Awatarariki catchment debris flow early warning system framework

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GNS Science Report 2019/77
February 2020

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BIBLIOGRAPHIC REFERENCE

Massey CI, Potter SH, Leonard GS, Strawbridge G, Rosser BJ. 2020. Awatarariki catchment debris flow early warning system design framework. Lower Hutt (NZ): GNS Science. 54 p. (GNS Science report; 2019/77). doi:10.21420/8D3K-HD78.

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ISSN 2350-3424 (online)
ISBN 978-1-99-001013-2 (online)
http://dx.doi.org/10.21420/8D3K-HD78

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ABSTRACT

In 2005, a large debris flow occurred in the Awatarariki catchment, above the township of Matatā, in the North Island of New Zealand. The debris flow damaged homes and infrastructure in Matatā. Risk assessments have been carried out by Tonkin & Taylor, and the calculated annual individual fatality risk to dwelling occupants in the area affected by debris flow hazards has been assessed as being intolerable by Whakatāne District Council (WDC) and most of the local community.

In November 2019, GNS Science was commissioned by WDC to scope out the potential design and effectiveness-evaluation framework for a public-facing Early Warning System (EWS) for debris flows on the Awatarariki Fan, Matatā. As part of this work, GNS Science was asked to identify any initially obvious issues that could reduce the effectiveness of the EWS (i.e. 'show stoppers') and whether an EWS would be suitable/unsuitable for the Council to consider as an option to manage the risk.

This report evaluates a multi-staged debris flow EWS based on the proposed design and effectiveness framework. Results from the three scenarios discussed indicate that a multi-stage EWS is unlikely to allow all potential people present in the hazard zone at the time that a debris flow event is initiated to evacuate to safe areas. Therefore, people who do not or cannot evacuate would continue to be exposed to the risk levels calculated by Tonkin & Taylor, depending on their location on the fan.

Given the uncertainties associated with a debris flow EWS, as listed in this report, adopting such a system as the means to mitigate the risk to people living on the fan is not aligned with taking a precautionary approach, as stated in Section 1.7 of the Bay of Plenty Regional Council's Regional Policy Statement.

In writing this report, our thoughts are with everyone effected by the debris flow in 2005. This was a traumatic event, and many have experienced ongoing difficulties in recovery. We acknowledge these past and current residents and property owners, as well as any future potential users of the land.

KEYWORDS

Early Warning System, risk, Matatā, Bay of Plenty, Disaster Risk Reduction, alert, debris flow

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1.0 INTRODUCTION

In 2005, a large debris flow occurred in the Awatarariki catchment, above the township of Matatā, in the North Island of New Zealand. The debris flow damaged homes and infrastructure in Matatā (McSaveney et al. 2005; Davies 2005).

Risk analyses have been carried out by Tonkin & Taylor (2013, 2015), and the calculated annual individual fatality risk to dwelling occupants in the area affected by debris flow hazards has been assessed as being intolerable by Whakatāne District Council (WDC) and most of the local community.

Community members were interested to know whether an Early Warning System (EWS) may be able to mitigate the risk to occupants from a debris flow in the Awatarariki catchment. The purpose of the debris flow EWS would be to warn users of the council reserve land, road and rail users, and any dwelling occupants, of the possible imminent threat of a potentially dangerous debris flow in the catchment.

1.1 Background

After the 2005 debris flow, much effort has gone into understanding the future debris flow hazard to the town and how to best manage the associated risks to people, dwellings and infrastructure. A plan to manage the risks has been developed via a district and regional plan change process. The District Plan change will give effect to the Bay of Plenty Regional Council Regional Policy Statement by formally recognising the debris flow risk in the Plan. The objective is to rezone the area of high debris flow risk from 'Residential' to 'Coastal Protection', a zone that better recognises the natural hazard risk. The Bay of Plenty Regional Council Regional Natural Resources Plan change also gives effect to the Regional Policy Statement, but in the regional context. In that regard, it recognises that the Resource Management Act (RMA) provides for regional councils only to manage risk to existing uses – specifically, in this situation, 21 properties in the high-risk area with dwellings or temporary structures (e.g. containers, illegal buildings and buildings exempt from a building consent). The regional plan change proposes to extinguish the rights to those existing uses. In the absence of the regional plan change going ahead, one potential risk-management option is the installation, maintenance and operation of a landslide EWS.

In 2015, WDC contacted GNS Science to discuss the feasibility of installing a landslide EWS as a potential option that could reduce the risk to tolerable levels. A meeting between GNS Science and WDC was held in Wellington on 7/12/2015. In this meeting, WDC requested that GNS Science provide information as to how they would go about designing a debris flow EWS for the Awatarariki catchment and fan. These discussions were summarised in a memo sent by GNS Science to WDC on 10/12/2015 (Appendix 1).

In 2017, Prof T Davies was commissioned by WDC to assess the feasibility of an EWS to reduce the risk to people living on the Awatarariki Fan. This work followed the steps outlined in the GNS Science 10/12/2015 memo. The work comprised:

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; and
6. The system cost – set-up, operation and maintenance.

The report (Davies 2017) focused primarily on items (1) to (4). The main findings from this report were that:

- It is feasible to develop a reliable debris flow warning system that will reduce risk-to-life to road and rail users crossing the Awatarariki Fan.
- Trip-wire detectors were the preferred sensor to detect whether a debris flow had been initiated. These would comprise 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) would be connected to an electrical circuit such that an alarm is triggered if a wire breaks.
- 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 – e.g. when an alert is triggered but no debris flow occurs.

Although Davies (2017) states that it is feasible to develop a reliable EWS, he goes on to conclude that:

- The trip-wire system cannot provide adequate warning time to guarantee the ability of residents to exit dwellings and reach safety, due to the short distance between the detector sites (trip wires) and the dwellings on the fan and the need to apply a realistic factor of safety to calculations of warning and evacuation times.
- Debris flow velocities were estimated to be in the order of 5 m/s in the catchment and 3 m/s on the fan. For the furthest dwelling on the fan, the warning time (time from when the trip wire breaks to debris impacting a given location) was estimated to be about 3–6 minutes, and 3–5 minutes around the road and rail corridors. Evacuation distances for the furthest dwelling to relative safety were assessed as being about 600 m.

1.2 Project Objectives

In November 2019, GNS Science was commissioned by WDC to scope out the potential design and effectiveness-evaluation framework of a public-facing EWS for debris flows on the Awatarariki Fan, Matatā. As part of this work, GNS Science was asked to identify any initially obvious issues that could reduce the effectiveness of the EWS (i.e. ‘show stoppers’) and whether an EWS would be suitable/unsuitable for the Council to consider as an option to manage the risk. The results from this work are contained in this report.

The key objectives of this project are to describe:

1. How to design and evaluate an EWS.
2. The necessary community consultation required as input to the EWS.
3. A summary of potential show stoppers.
4. Recommendations for next steps.

2.0 LANDSLIDE RISK AND MITIGATION ANALYSIS

This section contains: 1) a brief description of the 2005 debris flow, 2) an overview of landslide risk analysis methods and practice and 3) an overview of the role of landslide EWS as a method to mitigate risk.

2.1 2005 Debris Flow at Awatarariki Fan, Matatā

The 18 May 2005 debris flow at Awatarariki Stream, Matatā, was triggered by exceptionally heavy rain falling on already saturated ground over much, if not all, of the upper catchment area. Although the rain was the trigger, the cause of the debris flow event was the many slope failures that were triggered by the rainfall, which caused landslides to fall into already flooded stream channels. The evidence for widespread slope failures was two-fold: 1) debris flows occurred more-or-less simultaneously in almost every tributary stream in the catchment area, and in most adjacent catchments in the Matatā area, and 2) there were a great many debris-avalanche scars on the steeper slopes after 2005 than were present before 2005, as shown by space imagery available on Google Earth (McSaveney et al. 2005).

A debris flow is a dense mixture of sediment and water that flows under the influence of the mass of sediment it contains. The most common analogy is to liken the flow to that of wet concrete. The proportion of sediment to water in debris flows is highly variable. There is no characteristic ratio of water to sediment, even in a single debris flow, and the ratio does not remain constant during the flow. The flow characteristics of a natural debris flow are determined by the interactions between the sediment particles and the proportion of water present (McSaveney et al. 2005).

A remarkable and fortunate feature of the debris flow of 2005 was the absence of fatalities or even injuries. None of the people transported by the flow were exposed directly to the debris; they were inside homes or vehicles. Through much of the event there was heavy rain falling at Matatā and, consequently, few people moving about outdoors on foot other than a few people alerted to the danger and checking on the safety of neighbours. The state highway had been closed by bridge washouts earlier in the day, so the only reported traffic on the highway across the fan was a heavy truck that crossed the highway culvert before it was destroyed, which was early in the debris flow event (McSaveney et al. 2005).

2.2 Overview of Landslide Risk Analysis Approaches and Methods

Risk means many things to different people, so it is important always to define what is meant by the term. The general framework for managing risks is that:

1. hazards with the potential to harm people are identified,
2. the associated risk is then estimated in quantitative terms, and
3. criteria are established as to what level of control over risk is appropriate and/or achievable.

It is the role of the technical expert to provide information relating to items (1) and (2). It is not the role of the technical experts to make decisions about what level of risk might be too risky (e.g. setting risk tolerability thresholds); item (3). Risk thresholds and levels of control should be set by the decision makers in consultation with those at risk.

Landslide risk is defined as a measure of the probability of a landslide hazard occurring and the severity of a consequence to life, health, property or the environment (Corominas et al. 2015). Landslide risk needs to be analysed first in order to: a) assess it and b) manage it, if the risks are too risky. Risk management addresses the following questions (adapted from Ho et al. 2000; Lee and Jones 2014):

1. What can cause harm (Landslide Characterisation, e.g. the type and nature of the landslide)?
2. How often does this occur? (Frequency Analysis)
3. What can go wrong, and how bad could it be? (Consequence Analysis)
4. What is the probability of damage (extent and severity) occurring? (Risk Estimation)
5. So, what (Risk Evaluation)?
6. What can be done, at what cost, to manage and reduce unacceptable levels of damage? (Risk Treatment)
7. Was the treatment successful; has the risk changed and/or needs re-analysis and re-assessment?

The overall risk management framework, adapted from AGS (2007c) and Standards Association of Australia / Standards New Zealand (2004) is shown in Figure 2.1, which comprises: Risk analysis, items (1) to (4) above; Risk assessment, item (5); and Risk management, item (6).

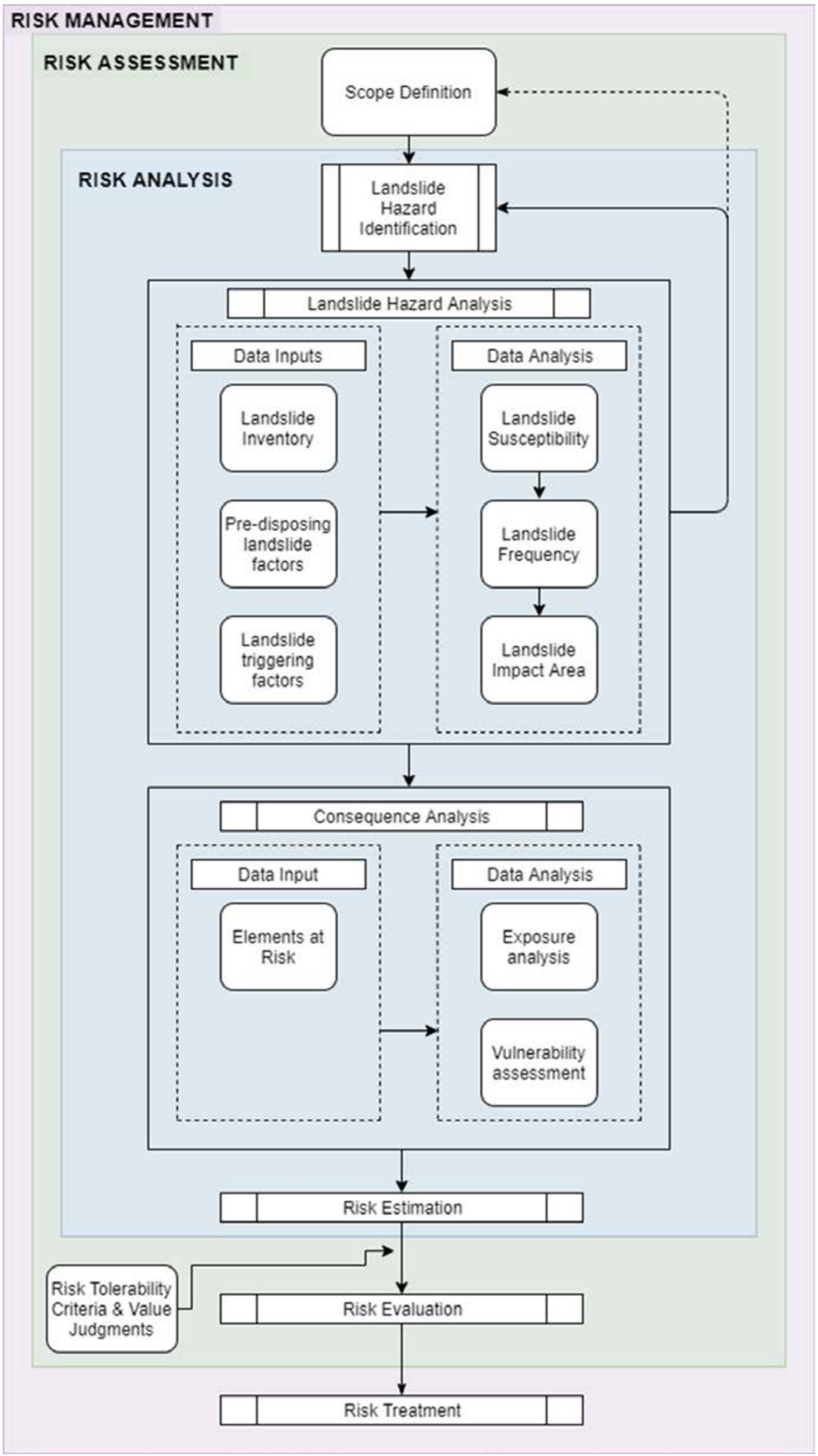

Figure 2.1 Landslide risk management framework (adapted from AGS 2007c; Standards Association of Australia / Standards New Zealand 2004).

Quantitative risk analysis is systematic, objective and reproducible (Corominas et al. 2014). This enables the risk from multiple hazards, spanning the full range of severity (from small to large) that could feasibly occur at the site, at the same location or various locations, to be compared. This allows risk tolerance and acceptability levels to be more readily determined and provides stakeholders, planners and policy makers (the decision makers) with an objective pathway upon which to base their decisions.

The risk to people living on the Awatarariki Fan has been analysed by Tonkin & Taylor (2013, 2015) by quantifying the landslide risk to a single individual, adopting the annual individual fatality risk as the metric of choice.

The main landslide hazards – defined as the probability of a given type of landslide occurring within a defined time period and area (Corominas et al. 2014) – that were identified and analysed by Tonkin & Taylor (2013, 2015) as affecting the site are debris flows, initiated by high-intensity rain (McSaveney et al. 2005; Davies 2005). Other types of landslide from different types of triggers, such as earthquakes, have not been analysed by Tonkin & Taylor (2013, 2015).

The risk from debris flow hazards to people living on Awatarariki Fan was calculated by Tonkin & Taylor (2013, 2015) following the AGS (2007c) guidelines and adopting the following equation from AGS (2007d):

$R_{(D)} = P_{(H)} \times P_{(T:S)} \times P_{(S:H)} \times V_{(D:T)}$ where:

- $R_{(D)}$ is the annual risk (probability) of loss of life (death) of a person from landslides, the annual individual fatality risk (AIFR);
- $P_{(H)}$ is the annual probability of the initiating event (rain) and the likely size of the debris flow(s) initiated by the event, spanning the range of events and debris flows from small to large, which could feasibly occur at the site;
- $P_{(T:S)}$ the probability that an element at risk is present at that location when the debris reaches or passes through it;
- $P_{(S:H)}$ is the probability that the element at risk, if present, is in the path of the debris at a given location; and
- $V_{(D:T)}$ is the vulnerability of the element at risk to the debris or, in this case, the probability that a person is killed if present and in the path of debris.

The estimated AIFR estimates produced by Tonkin & Taylor (2013, 2015) were peer reviewed by Dr McSaveney and Prof Davies, who identified an area on the fan that was considered unsuitable for residential use. This area reflected the area bound by the Tonkin & Taylor (2013, 2015) -modelled AIFR contour line of 10^{-5}, which the peer reviewers considered to better reflect an AIFR level of 10^{-4}. The District Council accepted the advice of Dr McSaveney and Prof Davies. An AIFR of 10^{-4} was adopted as ‘intolerable for existing development’ by the District Council. This is also the level recommended by the Australian Geomechanics Society for contexts including slope collapse, and it roughly corresponds to the lifetime average risk faced by New Zealanders from road accidents. This is also the risk level adopted by the Canterbury Earthquake Recovery Authority and Christchurch City Council for their decision making post-2010/11 Canterbury Earthquakes (e.g. Taig et al. 2011).

The District Council then reviewed various risk treatment (mitigation) options to try to reduce the AIFR to below 10^{-4}. These included the design of debris retention structures, chute to sea, relocation of people, catchment management and EWS.

2.3 Overview of Early Warning Systems

An EWS is "an integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities, systems and processes that enables individuals, communities, governments, businesses and others to take timely action to reduce disaster risks in advance of hazardous events" (United Nations 2016).

It is best practice to develop an EWS that can be used for multiple hazards (Multi-hazard…c2020). A people-centred EWS empowers individuals and communities threatened by hazards to act in a timely and appropriate manner and to reduce the chance of death, injury and illness, and impacts to property, assets and the environment (Multi-hazard…c2020). There are four key elements of a people-centred, end-to-end EWS (Basher 2006; Multi-hazard…c2020). Disaster risk knowledge; Detection, monitoring, analysis and forecasting of the hazards and possible consequences; Warning dissemination and communication; and Preparedness and response capabilities (Figure 2.2).

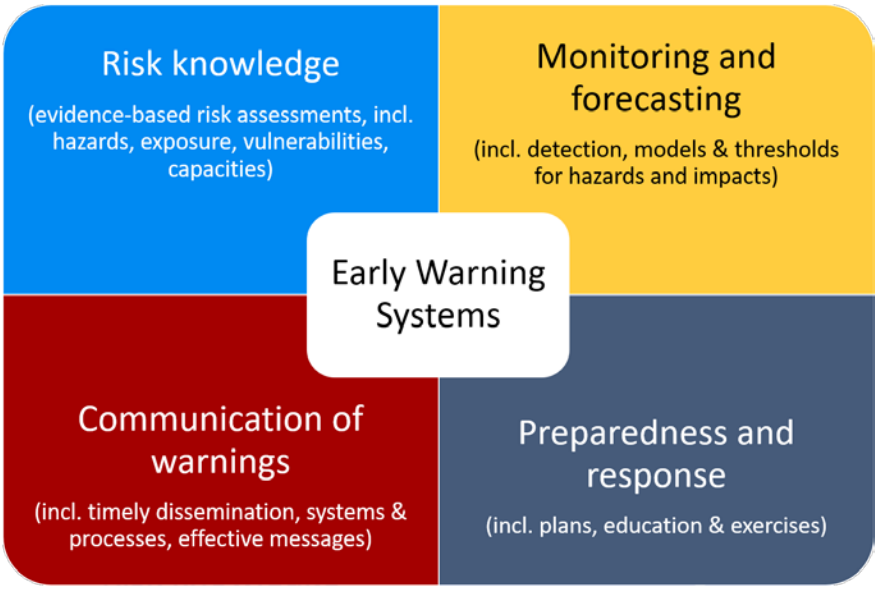

Figure 2.2 Critical elements of people-centred EWS. Adapted from Basher (2006) and guidance by the World Meteorological Organization (Multi-hazard…c2020).

The elements, or components, of an EWS need to link seamlessly in order for the EWS to be effective, and they need to be flexible to adjust to local events and contexts. Factors that can assist the linkages between the elements are described by Garcia and Fearnley (2012):

1. Establish effective communication networks between all parties.
2. Empower the community at risk by making scientific knowledge and risk assessments available and comprehendible.
3. Develop effective decision-making processes, including acknowledging the local context and defining accountability and responsibility.
4. Incorporate elements of behavioural response, such as understanding risk perceptions, levels of awareness, preparedness and trust.
5. Consider technocratic and participatory approaches in EWS (i.e. increasing public participation in processes).

It is also important to allow for the local context to drive warning system design and implementation, as set out in Figure 2.3.

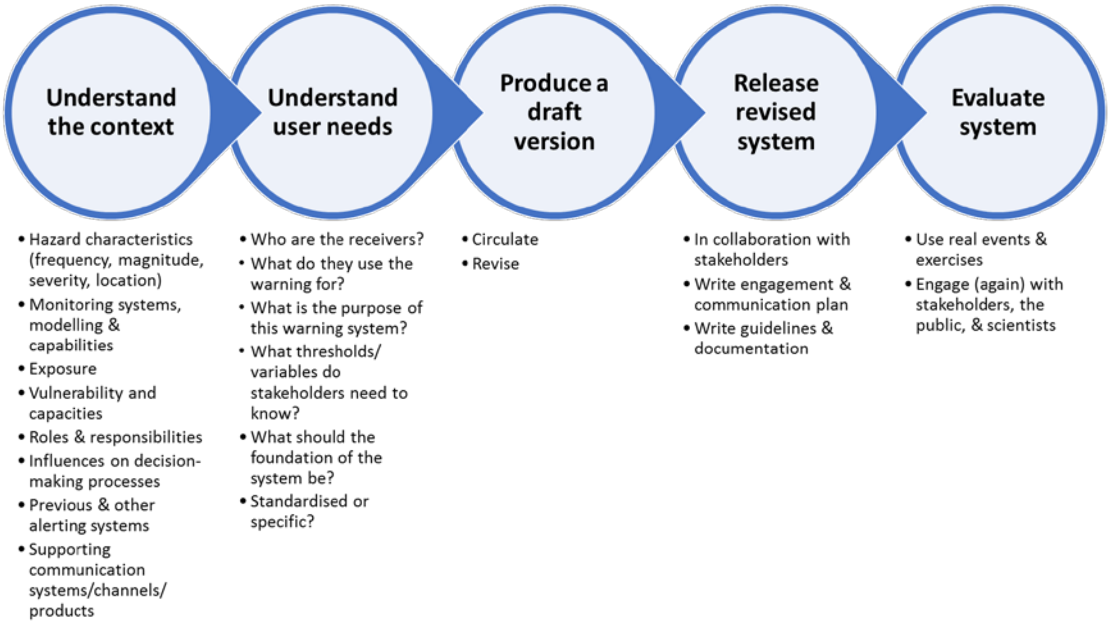

Figure 2.3 Overview of developing a warning system. Adapted from Potter et al. (2018).

2.4 Understanding the Context

Wright et al. (2014) summarised the factors controlling the effectiveness of public-facing EWS options. Section 2 of Wright et al. (2014) covers:

- Risk reduction and community resilience
- Consideration of other mitigation
- Timeframes of hazards and alerting
- Spatial variability of hazards and warnings
- Local vs. regional and national alerting options
- Minimum notification requirements
- Redundancy spatially and across systems
- Geographic targeting
- Receiver characteristics
- Other sources of information to official warnings
- All-clear messages
- Cost-effectiveness
- Potential to increase risk through reliance on ineffective systems.

Given the components of EWS effectiveness have been summarised in Wright et al. (2014), in this report we focus on describing some of the key aspects that will potentially influence the effectiveness of the EWS for the Awatarariki Stream and Fan. These are mainly: 1) hazard detection, telemetry and alerting; and 2) behavioural response to warnings. These are described in the following sections.

2.4.1 Hazard Detection, Telemetry and Alerting

To determine the best methods to detect and alert those at risk from a potentially hazardous landslide, it is important to firstly understand the characteristics of the landslide.

The characteristics of the debris flow hazards affecting the Awatarariki Stream and fan are discussed by McSaveney et al. (2005) and Davies (2005), and the risk to people, buildings and infrastructure from such hazards has been calculated by Tonkin & Taylor (2013, 2015). The main characteristics of such debris flow hazards are that:

- they are triggered by intense rainfall;
- they require widespread slope failures, where the debris from multiple landslides coalesces to form a large one, or one or a few larger slope failures; and
- the debris travels rapidly down slope – Davies (2017) estimated that the debris flow velocities of the 2005 event were in the order of 5 m/s in the Awatarariki catchment and 3 m/s on the fan. These velocities can be classified as 'rapid' to 'extremely rapid' under the landslide classification scheme of Hungr et al. (2014).

Internationally, most debris flow EWS are based on rainfall forecasts and measurements to estimate the probability of a potentially hazardous debris flow occurring, combined with physical sensors such as trip wires to detect when such hazards have occurred. A summary of the current literature on landslide EWS, which has been reviewed by the authors, is contained in Appendix 2. In nearly all of the 29 examples reviewed, the landslide types being monitored were debris flows with the potential for the debris to move rapidly downslope, thus giving little warning time between the landslide initiating and the debris impacting the at-risk people, buildings and/or infrastructure, assuming the hazard is relatively close to the built environment. These have then been reviewed to investigate what data, technology and sensors have or are being used to detect the hazard, telemeter the data and issue alerts.

2.4.1.1 Hazard Detection

Detecting the hazard typically requires measuring some factor(s) that relate to the perceived characteristics of the landslide that can be used to forecast its behaviour. In summary, out of the 29 landslide EWS presented in the literature and reviewed by the authors for this study:

- 14 adopt rainfall forecasts and sensors to measure rain, e.g. synoptic charts, rain radar and rain gauges. These are combined with landslide-triggering rainfall intensity/duration thresholds – determined from past rainfall-induced landslide events – to estimate the probability of the given rainfall triggering a landslide.
- 11 adopt sensors that physically measure landslide initiation in the potential landslide source area. Sensors typically used are, for example, pore-water pressure transducers to measure pore-water pressures as a landslide triggering factor, inclinometers installed in the landslide to detect movement at depth, and geophysics such as acoustic and ground-motion sensors used to detect movement. These are used to then estimate the probability of the landslide triggering (initiating) and potentially moving rapidly.

- 3 only adopt post-initiation movement of the landslide debris once the source has failed. These sensors are used to detect the rapid movement of debris along a potential flow path(s). Sensors typically used are flow height, e.g. radar and river stage gauges; trip wires strung across the flow path, which break when hit by debris; and geophysical sensors that monitor acoustic emissions and ground shaking associated with the debris moving rapidly downslope.
- 9 adopt a combination of rainfall forecasts and measurements coupled with landslide initiation and post-initiation debris-movement sensors.

In most of the landslide EWS examples reviewed, hazard detection thresholds were established based on detailed reviews of historical landslides of similar types and in similar materials to those being monitored as part of the EWS. In many cases, mathematical relationships ('algorithms') were established from such observations, which were then used to define trigger levels for different types of alert and warning messaging. The most widely used relationship cited in the literature is the one between rainfall intensity (e.g. millimetres of rain per hour) and the duration of rain (e.g., over time periods of minutes, hours and days) (e.g. Guzzetti et al. 2008). Other thresholds, based mainly on the amount of movement measured in the source area (e.g. millimetres, centimetres and metres), have been used to estimate whether the moving debris is likely to transition into a more mobile debris flow.

Once the debris leaves the source and begins to move rapidly downslope, the only effective way to identify such behaviour is by measuring the approach or passing of the debris. If trip wires are used, they typically trigger warnings because they break, e.g. the electrical circuit breaks once impacted by the debris. If acoustic or ground motion sensors are used, they require calibration and thresholds to be set to ensure false warnings are kept to a minimum.

2.4.1.2 Telemetry

In most EWS, telemetry is needed for: 1) data collection – transferring the data from the forecasts (e.g. synoptic and rain radar, etc.) and sensors (e.g. rain gauges, inclinometers, etc.) and sending it to wherever the data is evaluated by the software containing the algorithm with the pre-programmed alerting thresholds; and 2) notification – providing the alerts if the thresholds are exceeded. Of the 29 cases reviewed, the different technology used to do this comprised:

- Mobile phone networks (five examples)
- Local radio networks established on the landslides (one example)
- Wi-Fi networks (six examples)
- Satellite networks (one example)
- Door knocking with alerts delivered verbally and no data processing needed (one example).

Each of these different technologies/approaches have their advantages and disadvantages and are very much dependent on the character of the landslide and the location of the landslide hazard and the people, buildings and infrastructure exposed to it. For example, a mobile phone network may not be available at the landslide site, satellite networks may be too slow to transfer the data from the sensors and deliver the alerts, and door knocking and verbal alerting may not be feasible for a large landslide where many people are exposed to the hazard. It is clear from the examples reviewed that each EWS is specifically designed for the local conditions, taking into the account the character of the landslide, the types of data being collected and the purpose of the notifications/alerting.

2.4.1.3 Alerting

To issue a notification, alert or warning requires the hazard (threat) to be recognised. Once recognised, there are multiple ways a person can be notified, thus allowing them to take action if needed. From the literature reviewed, the main methods of alerting were:

- Door knocking with verbal notifications (one example)
- Text messaging (SMS) (three examples)
- Email (one example)
- Sirens and flashing lights (two examples).

As with telemetry, each method of alert has its advantages and disadvantages. For example: door knocking ensures the notifications and required responses are communicated clearly with little confusion; however, such notifications take time to deliver; text messaging and emails can deliver clear messaging with advice to instruct people about how to act, relatively rapidly; however, they rely on the mobile phone network; and sirens do not require a mobile phone network as they can be triggered rapidly if, for example, a trip wire is broken, without the need for processing data from instruments and running algorithms; however, if flashing lights or non-voice sirens are used, confusion about how to act can occur.

2.4.2 Behavioural Response to Warnings

Why do some people not respond to a warning? On receipt of information about a threat, people tend to go through the following steps: understanding the meaning of the message, believing whether the warning is real, personalising the warning, deciding what to do and searching for additional information and confirming it (e.g. as described by National Academies of Sciences [2018] and references within). There are many influences on people's response to warning information, whether it comes from an official source (e.g. emergency management or via the radio) or an unofficial source (e.g. seeing what neighbours are doing, or a natural warning, such as seeing or hearing a debris flow). Theoretical models, such as the Protective Action Decision Model by Lindell and Perry (2012) describe these influences (Figure 2.4). Several of the influences can be altered to change people's response (e.g. by increasing the sense of threat through describing potential impacts in a warning message). The first set of influences are:

- Ensuring the population at risk are aware of **environmental cues** that could lead to an event occurring or indicate that it is more likely to occur. In the case of Matatā, this would mean ensuring all people at risk are aware of the rainfall (intensity and duration) thresholds that mean a debris flow is more likely to occur. It could also be that they know what a debris flow looks and sounds like to ensure it is recognised straight away, enabling a prompt response. The at-risk people should also know about the potential lack of environmental cues, especially at times of low visibility (at night or with heavy rain or fog), or if the sound is muffled by other noise (e.g. heavy rain), so that they do not wait for the presence of all the environmental cues as confirmation of a debris flow.
- **Social cues**, such as noticing what others around you are doing and receiving information from friends and neighbours, as well as the availability of assistance (including transport and shelters), can influence a response. Being aware of neighbours preparing for an event, evacuating in a hurry, hearing shouting or noticing that traffic has stopped on the main road can alert people at risk that an event is occurring.

- **Information sources** are people who transmit information about a hazard, impact or protective actions. They may also provide assistance (such as transport or shelter) or otherwise influence the decision to respond. Sources could include friends, relatives, neighbours, co-workers, official responding or warning agencies, and strangers. They differ in the level of detail they can communicate, the level of trust the receiver has in their message, their accuracy, how frequently the message is provided, and what equipment is needed to receive the message (e.g. in situations where rapid official warnings are provided on new models of smart phones through Emergency Mobile Alerts [EMA], in comparison to talking to a neighbour in person). The social network of the receiver influences their ability to receive a message. People who are well-connected with their neighbours and community will be more likely to receive threat information than someone who is isolated.
- **Channel access and preference** of the receiver influences their response to a threat. The potential channels that carry the information include face-to-face, by phone (voice, live visual of the person you are talking to [‘FaceTime’], or by written message such as through an EMA), radio, TV, print media, social media, internet, message-capable audio alerts, and tone-only alerts or sirens.
    - A specific in-house alerting device can be used for automatically disseminating a message.
    - The cost of the channels and ability for the population to afford the equipment influences whether the message is received. Cheap or free options (such as subsidised in-house alerting devices) are more likely to be taken up than requiring, for example, new model cell phones to receive EMAs.
    - The channels vary in terms of the level of detail they can contain in a message, their ability to interrupt activities and gain attention and the speed at which they are received. For example, a New-Zealand-wide EMA may have less specific location information in it and may not interrupt activities, but be faster to receive, in comparison to someone knocking on the door of people at risk with location-specific information and the ability to interrupt activities, as this can be a slower process.
    - Determining the channel for an alert is an important aspect of optimising response. An example is that a population at risk may listen to a radio station in a different language (e.g. Te Reo) than the one chosen to carry a warning (a mainstream English language radio station). Additionally, alerting channels differ in their ability to gain attention. An alert requiring immediate action needs to be audible and visual. The tone or audible message must be instantly recognisable for an educated audience in order to reduce the need to stop and read a message, which would slow down a response. Audible messages that use words to instruct the receiver on what is happening and what to do are much more effective in getting compliance than a tone-only alert (such as a siren; MCDEM 2014). Messages that do not require an immediate response should have more written/visual information within them to reduce ambiguity and guide a response action.
    - Finally, the technical requirements of the equipment being used as a channel can influence a response. For example, cellphone reception is a requirement of EMA messages, and telemetry network functionality of monitoring equipment and the alerting network influences whether the message gets received.

- The content and format of a **warning message** influences a receiver's response. Key elements of a warning message are the information source (agency), guidance (protective actions people should take), hazard, potential impacts, locations at risk, the time by which actions should have been taken, the time of issue and links to further information. Potter (2018) describes these elements in further detail in addition to giving examples of short warning messages, such as for EMAs. Potter (2018) also describes the optimal order for those elements to be presented according to the length of the message, based on international research findings. A message should also be specific, clear, effective and accurate (Figure 2.5) in order to get an optimal response. Additionally, people tend to search for further information when there is ambiguity in the message in order to confirm their decision to respond (e.g. Wood et al. 2018), which is referred to as 'milling'. Providing multiple channels with consistent messages and providing links to further information within the message minimises the milling time.

Finally, the **receiver's characteristics** influence their response to threat information. This includes their demographic details and languages spoken, their physical and psychological ability to become aware that the hazard event is occurring and to respond in the suggested manner, their available resources to respond (such as whether they can afford to stay elsewhere or to have a car to evacuate quickly), their social resources (such as having friends nearby to stay with or for support in general) and their mental models (such as their worldview, prior experience and level of trust in official agencies).

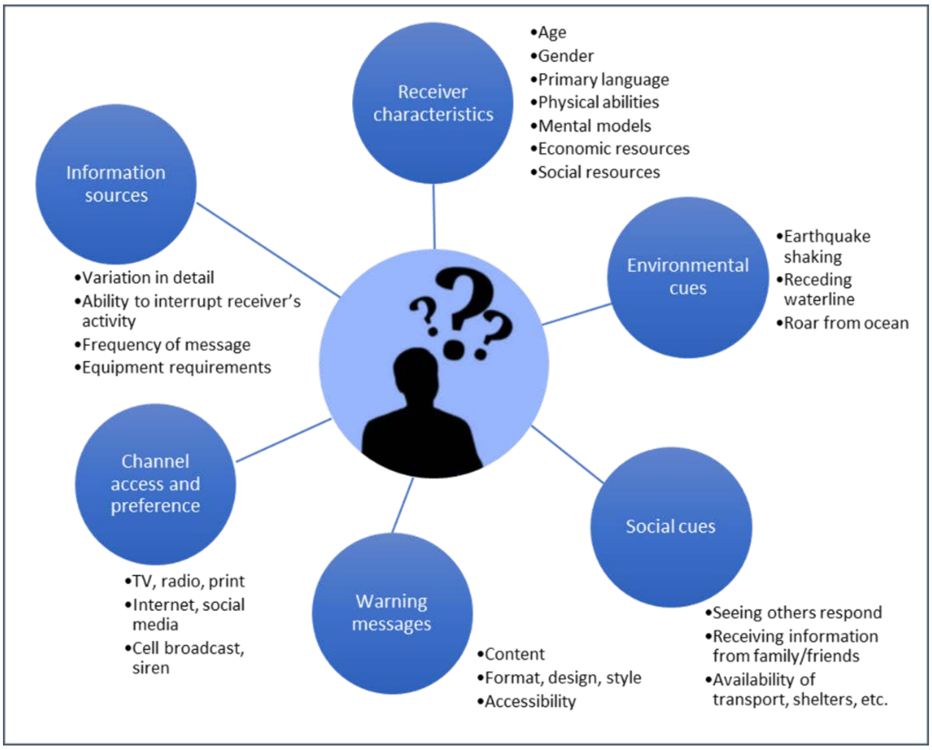

Figure 2.4 Influences on deciding to respond to a warning. From Potter (2018), based on Lindell and Perry (2012).

Specific	• Personalise the message as much as possible • Include specific location names
Clear	• Simple and clear, with no acronyms
Effective	• Achievable, affordable and effective actions given to reduce the risk
Accurate	• No spelling or grammatical mistakes

Figure 2.5 Best practice for constructing a warning message.

The factors described above influence how people receive information about the threat. These then initiate pre-decisional processes, which are largely automatic and outside of people's consciousness. These processes include the amount of exposure that the receiver has to the information, the attention they pay to it, and how well they comprehend it. The warning information source and channel especially influence these pre-decisional processes.

- **Exposure** to the message (i.e. whether people receive it or not) is largely a factor of the channel characteristics. For example, people with mobile phone reception may receive EMAs, and people in areas without reception will not. Whether people have the required equipment also determines exposure to the message (e.g. whether they have an in-house alerting device and are inside to hear it).
- **Attention** given to the message is influenced by people's expectations of receiving the information, their competing attention demands and how intrusive the information is (Lindell and Perry 2012). These factors could be taken into consideration when designing an EWS. For example, if there is a warning system with multiple levels (e.g. advisory, watch and warning), with the lower levels activated in the days and hours prior to a debris flow, then people may be more expectant of a 'warning' alert to be received. Designing an alert to be intrusive (e.g. noisy enough to interrupt other activities and/or sleep) can also be factored in so that people heed the warning.
- **Comprehension** of the message is how well people understand it. Including jargon (specialist terms, which in the Matatā context may include 'debris flow', 'precipitation', 'inundation') or acronyms in the message decreases people's comprehension of the message and therefore increases the milling time while they search for further information. Additionally, if the language used does not match the primary language of the recipient they are less likely to respond.

The receiver of threat information then considers the information in the context of their perceptions about the threat, the possible protective actions, and the stakeholders. People differ in the strength of the following perceptions, which are embedded in their world views.

Threat perception is the level of personal impact people expect to receive from the hazard. This could include disruption to daily activities, property damage, injury and death. Threat perception takes into account likelihood and consequences/impacts, although dread can also be considered (Lindell and Perry 2012). The threats can vary in terms of how often people at risk think about them (‘intrusiveness’), which, along with expected personal impacts, relates to the “recency, frequency, and intensity of people’s personal experience with hazard events” (Lindell and Perry 2012), as well as their proximity to the hazard. Given the recency and high severity of impacts as a result of the Awatarariki catchment debris flow in 2005, and the proximity of the properties to the hazard, it could be expected that some residents in the affected area will be highly conscious of the potential impact and therefore more likely to evacuate in future conditions of high risk. However, as time goes on and the memories become more distant, or new people begin to reside in the hazard zones, the intrusiveness of the threat perception and understanding of the potential severity of the consequences will decrease, lowering threat perception and therefore the likelihood of people responding to warnings. Threat perception is influenced by the proximity of the person to the hazard (e.g. as cited in Lindell and Perry 2012). For example, if people know there is a nearby fault line, or that they are near the coast, or in a flood-prone valley, they are more likely to perceive to be at threat from an earthquake, tsunami and flood, respectively.

People’s perceptions on the suggested ‘hazard adjustments’ or **protective action perceptions** may influence their response (i.e., the suggested action that they should take to reduce the risk, such as ‘evacuate’, or ‘prepare a grab bag’). This includes the perceived effectiveness in reducing the risk, the cost, time commitment, effort required, required knowledge or skill, whether other people need to be involved and how useful the action or product is for other purposes (e.g. Lindell and Prater 2002). More research needs to be conducted to understand the strength of this influence, particularly in a context of short lead-time warnings for natural hazards and with varying levels of threat.

The **perception of stakeholders** also influences people’s response to a threat. Stakeholders can include authorities, evaluators (including scientists), media, citizen groups, employers and households. Trust in those stakeholders, their perceived credibility and expertise, and the perceived responsibility for protection against threats, are influences in responding to a threat (e.g. Arlikatti et al. 2007; Peters et al. 1997).

People will also cognitively assess how serious an emergency is and, if there is any doubt over the seriousness of the situation, they will be slower to respond (Whitmer et al. 2017). Sorensen (2000) summarises factors found by social scientists to influence warning response (Table 2.1). Some of these factors are addressed in the above section, while others are not explicitly in Lindell and Perry’s model. Many of these factors relate to the demographics of the population at risk (e.g. gender, age, size of family, available resources). As determining the details of demographics of the population at risk in the Awatarariki catchment was out of scope for this project, we are not able to consider many of these influences directly in our estimate of the probabilities of failure of each of the relevant EWS components. We also acknowledge that the demographics of the population would likely change over time. This means that if an EWS was to be designed for this catchment, the population would need to be surveyed on a regular basis to gain accurate and detailed demographic information that could help refine the probability estimates, as well as help plan for an effective response (e.g. understanding what assistance would be required, with specified lead times).

Table 2.1 Factors influencing response to warnings (Sorenson 2000).

Factor (1)	Response Due to Factor Increase (2)	Level of Empirical Support (3)
Physical cues	Increases	High
Social cues	Increases	High
Perceived risk	Increases	Moderate
Knowledge of hazard	Increases	High
Experience with hazard	Mixed	High
Education	Increases	High
Family planning	Increases	Low
Fatalistic beliefs	Decreases	Low
Resource level	Increases	Moderate
Family united	Increases	High
Family size	Increases	Moderate
Kin relations (number)	Increases	High
Community involvement	Increases	High
Ethnic group member	Decreases	High
Age	Mixed	High
Socioeconomic status	Increases	High
Being female versus male	Increases	Moderate
Having children	Increases	Moderate
Channel: Electronic	Mixed	Low
Media	Mixed	Low
Siren	Decreases	Low
Personal warning versus impersonal	Increases	High
Proximity to threat	Increases	Low
Message specificity	Increases	High
Number of channels	Increases	Low
Frequency	Increases	High
Message consistency	Increases	High
Message certainty	Increases	High
Source credibility	Decreases	High
Fear of looting	Decreases	Moderate
Time to impact	Decreases	Moderate
Source familiarity	Increases	High

3.0 PROJECT DESIGN / METHODOLOGY

3.1 Methodology

The methodology presented here is for the development of an effectiveness-evaluation framework of a public-facing EWS for debris flows on the Awatarariki Fan, which considers the context and user needs as set out in Figure 2.3. It should be noted that it is not the intent of this work to carry out the detailed design of an EWS. To design the framework we have relied on information contained in McSaveney et al. (2005), Tonkin & Taylor (2013, 2015) and Davies (2005, 2017) to help set the site-specific context for the EWS. Information with regards to user needs was derived from discussions with WDC and others present at the expert's workshop (organised by WDC and held in Whakatāne on 15/08/2019) and during various other meetings, as community consultation and discussion was not feasible at the time.

Three different EWS stages typically used for debris flows (as shown in Appendix 2) were adopted and combined as part of the debris flow EWS design. These stages were based around the minimum time between a 'positive' on the EWS algorithm, which triggers a warning that a debris flow could potentially occur, and the potential debris flow hitting dwellings on the fan.

In the literature review (Appendix 2), most EWS (about 80%), rely on a multi-stage approach using different types of data to trigger the alerts. Most EWS adopt rainfall data from synoptic, radar and gauges for the first stages of the EWS (1–24 hours) linked to rainfall intensity/duration thresholds established using precedent and local knowledge of landsliding. Tilt meters and trip wires are then typically used for the later stages to detect when a landslide initiates or landslide movement exceeds a given threshold.

The stages and lead times for the alerts evaluated as part of the debris flow EWS effectiveness-evaluation framework for the Awatarariki Fan are:

- Stage 1: 24 hours (lead-in time) – based on Synoptic meteorological data from MetService;
- Stage 2: 2–7 hours (lead-in time) – based on rain radar (MetService) augmented with onsite rain gauge(s); and
- Stage 3: About 3–6 minutes (lead-in time) – based on trip wire(s) located as per those shown in Davies (2017);

where the first alerts are given 24 hours and then 7 and 2 hours ahead of a potential rainfall event (with a forecast rain intensity over the given duration that would exceed the threshold for landslide triggering) impacting the area, and the last alert when a debris flow event has actually been triggered, giving between 3–6 minutes of warning from the detection of the debris flow to the debris impacting the fan.

3.1.1 Design Framework Structure

This study utilises an EWS design framework modified from the warning chain illustrated by Carsell et al. (2004) (Figure 3.1). Sub-components with demonstrably different probabilities of failure/success are further broken out in the framework and named in relation to their contribution to the probability of warning failure as follows: 'Data collection' is broken out to 'sensor' and 'telemetry'. 'Evaluation' is broken out to 'software' and 'missed alarms'. 'Notification' is broken out to 'telemetry', 'public alerting technology' and 'public don't notice'. Decision making is referred to as 'Public don't act' and Action is referred to as 'Public not safe fast enough'.

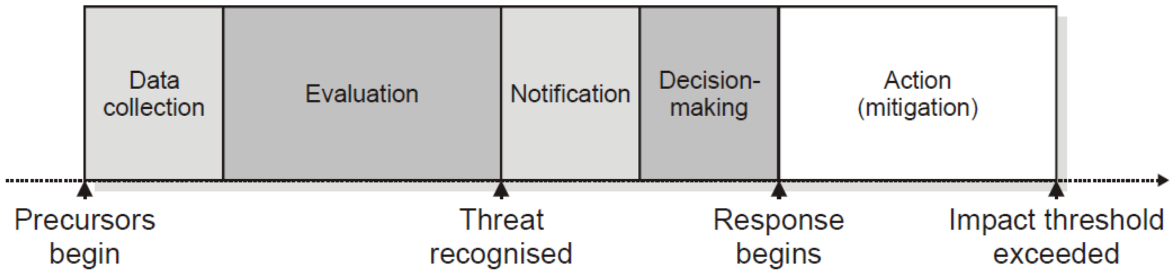

Figure 3.1 Warning timeline from Carsell et al. (2004) used as a basis for the design framework for this project.

3.1.2 Scenarios

Three scenarios are given to encompass the uncertainty in the range of probabilities of failure of each component of the EWS.

The ‘Good’ scenario reflects the best-case situation that could happen at Awatarariki catchment in the future, where the lower probability of failure estimates for each component are adopted. In this ‘Good’ scenario, all people present in the hazard zone would be contacted (e.g. door-to-door knocking for the 2–24-hour stages) and they willingly and are physically able to evacuate with enough time to avoid the debris flow. This results in no people being exposed to the hazard. Unfortunately, there remains a small chance that there is a debris flow that will not be detected for the time period required to fully evacuate the hazard zones, as we describe later in this report.

The ‘Middle’ scenario is what we think is the most likely situation to occur. This scenario adopts our ‘best estimates’ of the probability of failure for each component. In this scenario, we assume people receive a notification of possible threat with a 24-hour lead time based on rain forecasts, and a warning message is received with two or more hours lead time. Despite this, people may choose not to evacuate, as they tend to wait until the threat has been confirmed (i.e. the trip wire has been triggered, giving 3–6 minutes of warning) before evacuating.

The ‘Worst Case’ scenario is where things do not go according to plan. This scenario adopts our highest estimates of the probability of failure for each component. In this scenario, people in the hazard zones do not evacuate with two or more hours’ notice (based on rain forecasts and data) as people tend to only evacuate under imminent threat (when the uncertainty is reduced and they have confirmed the existence of the threat). By the time the threat has been confirmed (i.e. the trip wire has been triggered), or they can see or hear the debris flow and there is less than three minutes to evacuate, there is not enough time for everyone to successfully evacuate the hazard zones.

3.1.3 Probability of Component Failure

The probabilities of component failure for the three scenarios across the EWS components are roughly estimated as example values in the tables in Sections 4.3–4.11. The basis for these estimations is described in each of those sections, ranging for known behaviour of chosen technologies, expert judgements based on reviews of warning system types, and evidence from human behaviour in other natural hazard warnings. These are given as example place-holder values only for demonstrating the framework and highlighting any ‘show-stoppers’ that are already evident at this framework development stage. For the detailed design of an EWS, the probabilities will need further work and justification and will need to be re-evaluated using the framework developed here.

The failure probabilities for each component were combined using the following equation to derive a total probability (P_{SUM}) of failure for each scenario at each stage of the EWS, where:

$$P_{SUM} = 1 - (1 - P_{component:1}) \times (1 - P_{component:2}) \times (1 - P_{component:n}) \qquad \text{Equation 3.1}$$

These probabilities of failure were then used to estimate the long-term average number of people who could be exposed to the hazard in each event, for scenarios (1)–(3), expressed as a percentage of all the people living on the fan. This was done to indicate the range of likely effectiveness of the EWS.

3.2 Limitations

This project lays out a framework for designing an EWS, which can be used as an example to evaluate its probability of failure/success in a Matatā context. It is not the scope of this work to carry out the detailed design or evaluation of an EWS. The latter will require substantial community consultation and demographic details and an in-depth review of warning system functional data and human behaviour data. It is out of scope to do a detailed and thorough literature review for each stage of the EWS. Numbers are indicative only.

4.0 EARLY WARNING SYSTEM DESIGN FRAMEWORK

4.1 Overview of the EWS Design Framework

The effectiveness framework is based around nine components of an EWS system (shown in Figure 4.1), along with estimates of their probability of failing. These are:

1. Sensors (and associated technology) used at each of the three stages: Stage 1: 24 hours = synoptic (from MetService); Stage 2: 2–7 hours = rain radar (from MetService) and local rain gauge(s); and Stage 3: 3–6 minutes = trip wire(s).
2. Telemetry: to transfer data from the instruments on-site e.g., from the rain gauges and trip wires, and to get it the place where it is needed. For MetService data, the data is provided via cloud-based data services, thus not requiring any on-site sensors or telemetry.
3. Software and computer processing: Data from the various sensors are processed and compared to pre-determined thresholds, typically carried out by an algorithm trained on past events, which then issues the alarm if the threshold(s) are exceeded.
4. Missed alarms: This relates to an event that the algorithm misses and only relates to the rainfall data streams as the trip wires would be linked directly to the public alerting technology, thus not needing any data-processing algorithm.
5. Telemetry: to issue alerts e.g., satellite, cell, Wi-Fi, and Wi-Fi and cell combined, to trigger the public alerting technology. For example, in the case of Stage 3, the trip wire would be linked by Wi-Fi, for example, with less than a minute for siren/lights to operate after the trip wire triggers. This time might be slightly longer for text messages to be issued.
6. Public alerting (technology): e.g. door knocking, voice sirens (with instructions about what to do), US Federal audible sirens, home-made sirens and flashing lights.
7. Public don't notice: the public might not see the alert e.g. text message or flashing lights or hear the sirens.
8. Public don't act, including the effect of false alarms: the public decide not to act, e.g. 24 hours prior, there will be a low certainty about the event (debris flow) occurring. There would be many false alarms and thus a fostering of a low threat perception and decrease in trust of the warnings. The rate of false alarms will depend on the sensor type / data used. Even at the 3-minute stage, people tend to delay acting in order to confirm the threat, especially if they cannot directly see it, which leaves very little time to respond.
9. Public not safe fast enough: From international literature, at the 2- or 24-hour stages there is typically a low evacuation rate (if not mandatory and forced) due to many reasons. High rates of evacuation do not usually occur until the 3-minute stage due to the certainty at that time about the hazard. However, if people leave it too late, e.g. at the 3-minute stage, then flooding may prevent them from evacuating.

This framework was applied to the three stages (24 hours, 2–7 hours and 3–6 minutes) by adopting three component-failure probability scenarios (Good, Middle and Worst Case) across each. The stages of the EWS Design Framework are now described, including why each of the stages have been included and the basis for the derived probabilities for failure.

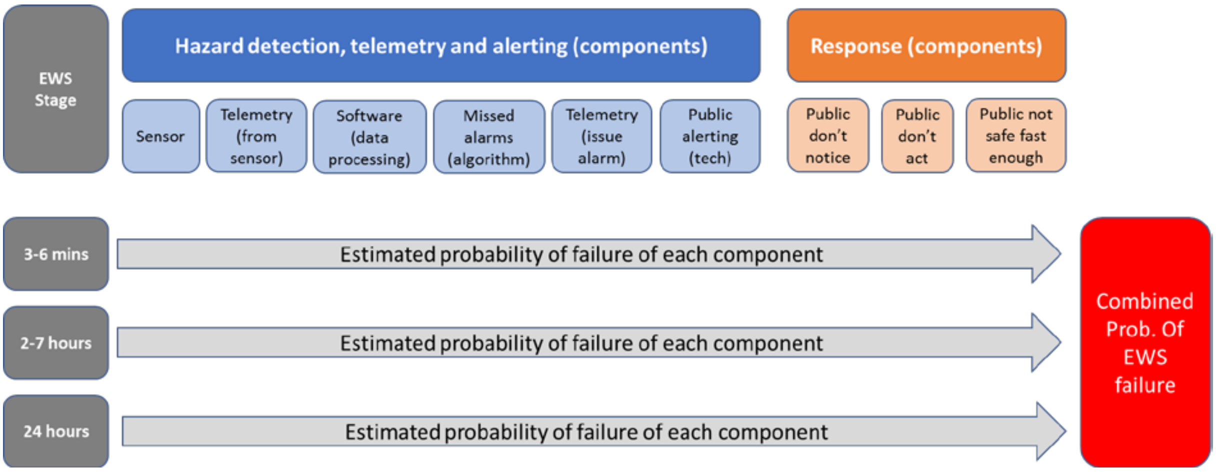

Figure 4.1 Effectiveness-evaluation framework of a public-facing EWS for debris flows on the Awatarariki Fan.

4.2 Sensor

Sensors (and associated technology): 24 hours = synoptic (from MetService); 2–7 hours = rain radar (from MetService) and local rain gauge(s); and 3–6 minutes = trip wire(s). The probability of failure for the different sensors / data services were estimated based on discussions with North Canterbury Transport Infrastructure Recovery (NCTIR) alliance, MetService, NIWA and GeoNet technicians (Table 4.1).

It should be noted that trip wires are notoriously difficult to maintain and can give a high percentage of false alerts. One such system, the Eastern Ruapehu Lahar Alarm and Warning System (ERLAWS) is a lahar warning system that was installed on Mount Ruapehu, New Zealand following volcanic eruptions in 1995–1996. The system successfully detected and warned of an imminent lahar in March 2007 (Massey et al. 2010) and the trip wires were generally reliable (Keys et al. 2008), but for those installed by NCTIR there was about a 25% failure rate.

Table 4.1 Probability of failure for the 'sensor' stage of the EWS design framework.

	Scenario		
Stage (Lead Time)	**Worst Case**	**Middle**	**Good**
3–6 minutes	0.25	0.25	0.25
2–7 hours*	0.05	0.05	0.05
Over 24 hours*	0.10	0.10	0.10

* MetService would provide the Synoptic and rain radar forecast data via web-based data service.

4.3 Telemetry (from Sensor)

Telemetry: to transfer data from the instruments on-site e.g. from the rain gauges and trip wires, and to get it the place where it is needed. For MetService data, the data is provided via cloud-based data services, thus not requiring any on-site sensors or telemetry. The probability of failure for the different sensors / data services were estimated based on discussions with the NCTIR alliance, MetService, NIWA and GeoNet technicians (Table 4.2).

Table 4.2 Probability of failure for the ‘telemetry (from sensor)’ stage of the EWS design framework.

	Scenario		
Stage (Lead Time)	**Worst Case**	**Middle**	**Good**
3–6 minutes	0.10	0.08	0.05
2–7 hours	0.10	0.08	0.05
Over 24 hours	0.10	0.10	0.10

4.4 Software (Data Processing)

Software and computer processing: Data from the various sensors is processed and compared to pre-determined thresholds, typically carried out by an algorithm trained on past events, which then issues the alarm if the threshold(s) are exceeded. The probability of failure for the different sensors / data services were estimated based on discussions with GNS Science software engineers (Table 4.3).

Table 4.3 Probability of failure for the ‘software’ stage of the EWS design framework.

	Scenario		
Stage (Lead Time)	**Worst Case**	**Middle**	**Good**
3–6 minutes	0.01	0.01	0.01
2–7 hours	0.01	0.01	0.01
Over 24 hours	0.01	0.01	0.01

4.5 Missed Alerts (Algorithm)

Missed alerts: This relates to an event that the algorithm misses and only relates to the rainfall data streams, as the trip wires would be linked directly to the public alerting technology, thus not needing any data-processing algorithm. The algorithm used for Stages 1 and 2 (24- to 2-hour lead time) would be based on rainfall intensity and duration relationship shown in Figure 4.2 for landslides that have occurred during periods of rain in the Bay of Plenty. This relationship is based on the work of Rosser et al. (in prep). The dashed power law fitted to the data represents the 2% triggering threshold, meaning that, for rainfall intensities and durations that exceed this line, there is a >2% chance of landslides occurring. For comparison purposes, the rainfall recorded at Awakaponga during the 2005 debris flow at Matatā are also shown. Note the Awakaponga rainfall plots at the upper part of the graph, around the 95% triggering threshold, which confirms the opinion of McSaveney et al. (2005) that the cause of the 2005 debris flow event was the many slope failures that were triggered by the rainfall which caused landslides to fall into already flooded stream channels.

These data are uncertain; thus much thought would be needed to establish the rainfall intensity/duration relationship thresholds to use for the alerting. For Stage 1 and 2 (24- to 2-hour lead time) relatively high failure probabilities of 50% and 25%, respectively, have been adopted in order to represent this uncertainty (Table 4.4). Setting these thresholds needs to balance the probability of missing a debris-flow-triggering rain event, with the need to reduce the number of false alarms.

In Japan, the number of false alarms has been shown to reduce when the rainfall intensity/duration relationships are coupled with catchment specific rain measurements and measurements of soil moisture at the time of the rain (e.g. Brocca et al. 2012). If an EWS were feasible at Awatarariki Stream, such instruments could be installed and the relationships eventually established. However, establishing such relationships takes time and data.

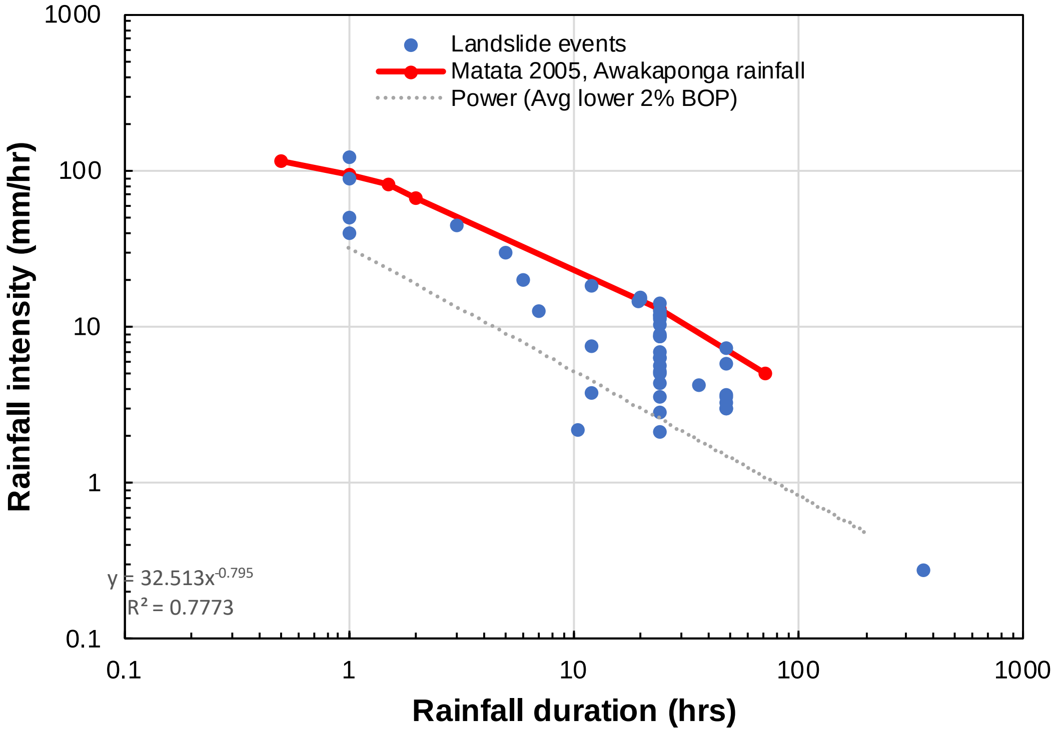

Figure 4.2 Rainfall intensity and rainfall duration relationship for the Bay of Plenty. The data shown represent rain that has triggered landslides in the past. The relationship is taken from Rosser et al. (in prep). The rainfall recorded at the Awakaponga rain gauge during the 2005 debris flow at Matatā is shown in red.

Table 4.4 Probability of failure for the 'missed alerts' stage of the EWS design framework.

	Scenario		
Stage (Lead Time)	**Worst Case**	**Middle**	**Good**
3–6 minutes	0.01	0.01	0.01
2–7 hours	0.25	0.25	0.25
Over 24 hours	0.50	0.50	0.50

4.6 Telemetry (Issue Alert)

Telemetry: to issue alerts e.g. satellite, cell, Wi-Fi, and Wi-Fi and cell combined, and to trigger the public alerting technology. For example, in the case of Stage 3 (3–6 minutes lead time), the trip wire would be linked by Wi-Fi, for example, with less than a minute for the siren/lights to operate after the trip wire triggers. This time might be slightly longer for text messages to be issued. The probabilities of failure for the different telemetry options were estimated based on discussions with the NCTIR alliance, who relied on trip wires to alert them of rockfalls and other landslides, as well as ground deformation hazards; and GeoNet technicians (Table 4.5).

Table 4.5 Probability of failure for the ‘telemetry (issue alert)’ stage of the EWS design framework.

	Scenario		
Stage (Lead Time)	**Worst Case**	**Middle**	**Good**
3–6 minutes	0.10	0.10	0.05
2–7 hours	0.05	0.05	0.05
Over 24 hours	0.05	0.05	0.05

4.7 Public Alerting (Technology)

Public alerting (technology): e.g. door knocking; voice sirens (giving instructions about what to do), e.g. US Federal or similar commercial audible sirens; home-made sirens and flashing lights. These values are expert judgements based on the relative qualitative effectiveness of each alerting technology as reviewed in Wright et al. (2014) (Table 4.6). Door knocking is expected to have ample time for full effectiveness in the Good scenario with more than 2 hours of lead time. Throughout the Worst Case and Middle scenario, flashing lights and homemade sirens are allocated an expert-judged rate of not being noticed, with a nominal low probability of failure. Similarly, for Stage 3 in the Good scenario (3–6 minutes lead time), a nominal failure rate for voice sirens is used in all scenarios, but further work on the actual failure rate will be needed.

Table 4.6 Probability of failure for the ‘public alerting (technology)’ stage of the EWS design framework.

	Scenario		
Stage (Lead Time)	**Worst Case**	**Middle**	**Good**
3–6 minutes	0.10	0.10	0.05
2–7 hours	0.10	0.10	0.00
Over 24 hours	0.10	0.10	0.00

4.8 Noticeability of Alert

Public don’t notice: the public might not see the alert e.g. text message or flashing lights or hear the sirens. These values are expert judgements based on the relative qualitative effectiveness of each alerting technology as reviewed in Wright et al. (2014) (Table 4.7). In the Good scenario at more than 2 hours, it is assumed that all people are able to be found by door knocking and are forced (by Police action) to leave. Throughout the Worst Case and Middle scenarios flashing lights and homemade sirens are allocated an expert-judged rate of not being noticed.

Table 4.7 Probability of failure for the ‘noticeability of alert’ stage of the EWS design framework.

	Scenario		
Stage (Lead Time)	**Worst Case**	**Middle**	**Good**
3–6 minutes	0.90	0.20	0.05
2–7 hours	0.50	0.10	0.00
Over 24 hours	0.20	0.05	0.00

4.9 Public Response to Alert

Taking into account the receiver's response to an alert is a critical component of understanding the effectiveness of an EWS. As described earlier in this report, there are many influences on the decision to respond to an alert/warning. All of these influences are absorbed into the EWS stage labelled 'public don't act / public response to alert' in this report, but they could be further interrogated from the literature to understand their quantitative influence on the probability of failure to respond, and what could be done to increase responses. In determining the probabilities of failure for this EWS stage, we searched for literature on people's physical response to warnings for natural hazards (especially evacuations) with lead times matching those used in this report (3–6 minutes, 2–7 hours and 24 hours). Many research articles on behavioural response are qualitative and did not provide an estimate of response rate. Others did not clearly state the response rate as a proportion of people who received a warning message, making it difficult to relate to the Awatarariki catchment context. As is common in social science for natural hazards, some articles use a hypothetical scenario or exercises to estimate response rates, which has a limitation on how accurate the results would be in a real situation. Further literature searching and reporting of evacuation rates from real events needs to be done internationally in future, to assist with understanding the effectiveness of warnings.

Once an alert or warning has been received and noticed, there are a number of factors that influence whether the receiver (person under threat) responds in an appropriate and timely manner to reduce the chance of threat. The factors, and steps people go through when deciding when and how to act, are described below. First, we give a description of the proportion of people that tend to respond to an imminent threat, based on international case studies from hazardous events. The probability of failure numbers used in the EWS design framework (reproduced in Table 4.8) are based on this literature, as well as the expert judgement of the authors, taking into account the influencing factors described below to reflect the Awatarariki catchment context, including the debris flow hazard and experience of the residents in that area.

Table 4.8 Probability of failure for the 'public response to alert' stage of the EWS design framework.

	Scenario		
Stage (Lead Time)	**Worst Case**	**Middle**	**Good**
3–6 minutes	0.90	0.10	0.01
2–7 hours	0.99	0.90	0.00
Over 24 hours	0.99	0.95	0.00

People's tendency to respond to very short-fuse warnings (3–6 minutes lead time) varies widely. Relating to the Worst Case scenario, 96% of survey respondents did not immediately evacuate from a tsunami in New Zealand following earthquake shaking (Blake et al. 2018). While tsunami pose a similar threat to life as a debris flow and Blake et al.'s study was in a New Zealand context involving a real event, there is no official warning for local-source tsunami, whereas the Awatarariki debris flow would involve an official warning (which may increase the evacuation response rate). In Japan, 90% of people receiving an Earthquake Early Warning message did not physically respond to the warning (e.g. drop, cover and hold) in the few seconds prior to the arrival of shaking (Nakayachi et al. 2019). In these examples, there may have been a low threat perception by receivers, influencing their response.

Our expert judgement (for the Middle scenario) assumes that residents in the Awatarariki catchment hazard zones would have a high threat perception, given their prior experience of the 2005 event, and that they would receive an official warning. However, we assume there would not be official response agencies actively evacuating the area (given the short lead time), and the debris flow may not be visually or audibly noticeable as it moves down the catchment. Therefore, we estimate there is a 10% chance that people would not respond to a warning with a 3-minute lead time.

Relating to Stage 3 (3–6 minutes lead time), in the Good scenario, only about 1–5% of people did not respond to tornado warnings in Joplin, Missouri, US, with less than 3 minutes of warning (Kuligowski et al. 2014). Most people receiving the warning could hear or see the tornado approaching. About 5–7% of skiers did not evacuate from lahar (volcanic mudflow) warnings during exercises on Ruapehu, New Zealand (Leonard et al. 2008). In this situation, employees at the ski field encouraged skiers to respond to the warning. Both of these situations required an immediate physical reaction to the warning to increase safety, and people in both examples are likely to have had a high threat perception.

In terms of Stage 2 (2–7 hours lead time), there is little in the way of hazard analogies to refer to. Literature on official tsunami warnings and tornado advisories were found; research on evacuation responses to flash flood advisories and bushfires were sought but not found – noting that more detailed literature searches are needed, given the recent bushfires in Australia. This lead time involves a higher level of uncertainty over the occurrence, location and severity of the hazard, than short lead time warnings. Response rates vary hugely, and there is a large uncertainty in these probability estimates.

For the Worst Case scenario, 97–99% of people in the Joplin, Missouri, US, area did not physically respond to an official tornado advisory with five hours lead time (Kuligowski et al. 2014). In terms of the best-case (Good) scenario, we assume a mandatory evacuation of all people in the hazard zones, and that the 2–7-hour lead time will enable enough time for official agencies to assist residents to leave – therefore there is a 0% failure rate. Our expert judgement for the Middle scenario also draws on the New Zealand survey on tsunami response, where 89% of people did not respond to the natural warning (Blake et al. 2018). Additionally, in this study 11% of survey respondents took 1–3 hours to take preparedness actions prior to evacuating.

For Stage 1 (24 hours lead time), there is a very high level of uncertainty over the hazard location (i.e. where the localised and intense precipitation will occur), severity, timing and occurrence. This means threat perception tends to be low, and the chance of false alarms is high – both of which contribute to a high level of failure to respond to a warning. In the Worst Case scenario, 99% of people do not respond to warnings with this amount of lead time (e.g. for tornado response; Kuligowski et al. 2014). However, for hurricane warnings in the US (which can involve mandatory evacuations), response rates vary with long lead times, from 19% to 90% of people not evacuating (Dow and Cutter 1998). As an interesting example, Myrtle Beach (South Carolina, US) residents evacuated for hurricanes in (at least) 1984 and 1989, and for two in 1996. Respectively, evacuation rates for this community were 48% (Category 2), 79% (Category 4), 27–34% (Category 1) and 37–53% (Category 3) (as cited in Dow and Cutter 1998). While these response rates are quite high with a long lead time (especially for the Category 4 hurricane, with presumably high threat perceptions), mandatory evacuations increase the response rate, and hurricane forecasts may be more accurate than the uncertain locations of localised high-intensity precipitation that can cause debris flows in the Awatarariki catchment.

Our expert judgement (Middle scenario) is that, without mandatory evacuation, there is a 95% chance that people will not evacuate with a lead time of 24 hours at the Awatarariki catchment hazard zones. With mandatory evacuation (Good scenario), there is a 0% chance of failure to evacuate, as all people could successfully be removed from the hazard area, given the long lead time.

4.10 Timeliness of Public Response

The component 'Public not safe fast enough' estimates people's probability of not getting to safety in time for those who have received the alert and decided to evacuate (as that is accounted for in the previous stage). This component includes how long it takes them to leave and their travel time (Table 4.9).

This assumes in the Worst Case scenario for Stage 3 (3–6 minutes lead time) and Stage 2 (2–7 hours lead time) that flooding prevents people from leaving and, for Stage 1 (24 hours lead time), that there is ample time to evacuate with no impediment.

We use travel speeds from a range of data sources summarised by Fraser et al. (2014) for the purpose of evacuation in tsunami. We assume an average travel distance of 300 m, while acknowledging that this will vary depending upon where a person may be on the fan. 300 m is in the middle of the range of actual travel distances from a few tens-of-metres to a maximum of 600 m, from Davies (2017). Detailed design and evaluation of any EWS will need to model actual travel times, perhaps using 'least-cost distance' evacuation modelling in GIS (see Fraser et al. 2014).

In Stage 3 (3–6 minutes lead time), for the Good scenario, it assumes that flooding does not slow people, that 80% of people will be able to run and that all of those will reach safety in time as they are running well over 1.79 m/s. However, people walking are assumed to total 20%, and some of those will not get to safety in time at an average walking speed of 1.5 m/s. We assume a 30 second delay in departure. We assume the departure delay will be higher than 30 seconds for the Middle scenario and qualitatively have allowed for this in the 0.80 probability, given in Table 4.9.

For the Middle case, we assume a position somewhere between the Worst and Good cases, where some people are stopped by flooding, some delay by 30 seconds or more, and some are not running fast enough.

In Stage 2 (2–7 hours lead time), the Middle scenario is based on some people being stopped from leaving due to flooding, and the Good scenario assumes 5% of people are immobile and can simply not evacuate.

In Stage 1 (24 hours lead time), in all scenarios, there is assumed to be virtually no impediment to evacuating people in time, including those who are immobile.

Table 4.9 Probability of failure for the 'timeliness of public response' stage of the EWS design framework.

	Scenario		
Stage (Lead Time)	**Worst Case**	**Middle**	**Good**
3–6 minutes	1.00	0.80	0.20
2–7 hours	1.00	0.10	0.05
Over 24 hours	0.01	0.01	0.00

4.11 Combined Probability of EWS Failure

To estimate the effectiveness of the EWS, we have calculated the combined probability of failure of the EWS for each scenario and stage (Table 4.10). We have then used these to estimate the proportion of people still exposed to the debris flow should it occur – combining the failure probabilities across the three stages for each scenario in Table 4.11 – as a proportion of the total number of people who may live on the Awatarariki Fan and be exposed to debris flow hazards.

Table 4.11 gives the probability of people being left behind at each stage as an accumulation (multiplication) of the probability of failure at that stage by the probability of EWS failure during the previous stages and the numbers of people who could potentially be left behind.

A more robust calculation method could be applied to a figure for the actual number of people at risk, following community consultation. However, although the probability of being left behind decreases from each stage, from 24 to 2–7 hours, and again from 2–7 hours to 3–6 minutes, the key message is it that the probability of leaving somebody behind at the later stages is not '0' due to the probability of the EWS failing either at the given stage or during an earlier stage.

Table 4.10 Combined probability of failure across all nine components (Tables 4.1–4.9) for the EWS design framework.

	Scenario		
Stage (Lead Time)	**Worst Case**	**Middle**	**Good**
3–6 minutes	1.00	0.92	0.53
2–7 hours	1.00	0.95	0.40
Over 24 hours	1.00	0.98	0.58

Table 4.11 Estimated proportion of people exposed to the debris flow hazard at each stage (lead time) and for a given scenario, as a proportion of the total number of people who live on the Awatarariki Fan and could be exposed. The probability of people being left behind at each stage is the probability of failure at that stage multiplied by the probability of failure of the previous stages. Thus, the probability of being left behind decreases from 24 to 2–7 hours, and again from 2–7 hours to 3–6 minutes, but it never gets to '0' due to the probability of the EWS failing at an earlier stage or at the given stage.

	Scenario (Cumulative Proportion of People Left Behind)		
Stage (Lead Time)	**Worst Case**	**Middle**	**Good**
3–6 minutes	1.00	0.86	0.12
2–7 hours	1.00	0.94	0.23
Over 24 hours	1.00	0.98	0.58

5.0 DISCUSSION OF 'SHOW STOPPERS'

The main aim of this work was to scope out the potential design and effectiveness-evaluation framework of a public-facing EWS for debris flows on the Awatarariki Fan, Matatā. As part of this work, GNS Science was asked to identify any initially obvious issues that could reduce he effectiveness of the EWS (i.e. 'show stoppers') and whether an EWS would be suitable/unsuitable for the Council to consider as an option to manage the risk.

The main findings / show stoppers relating to using an EWS to manage the risk to people on the fan from debris flow hazards are:

1. For Stages 1 and 2 (2–24 hours): The **'public don't act'** component dominates the probability of failure of the EWS under scenarios Worst Case and Middle.
    a. The Good Scenarios all rely on mandatory forced evacuation at least 24 to 2 hours ahead of a potential debris flow, which may or may not be feasible from logistical or legal perspectives (such perspectives are outside the scope of our technical expertise). In the Good scenario, it could be that 50–60% of the people in the hazard zone are still present when the hazard occurs. This is because there is still a residual risk that an alarm is not given and thus forced evacuation does not occur if, for example, an event is missed or the equipment fails.
    b. The Middle and Worst Case scenarios rely on people making the decision to act for themselves. If the alert is given early, most people will not evacuate and/or leave it too late to do so, and then will not be able to evacuate due to, for example, flooding or even smaller debris flows that may not threaten life but impede evacuation. In these scenarios, it could be that as high as 90% of the people in the hazard zone are still present when the hazard occurs.
2. For Stage 3 (3–6 minutes lead time; adopting trip wire sensors and assuming some people are evacuated during Stages 1 and 2): the 'public don't notice' the alert and 'public not safe fast enough' are the components that dominate the probability of failure of the EWS. This is because the trip wire has a very 'short fuse' (meaning minimal time between the event occurring and the debris impacting the fan, which hampers awareness, decision making and evacuation), so some or many people would not be able to move fast enough to evacuate from the hazard zone, especially if the area is flooded by water preceding the first surge of a debris flow.
    a. In the Good scenario, which assumes most people are still present in the hazard zone – even after being issued with alerts 24 hours and 2 hours prior, based on the rain radar and rain gauge and synoptic data – there is a relatively high probability of failure of the trip wire (up to 25% failure rate based on precedent) to initiate the siren telling people to evacuate.
    b. In the Good scenario, it could be that 10–20% of people still in the hazard zone are present when the hazard occurs because either the trip wire fails after the two phases of mandatory warning – in Stages 1 and 2 – have not been triggered in a subset of events and, finally, even if the EWS, works people may have to run through flood waters to evacuate to safe areas.
    c. In the Middle scenario, the more realistic scenario, it could be that up to 80% of the people still in the hazard zone are present when the hazard occurs, especially if most people cannot run or evacuate due to flooding.

3. Other factors that might prevent people from evacuating at the different stages are, for example, missed alarms, which will vary for sensor types, and the number of false alarms, which would be higher at the 2- to 24-hour stages, thus fostering a low threat perception.
4. Flooding is a potential impediment for people evacuating. According to McSaveney et al. (2005), flooding occurred several hours prior to the debris from the 2005 debris flow reaching the fan. Flooding may also be accompanied by relatively small volume debris flows, which may not threaten life but could impede evacuation.
5. Section 1.7 of the Bay of Plenty Regional Council's Regional Policy Statement calls for a 'precautionary approach' where uncertainty exists.

Based on the points above, and given the uncertainties associated with a debris flow EWS as discussed in this report, the likelihood of evacuating everyone who may be exposed to debris flows hazards from the Awatarariki Fan is low, meaning that some people are likely to still be present in the hazard area should a debris flow occur, given the high probability of failures of the EWS. This would mean that some people may still be living with levels of risk as presented by Tonkin & Taylor (2013, 2015). Thus, adopting such a system as the means to mitigate the risk to people living on the fan is not, in our opinion, aligned with taking a precautionary approach, as stated in Section 1.7 of the Bay of Plenty Regional Council's Regional Policy Statement.

6.0 ADDRESSING THE KEY OBJECTIVES

6.1 Objective 1: How to Design and Evaluate an EWS

The framework presented in this report can be used to design and evaluate an EWS, which covers the following aspects:

- How to understand the context (Section 2).
- How to define effective response/user needs, including time, location, distance and numbers of people (Sections 3 and 4).
- Preliminary review of 'case studies' with respect to effectiveness of short-fuse warnings (the scenarios and estimated probabilities in Section 4).
- How to drive better human behaviour (e.g. message channels, education, exercises; Section 2).
- How to estimate ongoing (post-installation) residual risk (Section 4).
- What metrics and triggering thresholds are needed versus what is possible (Sections 3 and 4).
- What technology is required (including consideration of the effect of forecast scale/ period to certainty) (Sections 3 and 4).
- Alerting (Sections 3 and 4).
- Triggering (automation) (Sections 3 and 4).
- Detection (including telemetry) (Sections 3 and 4).
- Data streams (automation) (Sections 3 and 4).

Given the scope of this work, and the time constraints under which the work has been carried out, any future detailed design would also need to consider the following:

- Writing of guidelines and response plans and integrating with existing CDEM requirements.
- How to estimate start up and ongoing costs (including staff time, community involvement and ongoing effectiveness certification).
- Recommendations for peer review.
- How to evaluate the system including uncertainties (initially theoretical and post-installation based on the performance of the EWS).
- Human response and residual risk.
- Technological failure and false alarm rates, including levels of redundancy; ownership and operational responsibilities, including inspection and maintenance; reliability; insurability; and liability in the event of failure.

6.2 Objective 2: Outline of Necessary Community Consultation

Community consultation is critical for the success of the EWS. Regarding the work carried out for this report, it was not possible to contact those people living on the Awatarariki Fan. This was due to the Bay of Plenty Regional Council Regional Natural Resources Plan change process currently underway and the related Plan Change Hearing.

The National Disaster Resilience Strategy states that an objective is to “enable and empower community-level response, and ensure it is connected into wider coordinated responses, when and where necessary” (MCDEM 2019). Enabling and empowering the public, and developing a people-centred EWS, requires engagement with the community at risk. If there is little engagement of the community in the design and operation of the system, there is a risk that there is a lack of trust or ownership of the system (Basher 2006), which can lead to little ongoing political support and, potentially, a lack of appropriate behavioural response to warnings.

Adopting people-centred approaches can have difficulties, primarily to do with a lack of willingness among the public at risk to share responsibility for disaster risk management with authorities in some cases, and the potential for conflict between public and private interests (Scolobig et al. 2015). Local communities need to be resourced adequately, and authorities need to understand the public’s perspectives and responsibility expectations, improve their communication skills and be willing to undertake long-term engagement (Scolobig et al. 2015).

The International Association for Public Participation (IAP2; www.iap2.org/) describes various uses of community engagement; how to design the engagement (including understanding the context); how to decide on the level of influence of the public on the outcome, which ranges from ‘informing’ the public through to ‘empowering’ the public; and the many methods of engagement to choose from. The steps that one must go through to design the engagement (from the IAP2 resources) are:

1. Understand the context (at local to international levels).
2. Scope the project to determine the focus of the engagement.
3. Understand the people and stakeholders involved.
4. Set the purpose of the engagement.
5. Shape the influence each party has on the outcomes.

Should an EWS be designed in future for Awatarariki catchment, or other areas at risk of debris flow, we recommend that authorities ensure they are trained in community engagement practices so that an effective engagement plan can be designed and carried out.

6.3 Objective 3: Summary of ‘Show Stoppers’

Objective 3: Identify any initially obvious issues ‘show stoppers’, that could reduce the effectiveness of the EWS (i.e. ‘show stoppers’) and whether an EWS would be suitable/ unsuitable for the Council to consider as an option to manage the risk. The main show stoppers identified from this current work are:

- For Stages 1 and 2 (2–24 hours lead time, based on synoptic, rain radar and rain measurements and rain intensity/duration thresholds for triggering landslides): The ‘public don’t act’ component dominates the probability of failure of the EWS under the Worst Case and Middle scenarios.
- For Stage 3 (3–6 minute lead time; adopting trip wire sensors and assuming some people are evacuated during Stages 1 and 2): the ‘public don’t notice’ the alert and ‘public not safe fast enough’ are the components that dominate the probability of failure of the EWS.
- Flooding, which would prevent people from evacuating to safety.

Although the probabilities of failure estimated for each of the nine EWS components presented in this report are preliminary and not based on any community consultation, it is unlikely that any future research would significantly reduce those estimated for the: 1) 'public don't act', 2) 'public don't notice'; or 3) 'public not safe fast enough' components.

6.4 Objective 4: Recommendations for Next Steps

Given the outcome of this report, we recommend that the community at risk is engaged in order to inform them. It will be important to ensure that the authorities carrying out the engagement:

- are aware of the context and history at Awatarariki catchment,
- understand the community members,
- are trained and/or experienced in community engagement,
- are clear on the purpose of the engagement (and share this in advance with the community), and
- have determined the influence the community has on the outcome (and make this known).

A key point to communicate could include that, even assuming evacuation is 100% successful prior to the arrival of an impending storm, there is still a residual risk due to the possibility that the rainfall or resulting debris flow are not detected, or the alert is not communicated due to telemetry failure. This means that, in these cases, the authorities and members of the public would not be aware that a potentially life-threatening debris flow is moving towards the community.

It is also worth highlighting with the community that 100% successful evacuation, in cases where detection and telemetry succeed, still relies on early mandatory evacuation, which is highly invasive. Further, that mandatory evacuation will occur, by its inherently early precautionary nature, many times in which the storm does not eventuate in any debris flow, each time being highly disruptive (evacuation for many hours) and cumulatively eroding trust and buy-in to the EWS – effectively as 'false alarms'. This distrust and lack of buy-in is likely to grow as properties are sold to new owners or rented to new tenants who were not part of the initial risk-acceptance and warning-system-acceptance discussion and agreement.

7.0 SUMMARY/CONCLUSIONS

This report presents a framework for EWS design and for the evaluation of likelihood of EWS failure. We summarise considerations related to more effective EWS and provide indicative failure probability estimates. We also provide recommendations for further work if an EWS was going to be designed using this framework.

In developing the framework and researching indicative failure probabilities, the main findings / show stoppers relating to an EWS to manage the risk to people on the fan from debris flow hazards are:

1. For Stages 1 and 2 (2–7, and 24 hours lead time): The ‘public don’t act’ component dominates the probability of failure of the EWS under the Worst Case and Middle scenarios.
2. For Stage 3 (3–6 minutes; adopting trip wire sensors and assuming some people are evacuated during earlier Stages 1 and 2): The ‘sensor’, the ‘public don’t notice’ the alert and ‘public not safe fast enough’ are the components that dominate the probability of failure of the EWS. This is because the trip wire has an up-to-25% failure rate and has a very ‘short fuse’ (meaning minimal time between the event occurring and the debris impacting the fan, which hampers awareness, decision making and evacuation), so some or many people would not be able to move fast enough to evacuate from the hazard zone, especially if the area is flooded by water preceding the first surge of a debris flow.
3. Other factors that might prevent people from evacuating at the different stages are, for example, missed alarms, which will vary for sensor types, and the number of false alarms, which would be higher at the 2- to 24-hour stages, thus fostering a low threat perception and lack of trust in the warning system.
4. Flooding is a potential impediment for people evacuating. According to McSaveney et al. (2005), flooding occurred several hours prior to the debris from the 2005 debris flow reaching the fan. Flooding may also be accompanied by relatively small volume debris flows, which may not threaten life but could impede evacuation.
5. Section 1.7 of the Bay of Plenty Regional Council’s Regional Policy Statement calls for a ‘precautionary approach’ where uncertainty exists. Given the uncertainties associated with a debris flow EWS’s effectiveness at protecting life safety as listed in this report, adopting an EWS as the means to mitigate the risk to people living on the fan is not, in our opinion, aligned with taking a precautionary approach.

8.0 ACKNOWLEDGMENTS

In writing this report, our thoughts are with everyone effected by the debris flow in 2005. This was a traumatic event, and many have experienced ongoing difficulties in recovery. We acknowledge these past and current residents and property owners, as well as any future potential users of the land.

We would also like to acknowledge Whakatāne District Council (WDC) for its endeavours over the past 15 years to deliver a solution to the community living with this hazard.

The authors would like to thank Dr Julia Becker (Massey University) and Sally Dellow (GNS Science) for reviewing this report, and Jeff Farrell (WDC), Tim Davies (University of Canterbury) and Andrew Green (Brookfields) for providing comments on previous drafts of this report.

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APPENDICES

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APPENDIX 1 DEBRIS FLOW RISK, AWATARARIKI CATCHMENT – EARLY WARNING SYSTEM WORK STREAM

Memo sent on 10/12/2015, from GNS Science to Whakatāne District Council.

Introduction

Jeff Farrell of Whakatāne District Council (WDC) asked GNS Science to provide information relating to the design of a debris flow early warning system for the Awatarariki catchment above the township of Matatā. In 2005, a large debris flow occurred in this catchment, which damaged homes and infrastructure in Matatā.

Risk assessments have been carried out by Tonkin & Taylor, and the assessed annual individual fatality risk to dwelling occupants in the area affected by debris flow hazards has been assessed as being intolerable by WDC and most of the local community.

The purpose of the debris flow early warning system is to warn users of the council reserve land, road and rail users and any dwelling occupants who choose to remain after the retreat, of the possible imminent hazard of a dangerous debris flow in the area.

This email provides preliminary information relating to the development of a debris flow early warning system. This potential design of a system might follow the 'Components of an Effective Early Warning System' developed by GNS Science. The main components would comprise:

1. Roles and responsibilities of the various stakeholders and GNS Science.
2. The effectiveness of debris flow early warning systems.
3. The design of a potential early warning system.
    a. Alert and warning thresholds
    b. Hardware, installation, software and communication
    c. Annual review of the alert and warning thresholds
    d. Peer review
    e. Maintenance
4. Planning, communication, education, participation and exercises.

1. Roles and Responsibilities

GNS Science: To establish the alert and warning thresholds, scope the hardware and install the monitoring and data transfer equipment (from site to office). Analyse the collected data from the installed instruments and review the thresholds on an annual basis. We would also work with WDC and Environment Bay of Plenty (EBoP) to help with the planning, communication, education and participation, components of the warning system. GNS Science could also provide technical maintenance of the equipment.

WDC and EBoP: To operate the warning system and lead the planning, communication, education and participation components of the system. WDC and EBoP would also issue the alerts and warning.

NZTA: To action the alerts and issue warnings to road users, and possibly operate barriers / warning lights to prevent access to the section of road affected by debris flow hazards.

KiwiRail: To action the alerts and issue warnings to rail users, and possibly operate barriers / warning lights to prevent access to the section of road affected by debris flow hazards.

2. The Effectiveness of Debris Flow Early Warning Systems

Given the velocity and volume of potential debris flows in the Awatarariki catchment and the risk to residents and road and rail users, it is unlikely that an early warning system based on detecting a debris flow once it initiates would be effective. This is because there would be little notification time between: i) the identification of a debris flow, ii) a warning being issued and acted upon and iii) the debris reaching the at-risk people and infrastructure. Therefore, the system would need to be based on debris flow triggering rainfall intensity/duration thresholds, rather than trip wires and stream flows alone.

However, even if such a system based on rainfall thresholds were to be installed, it is still possible that the warnings, once issued, may not be received by those affected in time for them to take protective action. It is therefore possible that, should a debris flow initiate, not everybody in the affected area will be able to evacuate, possibly resulting in deaths. Therefore, it should not be assumed that a debris flow early warning system would be infallible.

In order to ensure that a debris flow does not occur without a warning being given, it is necessary that there will be false warnings given where no debris flow occurs. This must not be allowed to undermine the credibility of the system and would need to be managed by WDC. Experience from Japan suggests that false warnings (where a warning is given and no debris flow occurs) happen between 40 and 50% of the time. This must be balanced against the consequences of a failure to warn, which may have more legal consequences than does failure to act on a warning, once given.

3. The Design of a Potential Debris Flow Warning System

Alert and warning thresholds: An alert indicates that something significant has happened or is likely to happen. A warning typically follows an alert and provides more detailed information, indicating what protective action should be taken.

In Japan and Taiwan, typical debris flow alerts and warnings arise when:

1. Alert: Rainfall of a given intensity/duration and amount (that exceeds the threshold) is expected to occur in the catchment.
2. Alert: Rainfall in the catchment is approaching the thresholds where debris flows may initiate.
3. Warning: Rainfall in the catchment has exceeded the threshold when debris flows initiate, and warnings are issued in multiple ways, including social media.

At the Awatarariki catchment, the alert and warning thresholds would be based on precedence, i.e. what rainfall intensities and amounts have, in the past, triggered landslides in the area, and not just in the Awatarariki catchment. These thresholds would form the basis of the monitoring system.

Although no soil moisture data is currently available locally for the catchment, over time soil moisture conditions (rather than its proxy of antecedent rainfall) would be used to refine the alert and warning thresholds. In Japan, the lack of such data (at the site scale) is thought to be the cause of many of the false warnings.

Once the thresholds are set, MetService would issue rainfall warnings to WDC and EBoP (as currently happens), and discussions with them should be undertaken at the earliest time to ensure collaboration and that the correct information is provided at the scale needed. There should be discussions around the uncertainties of these predictions.

Hardware, installation, software and communication: It is anticipated that: i) rainfall, ii) soil moisture and iii) stream flow would need to be monitored within the catchment. These instruments would need to be able to record the data at the correct temporal resolution and be able to transmit the data in real time remotely to locations where it can be plotted and displayed, alert and warnings given and the data analysed and interpreted by the end user.

Annual review of the alert and warning thresholds: There would need to be carried out to assess what has happened within the catchment during the monitoring period, using the data collected from the instruments and any local observations. The thresholds may then be revised based on these observations. In Japan, thresholds are fixed and do not change. This is believed to have led to many false warnings being issued.

Peer review: The thresholds and system will need to be independently peer reviewed.

Maintenance: This is needed on an ‘as needed’ and periodic basis, often-requiring immediate response if equipment malfunctions. Redundancy must be built into the system to ensure a robust warning system.

4. Planning, Communication, Education, Participation and Exercises

These components are essential to any warning system. GNS Science social scientists could work with WDC and EBoP to develop these. GNS Science has much experience with this, i.e. the Tongariro warning system and ERLAWS Crater Lake warning system.

Approximate Cost of the Early Warning System Components

Establish alert and warning thresholds: $20K

Design the system: $10K

Purchase, install and establish the hardware [based on three field stations: i) soil moisture, ii) rain and iii) stream flow]: $70–90K

Reporting: $40K

Peer review (GNS only): $10K

Total $150K to 170K

Items (1), (4), the annual review, and developing the software required to receive and plot the data, alert the responsible people and issue the warnings are not included in this cost. This cost would depend on how and whether EBoP could incorporate such a system into their current hazard management process, e.g. flood management processes.

Maintenance is also not included in the cost and is largely uncertain. This will depend on how the equipment performs.

24/7 monitoring of incoming data (by WDC or EBOP) is not included in the cost.

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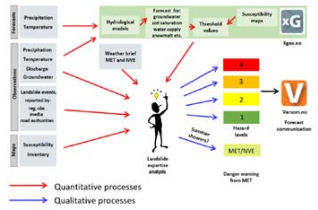
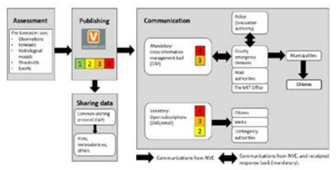
APPENDIX 2 LANDSLIDE EARLY WARNING SYSTEM LITERATURE REVIEW

	Badoux A, Graf C, Rhyner J, Kuntner R, McArdell BW. 2009. A debris-flow alarm system for the Alpine Illgraben catchment: design and performance. *Natural Hazards*. 49(3):517–539. doi:10.1007/s11069-008-9303-x.	Baudoin M-A, Henly-Shepard S, Fernando N, Sitati A, Zommers Z. 2016. From top-down to "community-centric" approaches to early warning systems: exploring pathways to improve disaster risk reduction through community participation. International *Journal of Disaster Risk Science*. 7(2):163–174. doi:10.1007/s13753-016-0085-6.	Capparelli G, Tiranti D. 2010. Application of the MoniFLaIR early warning system for rainfall-induced landslides in Piedmont region (Italy). *Landslides*. 7(4):401–410. doi:10.1007/s10346-009-0189-9.	Coles AR, Quintero-Angel M. 2018. From silence to resilience: prospects and limitations for incorporating non-expert knowledge into hazard management. *Environmental Hazards*. 17(2):128–145. doi:10.1080/17477891.2017.1382319.
Comments	Review of the design performance of a working alarm system. Out of 20 alerts issued, only one was a false alarm.	A look into community-centric approaches to a range of EWS not specific to landslides. One case study looks into Sri Lanka, where 30% of the land area is prone to landslides. A 2009 pilot project introduced a number of community based EWS in vulnerable areas and engaged the community in risk education programs, training on evacuation paths and evacuation drills in an emergency situations; and also involving them in the risk detection process. In 2010, 121 families evacuated their homes on the basis of the gauge warning, and over time some community leaders decided to relocate to areas of reduced risk on the basis of this study.	A 'MoniFLaIR System' was developed to determine rain thresholds, and a case study on a previously analysed slope "confirmed its reliability as an effective warning in the case of situations that might cause new movement".	Cannot find access online, but it is referenced in Marchezini et al. (2018) discussing landslides in Colombia: "Another participatory EWS experience involving women was reported in Manizales, Colombia. The program 'Guardians of the Slope' hires female heads of household to communicate landslide risk to the residents and to maintain landslide-prevention infrastructure. The women guardians are also responsible for conducting door-to-door educational activities and also to share their knowledge with children and youth in school meetings."
Landslide Type	Debris flow within a debris fan area.	Not specified.	Slope debris flow.	N/A
At-Risk Facilities/People	Residents in Susten (municipality Leuk), tourists and other land users.	Vulnerable populations in Sri Lanka.	General population.	N/A
Location	Illgraben catchment (9.5 km^2), located in the Canton of Valais, Switzerland.	Case studies from Kenya, Hawai'i and Sri Lanka (Sri Lanka case is specific to landslides).	North-western Italy.	N/A
Metrics Used to Initiate Alerts/Warnings	If flows with a depth larger than ~0.25–0.3 m and/or Geophone impulses exceed the threshold for more than 5 seconds.	Water gauge height. Green for water height between 75 and 100 mm, yellow for water height between 100 and 150 mm and red for water height of 150 mm or above. The red zone indicates that it is time for communities to evacuate for safety.	Rainfall based on the threshold determined by using historical rain and landslide data.	N/A
Sensors Used	Geophones (for front velocity determination and system triggering), radar, laser and ultrasonic devices to determine flow depth, video cameras and a debris flow force plate. Three rain gauges (data only used from one as it is most reliable).	Fibreglass rain gauges.	Rain gauges located near the case study landslide site.	N/A
Telemetry System	Alert system uses the public mobile phone network (GSM) for communication and data exchange.	Verbal communication between the community observers who monitored the gauges daily and the surrounding households.	The system acquires rainfall data transmitted in real time by the rain gauges located near the landslide site.	N/A
Detection Time	"The shortest possible detection-to-alert time is 5 seconds (and additionally a few to a few tens-of-seconds for transmission." Automated alert signals near the active channel prior to (5–15 minutes) the arrival of a debris flow.	N/A	The system calculates the value of the mobility function every 30 minutes.	N/A
Analysis of Data and Threshold Relationships	If thresholds are exceeded for more than 5 seconds it is transmitted to automatic alert systems.	N/A	Rainfall was the only threshold used. The identified threshold value of the mobility function is: Ycr = 65.89.	N/A
Warning Time	Alerts go off 5–15 minutes before the debris arrive.	Not specified.	The system is able to indicate possible developments over the coming 24 hours.	N/A
Types of Warning	Alarms both acoustic and visual to warn people on footpaths of the channel to evacuate.	Green, yellow and red. Red is the warning level where evacuation shall occur. Delivered verbally.	N/A	N/A

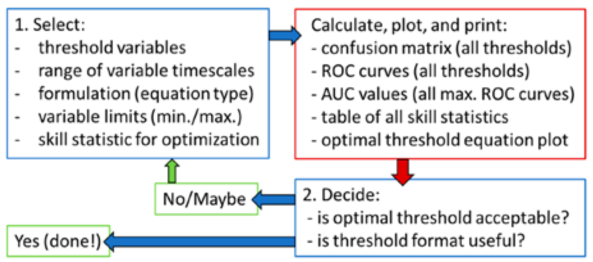
	Crosta GB, Agliardi F, Rivolta C, Alberti S, Dei Cas L. 2017. Long-term evolution and early warning strategies for complex rockslides by real-time monitoring. *Landslides*. 14(5):1615–1632. doi:10.1007/s10346-017-0817-8.	Dixon N, Smith A, Flint JA, Khanna R, Clark B, Andjelkovic M. 2018. An acoustic emission landslide early warning system for communities in low-income and middle-income countries. *Landslides*. 15(8):1631–1644. doi:10.1007/s10346-018-0977-1.	Glade T, Crozier M, Smith P. 2000. Applying probability determination to refine landslide-triggering rainfall thresholds using an empirical “antecedent daily rainfall model”. *Pure and Applied Geophysics*. 157(6-8):1059–1079. doi:10.1007/s000240050017.
Comments	The study looks into using ground-based radar interferometry to understand mechanisms to produce early warning criteria for complex landslides. Results found that it is useful to predict displacements of rainfall sensitive areas, but not for rockslides affected by longer-term progressive failure. Fairly extensive workflow process to define quantitative early warning thresholds.	An alert system which is relatively cheap and relies on acoustic emissions to measure slope displacement rate. Aimed at low income areas.	Thresholds were created using historical landslide and daily and antecedent rainfall. This was in turn used to create theoretical regional models that show the probability of a landslide occuring given rainfall conditions.
Landslide Type	Rockslide, which is nested into a larger deep-seated gravitational slope deformation.	Not specified.	Various due to the different study areas used.
At-Risk Facilities/People	State road.	Populations from middle- and low-income countries.	Infrastructure and general population within the regions.
Location	Central Italian Alps.	N/A	New Zealand. Three study areas were used: Hawke’s Bay, Wairarapa and Wellington.
Metrics Used to Initiate Alerts/Warnings	Displacement. Rainfall.	Acoustic emission (which is indicative of slope displacement rate). A threshold slope displacement rate in the range 5 to 10 mm/min (i.e. Moderate rate) is proposed.	N/A
Sensors Used	Ground-based radar interferometry.	Acoustic emission (AE) monitoring.	Historical rainfall data was provided by the NIWA climatic database.
Telemetry System	Not specified?	Unitary battery operated sensor monitors AE continuously in (near) real time. It is linked to a wireless node to provide alert messages to a nominated person using a standard mobile telecommunications network.	N/A
Detection Time	Not specified?	At the end of each monitoring period of 15–30 minutes, an alert can be triggered if the threshold is exceeded.	Theoretically, weather forecasting could be used to predict rainfall and therefore landslide probabilities within regions.
Analysis of Data and Threshold Relationships	The quantitative analysis of GB-InSAR data consists in setting up *a posteriori* monitoring networks, characterised by an improved capability of mirror-specific mechanisms or aspects of slope instability by fully exploiting radar displacement fields. Data, validated by ground-based measurements, allows identifying homogeneous rockslide sub-areas and interpreting their behaviour in order to establish domain-specific warning thresholds consistent to the dominant deformation and failure processes mirrored by monitoring data in different domains.	AE is quantified by counting the number of times the AE signal exceeds a pre-determined voltage threshold.	24-hour rainfall and antecedent period of 10 days. *Regional equations for calculation of thresholds with different probabilities of occurrence (with P = probability of landslide occurrence at a given value of r and r_a; r = daily rainfall; r_a = antecedent daily rainfall).* Region — Threshold probability equation Wairarapaa — $\log\left(\frac{P}{1-P}\right) = -8.45 + 0.033 * r + 0.036 * r_a$ Hawke's Bay — $\log\left(\frac{P}{1-P}\right) = -8.82 + 0.033 * r + 0.75 * r_a - 0.0052 * r_a^2 + 0.00000012 * r_a^3$ Wellington — $\log\left(\frac{P}{1-P}\right) = -8.08 + 0.072 * r + 0.00036 * r_a^2$
Warning Time	Real-time / early warning.	Near real time.	N/A
Types of Warning	Pre-alert, alert and emergency.	Alert via text message.	N/A

	Guzzetti F, Gariano SL, Peruccacci S, Brunetti MT, Marchesini I, Rossi M, Melillo M. 2020. Geographical landslide early warning systems. *Earth-Science Reviews*. 200:102973. doi:10.1016/j.earscirev.2019.102973.	Hong Y, Adler RF, Huffman G. 2007. An experimental global prediction system for rainfall-triggered landslides using satellite remote sensing and geospatial datasets. *IEEE Transactions on Geoscience and Remote Sensing*. 45(6):1671–1680. doi:10.1109/TGRS.2006.888436.	Hürlimann M, Coviello V, Bel C, Guo X, Berti M, Graf C, Hübl J, Miyata S, Smith JB, Yin H-Y. 2019. Debris-flow monitoring and warning: review and examples. *Earth-Science Reviews*. 199:102981. doi:10.1016/j.earscirev.2019.102981.
Comments	A comprehensive review of the current and past implemented landslide EWS. Includes critical analysis of 26 systems. “We find that currently only five nations, 13 regions, and four metropolitan areas benefit from landslide EWS.” They conclude that operational forecast of weather-induced landslides is feasible, and they give 30 recommendations to further develop and improve geographical landslide EWS.	A framework for developing a real time prediction system based on landslide surface susceptibility and real-time space based rainfall analysis system.	This review describes the available debris-flow monitoring techniques and proposes recommendations to inform the design of future monitoring and warning/alarm systems. Detailed descriptions of nine monitoring sites.
Landslide Type	N/A	Focus on shallow landslides. Debris flows, mudslides, mudflows or debris avalanches.	Debris flow
At-Risk Facilities/People	N/A	Global population.	N/A
Location	Regional systems: Hong Kong (since 1977). San Francisco Bay area, California, USA (1985–1995). Western Oregon, USA (1997–2007). Seattle, Washington, USA (since 2002). Southern California, USA (2005). Vancouver, British Columbia, Canada (2009-2010). Combeima Valley, Colombia (2009). Rio de Janeiro, Brazil (1996). Java, Indonesia (2010). Southern Taiwan (2018). Piedmont, northern Italy (2008). Emilia-Romagna, northern Italy (2006). Umbria, central Italy (2013). Tuscany, central Italy (2015). Sicily, southern Italy (2017). National Systems: Taiwan. Italy. Norway. Central America and the Caribbean. Indonesia. Scotland. Global system (since 2007).	Global.	Five systems in Europe, three in Asia and one in the USA.
Metrics Used to Initiate Alerts/Warnings	N/A	Landslide susceptibility, which is classified into six relative categories (based on variables such as slope, soil, elevation, aspect, landcover, lithology) and real-time satellite rainfall data to detect hazards.	N/A
Sensors Used	Operational landslide EWS use information from rain gauge networks, meteorological models, weather radars and satellite estimates; most systems use two sources of rainfall information.	TRMM Multisatellite Precipitation Analysis (TMPA).	“Sensors found in these monitoring systems can be separated into two classes: a class measuring the initiation mechanisms, and another class measuring the flow dynamics.” The first class includes rain gauges, soil moisture and pore water pressure sensors. The second involves a variety of sensors focusing on flow stage or ground vibrations with cameras to validate data interpretation.
Telemetry System	N/A	N/A	N/A
Detection Time	N/A	Real time.	N/A
Analysis of Data and Threshold Relationships	Landslide EWS use one or more types of landslide forecast models, including rainfall thresholds, distributed slope stability models and soil water balance models; most systems use landslide susceptibility zonations.	A worldwide threshold was used, based on previous studies. The rainfall totals are accumulated from the TRMM database and the sliding susceptibility category is taken from a global Landslide Susceptibility map.	N/A
Warning Time	N/A	Real time (authors suggest the lag between peak rainfall and failure would give enough warning time), but the model could also use forecasted rainfall for early warning.	N/A
Types of Warning	N/A	N/A	N/A

	International Network for Multi-hazard Early Warning Systems. c2018. Multi-hazard early warning systems: a checklist. Geneva (CH): World Meteorological Organization. Outcome of the first Multi-hazard Early Warning Conference 22 to 23 May 2017 – Cancún, Mexico.	Intrieri E, Gigli G, Mugnai F, Fanti R, Casagli N. 2012. Design and implementation of a landslide early warning system. *Engineering Geology*. 147–148:124-136. doi:10.1016/j.enggeo.2012.07.017.	Krøgli IK, Devoli G, Colleuille H, Boje S, Sund M, Engen IK. 2018. The Norwegian forecasting and warning service for rainfall- and snowmelt-induced landslides. *Natural Hazards and Earth System Sciences*. 18(5):1427–1450. doi:10.5194/nhess-18-1427-2018.	Lagomarsino D, Segoni S, Fanti R, Catani F. 2013. Updating and tuning a regional-scale landslide early warning system. *Landslides*. 10(1):91–97. doi:10.1007/s10346-012-0376-y.
Comments	Nothing specific to landslides (the word 'landslide(s)' was only used one time in the entire issue). The first part gives background information on four aspects to early warning systems: Disaster risk knowledge; Detection, monitoring, analysis and forecasting of the hazards and possible consequences; Warning dissemination and communication; and Preparedness and response capabilities. Each aspect has a checklist which "if followed, will provide a solid basis upon which to build or assess an early warning system."	This is a very localised warning system that does not have an immediate response/action plan due to the slow nature of the expected failure.	Comprehensive report on the National Norwegian forecasting and warning service. A rate of over 95% correct daily assessments.	Based on the SIGMA warning system, same system as (Martelloni et al. 2012). This version is "able to predict, in a completely automated and objective way, a quantitative risk scenario (number of landslides in each alert zone) in full accordance with civil protection standards" (unlike previous versions). It also discusses the implications of the size and number of territorial units and updating rain thresholds with larger calibration datasets.
Landslide Type	N/A	182,000 m^3 rock wedge slide.	Rainfall- and/or snowmelt-induced.	Forecasts shallow and deep landslides using different methods.
At-Risk Facilities/People	N/A	Two roads that are important for local transportation. No homes or local populations at risk (only those using the road).	Regional stakeholders and the general public.	N/A
Location	N/A	Torgiovannetto in Central Italy.	Norway (national scale).	In the Emilia-Romagna region (northern Italy).
Metrics Used to Initiate Alerts/Warnings	N/A	Deformation (averaged over 24 hours).	Automatic hydrological and meteorological stations, landslide and flood historical database, hydro-meteorological forecasting models, thresholds or return periods, and a trained group of forecasters.	Rainfall thresholds based on an algorithm. For shallow slides it takes into account daily and 1-, 2- and 3-day cumulative rainfall. For deep slides it takes into account cumulative rainfall from periods stretching 4–243 days.
Sensors Used	N/A	13 wire extensometers, 1 thermometer, 1 rain gauge and 3 cameras.	Meteorological stations include rain gauge (hourly and daily data), temperature sensors, and snow and wind sensors. Hydrological stations (over 400) are used to measure discharge in rivers, snow depth and coverage, and 70 stations measure ground water levels.	N/A
Telemetry System	N/A	The sensor network is based on five sets of macro-components: radio processors, transducers, analogue-digital converter, data-logger and gateway. Nine extensometers are connected through cables to a data logger, and four are connected through radio to another data logger. The thermometer and rain gauge is also connected through radio.	Regional danger level is communicated through a web bulletin (varsom.no). The public can also subscribe to SMS and/or email notifications based on their preferences (which type of hazard and what warning level).	N/A
Detection Time	N/A	Data is checked daily during periods of no warning, but the sensors of the WSN make an acquisition every 60 seconds; only a 5-minute mean datum is sent to the data-logger in order to save energy.	Real-time/forecasts.	N/A

	International Network for Multi-hazard Early Warning Systems. c2018. Multi-hazard early warning systems: a checklist. Geneva (CH): World Meteorological Organization. Outcome of the first Multi-hazard Early Warning Conference 22 to 23 May 2017 – Cancún, Mexico.	Intrieri E, Gigli G, Mugnai F, Fanti R, Casagli N. 2012. Design and implementation of a landslide early warning system. *Engineering Geology*. 147–148:124-136. doi:10.1016/j.enggeo.2012.07.017.	Krøgli IK, Devoli G, Colleuille H, Boje S, Sund M, Engen IK. 2018. The Norwegian forecasting and warning service for rainfall- and snowmelt-induced landslides. *Natural Hazards and Earth System Sciences*. 18(5):1427–1450. doi:10.5194/nhess-18-1427-2018.	Lagomarsino D, Segoni S, Fanti R, Catani F. 2013. Updating and tuning a regional-scale landslide early warning system. *Landslides*. 10(1):91–97. doi:10.1007/s10346-012-0376-y.
Analysis of Data and Threshold Relationships	N/A	Extensometers are used to determine alerts, with thresholds (velocity) range depending on location from 0.50–1.00 mm/day. Once two instruments have been found to breach their thresholds, an alert is manually sent to all stakeholders and monitoring and alert level is increased to 'attention'. Expert opinion is then used to analyse the other data sources.	Daily landslide assessment routine is summarised: • Weather forecast, also as input for the hydrological model. • Model run, forecasted hydro-meteorological parameters, forecasted threshold. • Collection of real-time data. • Interpretation of model results and use of additional information from simulated hydro-meteorological parameters, i.e. snow and groundwater conditions. • Analysis of forecasted thresholds also corrected with susceptibility information. • Preparation of forecast information and warning messages with description of possible events and expected impact. • Communication and dissemination of messages to warn the public and local authorities. • Provision of hydrological situation updates and answers to questions from media or another recipients. 	Based on spatially variable statistical rainfall thresholds.
Warning Time	N/A	Data is manually checked daily, and from here alerts are sent to 24-hour 'stakeholders' if the thresholds are met. They then decide, using expert opinion and increased monitoring, whether to manually close the road. "The landslide is expected to show an accelerating trend a few days before the failure, allowing some time for the emergency procedures."	Assessments are published at least twice a day and contain the forecast for today, tomorrow and the day after tomorrow.	N/A
Types of Warning	N/A	Three levels: • Ordinary (default) – Data is checked daily. • Attention level – Data is checked frequently and 24-hour stakeholders are alerted (preparing for an alarm). • Alarm level – Data is checked more, collapse is expected and the street is closed.	• Green awareness level, generally safe conditions. • Yellow awareness level, moderate landslide hazard. • Orange awareness level, high landslide hazard. • Red awareness level, very high landslide hazard. 	N/A

	Liao Z, Hong Y, Wang J, Fukuoka H, Sassa K, Karnawati D, Fathani F. 2010. Prototyping an experimental early warning system for rainfall-induced landslides in Indonesia using satellite remote sensing and geospatial datasets. *Landslides*. 7(3):317–324. doi:10.1007/s10346-010-0219-7.	Marchezini V, Horita FEA, Matsuo PM, Trajber R, Trejo-Rangel MA, Olivato D. 2018. A Review of studies on participatory early warning systems (P-EWS): pathways to support citizen science initiatives. *Frontiers in Earth Science*. 6:184. doi:10.3389/feart.2018.00184.	Martelloni G, Segoni S, Fanti R, Catani F. 2012. Rainfall thresholds for the forecasting of landslide occurrence at regional scale. *Landslides*. 9(4):485–495. doi:10.1007/s10346-011-0308-2.
Comments	Prototyped early warning system on a regional/local scale (using 30 m DEM) integrating a landslide susceptibility model, satellite precipitation monitoring system and a rainfall-induced landslide prediction model.	"This paper provides a social science framework to determine the elements of how citizen science and participatory early warning systems can be bridged." Framework is not specific to landslides, but further papers which include citizen science and landslide EWS were pulled out.	A large scale warning system (SIGMA). Spatial resolution of a few hundreds of square kilometres.
Landslide Type	"Rainfall-induced shallow landslides."	N/A	Shallow (soil slips and rapid flows) and deep-seated landslides (mainly rotational–translational slides, slow earth flows and complex movements).
At-Risk Facilities/People	Population in Karaganyar.	N/A	All population within the regional scale and territorial units.
Location	Karanganyar, Java Island, Indonesia.	N/A	Emilia-Romagna region (northern Italy).
Metrics Used to Initiate Alerts/Warnings	A landslide warning would be issued when the factor of safety value reaches below the critical value of 1.	N/A	Periods of cumulative rainfall. 1-, 2- and 3-day day checks for shallow landslides and 4–243 days to forecast deep-seated landslides.
Sensors Used	Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data. DEM. Soil maps. Precipitation from real time satellite data (NASA). Weather Research Forecasting (WRF) precipitation forecasts.	N/A	Pluviometers and rainfall forecasts.
Telemetry System	Not specified.	N/A	For each reference rain-gauge a software combines rainfall recordings from the regional automated network with rainfall forecasts and compares the resulting cumulative rainfalls with the thresholds. In the territorial units where the latter are exceeded, the software provides the corresponding alert level.
Detection Time	Prediction time shows a 3-hour delay.	N/A	Data is automated hourly from rain gauges and, from this and the warning model, could theoretically be automated to be real time.
Analysis of Data and Threshold Relationships	A threshold is determined using a rainfall-induced prediction model (SLIDE); when the factor of safety falls below 1 it is classified from moderate to high risk. Factor of safety can be determined by input data from the land susceptibility database, a satellite based precipitation monitoring system, a precipitation forecasting model. $F_s = \frac{\cot\beta \cdot \tan\emptyset' \cdot [\Gamma + m \cdot (n_w - 1)] + C' \cdot \Omega}{\Gamma + m \cdot n_w}$	N/A	Integrates an equation that represents the threshold in which landslides have happened in the past and applies this to future predictions using the data from integrated rain gauges (hourly) and rainfall forecasts. From this, alert levels are produced through decision algorithms. Each territorial unit will have different thresholds based on the data.
Warning Time	N/A	N/A	The model could theoretically be used to automatically generate warnings and alerts in real time, but longer calibration and validation periods would be required.
Types of Warning	N/A	N/A	A regional four-level alert scale (coded from 0 to 3), ranging from no landslides expected to alerting civil protection and public authorities.

	Michoud C, Bazin S, Blikra LH, Derron MH, Jaboyedoff M. 2013. Experiences from site-specific landslide early warning systems. *Natural Hazards and Earth System Sciences*. 13(10):2659–2673. doi:10.5194/nhess-13-2659-2013.	Mirus BB, Morphew MD, Smith JB. 2018. Developing hydro-meteorological thresholds for shallow landslide initiation and early warning. *Water*. 10(9):1–19. doi:10.3390/w10091274.	Peruccacci S, Brunetti MT, Gariano SL, Melillo M, Rossi M, Guzzetti F. 2017. Rainfall thresholds for possible landslide occurrence in Italy. *Geomorphology*. 290:39–57. doi:10.1016/j.geomorph.2017.03.031.	Preuner P, Scolobig A, Linnerooth Bayer J, Ottowitz D, Hoyer S, Jochum B. 2017. A participatory process to develop a landslide warning system: paradoxes of responsibility sharing in a case study in upper Austria. *Resources*. 6(4):54. doi:10.3390/resources6040054.
Comments	Surveyed 100 institutions in charge of landslide hazard. 21 institutions had operating early warning systems. Contains information and references to various early warning systems.	"Develop daily bi-linear thresholds within a two-dimensional parameter space, which rely on accurate 24-hour forecasts, measured recent rainfall and *in situ* soil saturation." The method is semi-automated.	Conclusion was that empirical rainfall amounts could be used to forecast landslides in Italy regardless of environmental differences on a large scale, but not regional.	The paper discusses the process and policy outcome of a case study of how responsibilities can be shared among the residents, experts and public authorities during the design and operation of landslide warning systems. It explores conflict and resolutions between stakeholders. Responsibility sharing includes (1) financial responsibility for the costs of the system and maintenance; (2) system responsibility for assuring that the system is designed, built, and maintained; and (3) information responsibility for ensuring regular information and timely warning.
Landslide Type	N/A	Shallow landslides, translational slope failures.	"Mostly shallow."	N/A
At-Risk Facilities/People	N/A	General population.	General population.	About 100 people live in and around the landslide-prone area and are directly or indirectly at risk. Approximately 55 buildings are in the risk area, which is popular among tourists.
Location	N/A	Seattle, Washington (the Seattle-Everett railway,) and in Portland, Oregon, USA.	Study area encompasses the whole of Italy, with thresholds also determined for 26 regions.	Gmunden, Austria.
Metrics Used to Initiate Alerts/Warnings	N/A	Soil saturation; recent and forecasted precipitation.	Rainfall.	N/A
Sensors Used	N/A	VWC sensors for soil saturation. Five sensors for the Seattle site and 11 for the Portland site.	2228 rain gauges.	Final solution included a precipitation measurement weather station. An inclinometer, a piezometer, discharge measurement and laser scan and inspections on demand.
Telemetry System	N/A	Not specified.	Not specified.	N/A
Detection Time	N/A	Calculate threshold variables 24 hours before the time of interest (for this study, retroactive measurements were taken instead of forecasted rainfall amounts). Study used both hourly and 24-hourly data inputs.	Not specified.	N/A
Analysis of Data and Threshold Relationships	N/A	 **Figure 1.** Schematic flow-chart of iterative, semi-automated process to identify appropriate threshold space, defined by input variables and timescales and optimize preferred threshold equation using receiver operating characteristics (ROC) analysis. Blue boxes and arrows indicate user input, red boxes and arrows indicate automated calculations, green boxes and arrows indicate user decisions.	A 20% exceedance probability national threshold was found to be capable of predicting all of the rainfall-induced landslides with casualties between 1996 and 2014. This could be used in future forecasting. It was concluded that accurate smaller scale regional thresholds could not be made through this study due to empirical limitations.	N/A
Warning Time	N/A	Theoretically it should be 24 hours before.	Not specified.	N/A
Types of Warning	N/A	Three levels of warning. Landslides unlikely, Landslides possible, Landslides probable.	N/A	N/A

	Ramesh MV. 2009. Real-time wireless sensor network for landslide detection. In: *SENSORCOMM 2009: proceedings, the Third International Conference on Sensor Technologies and Applications*. 2009 Jun 18–23; Athens, Greece. Los Alamitos (CA): IEEE. p. 405–409. doi:10.1109/sensorcomm.2009.67.	Sassa K, Picarelli L, Yueping Y. 2009. Monitoring, prediction and early warning. In: Sassa K, Canuti P, editors. Landslides – disaster risk reduction. Berlin (DE): Springer. p. 351–375. doi:10.1007/978-3-540-69970-5_20.	Terzis A, Anandarajah A, Moore K, Wang I. 2006. Slip surface localization in wireless sensor networks for landslide prediction. In: *ISPN 2006: the 5th International Conference on Information Processing in Sensor Networks*. 2006 Apr 19-21; Nashville, TN. New York (NY): ACM. p. 109–116. doi:10.1109/ipsn.2006.244105.	Thiebes B. 2012. Landslide analysis and early warning systems: local and regional case study in the Swabian Alb, Germany. Heidelberg (DE): Springer. 260 p. (Springer theses). doi:10.1007/978-3-642-27526-5.
Comments	A pilot deployment of wireless sensors on a hillslope which sent 'real-time data' to a data management centre for analysis. No type of warning system was explored.	A very basic set up of using rain gauges and simple extensometers connected to local sirens.	A proposed network of wireless sensor columns deployed at hills with landslide potential with the purpose of detecting the early signals preceding a catastrophic event. Simulated landslides showed accuracy in the order of cm.	Good PhD Thesis (Springer thesis/book). See Thiebes et al. 2014 for details.
Landslide Type	Not specified.	Not specified, but mountainous and hilly areas of weathered volcanic rocks.	Not specified, but those with a slip surface.	Deep-seated slides.
At-Risk Facilities/People	General population.	Local populations of low socioeconomic status who use the at-risk areas for agriculture practices / settlements.	N/A	Infrastructure and people.
Location	Idukki district of the Southern state of Kerala, India.	Banjarnegara Regency, Central Java Province.	N/A	Austria.
Metrics Used to Initiate Alerts/Warnings	Not specified.	Deformation and rain.	The slip plane is calculated and used to back-calculate the input parameters of a Finite Element model, which predicts the possibility of a catastrophic landslide.	Rain, pore-water pressure and displacement.
Sensors Used	Wireless sensor network (WSN) which includes pore pressure transducers, soil moisture sensors, geophones, stain gauges and tiltmeters. In a pilot test, two sensor columns, with ten sensors, were deployed with six wireless sensor nodes.	Long-span extensometers, rain gauge, pore pressure sensor, and monitoring scene by IP camera	Each wireless sensor column is equipped with a range of instruments such as strain gages, tensiometers, geophones, seismic sources and pore pressure transducers.	See Thiebes et al. 2014.
Telemetry System	Data is sent from the sensor to a sink node at kept near the deployment site. It is then transmitted 500 m to a field management centre over a Wi-Fi network. It is then sent to a data management centre 300 km away through a VSAT satellite earth station and a broadband connection.	Field server is a sensing device with real-time online data display system that gathers the data from multiple sensors and shows them in a webserver.	A wireless system; data is passed to an analysis station through an internet connection.	See Thiebes et al. 2014.
Detection Time	Not specified, but data is sent to the upper level sensor nodes every five minutes.	Instant following threshold.	Not specified.	See Thiebes et al. 2014.
Analysis of Data and Threshold Relationships	Not specified, but data is analysed by the data management centre and is able "to determine factor of safety of the mountain and probability of landslide occurrence with respect to the signals received from the deployed sensors."	Not specified.	Sensors would detect small movements of a slip surface. A distributed voting algorithm would then separate the subset of sensors that moved from the static ones. The direction of the displacements, as well as the locations of the moved nodes are used to estimate the position of the slip surface. This data would then be put through a "Finite Element model which would predict weather a landslide will occur".	See Thiebes et al. 2014.
Warning Time	Has potential for real-time warning.	Direct trigger from the extensometers once the threshold is met.	N/A	See Thiebes et al. 2014.
Types of Warning	N/A	Sirens directly connected to the sensors.	N/A	See Thiebes et al. 2014.

	Thiebes B, Bell R, Glade T, Jäger S, Mayer J, Anderson M, Holcombe L. 2014. Integration of a limit-equilibrium model into a landslide early warning system. *Landslides*. 11(5):859–875. doi:10.1007/s10346-013-0416-2.	Thomas MA, Mirus BB, Collins BD, Lu N, Godt JW. 2017. Variability in soil-water retention properties and implications for physics-based simulation of landslide early warning criteria [abstract]. In: *2017 GSA Annual Meeting*; 2017 Oct 22–25; Seattle, WA. Boulder (CO): Geological Society of America. Paper 216-2. doi:10.1130/abs/2017am-297875.	United Nations Development Programme. 2018. Five approaches to build functional early warning systems. Istanbul (TR): United Nations Development Programme. 66 p.	Valenzuela P, Zêzere JL, Domínguez-Cuesta MJ, Mora García MA. 2019. Empirical rainfall thresholds for the triggering of landslides in Asturias (NW Spain). *Landslides*. 16(7):1285–1300. doi:10.1007/s10346-019-01170-2.
Comments	Based on Thiebes thesis. It is a physically based slope stability model named CHASM (Combined Hydrology and Stability Model) that was integrated into a prototype semi-automated landslide EWS. For this study, only historic rainfalls were used and no realistic early warnings were issued.	An ensemble of texture-, laboratory- and field-based soil water retention properties for a monitored landslide-prone hillslope to examine simulated soil-water content (θ), pore-water pressure (uw), and the resultant factor of safety time series for conditions relevant to widespread shallow landslide initiation. “Results suggest that variability in soil-water retention properties should be considered for objective physics-based simulation of landslide early warning criteria.”	Nothing specific to landslides (the word ‘landslide(s)’ was only used seven times in the entire issue). The issue is separated into two parts. The first is the theoretical tools to understand the legal and institutional framework needed for EWS processes. The second part is a catalogue of practical solutions for the previous section. The solutions cover five topics; Institutional and legal capacity development, Technology deployment, Community outreach and community based solutions, Private sector engagement, and International co-operation and data sharing.	No practical application of landslide forecasting/warning system. Based on rain thresholds using historic landslide data.
Landslide Type	Not specified? “Reactivated landslide” on a slope of 0.5 km^2.	Shallow landslide. “The site consists of an approximately 1000 m^2 grassland hollow with shallow (≈ 1 m in depth) silty sand to silty clay soils overlying sandstone bedrock of the Orinda Formation.”	N/A	Not specified, but most frequent are small (metric to decimetric) and shallow.
At-Risk Facilities/ People	Local population, including houses nearby.	N/A	N/A	General population.
Location	Swabian Alb (Alps), Germany.	Information used was from the shallow landslide monitoring station operated by the US Geological Survey in the San Francisco Bay region, California, USA.	N/A	Asturias (NW Spain).
Metrics Used to Initiate Alerts/Warnings	Automated notifications are automatically issued if the factor of safety falls below a pre-defined threshold.	N/A	N/A	Daily precipitation data (24 hours) based on the statistical analysis of individual or multiple rainfall events that resulted in landslides in the past.
Sensors Used	Inclinometers, geodetic levelling and temporary tiltmeter measurements. Hydrological monitoring system, comprising TDR sensors and tensiometers located in three depths between 2 and 10 m at nine different locations. Two geoelectric resistivity profiles were installed.	Decagon EC-5 volumetric soil water content sensors. Stevens Greenspan PS7000 positive uw sensor. Onset Hobo U30 tipping bucket rain gauge. Soil-water content and soil suction sensors. MPS-1 sensors.	N/A	Six weather stations.
Telemetry System	A web processing service runs the CHASM algorithm on a server. Then a web notification service, automatically sends an SMS to stakeholders when there is a breach.	Telemetered instrumentation and non-telemetered (soil content and suction sensors. 15 minutes).	N/A	N/A
Detection Time	Real-time data, but experts are brought in to interpret the data outputs when thresholds are breached.	Not specified.	N/A	Not specified.

	Thiebes B, Bell R, Glade T, Jäger S, Mayer J, Anderson M, Holcombe L. 2014. Integration of a limit-equilibrium model into a landslide early warning system. *Landslides*. 11(5):859–875. doi:10.1007/s10346-013-0416-2.	Thomas MA, Mirus BB, Collins BD, Lu N, Godt JW. 2017. Variability in soil-water retention properties and implications for physics-based simulation of landslide early warning criteria [abstract]. In: *2017 GSA Annual Meeting*; 2017 Oct 22–25; Seattle, WA. Boulder (CO): Geological Society of America. Paper 216-2. doi:10.1130/abs/2017am-297875.	United Nations Development Programme. 2018. Five approaches to build functional early warning systems. Istanbul (TR): United Nations Development Programme. 66 p.	Valenzuela P, Zêzere JL, Domínguez-Cuesta MJ, Mora García MA. 2019. Empirical rainfall thresholds for the triggering of landslides in Asturias (NW Spain). *Landslides*. 16(7):1285–1300. doi:10.1007/s10346-019-01170-2.
Analysis of Data and Threshold Relationships	"CHASM combines the simulation of saturated and unsaturated hydrological processes to calculate pore-water pressures, which are then incorporated into the computation of slope stability by means of limit-equilibrium analysis." "The CHASM algorithm is automatically run as a web processing service, utilising fixed, predetermined input data, and variable input data including hydrological monitoring data and quantitative rainfall forecasts".	N/A	N/A	For each rain gauge, the best-fit line threshold was calculated through linear regression, considering all the rain and duration conditions that triggered landslides.
Warning Time	"Once pre-defined modelling or monitoring thresholds are exceeded, a web notification service distributes SMS and email messages to relevant experts, who then determine whether to issue an early warning to local and regional stakeholders, as well as providing appropriate action advice."	N/A	N/A	Not specified, but limited amount of rain gauges / detection is a constraining factor in accurate warnings.
Types of Warning	Three warning types: • Green – Uncritical • Yellow – The system is being checked (thresholds breached) • Red – Activation of alarm, plan/information to emergency services.	N/A	N/A	N/A

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