need for at least a 3 month warning to implement an effective evacuation of all livestock. It is highly unlikely to have such a warning, with volcanic warning systems in New Zealand more likely to give useful warning in the order of weeks or days for an Inglewood style event. Even then, precursory signs are not guaranteed to culminate in an eruptive event. Furthermore, it is highly unlikely farmers, or even government, would be inclined to evacuate livestock given the cost (transport and disruption) before near certain evidence existed of an impending eruption. Even if such precursory evidence did exist, it is unlikely livestock evacuation would occur, as priority would be given to evacuating people (Taranaki Regional Council 2000).

Limitations of the livestock evacuation model
The following key limitations exist when applying this model:

- the model does not consider the capacity of farmland surrounding the destination towns to support the influx of arriving dairy cows;
- there is no consideration of whether livestock truck and trailer units are able to drive on roads covered with 50 mm of ash, or of bridges and roads being destroyed by pyroclastic flows or lahars from the volcano;
- there is no consideration of other road users, such as emergency services or human evacuation traffic;
- control of the evacuation, such as determining the priority of which farms are evacuated in what order, and consideration of evacuating livestock with high genetic or monetary value;
- the model assumes the transport network is clear. (there is no consideration of how many livestock have already died, been culled or self-evacuated by farmers before evacuation transport arrives);
- no consideration is made of using roads other than the state highway network. District and local roads may provide more efficient routes than the state highway network;
- downtime for the trucks (e.g., driver rest, fuelling or maintenance) is not directly considered;
- the disruption costs of removing livestock from farms and the cost of taking livestock transport resources away from normal activities have not been included.

The assumptions made within this livestock evacuation model (if used during a crisis) should be supplemented by local information that could affect the efficiency of the evacuation. For example, destinations which are within the 200 km exclusion zone but are deemed safe to receive livestock, or roads which are being over- or under-utilised. The limitations identified here suggest the total evacuation time and cost could be greater (potentially significantly greater) than estimated by this model.

CONCLUSIONS
The findings from this study indicate a large-scale time-pressured livestock evacuation presents significant logistical challenges, particularly:

- evacuation time—it is unlikely the large number of livestock requiring evacuation could be evacuated with existing transport assets before food and water requirements become dire;
- evacuation transport resources—a significant number of truck and trailer assets would be required to evacuate all livestock in a timely manner. Efficiencies can be gained by using a “system optimal” traffic assignment as described here;
- it is doubtful that farms in surrounding regions, or indeed throughout New Zealand, have the capacity to accommodate the large redistribution of livestock described within this paper.

These challenges should be considered in any future livestock evacuation planning for natural disasters or other extreme event threatening large numbers of livestock. It is recommended that full livestock evacuation is not considered in future volcanic eruptions, especially large magnitude volcanic eruptions which deposit a significant amount of ash. Instead of evacuation, further research and planning efforts should be focused on mitigation strategies to allow livestock to survive moderate to heavy ashfalls, or on considering humane, large-scale destruction methods.

Further analysis should be made of livestock evacuations in New Zealand and worldwide to better understand the constraints of moving significant numbers of animals before, during or following a significant crisis, such as a natural disaster. This may include the capacity of the transport networks to sustain the movement; whether there is sufficient availability of livestock-transportation vehicles; capacity of the wider regional or national agricultural system to absorb evacuated livestock; the capacity of abattoirs to process evacuated livestock; and if sold, the capacity of the livestock market to fairly compensate farmers. Analysis of the agricultural and
economic effect of losing a large number of livestock (i.e., greater than 100,000) from the national herd should also be considered.

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