AWATARARIKI FAN, MATATA: DEBRIS-FLOW EARLY WARNING SYSTEMS FEASIBILITY STUDY

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Introduction

Without risk reduction procedures in place, the risk-to-life to residents on some occupied parts of Awatarariki fan, Matata is unacceptable. It has been established that engineering structures to reduce debris-flow risk in this location are insufficiently reliable and affordable to be useable. The only remaining possibility to allow use of the fan for residential purposes is to install a warning-evacuation system that would reduce risk-to-life to an acceptable level by enabling residents to evacuate when it is known that a debris-flow is moving down the catchment, so that they are not in the flow-path when the debris-flow passes.

A further value of such a system would be to allow the road and rail corridors to be closed to traffic when a debris-flow impact is anticipated, again preventing possible deaths. In all these cases, the residual risk to life may be reduced substantially if an effective and reliable warning-evacuation system can be implemented.

This report assesses the feasibility of such a system at Awatarariki Stream.

Critical factors in the assessment of a debris-flow warning system are:

1. The reliability of the debris-flow detection or inference system (false alarms and false negatives)
2. The impacts of a debris-flow on the assets exposed and consequences
3. The time between the warning being issued and the debris-flow impacting the asset
4. The time taken to remove assets from the hazard zone when the warning has been issued
5. The residual risk once the system is operational
6. System cost – setup, operation and maintenance.

Reliability – that is, the correspondence of alarms to the presence of debris-flows - is possibly the most critical issue. If a debris flow occurs but is not detected or inferred, there is a high life-risk to those exposed. Conversely, false detection or inference when no debris flow occurs leads to a false alarm; if a series of false alarms occurs the unnecessary evacuations will soon lead to densitisation of the evacuees and likely failure to respond to future alarms.

Assets exposed to debris-flow impact at Awatarariki Stream

Table 1 Assets at risk, consequence of unexpected event, response to warning and time to effect

Assets at risk	Consequences	Response	Time to effect
Dwellings	Occupants' deaths	Evacuate to safety	Not immediate
Rail crossing	Crew deaths	Close rail	Immediate
Road crossing	Travellers' deaths	Close road	Immediate

Types of debris-flow detection or inference system (Table 1)

In order to issue a warning that a debris-flow is (believed to be) travelling down the stream system, the flow must either be detected or inferred.

1. **Debris-flow detection**. Passage of a debris flow at a location is detected (by trip-wire, Doppler-radar or seismometer) and an alarm triggered. Positive detection results in minimal false alarms. Issues include: alternative triggering (e.g. animal, treefall or earthquake), which can be minimised by using two detectors say 100 m apart; and trigger event size selection (e.g. height of trip-wire (can use multiple wires), intensity of vibration (requires calibration)).
   Note however that Awatarariki is not a conventional debris-flow stream; in particular it has a low ratio of relief to catchment area, and is of unusually low gradient (Welsh and Davies, 2010). This means that thresholds for inferring debris-flow motion from e.g. seismometers and infrasound (Schimmel and Hubl, 2005; Badoux et al., 2009) cannot be transferred from other environments and would need to be developed from empirical data in Awatarariki Stream. No such data are available and would take centuries to acquire.
   The outcome is that the only available, calibration-free system that is well proven is trip-wires. This has the advantage of being simple to install and operate. (Table 1).

Sensors	Operation	Advantages	Limitations
Ultrasonic, radar and laser sensors.	Measurement of the flow stage.	Easy to set warning thresholds.	Ultrasonic sensors have to be hung over the channel; installation can prove difficult if the channel banks are unstable.
Geophones and seismometers.	Measurement of ground vibrations caused by debris flow.	Easy and safe installation (the sensors are buried in safe places on stream banks).	Setting warning thresholds can be quite complicated. Risk of false alarms due to other sources of ground vibration (passage of trains or trucks, rockfalls, etc.). The need to filter the signal may increase system complexity.
Pendulums.	Detection of the debris-flow from the tilting of the pendulum.	Simple and robust device.	The pendulum must be hung over the channel; installation can prove difficult if the channel banks are unstable.
Wire sensors.	Detection of the debris-flow from wire breaking.	Simple and robust device.	Need for restoration after activation. Risk of false alarms due to accidental circumstances (passage of animals, falling trees, etc.).
Photocells (infrared photobeams, etc.).	Detection of debris-flow passage.	Non-contact detectors: do not need restoration after activation.	A careful installation is needed to avoid having the sensors come into contact with the flow.
CCD camera for machine-vision detection.	Recognition of debris flows.	Safe installation (the camera can be placed beside the channel).	The presence of fog or the occurrence of debris flow at night may complicate the use of the system and its workability.

Table 1 Principal debris-flow sensors (Arratano & Marchi, 2008)

2. **Debris-flow inference by rainfall threshold**. An alarm is triggered when rainfall (and/or intensity) exceeds the threshold beyond which it is believed that a debris flow will be present in the channel. This system has a major issue: setting a reliable trigger threshold requires sufficient catchment-specific data on debris-flow occurrence related to rainfall, in order that there are not excessive false alarms and that there are no false negatives (i.e. a debris flow

occurs but is not inferred). These data are not available for Awatararariki Stream, and, given the rarity of debris-flows in this system, would take decades or centuries to acquire.
This is the type of system recently found to be too risky for those responsible to be able to purchase insurance against its failure (Jakob et al., 2012; http://www.nsnews.com/news/dnv-re-engineers-slide-warning-system-1.352521).

3. **Hybrid**: Uses meteorological data (antecedent, anticipated and measured) to establish readiness and warning, with evacuation then based on event detection. Rainfall monitoring as in 2. above (synoptic, radar, gauge data) can be the basis of all but the final step in a sequence of *readiness* (catchment moisture status) -> *warning* (synoptic/radar indication of intense precipitation) -> *critical* (threshold exceeded) -> *evacuate* (event detected). A major advantage of a hybrid system is that the sequence of preparatory states allows reduced total evacuation time following the alarm; individuals may choose to evacuate before an event is detected and the alarm activated. However, this system depends on the alarm giving sufficient time to evacuate safely.

Type chosen

In order to maximise reliability (minimising false alarms and eliminating false negatives) and to avoid the need for calibration for Awatarariki Stream, the **trip-wire detector** type is preferred. This consists of one or several wires installed across the stream at a height above the channel bed greater than that of the water surface in a flood but lower than the depth of a debris flow. The wire(s) is/are connected to an electrical circuit such that an alarm is triggered if a wire breaks. False alarms due to wire breakage by e.g. falling trees or animal motion can be avoided by setting up two detectors say 100 m apart along the stream, breakage of both being required to trigger an alarm.

Obviously the system would need regular inspection and testing, but is relatively robust and inexpensive to install and maintain.

Location

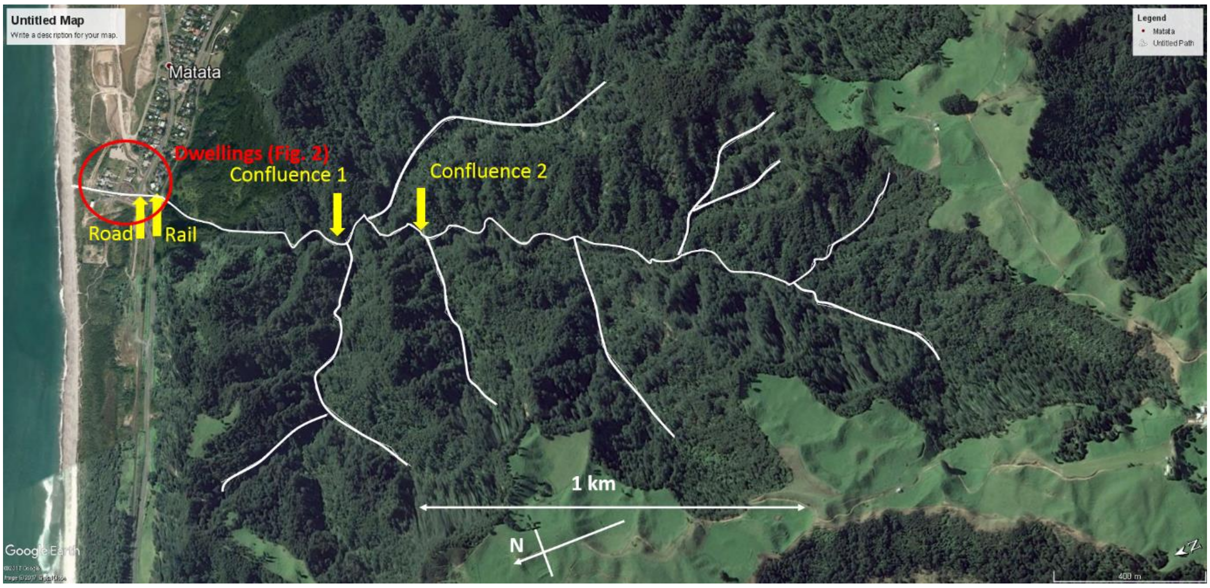

Fig. 1 Awatarariki Stream channel system and assets at risk (Google Earth image). For more detail of location of dwellings see Fig. 2

The obvious locations for trip-wire detectors are immediately downstream of the two major confluences in the lower part of the catchment (Fig. 1). A detector downstream of confluence 1 will detect all debris flows in the system, but is close to the assets at risk so provides shorter warning times. A detector downstream of confluence 2 provides longer warning times but will not detect debris flows generated in the approximately 35% of the catchment downstream of it.

Location of assets

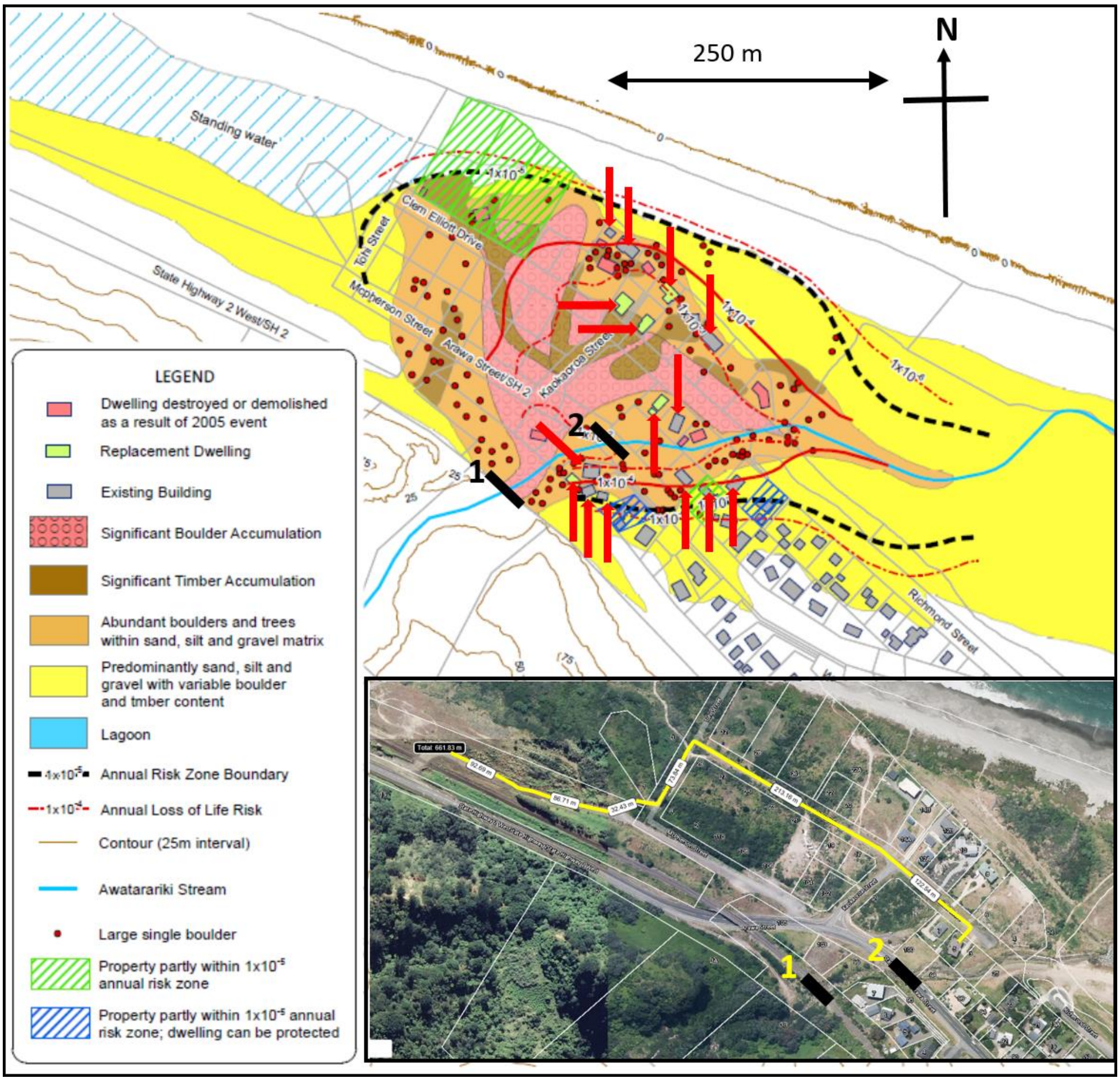

Fig. 2 Dwellings and risk zones on Awatarariki Stream fan (adapted from Davies & McSaveney, 2015). Red arrows indicate dwellings in the high-risk (10^{-5} /year) zone; black lines are rail (1) and road (2) crossings. Designated “escape” route (yellow) servicing dwellings north of stream course shown in yellow in inset.

Figure 2 shows the locations of the road and rail crossings and of the dwellings remaining on the fan. Table 2 shows the distances of the road and rail crossings, and of the farthest dwellings, from the two detector locations in Fig. 1. The dwellings most distant from the detectors are chosen for analysis because if there is insufficient warning time to evacuate these, the closer dwellings will have even less time. These distances are split into two components: within-catchment distance (i.e. within the confined channels in the catchment) and distance on the more open fan downstream of the rail crossing, so that the lower propagation velocity of a debris-flow surge across the more open fan can be factored into the warning time.

Table 2 Distances of assets on Awatararariki Fan from detector sites

Asset	Confluence 1 (m)	Confluence 2 (m)
Rail crossing	740 + *0*	1440 + *0*
Road crossing	740 + *75*	1440 + *75*
Farthest dwelling	740 + *230*	1440 + *230*

Figures in italics are distances of assets from catchment exit (fan head); non-italic figures are within-catchment distances.

Debris-flow velocities

When a debris flow has been detected or inferred, the time that elapses between detection and the flow impacting assets depends on the speed of advance of the flow.

The speed at which a debris-flow surge propagates along a channel varies widely, depending on the volume of the surge, its composition, the channel slope and the degree of confinement. A few data are available from published research: e.g. up to ~ 2.2 m/s in a small laboratory channel (Bettella et al, 2015); up to 3.5 m/s in a small field channel (Navratil et al., 2013), and up to 7 m/s in the experimental channel at Illgraben, Switzerland (Badoux et al., 2009). In the Moscardo torrent, Italy, Marchi et al (2002) reported speeds of up to 5 m/s.

Specific to the Awatarariki Stream event of 2005, Tonkin and Taylor (2011) reported that

- Environment Bay of Plenty estimated a flow velocity of 4.7 m/s for the 2005 debris flow event at the time of peak discharge based on flow super-elevation indicated by deposits;
- Numerical modelling (Tonkin and Taylor, 2009a) indicated a velocity of approximately 3 m/s for the larger surges;
- Based on international experience, Geobrugg considered 4 m/s to be an appropriate velocity for the gently sloping Awatarariki Stream. This design velocity was independently assessed using a methodology developed by Dr. Dieter Rickenmann of Swiss Federal Institute WSL.
- A design velocity of 7 m/s was adopted for the first surge to estimate impact loads on a proposed barrier

In addition, Tonkin & Taylor (2013) reported an eye-witness as noting that debris in the flow following a surge covered a distance of 100 m in about 3 seconds.

On the basis of the above, a debris-flow surge translation velocity of 5 m/s is assumed herein for the reach in which the flow is confined in a channel in the Awatarariki catchment. This is deliberately, lower than the 7 m/s assumed by Tonkin and Taylor (2011) for impact design, because that figure refers to the flow velocity immediately behind the nose of the surge, which is significantly faster than the surge advance velocity (Takahashi, 1980; Davies, 1988). It is also lower than the peak velocity recorded at Illgraben, because the average gradient of the Illgraben channel is 40% while that of the Awatarariki channel is 8%.

The translation velocity on the less confined area downstream of the rail crossing is assumed to be 3 m/s because the surge spreads laterally and reduces in depth.

Warning times

Based on the above velocities (5 m/s in the catchment, 3 m/s on the fan), the following total warning times (in seconds: **bold**) are estimated:

Asset	Confluence 1 (m)	Warning time (s)	Confluence 2 (m)	Warning time (s)
Rail crossing	740	**148**	1440	**288**
Road crossing	740 + *75*	148 + *25* = **173**	1440 + *75*	288 + *25* = **305**
Farthest dwelling	740 + *230*	148 + *77* = **225**	1440 + *230*	288 + *77* = **365**

Adequacy of warning times

Farthest dwellings

The maximum distance to a safe location from the dwellings on the fan is estimated to be 660 m (Jeff Farrell, Whakatane District Council, *pers. comm.* December 2017; Fig. 2, inset). How long it would take residents to cover this distance depends to a large degree on how long after receiving the alarm any given resident leaves a dwelling, and how fast the resident can travel; the latter also depending on conditions (e.g. daylight/darkness, storm/rain).

Assuming best-case conditions (a healthy person evacuating during daylight in good visibility), an average walking speed of about 1.3 m/s can be assumed (http://lermagazine.com/article/self-selected-gait-speed-a-critical-clinical-outcome; accessed 12 December 2017). Thus in the 365 seconds available, and assuming no delay in leaving the dwelling, a distance of 474 m can be covered. This is clearly inadequate. Assuming more realistically that it takes say 2 minutes to leave the dwelling, the distance covered will be only 318 m. Taking into account the need for less fit and healthy people to evacuate, the available warning time is clearly inadequate for the dwellings farthest from the safe location.

Evacuation by vehicle is an alternative. To drive 660 m at 50 km/hr takes about a minute, but to this must be added the time to exit the dwelling, get in the car, start it, reverse it out of a garage and drive to safety. Whether these actions can be safely completed in five minutes is uncertain; under ideal circumstances (residents awake and dressed, keys immediately to hand, car starts immediately) it is clearly feasible, but it is not difficult to envisage circumstances in which it would not be accomplished. Further, not every dwelling may have access to a vehicle nor every resident be able to drive.

While detailed study of the escape routes from other individual dwellings has not been undertaken, the closest dwellings to the fanhead have warning times similar to those for rail and road crossings, about 300 seconds maximum. Again, accepting that there will be a significant delay in leaving a dwelling especially if an alarm is activated at night when residents are likely to be asleep, this is insufficient time to guarantee that any given resident can reach safety before the debris flow impacts the dwelling or escape route.

Road and rail crossings

The warning times for rail and road crossings are upwards of two minutes, which should be adequate for automatic activation of warning signals and potentially barriers in order to prevent rail and road users entering the debris-flow path. Note however that road and rail users are present on the fan for different proportions of total time than residents, so specific risk analyses need to be undertaken to determine the acceptability or otherwise of their risk-to-life and hence the need or otherwise for a warning-closure system.

Acknowledging data imprecision; factor of safety

The above figures for warning times are obviously approximate; they are best estimates, based on data for the translation velocity of debris-flow surges and time required for evacuation to safety - which are extremely variable and poorly-defined. It is not unusual for serious decisions to be based on such data, but in these cases it is normal practice to apply a factor of safety that acknowledges the likelihood that the data are incorrect for a specific situation. For example, in civil engineering, a complex structure such as a bridge may be designed to carry 3 times the anticipated maximum working load in order to take account of imprecisions in foundation conditions, material strength, load distribution and weather (https://graduate.norwich.edu/resources-mce/articles-mce/4-insights-on-factor-of-safety-in-engineering/, accessed 12 December 2017). It is therefore appropriate to think in terms of a factor of safety in the assessment of debris-flow warning systems. Given that lives would be lost if evacuation time proved to be insufficient, a high factor of safety is appropriate. Thus to cover 660 m at 1.3 m/s requires 508 seconds; a factor of safety of only 2 would suggest that in this case the warning time would need to be 1016 seconds, plus a time allowance for waking up, dressing and exiting the dwelling – say 1150 seconds, bringing the required warning time to 20 minutes. A safety factor of 3 brings this up to about 30 minutes.

Evidently the systems considered above cannot provide anything approaching these warning times, and it is therefore my opinion that risk to life for residents on Awatarariki Stream fan cannot be reduced by provision of a debris-flow warning system. The only way to increase the available warning time is to utilise a meteorologically-based inference system, and as emphasised above, such systems require calibration data that are not available, and would result in false alarms that would desensitise the community and lead to alarms being ignored.

Conclusions

1. It is feasible to develop a reliable debris-flow warning system that will reduce risk-to-life to road and rail users crossing Awatarariki fan. A trip-wire debris-flow detection system at the lowest major confluence on Awatarariki Stream can trigger immediate deployments of lights and barriers on both road and rail corridors and prevent people from entering the high-risk area. The need for these measures can be assessed by specific risk analyses for road- and rail-users.
2. Other debris-flow warning systems, e.g. those based on rainfall totals and intensities that generate debris-flows or those that infer debris-flow presence via ultrasound or seismic signals, are not feasible in Awatarariki Stream due to the lack of the necessary calibration data and the time (decades to centuries) that would be required to collect such data, as well as inevitably generating a high proportion of false alarms.
3. The trip-wire system cannot, however, provide adequate warning time to guarantee the ability of residents to exit dwellings and reach safety, because of the short distance between the detector sites and the dwellings on the fan and the need to apply a realistic factor of safety to calculations of warning and evacuation times.

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